Sustainability - Energy Optimization - Daylight and Solar Gains

Sattrup, Peter Andreas; Beim, Anne

Publication date: 2012

Sustainability - Energy Optimization - Daylight and Solar Gains

PhD dissertation by

Peter Andreas Sattrup

Royal Danish Academy of Fine Arts School of Architecture, Design and Conservation
Institute of Architectural Technology

Supervisor:

Anne Beim
Professor, PhD Royal Danish Academy of Fine Arts School of Architecture

Committee:

Emanuele Naboni (Chair)
Associate Professor, PhD, Royal Danish Academy of Fine Arts School of Architecture

Ali M. Malkawi
Professor, PhD, University of Pennsylvania

Lotte Bjerregaard Jensen
Associate Professor, PhD, Technical University of Denmark
ABSTRACT

This thesis discusses how energy optimization focussed on daylight and solar gains may be qualified as an architectural design method, which does not just increase the energy efficiency of the built environment, but may potentially increase its overall qualities by offering new insights into the complex interrelationships between urban and building design, environmental performance, human needs and behaviour, technology and energy use.

The main hypothesis is that a hierarchy of scales related to energy optimization and environmental performance may be used to guide and support architectural design decisions in the earliest design stages. The hypothesis is examined through literature studies, empirical observations, interviews with practitioners, a series of simulation studies focussed on energy optimization, solar gains and daylight, and a final case study applying derived design principles in an architectural design competition.

The aims are:
1) To situate energy optimization and environmental performance as qualitative architectural design issues which should also be understood in quantitative terms, by discussing these in a wider cultural and social context of sustainability.

2) To investigate the impact of basic urban and building design decisions on energy use and environmental performance in Northern Europe, using the central city districts of Copenhagen as references.

3) To combine the insights gained into a theoretical framework, relating the various aspects of energy optimization focussed on daylight and solar gains into a coherent methodology.

The thesis demonstrates that not just one, but several functional and cultural hierarchies of scales can be found from practical and theoretical studies and combined into a coherent theoretical framework. It confirms that the most basic architectural design
decisions – urban density and pattern, building form and material choice, window to wall ratio, colour and insulation properties of facades, have great impacts on energy use and environmental performance, which is described with more detail and greater precision than previous studies, by adding climate based daylight analysis to thermal and energy simulations.

Design issues related to urban density receives particular attention as the bottom level of a hierarchy of scales, in addition to addressing the trend of increased urbanization and urban densification which is seen internationally as well as in Denmark. It is found that an optimal range of urban densities can be defined balancing building energy efficiency with access to sun and daylight depending on regional climate. In Northern Europe this density can be described as plot ratios between 100 - 300%. But great environmental performance differences among building typologies within this range indicates that there is plenty of design opportunity to improve environmental performance of buildings by working with urban design, building form and orientation and the geometry and properties of the building skin.

It is argued that it is more important to see energy optimization as a creative opportunity to create better, diverse and stimulating environments using urban and building design as the key instruments, rather than focussing on narrow optimization of technical sub-systems. The results demonstrate that daylight and solar access is more dependent on urban scale design decisions than energy use, and should therefore be considered primary design objectives in the very beginning of the design process in the context of Northern Europe.
Phase 3 – Qualitative discussion / 2nd stage theory generation ......................... 67
Paradigmatic shifts ........................................................................................................ 67
CHAPTER 3: Theory .............................................................................................................. 73
THEORY ............................................................................................................................. 75
Operational and Embodied Energy ................................................................................ 75
Hierarchies of Scale: Energy and performance optimization in practice .................. 77
Shearing Layers – Durability and Adaptability .............................................................. 80
Comfort and Delight .......................................................................................................... 82
Design Methods ................................................................................................................ 86
Passive/Active – Selective/Adaptive ............................................................................... 89
Adaptive Design ............................................................................................................... 90
Methodological Framework ............................................................................................ 92
Danish architectural research context .......................................................................... 95
Danish energy performance research .......................................................................... 97
Initial interests and assumptions .................................................................................. 101
CHAPTER 4: Observations ................................................................................................. 103
COPENHAGEN – Thermal and daylight studies ......................................................... 105
Winter, January 2009 ...................................................................................................... 109
The Medieval City .......................................................................................................... 109
The greenhouse effect in action .................................................................................... 110
The Atrium ...................................................................................................................... 111
Modernist urban space .................................................................................................. 112
Urban life, Comfort ....................................................................................................... 113
Our House – in the middle of our street ...................................................................... 114
Spring and early summer, April - June 2009 ............................................................... 117
Sunspot ............................................................................................................................ 117
Curved Canyon ................................................................................................................ 119
Terraced House ............................................................................................................. 122
CHAPTER 5: Practice ........................................................................................................... 125
Approach ........................................................................................................................ 127
Interviewee profiles ....................................................................................................... 129
DESIGN PHILOSOPHY AND SUSTAINABILITY ............................................................. 131
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Results and Discussion</td>
<td>217</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>221</td>
</tr>
<tr>
<td>PAPERS</td>
<td>233</td>
</tr>
<tr>
<td>PAPER I: Urban Canyon</td>
<td>235</td>
</tr>
<tr>
<td>PAPER II: Typologies</td>
<td>247</td>
</tr>
<tr>
<td>PAPER III: Methodology</td>
<td>271</td>
</tr>
<tr>
<td>PAPER IV: Urban Daylighting</td>
<td>283</td>
</tr>
<tr>
<td>PAPER VI: Architectural Research Paradigms</td>
<td>309</td>
</tr>
<tr>
<td>PAPER VII: Material Evidence</td>
<td>329</td>
</tr>
<tr>
<td>PAPER VIII: Can Architects Change the Weather?</td>
<td>335</td>
</tr>
<tr>
<td>Exhibition: Green Architecture for the Future</td>
<td>345</td>
</tr>
<tr>
<td>LIST OF PUBLICATIONS</td>
<td>349</td>
</tr>
<tr>
<td>PROFILE</td>
<td>352</td>
</tr>
</tbody>
</table>
This dissertation seeks to create an approach to energy optimization focussed on balancing daylight and solar gains as strategies in sustainable architectural design which is qualitative but supported by empirical observations and quantitative analysis.

It is demonstrated that several functional and cultural hierarchies of scale may be integrated into a methodological framework for architectural design, which may support decision making, particularly in the beginning of the design process, and serve the necessary integration of knowledge among architects and engineers.

The aim is to contribute to the continued relevance and development of the discipline of architecture, by pointing out the great impact and responsibility architectural design has on the quality of our daily environments, right from the very moment a design begins to take shape.
ACKNOWLEDGEMENTS

I wish to thank the many people who have in many ways supported my work as a PhD student, in particular my supervisor professor Anne Beim for all her guidance and my colleagues at the Royal Danish Academy of Fine Arts for interesting discussions. I am very grateful that the Academy gave me the fantastic opportunity to embark on a voyage of discovery as this research process has been. Special thanks also go to Jakob Strømann-Andersen, my partner in crime on the simulation studies, and Signe Kongebro at Henning Larsen Architects for promoting collaboration. I hope my early pitch of research results and design ideas has made it worthwhile, and notice with quite a bit of satisfaction that they have been integrated into design practice. Kjeld Kjeldsen and Mette-Marie Kallehauge opened many doors to me and this research project by inviting me to participate in the curation of the exhibition ‘Green Architecture for the Future’ at the Louisiana Museum of Modern Art, which I greatly appreciate. I owe my interview victims Dietmar Eberle, Mathias Schuler, Stefan Behling, Gerard Evenden, Irene Gallou and Bruno Moser and many others thanks for the invaluable information they supplied. I also need to thank Jens Hvass and Thomas Dresler for the opportunity to experiment with their thermal cameras.

The support of my family has been invaluable to me, and I want to thank my parents, my children Adam and Rebecca and especially my wife Naomi for their love and patience.
OVERVIEW

Chapter 1: Introduction - gives a short account of the background of the research and professional experiences and motivations that informed the beginnings of this research project, exemplified by the case of the transformation of Radiohuset.

Chapter 2: Research Process & Methods – explains the research approach and methods. As the research applies both architectural and engineering research methods and has evolved partly on the basis of cross-disciplinary collaboration, the paradigmatic differences are explained.

Chapter 3: Theory - A review of research in the field is presented in order to explain the point of departure and some particular traits of the research tradition within which this project is situated. A theoretical framework for energy optimization in architectural design is elaborated which situates energy optimization in the context of sustainability and architectural theory.

Chapter 4: Observations – is a series of observation studies using thermograms, photography and note making as methods to describe environmental phenomena spatially in the geographic context of Copenhagen. The studies inform a discussion of life-quality aspects of environmental performance in urban and building design related to daily and seasonal changes in daylight availability and solar access.

Chapter 5: Practice – examines the state of the art of energy optimization and the use of simulation in contemporary architectural practice based on interviews with leading international practitioners.

Chapter 6: Simulation Modelling Studies – introduces and summarizes the main findings of parametric modelling studies which use simulations to examine the impact of basic design decisions on buildings’ energy use and environmental performance. The studies have been published or are submitted for publication in research papers which are appended to the dissertation.
Chapter 7: Return to Practice – is a case study of a design process in which the research results were informing a competition project directly, discussing how the results of this study can inform architectural practice, and how they may be elaborated further in future research.

Chapter 8: Conclusions and Discussion – offers a brief summary of the most important findings and a discussion of their implications on future architectural design and research.
PAPERS:

The papers are grouped according to themes: Papers I – V are related to the simulation studies, and offer additional elaboration of the general themes summarized in chapter 6: Simulation Modelling, including more research background references, more detailed results and an elaborated discussion of their implications. Papers VI and VII are research papers delving deeper into the discussion of methods and research paradigms in architecture, while paper VIII is an essay that offers a general introduction to some of the recurring themes in this dissertation.

Paper I: Urban Canyon – is a paper published in Energy and Buildings, which examines the impact of the urban canyon – the space between buildings – on building energy use in the context of Northern Europe with Copenhagen as a case. Daylight reflection in the urban canyon emerges as a hitherto underestimated phenomenon.

Paper II: Typologies – is a paper accepted for publication in Journal of Architectural and Planning Research in which traditional and new building typologies, understood as urban patterns, are tested for daylight, solar access and energy performance.

Paper III: Methodology – is a paper published in the proceedings of SimAUD 2011. The paper describes a framework for daylight and energy simulation in the early design stages, and exemplifies its use in simulation studies.


**Paper VI: Architectural Research Paradigms** – a research paper presented at the symposium: When Architects Write/Draw/Build a PhD in 2011, discussing the multiple paradigmatic contexts of architectural research, offering the simulation modelling studies in this dissertation as an example of a cross-disciplinary collaborative effort that may expand the boundaries of architectural research.

**Paper VII: Material Evidence** - is a short paper on some of the more philosophical aspects of working with simulations as ‘evidence’ in architectural research.

**Paper VIII: Can Architects Change the Weather** is an essay commissioned by Daylight and Architecture on urban climates, that offers a general introduction to some of the recurring themes in this dissertation.

**Exhibition: Green Architecture for the Future** is a description of an exhibition at the Louisiana Museum of Modern Art in 2009, which I participated in curating as a consultant, and in which the thermographic studies in Chapter 4 were exhibited.
CHAPTER 1: Introduction
INTRODUCTION

As it is now widely recognized that the world is facing not one but several crises, where economic, environmental and social issues are entangled in conflicts over resources and environmental degradation, it becomes increasingly important for architects to navigate the consequences of architectural design choices in terms of sustainability and long term impacts. This is a very complex issue, as architecture as a design and research discipline integrates knowledge from virtually any field, be it the social and natural sciences, philosophy and the arts.

Bridging the gaps between diverse traditions of knowledge is difficult but necessary in architecture, and there is always a risk of applying methods developed in other fields in ways that would be perceived as superficial in the discipline in which they were developed. This dilemma was acknowledged by Vitruvius who stated that architects should be educated with knowledge of many disciplines, which the architect should master at a sufficient level so as to judge and integrate the work of other disciplines in architectural syntheses.¹

Architecture’s special kind of knowledge is a knowledge of making - in Greek it can be described in the two words techne and logia – which are fused in the modern word technology.² Architecture is technology in the wide sense of the word as knowledge of making. As Vitruvius explains, this knowledge is achieved through practice and theory, which must continually inform each other,³ and considering how ancient this general insight is, it seems a bit ironic that only in the last few decades has modern design theory elaborated this feedback loop in the lineage of theory by Rittel and Webber,

³ Vitruvius, bk. I: §1–3.
Schön, Buchanan and Nonaka among others. Architectural design may refer to the artefact of architecture, but may also refer to the discipline of conceptualizing and creating knowledge through design. Buildings and designs can also be understood as devices that serve technical purposes, as technology in a more narrow sense of the word, which integrates a wide range of other technologies in the processes of fabrication and to achieve the desired performance of the design. Much of the knowledge of making inherent in the discipline of architecture can be considered tacit knowledge, which is practical knowledge which may be made explicit theoretical knowledge, but which may also resist explicitation. Both tacit practical knowledge and explicit theoretical knowledge should inform each other in architectural research.

In this dissertation, technical issues of sustainability and energy optimization focussing on daylight and solar gains are discussed in a wider cultural context, through observational studies of phenomena of daylight and sun, literature studies and theorizing the practice of energy optimization, through interviews with practitioners and by producing a set of simulation studies giving first-hand practical experience with simulation for energy and environmental performance optimization. Copenhagen is used as a reference for a wider context of Northern Europe. The technical aspects of quantitative simulations based analysis are framed by an overall qualitative research strategy.

This chapter outlines the background of the study. As qualitative research strategies acknowledge the prior knowledge of the researcher and his or her active participation and involvement with the subject of research, some emphasis is given to the

---


assumptions which are brought into the research at the beginning of the research process.

BACKGROUND

Sustainability and Energy

“Sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future.”

“In essence, sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development; and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations.”

When the World Commission on Environment and Development (WCED) coined the term sustainable development in 1987, climate change was but one among many issues that were identified as potential risks to Earth’s environment and the future development of human societies. Since the release of Our Common Future in 1987 scientific evidence of global warming has been gathered from multiple research disciplines by the Intergovernmental Panel on Climate Change, and it is increasingly accepted that the development of Earth’s Climate requires deep societal changes and a shift from fossil fuels to renewable energy sources.

---


It does not make much sense to draw a sharp distinction between natural or artificial environments any more. Geologists declare that we have now entered the ‘Athroposcene’ - a new geological age, recognizing that the scale of the accumulated effects of man’s activity on the surface of the earth and its atmosphere are now so great that it is comparable with the scales of change that nature would take ages to produce.\textsuperscript{10} What is natural and what is artificial is rather a question of the relative influence of human activities on the environments we inhabit, and whether we conceive of these in the macro, meso or micro scale relative to our own bodies. The spaces we live in, our homes and workplaces and even regional weather systems such as the urban heat island phenomenon\textsuperscript{11} created by cities are all partially man-made, in the sense that every urban space and building creates and modifies the climate surrounding it and within it.\textsuperscript{12} The climate is both directly and indirectly affected by architects through planning and building design.

With the last decade’s political debate of whether climate change is real or not in mind,\textsuperscript{13} it may seem a surprise that global warming is old news. The effect of carbon dioxide levels on atmospheric warming was identified in 1896 by the chemist Svante Arrhenius who linked it specifically to human activities, in particular burning coal to fuel the processes of industrialization.\textsuperscript{14} It took close to a hundred years to accumulate sufficient

\textsuperscript{10} The extent of man made changes to the global natural environment has become so great as to merit a new geological era being introduced: the Anthropocene. Paul J. Crutzen, ‘Geology of Mankind’, Nature, 415 (2002), 23 (p. 23).
acceptance of this theory before it had any codified impact on international policy making, possibly because the full implications of weaning off industrialized societies of the fossil fuel use requires a difficult period of transition. So why is it so difficult to change? Sustainability and climate change are issues entangled in political, social and psychological questions of power and perceptions, which makes them extremely difficult to deal with. They are so called ‘Super-wicked problems’ – problems that are not only difficult to analyse and solve, but whose internal logics resist their solution. In this dissertation climate change is accepted as a fact, which is based on understandable physics and observed evidence. We do not yet fully understand the finer aspects of causes and mechanisms, and future research will certainly adjust the way we understand it today, but there is no reason to reject the idea of man made climate change.

Energy, Power and Desire

One may speak of energy in terms of economy or efficiency as is usually the case, but the most important aspect of energy is its association with quality of life. As Ralph Knowles puts it: “The purpose of energy conversion is the improvement in the quality of life.” Energy is associated with everything we desire: Freedom to move, ability to grow, virtually every amenity and service in our surroundings are built on the cheap availability of fossil fuels. Every moment of our life is saturated with energy processes, in our bodies, in our environment. The energy needed to sustain the metabolic processes of the human organism, basically converting food to human life and activity, is a tiny fraction of the total energy a citizen of the developed countries use for industrial products and processes, transport, building, maintaining and operating the cities and buildings and information exchanges etc. Differences in average total energy

---


16 A similar realization occurred around midway in the research process as a result of analysing the first simulation modelling studies, but was in fact realized much earlier by Ralph Knowles. R. L. Knowles, Sun, Rhythm, Form, New edn (MIT Press, 1985), p. x.
consumption per capita between developing and developed countries may exceed a factor of 1:300.17 With the increase in the world's population, the processes of urbanization and the general increase in life expectancy and consumption levels globally, the Earth's carrying capacity is called into question. It is argued that the rate with which humanity consumes resources exceeds the Earth's capacity to regenerate them, with resource depletion as a possible if not likely result.18 Conflicts over the access to resources have always played a major role in political history, and it is not likely to be different in the future. Energy has a vital security aspect too, as reflected in the experience of the oil crises of the 70'ies and contemporary politics.

Energy pervades all of life's processes from basic metabolic activity to the advanced activities of industrial and information societies. But we will have to be more intelligent in the ways we go about the use of energy, so we can reduce demand by optimizing technology, changing habits in order to eventually being able to rely on renewable energy. The construction, maintenance and operational processes of the built environment constitute a major share of the total energy use in industrialized societies. Understanding the dynamics of these relations is crucial to architects, but remains a relatively underdeveloped field in practice as in architectural theory.

Energy, Environment and Architecture

Energy - as light, heat, movement or processes of production of materials and construction of buildings have been recurrent themes in architectural theory since Vitruvius, who describes how to shape buildings according to climatic considerations, and how the temporal aspects of the climate, the rhythms of the day and of the seasons may shape and assist the daily rituals of life in buildings.19 But the reciprocity of climate,

---


architecture and human life shaping each other requires neither architects nor architectural theory. They seem to evolve naturally from and with each other, as is well documented in the vernacular building traditions highlighted by Rudofsky.\textsuperscript{20} And the traditional, intricate connection between human physiological necessities, an economy of means, locally available materials, cultural values and the local climatic conditions of the site has often been forwarded as a model of sustainable architecture.

It seems as these fundamentals in architecture’s relation to the land, to the climate and to the bodily and spiritual needs of its inhabitants have been forgotten in the now closing era of cheap fossil fuels. In the post war period, two types of buildings have become prevalent archetypes: The glass-box office building in the city and the single family home of the expanding periphery. These building types are problematic in terms of energy use in at least two dimensions: They both assume a segregated model of living and working in disparate monofunctional districts of the city, resulting in long distance commuting and very high energy use for transportation. They both tend to ignore the finer aspects of their environmental context, relying on energy use to maintain comfortable inside conditions, instead of centering the building design on environmental performance. The degree of influence modernist ideals of planning and architecture - the CIAM charter, Le Corbusier’s Ville Radieuse and Wright’s Broadacre City, the ‘International style’ and Mies van der Rohe’s glass architecture\textsuperscript{21} – had on this development may be discussed, but is a discussion not elaborated here. The high rise office building is an effective way to increase the value of a given plot of land by multiplying its area upwards, packing it with the maximum number of office workers environmental and safety controls would allow. The single family home is in its own right an attractive alternative to the crammed conditions of historical cities, offering air, light and a piece of nature represented in the garden. It is possible that technological advances in transportation, building and service technology made these urban and building designs feasible, and modernist architects did actively promote these building

\textsuperscript{20} Bernard Rudofsky, \textit{Architecture Without Architects: A Short Introduction to Non-Pedigreed Architecture} (University of New Mexico Press, 1987).

types in various ways, with little understanding of their long-term implications on sustainability, which was of course not conceptualized then.

Reyner Banham, one of the first modern writers to give environmental technology a prominent position in architectural theory notes in *Architecture of the Well-tempered Environment*, that the environmental aspects of architecture have been subdued in favour of visual aesthetics. With industrialization ‘s introduction of increasingly sophisticated climatization services and new professions minding them - mechanical engineers and plumbers – architects detach themselves from the dirty business of service technology and building’s environmental performance. Not only are environmental matters and technologies overlooked in much architectural thinking, Banham polemizises, they are actively disregarded and the subject of disdain: “Never mind all that environmental rubbish, get on with your architecture.”

This critique is echoed by more contemporary theorists such as phenomenologists Frampton, calling for an architecture which is informed by the regional environment, and Pallasmaa, critizing the ‘ocular-centrism’ of contemporary architecture. Pallasmaa calls for an architecture that cares for physical sensation involving all the senses of the body, not just vision. In fact this interest in sensation is shared in architectural phenomenology, environmental technology and climate engineering, albeit with very different motivations and value systems. However justified Banham’s critique may be of developments in the architectural mainstream, it would be pretentious to say architects just mind the visual aesthetics and ignore environmental performance. Le Corbusier and Wright – despite the failures of their urban planning visions ‘Ville Radieuse’ and ‘Broadacre City’ – both worked consistently with environment and technology. ‘Solar’ Corbusier and ‘Igneous’ Wright, Fernandez-Galiano calls them in respect of the interest in solar geometry, light and heat displayed in Le Corbusiers work, and the interest in

---


climatization technology, air-conditioning, heating and cooling in Wright’s Architecture. A strong pattern of environmental concerns underlies distinct lineages of thought in modern architecture, but has from time to time been subdued in the attention of the architectural mainstream. Later generations of modern architects such as Utzon and Murcutt have worked extensively with reconciling architecture and environment, and interests in ecology, resources and energy spawned architectural environmental theory classics such as Knowles’s *Sun, Rhythm, Form* outlining principles for solar architecture and planning, Stewart Brand’s *How Buildings Learn* introducing the ecological principles of Shearing Layers to Architecture and Lisa Heschong’s philosophical *Thermal Delight in Architecture* describing the rituals and speculating on the meanings of the interactions between humans, architecture and the environment.

**BEGINNINGS**

Environmental and climatic concerns have deeply affected Danish architectural design thinking, from its vernacular beginnings to the present. Steen Eiler Rasmussen in his classic ‘*Experiencing Architecture*’ bases his theory of architectural experience on the human body’s sensation and perception of environmental stimuli as mediated and articulated through architectural form, and the attention to climatic phenomena, particularly daylight, as an architectural quality a source of aesthetic delight and a driver for architectural form can easily be identified in the work of prominent Danish Architects, such as Vilhelm Lauritzen, Jørn Utzon, Henning Larsen and Lundgaard & Tranberg – to name just a few.

---

24 Fernandez-Galiano.
25 Knowles.
29 His book may be considered one of the founding theoretical works in what has later emerged as architectural phenomenology. Steen Eiler Rasmussen, *Experiencing Architecture* (Cambridge, MA: MIT, 1959).
In the education of architects in Denmark climatic concerns have their own particular spot mostly based on an experiential, intuitive approach to integrating environmental phenomena rather than a rationalistic, physics- or calculations-based approach, and a body of literature exists which identifies how climatic and environmental concerns may be turned into diverse design strategies, as for instance in Sørensen and Larsen’s ‘RENARCH’\(^{30}\) Beim, Larsen and Mossin’s ‘Økologi og arkitektonisk kvalitet’,\(^{31}\) and Dahl’s ‘Architecture and Climate’\(^{32}\). Environmental and climatic concerns are main themes in what may be identified as a regional identity or tradition in Danish architecture,\(^{33}\) and it is hardly coincidental that Kenneth Frampton used the work of Utzon as a prime example of ‘critical regionalism’ which he championed, as part of a renewed attention to architectural phenomenology.\(^{34}\) But while these intuitively elaborated-upon concerns may certainly enhance design qualities, the relative absence of quantitative analytic methods in design methods may be a weakness, when evaluating and trying to understand in greater detail how designs perform – which is supplementary and intricately connected to the experiential qualities they offer.

The attention to climatic and environmental concerns seemed to have been quite subdued in the frenzy of construction activity that marked the first years of the millennium, when the access to cheap loans fuelled a widely speculatively driven building boom. At the time, 3 years previous to the explosion in media attention towards anything sustainable leading up the 2009 United Nations COP15 summit in Copenhagen, sustainability and energy optimization had only quite rarely been developed as explicit, central themes in Danish architecture since the beginning of the

---

\(^{30}\) Peter Sørensen and Lena Larsen, *Renarch · Ressourceansvarlige Huse* (Copenhagen: Royal Danish Academy of Fine Arts School of Architecture, 2006).

\(^{31}\) Anne Beim, Lena Larsen and Natalie Mossin, *Økologi Og Arkitektonisk Kvalitet* (København: Arkitektskolens Forlag, 2002).

\(^{32}\) Torben Dahl, *Climate and Architecture*, 1st edn (Routledge, 2009).

\(^{33}\) How to identify regional identities and tradition in a dynamic field such as architecture which is very open to external influences is always an issue for debate, but this will not be pursued here.

\(^{34}\) Frampton, pp. 16–30.
As the 90’ies were a strong period for innovative environmental thinking in Danish architecture, it is thought provoking that in the 00’ies, Danish architects and their public and private clients were mostly content with satisficing the requirements of the Danish building code which, while strict as compared to other codes, did not require anything near a passivhaus standard of building energy use. At the same time ecological principles and low-energy architecture received strong attention particularly in German speaking countries and Green Building certification systems like BREEAM and LEED were beginning to penetrate the property markets in the English-speaking parts of the world. While an estimated 8000 buildings had been constructed to Passivhaus standards in Germany, Switzerland and Austria, none had been built to similar performance standards in Denmark until 2008. Denmark had in the meantime experienced the biggest and longest lasting building boom in history, and polemically stated all these new buildings were arguably technically obsolete if compared by their energy performance to the Passivhaus standard.

---

35 This development was most likely due to the change in government in 2001 which disregarded the previous government’s investments in green energy technologies and research. PM Fogh Rasmussen even acknowledged having committed an error disregarding climate change and cutting back on investments in green technology and research introduced by former minister of the Environment Auken. Christian Lehmann, ‘For Fogh Er Fremtiden Grøn | Information.dk’, 2008 [http://www.information.dk/172071] [accessed 17 February 2011]; Svend Auken, ‘Syv Spildte År Med Fogh - Politiken.dk’, 2009 [http://politiken.dk/debat/kroniker/EC692268/syv-spildte-aar-med-fogh/] [accessed 17 February 2011].


38 This argument is wholly quantitative and does not enter a discussion of the passivhaus concept and its implications for architecture’s environmental qualities as compared to other concepts for low energy architecture. Erhvervs- og Byggestyrelsen, ‘8.4.2 Energrammen for Boliger - BR05’, 2005 [http://www.ebst.dk/bygningsreglementet.dk/br95_10_id163/0/42] [accessed 1 August 2011]; Erhvervs- og Byggestyrelsen, ‘8.4.3 Energramme for Andre Bygninger - BR05’, 2005 [http://www.ebst.dk/bygningsreglementet.dk/br95_10_id164/0/42] [accessed 1 August 2011].
In the absence of green building certification systems and low energy standards it would however be misleading to think that Danish architecture would not perform well in terms of sustainability. Rather than having explicit assessment systems, the issues of economic, environmental and social sustainability are internalized aspects of a design culture and have in many ways been understood as ‘common sense’ design decisions. Sustainable architectural design has widely been tacit knowledge – knowledge which is inherent in the ways things are done, but which is not theoretically explicit.\textsuperscript{39}

The intuitions gained from practical experience in a single specific project may come very close to the generally applicable insights gained through research. As the theorist of knowledge management Nonaka has pointed out,\textsuperscript{40} knowledge is created through continuous movements of information allowing knowledge to change state from tacit to explicit – and from explicit to tacit as when newly developed explicit knowledge gives rise to new modes of working practically. In terms of Nonaka’s SECI model,\textsuperscript{41} intuitions from practice can be understood as tacit knowledge which can become formalized and made explicit through knowledge exchanges with others who have different professional and disciplinary approaches.

In the following a professional experience which has informed the research process considerably is discussed, in order to offer an insight into the initial assumptions and the prior knowledge which was brought to bear on the research process, and as an example of how sustainable design capabilities may very well reside as tacit knowledge.

\textbf{Professional experience – transforming an iconic building}

Working as a project architect with Vilhelm Lauritzen Arkitekter, a project for the transformation of The Danish Broadcasting Corporation’s former headquarters, the 1938-1945 iconic ‘Radiohuset’ by Vilhelm Lauritzen (1894-1984) offered some fundamental insights into using culturally and functionally based decision hierarchies as

\textsuperscript{39} Vitruvius, bk. I: The Education of Architects.
\textsuperscript{40} Nonaka, 14–37.
\textsuperscript{41} Nonaka, 14–37.
design strategies for resource management, cross disciplinary collaboration on environmental performance optimization and the use of digital environmental simulation modelling as compared to full scale mock-ups tested through user interaction.

As one of the masterpieces of the modern movement in Denmark Radiohuset was originally tailor made for the purpose of journalism and music recording. In 2006 a process of transformation began, that would allow the building to house the Royal Danish Academy of Music (DKDM). Given the extraordinary status of the building, the question of cultural heritage values was important to address very precisely, as the change of programme would necessarily result in contradictions and conflicts with the architecture of the existing building.42 The building programme made little mention of sustainability or energy optimization. Nevertheless, the issues that had to be tackled, and the way they were addressed, were at the heart of both the sustainability agenda and energy optimization, when seen in retrospect.

Radiohuset (1936-45). Vilhelm Lauritzen’s modernist icon.

Design methods: cultural and functional hierarchical value systems

In the design process for the transformation of Radiohuset, a critical method developed was to identify cultural and functional hierarchical value systems to use as guides. A cultural hierarchy would for instance identify the inherent cultural value of a given space through its degree of preservation of the original design or its representational value which would be expressed in the architectural detailing of the interior surfaces. A functional hierarchy would clarify the structural and functional dependencies between different architectural scales that would govern the freedom to design for the new programme for the building.

DKDM I Radiohuset (competition entry 2006, Vilhelm Lauritzen Arkitekter): Functional hierarchy - Building structure and service system. Adhering to the original functional hierarchy offered both a pragmatic ‘path of least resistance’ in terms of construction and a way to creatively reinterpret the architecture while remaining true to its compositional principles.

With these hierarchies established it was possible to integrate the complex technical issues in a poetic architectural vision that saw the building transformation as a reinterpretation of the original composition, not unlike the way classical musicians interpret an original score.
Since the building was protected, every change had to be argued carefully against preservation values. To do so, two value hierarchies were established: one was based on the cultural values of the building’s spaces, the other and equally important, was the functional aspects of the building which were based on an analysis of the limitations posed by the load-bearing structure and service duct systems, and the relatively higher freedom we had in adjusting secondary walls, finishing surfaces and furniture. While this exercise was seen strictly in the light of architecture and economy, it was decided to remain true to the original composition of the building, which meant reinterpreting its functionalist idiom with a minimum of intervention - this meant analysing the building’s layers of durability and adaptability. As the budget was so limited it was neccessary to prioritize which aspects of the programme would be fully resolved, forcing the design team to think of the programme in terms of future scenarios, designing for possibilities of interventions ‘on top’ of the basic functionalities that were provided.

DKDM I Radiohuset (VLA 2006): Brand’s shearing layers: Structure, Services and Spaceplan can easily be identified in the construction sequence – though the concept was not known to the design team. Photos: Jens Lindhe.

This dual approach of working with the cultural values and the different degrees of permanence and adaptability to future changes of the building, comes very close to what Stewart Brand explains theoretically in his seminal book How Buildings Learn. The shearing layers theory, originally conceived in ecology studies and applied to architecture by Brand and Duffy, has proved instrumental in studies on buildings’ life cycles and embodied energy. But what Brand highlights, is that understanding both the cultural

43 Brand.
values and the functional hierarchy imposed by the different speeds of change of the building’s layers is necessary in order to minimize the resource use in construction.

The experienced gained from the Radiohuset project shows that the shearing layers theory is not just descriptive or explanatory theory, passively describing causes and relations. It shows that the shearing layers may be used actively to guide design decision by offering a simple but qualified decision hierarchy.

**Understanding and designing for performance – a cross-disciplinary effort**

Energy optimization was not in focus, but environmental performance was a key issue. Acoustics was the primary concern, given the program, and the main design driver behind the shape and materiality of the interventions proposed. But in reality the need for climate control informed the project deeply on all aspects of comfort. The Academy of Music educates the next generation of classical musicians, - people who are extremely aware of their bodies, their health and the atmosphere and response of the spaces that surround and influence their musical performances. Fine tuning these rooms to the very specific performance criteria of the users proved to be a difficult but valuable experience involving digital simulation modelling and full scale mock-ups, that were thoroughly tested and evaluated by the users, and eventually adjusted according to their wishes. Being able to adjust the indoor environment of those rooms according to their sensations, perceptions and needs, required the design team to design the rooms to specific quantitative performance criteria, and more importantly, to provide ample opportunities for the users to change, manipulate and control these for their own needs and purposes, in ways that were intuitive and easy to use. Quite possibly the process of user involvement in assessing the performance of the design contributed to improved acceptance of the design solutions and increased user satisfaction with the built results, though this has not been documented thoroughly.
These design considerations were, again seen in retrospect, an example of an adaptive comfort approach to indoor climate, in which the design provides the occupant plenty of adaptive opportunities to adjust the indoor climate according to his or her preferences, which in turn has the effect the occupant have better tolerance of a wider range of indoor climatic conditions and thus less need for the use of energy to condition the indoor climate. Integrating these comfort criteria in architectural and engineering solutions that adhered to the analysis of layers, required an intense flow of information among the participants in the design team. It was crucial to the success of the design that it evolved as a multidisciplinary effort, involving the services and structural engineers from day one, before anyone sketched anything. Visualizations, which included digital acoustics modelling animations and sketches drawn by hand of other environmental phenomena, were an important aid in transferring knowledge within the team.

**Digital modelling**

Ideas would be tested using acoustic simulation software, and the visualizations that were provided offered the team a shared understanding of some of the crucial aspects of how working with form and materials affected acoustic performance. Animations of sound dispersal allowed the design team to grasp the movement of sound intuitively. However, the aspects of sound that could be modelled digitally were quite limited.
compared to the experienced reality in the mock-ups, and it would be necessary to modify the design considerably due to the influence of the users, a point which also highlights that the feedback offered by digital environmental simulation concerns only a fraction of reality, and is limited by the capacity of computation at any given time. The promising aspect was that the simulation studies provided an opportunity to learn about the way the design would perform before anything was built.

The project was also chosen to serve as a pilot project for Building Information Modelling (BIM) a year before it was made statutory by the Danish authorities. A model was developed, but proved very cumbersome to work with, given the complexities of the existing building, and the lack of experience with BIM. It nevertheless showed considerable promise as an integrative tool, and since it was continually necessary to calculate the economy of design proposals for approval, the feasibility of linking design geometry to a database of construction types, including material properties and prices was evident.

DKDM I Radiohuset: Acoustics simulation (Alectia 2006) and building information modelling (VLA 2006).

The experience gained from the transformation of Radiohuset had great influence on the course taken in the research process, but the insights gained could only be more precisely formulated – made explicit – in the wider context of sustainability with the additional knowledge created through this research project, gained from many sources using diverse methods of inquiry.
Each theme – decision making hierarchies related to architectural scales, permanence and adaptability, environmental performance, cross disciplinary collaboration, simulation modelling and user interaction and adaptability have become important themes in this dissertation.
CHAPTER 2: Research Process and Methods
This chapter explains the research process and methods of this dissertation, and the changes that the epistemological and ontological assumptions behind it went through during the research process.

This is a Combined Methods study combining an overall Qualitative Research strategy based on Grounded Theory with simulation Modelling tactics. Since qualitative research and simulation modelling are typically associated with different research paradigms which have different systems of research assessment, the ontological and epistemological assumptions of these paradigms are presented, and the paradigms’ influences on different aspects of the research process are discussed. Groat and Wang’s Architectural Research Methods is used and discussed critically as a main reference to explain the project’s research methods, as it offers a comprehensive view of the diversity of research methods that may be used in architectural research, and their relations to traditional and emerging paradigms of research.

The role of design in the research process is discussed introducing Nonaka’s theory of knowledge creation to architectural research. Discussing how knowledge was converted from tacit knowledge to explicit knowledge and vice versa in the course of the research process, it is argued that design theory and practice are supplementary, overlapping and inseparable and continue to inform each other in processes of knowledge creation.

---


46 While it may arguably be somewhat limiting to use ‘Architectural Research Methods’ as a main reference, it is chosen as it has a unique position as a methodological guide which goes beyond individual methods and inquires into the underlying research paradigms. This is particularly valuable to a multi-method study such as this, and Groat and Wangs notions on research are consequently discussed critically in this chapter.

47 Nonaka, 14–37.

48 The term ‘tacit knowledge’ was originally introduced by Michael Polanyi to describe knowledge that is difficult or even impossible to explain verbally as it is bound in bodily or practical experience. “We can know more than we can tell” Polanyi, pp. 1–24.
At the end of the chapter the paradigmatic shifts that happened during the research process is mapped using a matrix of three different paradigmatic positions.

**Research Approach**

At the onset of the research process, information which seemed to have the potential to be grafted into a coherent theoretical framework for energy optimization focused on daylight and solar gains was gathered from literature and practitioners. It was deemed important that the research should strike a balance between theory and practice, so that the theoretical contributions achieved would offer insights that would be applicable directly and immediately into current architectural design practice, and offer a clearer understanding of principles, better procedures of design and new information to base future designs on. The intent would not only be to develop new theory, but also to develop new graphical work that would summarize and communicate the theories developed both diagrammatically and illustratively.

The overall research approach has been to develop a qualitative study which frames, informs and discusses a number of quantitative simulation studies. Initially the focus was mainly concentrated on understanding the physics and technology behind environmental simulation modelling and energy optimization as such – which would be somewhat of an effort to me, being educated in the beaux-arts tradition of my home institution – The Royal Danish Academy of Fine Arts School of Architecture - but it became evident that the quantitative information offered by simulation did not make much sense in architecture unless discussed qualitatively, both when it came to interpret the causes of results as well as their implications to architecture.

**RESEARCH METHODS**

This study is a *combined strategies* study, combining a *qualitative research strategy* with environmental *simulation modelling tactics*. It is an unusual combination insofar as the research methods used in qualitative research and environmental simulation modelling have connotations in the social and natural sciences respectively, and are therefore usually embedded in strong research traditions that employ different
paradigms and most often do not share the same research assessment criteria. While simulation modelling such as producing scale models and mock-ups have traditionally been used in architectural education and practice to make qualitative assessments, the newest generation of digital environmental simulation modelling software used for energy calculations and visualization of climatic phenomena in architecture have mostly been developed and used in engineering until now, which means that the methods applied in environmental simulation modelling are, at the moment, deeply associated with research assessment criteria derived from engineering. Since methods used in some research traditions are sometimes not considered relevant or even valid in others, it is therefore useful to explain the differences, so as to understand the ontological and epistemological implications they have on this research project, and how the project’s aim to bridge this gap between research traditions.

Research Paradigms

Groat and Wang discuss the limitations of traditional dichotomies that divide research into categories of ‘quantitative’ or ‘qualitative’ research, ‘hard’ or ‘soft’ science - or even ‘science’ versus ‘myth’. These dichotomies are, Groat and Wang argue, overly simplistic

49 The validity of knowledge generated in entire fields of research may even be contested by researchers working in other fields, as the clash between proponents of natural and social sciences known as the science wars demonstrated. See eg. Nick Jardine and Marina Frasca-Spada, ‘Splendours and Miseries of the Science Wars’, 1997 <http://www.math.tohoku.ac.jp/~kuroki/Sokal/science_wars.html> [accessed 28 February 2011].

50 I have on occasions experienced a lack of understanding of this mixed-mode approach when discussing methods in fora which were dominated by researchers of either tradition, be they architects or engineers. An example of this could be the peer review process of Paper 1: Urban Canyon, in the Journal Energy and Buildings. Only technical comments were received and one reviewer found that there were too many illustrations, to which was replied: “The number of illustrations have been reduced. However, we find that visualizations, spatial diagrams and drawings play an important role in architectural research equal to that of graphs in engineering, as it is spatial relations that are investigated.” And further: “Looking through the comments, we got the impression that neither of the reviewers are architects or architectural engineers. Since the topic of the paper is integrated energy design – a shared focus area in architecture and engineering – comments from one or both of these fields would have been useful.”

51 Groat and Wang, pp. 21–43.
and unproductive. Instead, one should distinguish between different research paradigms\(^5\) which employ different systems of inquiry. Further, discussing the difference between method and methodology, they argue that it is necessary to distinguish between research tactics and research strategy which may employ combinations of quantitative and qualitative research methods.

Groat and Wang propose a ‘cluster of systems of inquiry’ as an integrative framework for architectural research, drawing on contributions from methodological studies in architecture and the social sciences\(^5\). The cluster integrates knowledge from three main systems of inquiry, which are termed ‘postpositivist’, ‘naturalistic’ and ‘emancipatory’. Each system has different ontological and epistemological assumptions, and employs different criteria in judging research quality and validity:\(^5\)

\(^5\) The notion of scientific paradigms was originally introduced by Kuhn. Thomas S. Kuhn, The Structure of Scientific Revolutions, 24th edn (University of Chicago Press, 1957).
\(^5\) Groat and Wang, p. 32.
\(^5\) Groat and Wang synthesize and simplify discussions on research methodology in the social sciences. Among their sources are Guba and Lincoln who outline five paradigms which they note is an abstraction of several emerging systems of inquiry. The boundaries of paradigms are not clear, as new theories are
Postpositivist – The traditional scientific paradigm, which assumes an objective reality existing independently of the observer. Knowledge should be acquired through ‘dispassionate’ and ‘objective’ observations, in which the researcher interferes as little as possible with the subject.

Naturalistic – Acknowledges that knowledge and reality is constructed socially and multiple realities exist. Rather than believing in objectivity it emphasises that knowledge is reliable when backed by ‘thick’ descriptions giving it credibility and confirmability.

Conclusions are transferable rather than repeatable. Instead of formulating a hypothesis, the aim is rather to describe the complexities of a dilemma.

**Emancipatory** – In emancipatory research the researcher is not objective but an active participant who not only seeks to describe the realities of a dilemma, but actively seeks to change the relations of power surrounding it. The research is critical, even polemical and seeks to change reality.

As architectural research relates to bordering disciplines in which different paradigms are dominant and thus possibly has to integrate very different kinds of knowledge which may come from the natural or social sciences or the arts, it becomes imperative to clarify one’s paradigmatic stance as an architectural researcher. This is important, not only at the individual level, but at the institutional level too, as the assessment of research quality is likely to be judged according to the paradigmatic preferences of the assessors.55

In this research process a paradigmatic position has been maintained that could be termed ‘naturalistic’, but – as environmental simulation modelling has been used in collaboration with an engineer, and results have been published in technical journals – it has verged towards a ‘post positivist’ stance, before finally being influenced by the ‘emancipatory’ paradigm, when discussing the implications of research results. This is reflected in the styles of writing and theorizing which are used in this dissertation: Descriptive theory is used when interpreting data in terms of causes and effects. Normative theory is used when discussing the life quality aspects of energy optimization and environmental performance, which necessarily implies making value judgements. Polemical (however rarely) when discussing the implications of findings in terms of preferability of design options in terms of urban policy making. This is particularly pronounced in the case study found in chapter 8: Return to Practice, where active involvement in a design process, means that the role of the researcher is not neutral, but participatory and actively pursuing a specific agenda.

---

55 Groat and Wang, p. 34.
Strategy and Tactics

Distinguishing between a qualitative research *strategy* and environmental simulation *tactics*\(^{56}\) makes it more clear how the simulation studies that make up a considerable part of the evidence generated by this research, are framed by an overall qualitative research strategy. The simulation studies are perhaps some of the most important original research ‘evidence’ generated, - it certainly did take much of the time to develop the necessary skills to understand the results of the simulations, - but within the overall approach of qualitative research, the simulation studies feed data into the theory generation process as do other sources; literature studies, interviews, observations etc.

By taking the consequence of separating research methods, strategies and tactics from paradigms and systems of inquiry an original view on energy optimization and simulation modelling emerges. By framing simulation research by a qualitative research strategy three objectives are met that are contributions to knowledge:

- Through interviews and literature studies, the state of the art in architectural and engineering practice, theory and simulation modelling techniques is inquired, arriving at the formulation of a research problem and a series of research questions to be examined using simulation modelling.
- A qualitative discussion of the quantitative data that is generated by simulation modelling highlighting different aspects of the impact of urban form and material specifications on the energy use and environmental performance of buildings in Northern European urban contexts.
- A qualitative discussion of the activity of simulation modelling, a critique of its inherent logic originating in engineering concepts and a discussion of its future as an architectural generative tool for conceptualization, quantification, qualification and validation, promoting a multidisciplinary integrative design process.

\(^{56}\) As suggested by Groat and Wang - Groat and Wang, chap. 2.
Qualitative Research

“Qualitative research is multi-method in focus, involving an interpretative, naturalistic approach to its subject matter. This means that qualitative researchers study things in their natural settings, attempting to make sense of, or interpret phenomena in terms of the meanings people bring to them. Qualitative research involves the studied use of and collection of a variety of empirical materials.”

The approach to qualitative research known as grounded theory offers a format with which to understand the research process, as it has developed over time. Grounded theory is not a fixed format methodology, but an open ended approach which rather than applying a predetermined research method on a given subject, allows the method to develop organically in relation to the development of findings in the research process. Rather than proving or disproving a hypothesis, the emphasis is on creating new explanatory theory for social phenomena. Grounded theory is intended to generate synthesizing rather than analytical theory for the purpose of understanding social phenomena holistically. It is quite different from most other scientific theories (according to some paradigmatic positions it would not be recognised as science) in that it does not seek to validate an existing theory or hypothesis through experimentation or deductive thinking, instead it seeks to develop new theory with explanatory power regarding social processes drawing on data and information from multiple and diverse sources. In grounded theory, analysis is understood as interplay between data and researcher, presupposing that either has influence on the other. It emphasises the process of gathering and analysing data in a structured yet creative way, allowing the researcher to distil information from many sources, independently of media. As information is

accumulated, the researcher seeks to identify recurring thematic patterns in it, according to his or her particular research interests.

The emphasis on qualitative research as an overall frame for the studies in this dissertation is relevant to this dissertation in two different ways: When discussing energy optimization in the design process or as an aspect of the performance of a design object, - optimization is itself a social processes, which is directed towards social ends: The design process is a social process engaging a team of stakeholders; clients, designers, contractors etc. And the design object, be it an urban master plan, building or building component, is necessarily intended for some purpose in the social sphere, towards which the optimization process is directed, regardless of how technical the optimization criteria may be. Design without intent, which is rooted in the social sphere, does not exist. Understanding optimization as a social process for social purposes is crucial, but is a subdued interest in many technical studies, where technological objects or processes are often considered in terms of their functional properties, without much discussion of purpose.60

Environmental Simulation Modelling

Models have historically been used by architects to represent ideas spatially, and to assess these ideas qualitatively and quantitatively. In a wide sense of the word simulation, the processes of assessment of models may be considered simulations,

60 This notion of design may be extended to any object of design be it real, virtual or imagined. It may encompass entire world-views including the idea of science following K\'winter\'s statement "Science is about model building, not facts." Model building – physical or conceptual – is a design activity. The point is developed more fully in the article 'Research Paradigms – an Overview and a Research Example' but is not pursued further here.
Sanford K\'winter, 'Sanford K\'winter on: Science and Architecture', 2007
<http://www.manifoldmagazine.com/Manifold_01.pdf>; Peter Andreas Sattrup, 'Architectural Research Paradigms – an Overview and a Research Example' (presented at the When Architects and Designers Write / Draw / Build a PhD..., Aarhus, 2011)
<http://rum1.aarch.dk/uploads/media/Peter_Andreas_Sattrup_Architectural_Research_Paradigms_rev.pdf>.
whether this is done by empathic imagination of spatial characteristics, social experiments or other relevant methods inherent in architectural design. But usually, environmental simulation is understood in a narrower, technical sense, as a research method of more rigorous testing of properties and behaviour which has its origins in building physics and engineering.\textsuperscript{61} The use of simulation is so dominantly embedded in technical studies based in engineering that the emphasis on improving the validity and accuracy of the models is often taken for granted as some of the primary objectives of research in the majority of established research fora where environmental simulation software is used.\textsuperscript{62}

As environmental simulation is now migrating from engineering to the mainstream of architecture as software is becoming commercially available and not least practically usable to architects without a degree in engineering, architectural research may shift the focus from understanding ever more detailed aspects of technical functionalities to achieving a better holistic view of building performance and the role of simulation in the design process which are important issues in this dissertation.

Models may offer various kinds of quantifiable information as they may be used to test the performance of designs in terms of natural or social phenomena, depending on whether the intent is to test the model’s physical properties or user interaction with it, or both. An advantage of using modelling experiments in the design process, or in the research process, is the relative ease of producing a model experiment compared to constructing a full scale building for instance. As models are necessarily abstract to some degree relative to the real or imagined object they represent, the big question in

\textsuperscript{61} Here it should be noted that the borders between architecture and engineering are of course neither clear nor static, and variations occur between which competencies are associated with either discipline from one educational system to another.

\textsuperscript{62} I am here judging from the number of engineering technical papers relative to discursive architectural papers presented at the conferences I have been attending over the course of this research process, and the comments received in peer-reviews, which have predominantly regarded technical modelling criteria – not the qualitative discussion of the implications of results.
simulation modelling is how well and in which terms the model represents the simulated reality.\textsuperscript{63}

While analogue models require some physical interaction by external forces, be they natural or social, in order to simulate a social process or the physical behaviour of a model, the behaviour of digital models is programmed, and the programmes are themselves models based on mathematical algorithms. Since digital models easily integrate both spatial and temporal dimensions in models, discerning static representations from dynamic simulations is not that clear after all. As a consequence simulation is understood as an inherent part of the representative system of modelling in architecture in this dissertation. Simulations represent dynamic behaviours and properties as models imitating real-world phenomena.

In the simulation studies that are developed as part of this dissertation, two important relations of simulation model to reality are considered:

- **The geometric dimension:** In the design process information is accumulated and integrated into the design project. Geometrically, the design is developed with increasingly detailed geometric definition, as the main body of the design is articulated in elements and components. At a given point in the design process the state of definition that the project’s geometric articulation has achieved can be referred to as the geometric model’s level of detail.\textsuperscript{64} Considering the level of detail while modelling is a critical skill of a designer, particularly in the initial design stages. Simple models allow more design variations to be considered, while complex models allow more precise evaluation but are more cumbersome to produce and eventually change.

\textsuperscript{63} Advanced Building Simulation, ed. by Ali Malkawi and Godfried Augenbroe (Taylor & Francis, 2004), chap. 1–4.

\textsuperscript{64} Level of detail was originally conceived as a concept to describe how simple geometric models may represent more complex figures thereby achieving computational economy. James H. Clark, ‘Hierarchical Geometric Models for Visible Surface Algorithms’, *Communications of the ACM*, 19 (1976), 547.
- **The environmental dimension**: The external forces interacting with the building may be either natural or social forces which may be simulated digitally using mathematical algorithms to calculate and model the dynamic behaviour of climatic factors, material properties, service systems, user interaction etc. Each of these aspects may be simulated using particular software programmes to simulate discrete aspects of performance or software packages which combine several domains of simulations into a coherent model, accumulating results from separate calculations of environmental factors, eg. solar gains, daylight, wind etc. and integrating the information derived from these into the overall simulation results. Each of these partial simulations may be more or less sophisticated per se, and the overall simulation may include many or few environmental factors in the results.\(^6\)

The higher level of detail, the more effort it takes to design and build the model and to calculate the results. What level of detail is adequate, and how many layers of simulation results are included, is therefore both a question of economy to the organization undertaking the studies and a question of credibility of the results.

---

Fig: Variations of geometric level of definition of three generic building types: courtyard, terrace and pavilion, ranging from basic form (left) to basic form with windows and internal partitions (right).

One could assume that high level of definition would automatically give the most *useful* results (as opposed to most accurate), but that is not necessarily true. A very sophisticated model may yield very precise information, but as that model will have taken considerable time to design, build and simulate, and the time available is always limited in research as well as in practice, the precision comes at the price of narrowing the range of design options that can be investigated. In addition the simulation may rely on assumptions and conditions that are still negotiable and in the process of finding a definition, and thus risk becoming irrelevant as other design parameters are considered.66 Accepting less sophisticated models that are produced faster will increase the range of design options that are studied, and could therefore yield less accurate but perhaps more relevant information in a design process where simulation is used as a navigational tool comparing design options rather than a ‘validation’ tool for quantifying the dynamic properties of the final design. It is therefore important to have the necessary skills and knowledge to properly judge results, and considering these

66 The earlier in the design process, the more ‘wicked’ design problems are, as solutions to design problems are dependent on the formulation of their ‘problem’. Rittel and Webber, 155–169; Buchanan, 5–21; Richard Coyne, ‘Wicked Problems Revisited’, *Design Studies*, 26 (2005), 5–17 <doi:10.1016/j.destud.2004.06.005>.
uncertainties is essential in an environmental simulation process, but taking and architect’s approach to simulation it can be argued that it is at least equally important to an understanding of the architectural design process so as to be able to target relevant design issues precisely, as they appear in the design process.

In the simulation studies developed for this dissertation, generic models are used as abstractions to represent urban patterns and building types that are more complex in reality. Some basic considerations were made concerning the appropriate level of detail of both geometric and environmental dimensions of models. As the simulations were aiming at informing the initial stages of building design processes where a building’s form is considered in relation to its urban context and the design has quite little geometric detail, the geometric level of detail of the models developed is quite low, compared to a fully developed building design. In terms of urban planning however, the level of detail is quite high, as it includes the window to wall ratio as a design variable, which is typically not specified in Danish planning regulations. Additional geometric detail such as external shading devices were deliberately avoided, as the focus of the studies was to target the very basic relations between building and context.

The environmental simulation software used in the studies ranges from quite basic solar radiation studies performed using Autodesk Ecotect to fully dynamic climate based thermal and daylight simulations using IES-VE-radiance which is one of the most advanced software packages commercially available. Daylight and thermal performance are separate simulation domains with different calculation methods. A pilot study was performed to test the effect of adding daylight calculations to thermal simulations and energy calculations was explored in paper V: Urban Density versus Daylight and Solar

---


68 This point is further developed in chapter 4: Practice.

69 Generic models: Digital models with relatively low geometric level of detail representing simplified urban patterns. While the geometric LoD is low, the simulation process combines thermal and daylight simulation.
gains.\textsuperscript{70} The results showed that adding daylight simulation to thermal simulation affected the results considerably on relevant energy parameters: heating, cooling and artificial lighting. As a consequence the subsequent studies in paper I: Urban Canyon, paper II: Typologies and paper IV: Urban Daylighting used a full range of climate based thermal and daylight simulations.

Under some conditions the most sophisticated environmental simulation methods were not the most adequate tools to use for a given research or design purpose. As the simulation studies progressed and knowledge was gained, a general insight into the interrelationships and dynamics of design variables and performance metrics was developed, which allowed the liberty to use relatively simple solar access simulations to illustrate spatial/environmental correlations as their derived impact on daylight and energy use were well known.

\textbf{Research Design - Design Research}

Rather than being different than research, design is considered an inherent mode of thinking in research, which is a point developed in the paper \textit{Architectural Research Paradigms – an overview and a research example}.\textsuperscript{71} In this dissertation, design (and designing) is understood in three ways: As product, as process and as a mode of thinking:

\textbf{Design as Product:} The plan for the production of a design object, and the design object itself. The design object need not be a material object, it may be conceptual or it may be a process. The design is often expressed in multiple representational media: drawings, models, text which stand in relation to the design object itself.

\textsuperscript{70} Peter Andreas Sattrup and Jakob Strømann-Andersen, MMIX.

\textsuperscript{71} This notion is built on theory by Vitruvius, Rittel & Webber, Schön, Buchanan, Nonaka and Kwinter – see paper VI: Research Paradigms. Peter Andreas Sattrup.
In the dissertation digital models are used as abstract representations (types) of real-life buildings and environments and simulations are used to describe their performance as processes.

**Design as Process:** Designing is the activity of planning for the production of the design object. The design process is a process of embedding intents in the design object, navigating and calibrating the constraints and opportunities surrounding the project. The choice of studying the interstice of the urban and building scales in this dissertation is directed towards understanding their implications in the design process: Urban considerations usually form constraints on design decisions in the building scale, therefore they should be considered earliest in the process.

**Design as mode of thinking:** In recent design theory, design has been highlighted as a mode of thinking, involving continued reflection on action directed towards creating ideas. Influenced by Kwinter’s discussion of Science and Art, it is held that design is about creating new concepts, new models of thought and new realities which in the widest sense may encompass ideas on the level of world views and not just material artifacts. In this sense the prospective, experimental, argumentative and creative process of establishing new ideas and knowledge has an inherent element of design thinking.

**The SECI model**

Nonaka’s SECI model (Acronym for Socialization, Externalization, Combination and Internalization) is a theoretical framework describing the process of creating and managing knowledge in organizations through knowledge conversion between tacit and explicit states. In Nonaka’s view the Western tradition of research has “emphasized

---

72 See Buchanan, 5–21; Schon.


74 *Tacit* knowledge is knowledge tied up in practical experience, as are many skills. Knowing how to ride a bicycle is an example of tacit knowledge which is not transferred by language as is *Explicit* knowledge. Instead it must be acquired through training and practical experience. Polanyi.
explicit knowledge⁷⁵ and thereby neglected the active role practical, tacit knowledge plays in knowledge creation.⁷⁶ According to the SECI model, practical and theoretical knowledge inform each other when new knowledge is created, which is a crucial point considering this dissertation’s interest in architectural design’s theory and practice.

Nonaka’s fundamental observation is that knowledge is not just made explicit through research. Knowledge is returned to the practical, tacit state in the iterative process of creating knowledge, which can be described as four modes of knowledge transfer:

Socialization is the process of conveying practical knowledge and skills through training, transferring tacit knowledge from one person or group to tacit knowledge in another. Externalization is the process of making tacit knowledge explicit, as when reflecting on experience and creating theories. Combination is the process of combining different kinds of explicit knowledge to gain new knowledge, as when combining hitherto unconnected ideas to an original concept. Internalization is the process of adapting explicit knowledge to inform an individual’s or organization’s practical knowledge and skills, as when learning new skills from manuals or implementing well-defined methods in new practices.

Knowledge creation can be understood as a spiralling movement that moves knowledge from one state to another, regardless of whether this follows a structured or a more serendipitive approach, allowing chance insights and accepting the notion that some knowledge by nature remains tacit and resists explicitation. Knowledge creation is understood as a social endeavour taking place in the context of an organization, through communication. Nonaka highlights the use of metaphor and analogue, concepts that are traditionally associated with arts and poetic language in the western tradition, but are essential communication devices in the knowledge creation process leading to the formation of models⁷⁷ by which Nonaka means operable, instrumental concepts.

⁷⁶ Nonaka, 14–37.
⁷⁷ Nonaka, 96–104.
Knowledge creation is highly dependent on sharing a common conceptual and/or physical space which acknowledges differences and builds trust, and is fuelled by the differences among individuals and groups in the organization and depends on the intentionality, aspirations and ideals of those generating it.

Following Nonaka’s lead, it may well be argued that research always encompasses aspects of generative and analytical thinking, and that the integration of these modes of thought are the prerequisites for innovation, which ensures the originality and possibly the relevance of the knowledge generated. Applying methods from related disciplines of thought carries with it transformative potentials for innovation, relevance and originality. As demonstrated by Nonaka, difference is a driver for innovation, and knowledge is created by exchanges within a larger social space.

Nonakas SECI model can be adapted to explain the transformation of knowledge in the research process on two levels - the overall research process and the specific process of collaborating on environmental simulation modelling.

---

In the overall research process I was drawing on socialized knowledge from my experience in practice, in particular the experience gained from the Radiohuset project, as described in the introduction to this thesis. This knowledge of my own and knowledge of other practitioners I interviewed was made explicit and combined with explicit knowledge from the literature studies. The insights gained formed the basis for the simulation studies.

At the level of the simulation studies, these are themselves comprised of several iterations or loops of knowledge transformations informed by cross-disciplinary collaboration, in which knowledge is transformed through explicit and tacit states according to the SECI model. The knowledge gained through the simulation studies can then be socialized by teaching and dissemination in practice.

In the terms of the SECI model grounded theory can be understood as an externalization and combination process directed at making knowledge explicit through theory development (which is by itself a research practice requiring both tacit and explicit knowledge of research methods). In this sense the grounded theory approach framing the simulation studies and the SECI model supplement each other, highlighting different aspects of the research approach.

**Collaboration**

As very little knowledge of environmental simulation in practice was available in the research environments of the two Danish schools of architecture at the beginning of my studies (2008), and the market at that time offered very few simulation software packages intended for architects, it was necessary to develop the necessary skills. The solution to this problem was to collaborate with an engineering PhD student Jakob Strømann-Andersen, who was pursuing an Industrial PhD in collaboration with Henning Larsen Architects and the Technical University of Denmark with the topic of Integrated Energy Design in Master-planning. As our research interests were remarkably similar and our respective backgrounds as an architect and a civil engineer could supplement each other, it was decided to collaborate on a range of environmental simulation studies.
this way, the engineer’s understanding of the complexities of the physics and mathematical aspects of simulation modelling could be combined with the architect’s understanding of the initial design stages and the relevance of technical design criteria in the wider context of architectural design, with the aim of contributing new knowledge which would be relevant to both professions but would likely not have been achieved without this cross-disciplinary collaboration.

Having established the connection and common interest in collaboration from both sides, Jakob Strømann-Andersen was approached with an outlined design proposal of five different simulation studies to collaborate on, identifying some parametric variations that could be tested to identify the impact of urban scale design decisions on building energy performance. The design of the models where influenced by the theory developed from the interviews with various practitioners, who also gave indications on which software might be relevant to use. The aim was to find out which of the urban scale related design parameters had the greatest impacts, and to relate those possible findings to an overall idea of decision hierarchies in the design process.

The choice to use IES-VE as the core simulation software for the studies was influenced by interviewees from the Specialist Modelling Group of Foster and Partners. Jakob Strømann-Andersen on the other hand took great interest in developing fully climate-based simulation modelling procedures and applying these to urban scale architectural engineering, which he had plenty of opportunity to do due to his association with Henning Larsen Architects. The series of studies developed are addressing generally applicable principles, rather than the specific application articulations which case studies from HLA might have offered. In the latest stages of the research process Anne Iversen joined the collaboration, contributing to paper IV: Urban Daylighting. 

By collaborating closely through several iterations of studies, tacit and explicit knowledge from either discipline was transferred among us, and a common understanding of technical and design considerations emerged. As mutual understanding

---

79 For each of the research papers I, II, III, IV and V a document listing individual contributions have been produced, which is forwarded to the jury of this dissertation.
grew, it became increasingly difficult to distinguish individual conceptual contributions from those arrived at in common.

Interpreting the collaboration on simulation modelling according to the SECI model, it can be seen how each brings his own pool of tacit and explicit knowledge given by professional education in architecture and engineering as well as personal experience into the collaborative effort, – thereby Socializing, Externalizing, Combining and Internalizing the aspects of knowledge relevant to the process of environmental simulation – in order to create new knowledge from the iterative process of repeating the SECI cycle:

**Socialization:** Meeting up, explaining in more or less precise terms the intents with the knowledge creation process which is set in motion. I explained a desire to investigate collaboratively whether architectural scale would be linked to environmental performance and energy use, and whether it would be meaningful to use it as a decision hierarchy in the design process.

**Externalization** – making the background knowledge and practical knowledge each brings into the process explicit. I offered a set of simple typologically based designs to test initially. The designs are based on historical and contemporary building patterns in architecture, which ensures that the models may be relevant to architects and urban planners. I also offered ideas on the construction standards to be modelled, which would make the results of the simulations relevant to a discussion of contemporary and near-future construction standards.
**Combination** – sharing the theoretical knowledge and practical skills each collaborator possesses, making them available to the other and giving feedback on how to creatively combine ideas or skills from the common pool of tacit and explicit knowledge. While I encountered a limit to the sophistication of simulation modelling I was able to learn to use with proficiency in the time available, I gained sufficient insights into the engineering aspects of simulation so as to be able to understand and guide the studies in directions where they would offer relevant, new knowledge to architects.

**Internalization** – as explicit knowledge has been combined, it is now applied in new working procedures, and is thereby transformed to individual tacit knowledge. Simulation processes have become part of an inventory of tools and skills with which architectural design problems may be formulated and resolved, thereby adding simulation to the creative and interpretative intuition with which future design problems may be imagined.

As the results of each simulation process were discussed, new processes were planned and executed. The iterative process of simulation modelling research could continue, now with new problems and questions in focus, on the basis of an improved, cross-disciplinary knowledge base. As each of us was a representative of a knowledge creating organization feeding the knowledge we create into the education of future architects and engineers, the particular process we went through has the potential of starting new iterative processes of knowledge creation in the wider context of the professions, - if only ever so slightly – thereby altering the future of the cultures and the field of environmental performance which they share.
RESEARCH PROCESS

The research process can be understood in terms of three phases of research developed in parallel and continuously informing each other, but receiving different degrees of attention at times. The phases are in ‘order of appearance’ – or, that is, the turn in which they received most attention: 1) Theory generation, 2) environmental simulation modelling and 3) qualitative discussion / 2nd stage theory generation.

Phase 1 – Theory generation

The first phase of the research process focussed on clarifying the state of the art in theory and practice, but also included an important element of understanding the basics of energy calculation and building physics. Four research themes were investigated:

1) Theory of energy optimization in architecture as a sustainability strategy,
2) Contemporary design philosophies towards sustainability and energy optimization,
3) The use of environmental simulation in the design process, and
4) Qualitative dimensions of daylight and thermal environment in architecture.

This phase dominated the first year and a half of my studies (spring 2008 – summer 2009 interrupted by a leave of three months where I contributed to curating the exhibition: ‘Green Architecture for the Future’ at the Louisiana Museum of Modern Art), but continued while the other phases; simulation studies and critical discussion began taking up a greater share of time. Technical literature studies were continuously repeated as the results of simulations would point the research effort in new directions, whose state of the art would have to be checked and incorporated in to the research.

---

80 ‘Phase’ is understood here both as a ‘stretch of time’ and as a ‘mode’ of research.
81 Physics and maths are not part of the curriculum of the education of Danish architects. Instead design principles are explained combined with rules of thumb. As an architect educated in Denmark, this aspect of the design culture provided some challenges for me in order to be able to use and to evaluate using environmental simulation software as analytical tools in the design process and to analyse the performance of basic building designs.
Following a qualitative research strategy I began collecting data and categorizing personal experience from three principal sources: 1) Literature, 2) interviews and lectures by practitioners in architecture and engineering and 3) personal observations of daylight and thermal phenomena in architecture, recording these using thermograms, photographs and note making.

Identifying the notion that a hierarchy of architectural scales where guiding the environmental impact of design decisions, and seeing that these scales could be used as guides to structure the build-up of information in the design process, and having gained important in formation as to which environmental simulation software packages might be useful to the studies of the daylight and solar gains balance that were part of the objective of the research work, these research questions where informing the design and research process of Phase 2, the simulation studies:

- Can this connection of architectural scale, decision hierarchies in the design process and energy performance be identified through simulation studies?
- Which of the design decisions typically taken in the earliest stages of a building project carry the greatest relative impacts?
- What would be the qualitative aspects of the quantitative results of environmental simulation modelling?

The logic of creatively establishing a hypothesis follows Peirce’s principle of logical abduction, in which it (contrary to deduction) is allowed to infer a cause from a consequence as a temporary position. If we observe a phenomenon we may guess at its cause, which would be a simple attempt at establishing a theory. The explanation may be probable, but we cannot know for sure. If similar experiences show similar behaviour we may say that the probability of our explanatory theory increases, yet still we can not know for sure.\(^2\) Qualitative research accepts abductive logic as a condition for practical thinking. Therefore, grounded theory is never true or false, rather it shows fit to the

studied situation, it has relevance to the participant in the situation, it has workability if it sufficiently works as explanation, and it has modifiability as new data comparisons to old data will change its explanatory systems. Abductive logic is evolutionary, as it develops with changes in circumstances and do not seek abstract, universal truths.83

Figure 3: Research hypothesis: ‘The greater the scale, the greater impact on energy and environmental performance’ and three modelling studies designed for testing aspects of urban design decisions’ impact on performance.

**Phase 2 – Environmental Simulation Modelling**

Since a hypothetical connection between architectural scale, design process level of definition, information management and possibly the energy performance of buildings as a result of their urban site conditions had been established – which was a more advanced notion than the initial aim of understanding the impact of urban geometry on building performance described in the introduction, a series of modelling studies based on architectural typologies were designed, which intended to pinpoint important urban scale design decisions’ impact on building energy use, and maybe provide support for the

---

83 Kirkeby, pp. 122–152 (pp. 122–152).
idea of a hierarchy of scale connected to energy use.\textsuperscript{84} The initial impulse was to focus on the energy performance of buildings, specifically the energy use for heating, cooling and artificial lighting which are most directly influenced by architectural form. The feedback offered by energy calculations, typically given as the annual energy use pr. square meter (kWh/m²a), provided important information but offered neither sufficient nor adequate explanation of the qualitative dimensions of the built environments the models represented. For this reason later studies focussed more on environmental performance than energy use, and delved deeper into the spatial and temporal dimensions of daylight and solar access.

While environmental quality can be assessed numerically using visual and thermal comfort simulation tools, the simulations offer information on specific performance metrics only. These are indeed relevant to a discussion of architectural quality, but due to the fragmented nature of performance metrics which describe only discrete elements of environmental performance and since architecture is experienced using all senses simultaneously,\textsuperscript{85} they cannot replace a trained architect bringing his or her environmental imagination to bear on a design.\textsuperscript{86} As it is argued in chapter 3, the ideas of comfort inherent in energy performance metrics largely ignore the important aspect of delight as a fundamental aspect of environmental quality in the built environment. While this aspect evades the positivism inherent in simulation methods, it is an integral part of the extremely diverse discursive cultures in architecture.

As a consequence two interpretative stances were applied to the simulation studies: 1) A quantitatively oriented interpretation of the possible explanations of the results of simulations, understanding how these would result from the parametric variations studied, and 2) a qualitatively oriented interpretation of the possible consequences of the simulations on life conditions and experiential possibilities in the built environments the models represented.

\textsuperscript{84} Qualitative research does not seek ultimate causal explanations. Theory can be seen as transient, always subject to improvement when new information on a subject emerges.

\textsuperscript{85} Rasmussen.

\textsuperscript{86} Dean Hawkes, \textit{The Environmental Imagination}, 1st edn (Taylor & Francis, 2006).
The design of the models used in the simulation studies targeted four types of urban geometry governing the interstice of urban and building design:

1) The impact of the immediate urban space surrounding a building on its energy performance – the urban canyon.
2) The energy performance of building typologies in dense urban areas
3) Solar access and daylight availability as a result of zoning regulations
4) The impact of façade reflectivity resulting from glazing ratios and wall colour on daylight availability in the urban space and inside buildings.

Phase 3 – Qualitative discussion / 2nd stage theory generation
In the third mode, the experience gathered in the first two phases is discussed critically. A theoretical framework emerged by the end of the simulation studies that facilitates a discussion of simulation modelling as a generative tool in architecture as opposed to its use for validation in engineering, centering the focus for optimization on the user of the building and the experience of space, using architectural scale as the structuring element of the design process. The limitations of simulation modelling applying a deterministic approach to building performance is discussed critically and a mixed natural and social sciences approach where architecture as an applied art and science forms its integrative core is developed.

Paradigmatic shifts
As qualitative research and simulation modelling are associated with different research assessment systems, which do not necessarily share ontological and epistemological assumptions, the phases also represent paradigmatic shifts happening in the process of research.
In the first phase, data was gathered freely from the different sources, with the intent of creating a knowledge base of the state of the art in practice, theory and simulation technique which will be made operative in testing the hypothesis that emerged in the process. The paradigmatic stance of this phase was naturalistic in nature, ontologically presupposing an objective reality subject to individual and social interpretation and negotiation, while epistemologically following a critical approach to practice, theory and simulation modelling techniques. In the process of the first phase no predetermined theoretical matrix was applied or superimposed on interviews, literature or technical studies, instead theory was allowed to emerge, as 3 theoretical themes - 1) Design philosophy and sustainability, 2) Design methods, energy and environmental performance and the use of simulation in optimization and 3) Architectural qualities: comfort and delight - were investigated thematically over time. The first ideas of a theoretical framework based on the idea of a hierarchy of scales are sketched out.

In the second phase, my own qualitative stance encounters an inherently (post)positivist paradigmatic stance as three different aspects of urban form and materiality is investigated in cross-disciplinary collaborations. Studying the energy performance of buildings in dense urban contexts, each collaborator ‘goes native’ in an attempt to understand the others’ disciplinary research methodology, concerns and techniques.

Fig 4: Paradigmatic shifts according to 3 modes of research.

Graphics based on Lara – Groat and Wang
Writing three journal articles and two conference papers together on the results of the simulation studies a mixed-mode qualitative-quantitative style has been used to disseminate the results to an audience that (hopefully) includes both architects and engineers. In the process of collaboration, a degree of mutual understanding is achieved, in which our inherited professional disciplinary understandings are expanded.

In the third phase, the experience gathered in the first two phases is discussed. By the end of the research process, having gathered information from research and practice and having achieved first-hand experience as a simulationist from the simulation modelling studies, this information and experience offered a both tacit and explicit knowledge base to discuss critically, in terms of its implications to architectural design. A theoretical framework was crystallized that facilitates a discussion of simulation modelling as a generative tool in architecture as opposed to its use for validation in engineering, centering the focus for optimization on the user of the building and the experience of space. The limitations of simulation modelling applying a reductivist deterministic approach to building performance is highlighted in favour of a mixed natural and social sciences approach where architecture as an applied art and science forms its integrative core.

The matrix below describes the research process in terms of paradigmatic shifts.
<table>
<thead>
<tr>
<th>Research Phase</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Paradigm</strong></td>
<td>Naturalist</td>
<td>Naturalist (Postpositivist)</td>
<td>Naturalist (Emancipatory)</td>
</tr>
<tr>
<td><strong>Ontology</strong></td>
<td>&quot;Multiple, socially constructed realities&quot;</td>
<td>&quot;Multiple, socially constructed realities&quot; investigating the &quot;One reality, knowable within probability&quot; notion</td>
<td>&quot;Multiple realities shaped by social, political, cultural, economic values&quot;</td>
</tr>
<tr>
<td><strong>Epistemology</strong></td>
<td>&quot;Interactive link between researcher and participants, values are made explicit, created findings&quot;</td>
<td>&quot;Objectivity is important, researcher manipulates and observes in dispassionate, objective manner&quot;</td>
<td>&quot;Interactive link between researcher and participants, knowledge is socially and historically situated&quot;</td>
</tr>
<tr>
<td><strong>Hypothesis</strong></td>
<td>Under development, assuming that environmental simulation may be instrumental to improve sustainability through energy performance for daylight and thermal comfort</td>
<td>Urban density and Building Energy use are hierarchically dependent. The urban geometries surrounding and regulating a building's site have major influence on that building's energy performance over its lifetime.</td>
<td>The use of environmental simulation tools will change architectural culture, as new techniques offer improved control of design performance</td>
</tr>
<tr>
<td><strong>Research question</strong></td>
<td>What is the state of the art of architectural practice, theory and environmental simulation technology regarding energy performance?</td>
<td>How does urban form relate to building energy, daylight and thermal performance in the context of Copenhagen?</td>
<td>How may environmental simulation change architectural culture?</td>
</tr>
<tr>
<td><strong>Methodology</strong></td>
<td>Qualitative research, grounded theory, modified</td>
<td>Qualitative research framing a Mixed Mode Case Studies through - Simulation and Modelling</td>
<td>Critical discussion</td>
</tr>
<tr>
<td><strong>Strategy</strong></td>
<td>Collection of data from multiple sources to produce hypothesis: -Architectural and engineering practice - Theory - Environmental Simulation tools</td>
<td>Qualitative discussion of environmental simulation results.</td>
<td>Argumentation and critique based on observations and experience 'grounded theory' from phase 1 &amp; 2</td>
</tr>
<tr>
<td><strong>Tactics</strong></td>
<td>- Literature review - Interviews - Observations of climatic, cultural, physical behavioral phenomena - Review of simulation software types</td>
<td>Environmental Simulation Modelling experiments.</td>
<td>Critical discussion of research process</td>
</tr>
<tr>
<td><strong>Notational media</strong></td>
<td>written language, photography, thermography, diagrams</td>
<td>digital environmental simulation modelling diagrams</td>
<td>written language diagrams</td>
</tr>
<tr>
<td><strong>Interpretative logic</strong></td>
<td>abductive hermeneutic</td>
<td>inductive / deductive hermeneutic</td>
<td>abductive hermeneutic critical</td>
</tr>
<tr>
<td>Empirical matter / object of interpretation</td>
<td>State of Art Practice</td>
<td>Theory Technology</td>
<td>Digital models of generic urban environments: urban canyon urban pattern urban envelope</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>----------------------</td>
<td>------------------</td>
<td>----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Research Aims</td>
<td>understand</td>
<td>understand, control and predict</td>
<td>understand, control and predict</td>
</tr>
<tr>
<td>Position of Researcher</td>
<td>Independent Participant</td>
<td>Independent</td>
<td>Participatory</td>
</tr>
<tr>
<td>Type of Theory</td>
<td>descriptive / normative</td>
<td>descriptive / normative</td>
<td>descriptive / critical</td>
</tr>
<tr>
<td>Research assessment criteria</td>
<td>Credibility Transferability Dependability Confirmability</td>
<td>Credibility Transferability Dependability Confirmability</td>
<td>Credibility Transferability Dependability Confirmability</td>
</tr>
<tr>
<td>Theoretical scope S,M,L,XL</td>
<td>S &amp; M: from personal experience to professional boundaries</td>
<td>S &amp; M: from personal experience to professional boundaries</td>
<td>S,M &amp; L: from personal experience to professional boundaries and societal values</td>
</tr>
<tr>
<td>Conclusions (or, - following the logic of naturalist inquiry: 'tentative generalised claims' (Robertson 2008))</td>
<td>Experienced practitioners are using and developing environmental simulation tools to control energy performance of their projects. Both Eberle and Foster's office report a hierarchy of scale influencing energy demand and environmental impact. Emerging practices show ways to express environmental concerns that have previously been only theoretically described. Rich sources of theory on environmental performance has remained unattended in mainstream architecture</td>
<td>There are some hierarchical relations between scales but they change in dynamic ways when single parameters are varied. Urban geometries have significant impact on energy performance, but affect in particular the experiential qualities</td>
<td>Environmental simulation offers control of new scales of energy in architecture: intensity and Duration. To improve creative and qualitative aspects of the built environment, architects need to inform structure and control of energy performance. The regulatory framework guiding urban form in relation to energy performance of buildings in Denmark is simplistic and outdated. Integrated methods of quantitative and qualitative assessment to achieve environmental diversity in future developments.</td>
</tr>
<tr>
<td>Sources: Münk 2010, Lincoln &amp; Guba 2005, Groat &amp; Wang 2001, Robertson 2008</td>
<td>Architectural theory describes environmental performance in a variety of ways that are not necessarily quantifiable per se, but could be brought to bear on the way environmental performance is quantified and determined in engineering</td>
<td>Visualization and environmental simulation can aid architects in conceptualizing and achieving desired environmental performance, aiding architects in controlling the qualitative and some of the quantitative aspects of energy performance</td>
<td>Environmental simulation tools can be understood as extensions to our senses and intellects rather than sophisticated calculators. Using simulation to train perception and analysis can allow architects to creatively challenge the 'comfort zone' thinking</td>
</tr>
</tbody>
</table>
CHAPTER 3: Theory
“Architecture can be understood as a material organization that regulates and brings order to energy flows; and, simultaneously and inseparably, as an energetic organization that stabilizes and maintains material forms.”

Operational and Embodied Energy

Buildings require energy to be built, energy to be maintained, and eventually energy in process of their demolition. At the same time buildings house occupants whose needs and activities require continual energy use. As Margalef points out above, these relations between matter and energy in architecture are interdependent and can’t be separated from the processes of life, that the buildings are cultural and physical manifestations of. Indeed it makes good sense to understand the processes of the built environment as analogue to the biological processes of metabolism, in which the cells’ materials are constantly renewed and maintained by an inflow of energy, and metabolism has been adopted as a key term in sustainability and industrial ecology. Energy use in the built environment is deeply associated with cultural patterns and may exceed the energy use for basic human metabolism by a factor of more than a thousand in industrialized countries. The duality of material organization and energy flows that Margalef speaks of, can be recognized in the technical literature as ‘operational energy use’ and ‘embodied energy’ in the built environment.

Operational energy use is the energy used through building service systems; mainly heating, cooling, ventilation, lighting and hot water and may or may not include additional types of energy use by the occupants, depending on calculation method and

---

88 Fernandez-Galiano, p. 6.
90 Fernandez-Galiano, pp. 6–7.
the regulatory system it refers to.\textsuperscript{91} Operational energy use is generally accounted for in yearly energy use, reflecting the impact of the seasonal and diurnal variations of the climate, and the main objective of operational energy use is to maintain thermal and visual comfort for the building’s occupants. Architects may influence the operational energy performance of buildings in many ways, particularly through formal and material choices in the design process.

Embodied energy accounts for the energy used to build maintain and eventually demolish a building, including energy used for material extraction, processing and transport in a life cycle perspective. Calculation methods differ, depending on the conditions of the analysis,\textsuperscript{92} but it is held that the embodied energy of a building may constitute in the range of 10 - 40\% of the overall energy use in the entire lifecycle of a building, depending on its operational energy performance, its functional life time and other variables.\textsuperscript{93} While the energy use for material extraction and processing is typically outside their direct influence, architects may exert considerable influence on the embodied energy of a building through material and component specification. A preference for locally available or light-weight materials may reduce energy use for transportation, and organic and mineral materials have very different embodied energy profiles and other related environmental impacts.\textsuperscript{94} But of particular interest to

\textsuperscript{91} As an example, the Danish building regulations include electricity use for lighting in office building energy use, but do not include it in housing. The use of energy for electrical and electronic appliances are very likely to increase in the future potentially constituting a major part of overall energy use in buildings, but this is generally not accounted for. Erhvervs- og Byggestyrelsen, ‘7.2 Energirammer for Nye Bygninger - BR10’, 2010 <zotero://attachment/928/> [accessed 5 April 2011]; Rob Marsh, Vibeke Grupe Larsen and Jake Hacker, Bygninger Energi Klima: Mod Et Nyt Paradigme. (Statens Byggeforskningsinstitut, 2008) <http://www.bygninger-energi-klima.dk/bygninger-energi-klima.dk/Intro.html>.


\textsuperscript{93} Crowther.

\textsuperscript{94} Rob Marsh, Michael Lauring and Ebbe Holleris Petersen, Arkitektur Og Miljø: Form, Konstruktion, Materialer - Og Miljøbelastning (Aarhus: Arkitektskolens Forlag, 2000).
architects should be the lifecycle aspects of embodied energy in buildings, as this is linked to changes that happen to a building over its lifetime. The idea that architects should design for adaptability of a building, so as to facilitate ease of functional change and possibly the recovery of embodied energy invested in buildings and components is gaining momentum in contemporary design culture.95

Hierarchies of Scale: Energy and performance optimization in practice

“Consumption is a question of demand, and demand is dependent on design. Your demand for petrol depends on the design of your car, and your demand for a car depends on the way the city you live in is designed...
The same goes for buildings: it applies to all sorts of things. Architecture and planning can reduce the demand for energy through the way buildings, infrastructure and urban development work... If you add transportation, a total of 70% of energy consumption depends on buildings, the way people move among buildings, and the way the infrastructure works...
There’s a relation between sustainability and economy at all levels. Thinking about the way you organize your building, its shape and orientation, gives you the maximum environmental benefit, but costs very little. The form of the building mass is crucial to its energy consumption. If you go up a level, and for example start making sun screens, you can also save a lot of energy, but then it starts to cost a lot of money. And in the end you can put solar cells on it and install the latest in intelligent engineering technology, but that costs even more money. Look at things from the opposite angle: start with a ‘dumb’ building and you can put as many solar cells on it as you like - it won’t work. The same applies if you choose to put your building in the wrong place. It’s like aircraft and cars: If they have the wrong shape, they just won’t do.”96

This quote from an interview with Stefan Behling, senior partner in charge of sustainability with Foster and partners, inspired some of the most central research interests in this dissertation, as will be seen in the following chapters. Behling postulates that there is what may be called ‘a hierarchy of scale’ governing the environmental impact of architectural design decisions from urban planning to building and component design, in the sense that the greatest environmental benefit may be gained from large scale urban and building design, while applied façade, service and energy technology systems have little impact but comes at a high price. But is the idea valid, and how is it constructed? The theoretical background for the statement is considered, and it is tested whether such a hierarchy can be supported through simulation studies of energy and environmental performance optimization in a Danish urban context.

While it is the operational energy use and environmental performance that is in focus in this dissertation, other factors constitute important design considerations that need to be integrated in the design process, parallel to these:

“You will have to design the building so it is flexible and can have a long life, and that includes assessing the relationship between materials and energy. You can for example choose materials that have taken a lot of energy to produce, but which extend the lifecycle considerably. It could even happen that after 50 or 100 years these materials will have increased in value because they are recyclable... The important thing is the totality, the overall design.”97

Gerard Evenden, also senior partner at Foster and partners, adds another dimension to the hierarchy of scale Behling accounted for in terms of urban transport and operational energy use in buildings: that of embodied energy in a lifecycle perspective. Can it be integrated in the idea of a hierarchy of scales? Apparently yes:

---

97 Peter Andreas Sattrup, pp. 49–55 (pp. 49–50).
“This is the background and the reason why we speak about design on maybe 5 different levels parallel, you know. It’s on the level of the site, its on the level of structure, its on the level of skin and its on the level of the organisation of the building, of the programme, and on the level of the interiors and the materials. These different elements also relate to different lifetimes.98”

Employing a simplified life-cycle based hierarchy of scales to guide the design process, Dietmar Eberle of Baumschlager-Eberle Architekten has integrated a way to assess design decisions in terms of durability and adaptability, which may be linked to embodied energy. The hierarchy Eberle applies is based on the observation that large scales (urban site conditions and building form and structure) change more slowly than minor scales (eg. façade & service systems and the building’s interior organization), a notion which has been developed by Duffy and Brand as the Shearing Layers theory, which will be further elaborated below.

The higher turnover rate of windows, service systems and interior partitions implies that the embodied energy invested in minor scale components may constitute a larger part of buildings’ embodied energy in a life-cycle perspective with risks of being wasted as components are replaced:

“It is important here to note the relatively small portion of the embodied energy that goes into the structure, and the larger proportion that goes into those parts of the building that are subject to periodic replacement during renovation. It is these parts of the building, the facade, the services, and the internal fitout, that have the shortest life span but which contain most of the embodied energy. It is also worth noting that with the current continuing improvements and reductions in operational energy consumption, the importance of embodied energy is likely to become even greater.”99

99 Crowther, p. 3.
Conducting a life cycle energy use study of an office building, Crowther documents a link between the embodied energy of a building in a lifecycle perspective and architectural scale, which also has a cost implication similar to that stated by Behling at Foster and partners, arguing that recovery of this embodied energy should be facilitated by designing for disassembly and subsequent recycling. This argument for designing for adaptability can be found as a recurring theme among architectural ecologists, and maybe based on energy and carbon calculations. Following the logic of designing for recycling through adaptability, architectural detailing defines a structure that may or may not allow building materials to be recycled. We may label this design interest as a ‘resource management’ oriented approach to architecture.

One should note that the relative share the embodied energy thus constitutes of the overall energy use in a building is quite susceptible to design choices and changes in the course of the a lifetime of a building which the designers has little control of. But the general observation here is that it makes sense to judge design decisions’ implications on both operational and embodied energy, using architectural scale as a reference system.

Shearing Layers – Durability and Adaptability

The shearing layers theory adapted to architecture by Duffy and Brand explain the processes of change that happen to buildings in the course of their lifetime in terms of the rates of change of building layers. The theory suggests that building design should be clearly organised according to these temporal and spatial scales, so as to protect the resources invested in the building – its durability – by allowing for resource conscious and easy adaptability of the building over time. A building which is able to change over the course of its functional lifetime has less risk of becoming obsolete and thus

---

100 Crowther.
102 Brand, p. 20.
demolished. Decisions taken on large and slow changing scales such as the building’s relation to its site will constrain decisions taken at smaller and more rapidly changing scales. In short, the shearing layers theory is a simplified life-cycle theory of buildings, from their relation to their site to their functional programmes and components.

Through this dissertation Brand’s terms for the shearing layers: Site, Structure, Skin, Services and Spaceplan are used to denominate architectural design decisions related to scale as a common reference system. Similarly at the urban scale spatial, legislative, regulative and ownership layers with different permanence can be identified that frame the evolution of the city.

Left: Stewart Brand: Shearing Layers of Change. Buildings are subject to change over their lifetime, but different aspects of the building have different rates of change, from the slow change of a building’s context conditions (SITE) to the rapid turnover of furniture and internal organisation (STUFF and SPACEPLAN). Illustration from How Buildings Learn p. 13.

Left: Urban Shearing layers: 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.

Studying how buildings change over time, Stewart 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’ road of investing a high cultural value in a building, and the ‘low’ road of functional utility 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. Both ‘high road’ and ‘low road’ strategies play for social acceptance of the design: The low road through offering utility, the high road by investing aesthetic and cultural value, which may offer delight or a sense of affection.
Brand’s concept of adaptability is understood in terms of designing for ease of adaptation to changing demands over the lifetime of a building. Efficient use of resources should respect the life-cycle related temporal scales of a building’s shearing layers: “A design imperative emerges: An adaptive building has to allow slippage between differently-paced systems of Site, Structure, Skin, Services, Spaceplan and Stuff. Otherwise the slow systems block the flow of the quick ones, and the quick ones tear up the slow ones with their constant change. Embedding the systems together may seem efficient at first, but over time it is the opposite, and destructive as well.”

If we understand the shearing layers as a design imperative, as Brand suggests, another dimension of the hierarchy of scales is defined: As large scale design decisions relating to the urban site, building structure and form, they have impacts over design performance in the long term, which may add considerable cumulative effect to the performance implications of large scale, highly permanent design decisions.

**Comfort and Delight**

Returning to operational energy optimization: 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, as energy is used for heating cooling, ventilation and lighting to achieve comfortable indoor environmental conditions. 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. Etymologically comfort means ‘making stronger’ and is thus connected to physical and mental well-being and health, but may also, as the related word consolation, describe a strong emotional or even spiritual bond between people when facing hurt or loss. It is also related to convenience and security if one thinks of health in that way. With the word’s rich cultural connotations and its relation to the base elements of the human condition in mind, its use in building physics may be seen as quite reductive.
However many rich associations the word ‘comfort’ may inspire in a philosophically
minded reader, it has, in building physics, been reduced to a term indicating
environmental control, related to the satisfaction of the occupants with the indoor
climate. Technical comfort criteria have been developed with the aim to predict
responses to thermal, visual and aural stimuli. Thermal and visual comfort are
fundamental to operational energy use optimization, as heating, cooling and ventilation
are used to satisfy occupant’s thermal comfort and artificial lighting is used to satisfy
visual comfort requirements of adequate light levels for given tasks.

Two philosophies of thermal comfort have competed for position since they were
launched in the 70’ies: the thermal neutrality / heat balance theory and the theory of
adaptive comfort. The heat balance theory is integrated in the main international
standards ASHRAE 55-1992 in which comfort is defined as ‘that state of mind which
expresses satisfaction with the thermal environment’ and as ‘the absence of thermal
discomfort and a condition in which 80% of people do not express dissatisfaction’ 103,
and in the ISO 7730 (1994) which refers to the principle of thermal neutrality.104 In the
heat balance theory which was highly influenced by the pioneering work of Fanger105 the
basic notion is that any deviation from a balance between the heat produced by the
metabolic rate of the body and the body’s loss of heat to the environment will result in
varying degrees of discomfort as expressed by the PMV – the Predicted Mean Vote - of
the occupants.

Parallel to the development of the heat balance theory, the adaptive comfort theory was
being developed as an alternative philosophy, in part as a criticism of the weak points of
the heat balance model, in particular the inherent understanding of the occupant

103 Mary Ann Steane and Koen Steemers, ‘Environmental Diversity in Architecture’, in Environmental
104 Steane and Steemers, pp. 3–16 (p. 6).
105 P. O Fanger, Thermal Comfort: Analysis and Applications in Environmental Engineering (Lyngby:
One of the main differences between the two concepts is the shift in focus from physiology (bodily needs) to perception (psychology and behaviour). It is argued that the environmental conditions in the laboratory studies do not reflect real-world conditions in which a variety of environmental factors interact dynamically, and in which the occupant has varying degrees of control over the conditions. Using on-site observations it is found that occupants interact with their immediate environment in different ways, and show considerable tolerance to environmental conditions that would be unacceptable in the climate-chamber studies. When occupants have adaptive opportunities, - that is having the possibility of either adjusting the environment or adjusting their own activity, posture or position within it, - they are tolerant of a wider range of environmental conditions. A key finding is that this tolerance is not necessarily linked with actually changing environmental conditions nor behaviour, - the mere perception that adaptive opportunity is available is enough to increase tolerance by itself. As a result adaptive comfort is increasingly accepted as an important supplement to the heat balance theory and standards are changed to reflect this change.\textsuperscript{107}

The variety of physiological, psychological and behavioural factors is recognized in visual comfort definitions, listing illuminance levels, light distribution, glare and light directionality as visual comfort parameters affecting visibility. Visual amenity is a term accounting for the psychological factors in visual perception, - the influence of having outside views, the appearance of light patterns, apparent brightness and colour of light, privacy, social behaviour and health matters associated with light.\textsuperscript{108} The role of visual aesthetics are recognized in the term visual amenity, and achieving good light quality is the aim of Daylighting, - a design strategy aimed at extending daylight as far as possible into buildings for the longest period possible over the year, in order to offset energy use for artificial light.

While aesthetics and the sense of delight that may come from visual perception are recognized in visual comfort and amenity theory, this aspect has received relatively little attention in thermal comfort theory. Heschong’s ‘Thermal Delight in Architecture’ offers a philosophical study of the role the thermal environment plays in architectural and cultural expressions around the world. Necessity, Delight, Affection and Sacredness are the four levels of appreciation and interaction with the thermal environment Heschong identifies, in essence adding a philosophical superstructure to comfort theory. Necessity is the level at which thermal comfort in the technical sense operates, aimed at satisfying physiological needs and avoiding environmental extremes. Delight comes from a sense of aesthetic appreciation of the environment, that may very well be produced from sensations that would be deemed uncomfortable technically, such as experiencing strong heat, cold or light contrasts. Affection may come from the continued interaction between people, places and spaces that have perceived environmental qualities which are expressed in daily and seasonal cultural rituals surrounding them. This may even inspire a sense of sacredness, as expressed in the symbolic interpretations of the natural and the built environment found in many human cultures: the fireplace as the symbol of the life of a home in the temperate climates of the north, and the cool lush garden symbolizing the cycles of growth and decay in the middle-east. Reading Heschong with Maslow’s ‘theory of human motivation’ in mind – also known as the pyramid of needs, in which human motivation is ranked from the satisfaction of physiological need to psychological and spiritual self actualization, it is tempting to conceive of Heschong’s terms Necessity, Delight, Affection and Sacredness as a hierarchy of architectural design aspirations, placing technical comfort at the lower end, aesthetic appreciation higher and philosophical poignancy at the top. It would however be a networked sort of hierarchy with shortcuts to the top, as the mundane may inspire the sublime and the sacred found in everyday life.

Design Methods

Design methods may range from rational and systematic to empirical and intuitive in the design disciplines of the built environment, with a preference for the rational and systematic found in engineering and the empirical and intuitive in architecture. In a critique of overly rationalistic and determinist methods in planning and design, Rittel and Webber have effectively argued that design solutions can never be perceived of as true or false, but will always have to be judged as better or worse solutions to a design problem or demand, since solutions depend on the way that the design problem is defined. Design problems are ‘wicked’ rather than ‘tame’ and optimal solutions are never universally valid.\textsuperscript{110}

This notion has introduced some scepticism of rationalist methods in certain design cultures, particularly in the beaux-arts tradition, where the design process is understood as intuitive leaps guided by an empirically trained sense of adequacy of solutions. Contrary to this it can be argued that certain classes of design problems exist, and adequate solutions may be classified and dealt with according to overall design methodologies, relating design methods in an overall system.

Steemers’ Integrated Building Design System organizes an energy optimization procedure in discrete steps according to architectural scale, identifying four stages of optimization: Urban planning, Building Form, Façade design and building fabric. Each scale has a set of optimization strategies which can be cross-referenced in a matrix, allowing the designer to navigate the relations among them.\textsuperscript{111}

\textsuperscript{110} Rittel and Webber, 155–169.

Steemers’ Integrated Building Design System

Diagrams organizing the design process according to architectural scale can also be found in the IEA task 23 Integrated Design Process method\textsuperscript{112} and for daylighting in IEA task 21: Daylight in buildings.\textsuperscript{113} But where Steemers’ IBDS method emphasize passive solar design in the urban and building scale, the Integrated Design Process delves more into the role of mechanical and electrical engineering, and the IEA task 21 into daylighting façade systems and component. Taken together, these methods may constitute a fine grained web of design methods from urban to building component design, each complementing the others. Steemers studies include the influence of the urban context, using the LT-method of energy calculation, which does integrate energy use for artificial light based on daylight factors.\textsuperscript{114} Since the publication of Steemers’ results simulation technology has advanced considerably, and low-energy standards of construction are increasingly implemented. In this dissertation Climate based daylight modelling is integrated with advanced thermal simulations and energy modelling, giving


\textsuperscript{113} International Energy Agency task 21, p. 2.1.

much more detail to the dynamic character of buildings’ energy use and environmental performance.

The logic behind the way these methods organize design decisions according to architectural scale may follow two basic considerations:

The first, most pragmatic, consideration is the progress of project’s level of definition through the design process. As designs acquire more detail in the design process they also tend to become more cumbersome to change. Therefore the resolution of a design may generally advance from large scale to small scale decisions as a way of managing complexity. This notion does not exclude the possibility of going through several iterations in the design process testing various options at some level of detail.

The other consideration is the relation between energy quality and architectural scale. The way the daylight and sun is modified by urban context, building shape and the geometric and material properties of the façade is a spatial sequence in which the high quality energy state of light may be conserved or transferred to heat, each time it strikes a surface. The architectural scales relate to the ‘energy path’ of daylight and sunlight from sky to the inside of buildings where it is perceived by the occupants. As heat is a lower state of energy than light, this hierarchy is in principle given by energy quality as modified through the sequence of architectural scales it passes.

In this dissertation the emphasis is on the urban and building scale as in Steemers’ IBDS method, as these scales are typically the very first design considerations in the architectural design process. A methodological framework for environmental simulation is presented in paper III: Methodology appended to the dissertation.

---

Passive/Active – Selective/Adaptive

Originally the active/passive dichotomy stems from solar energy principles and describes whether a solar energy system requires mechanical or electrical power to operate.¹¹⁶ A passive system is able to operate with no or minimal mechanical or electrical power. This includes direct and indirect solar gains through the building envelope which can be enhanced using glazed constructions, and the energy stored in the building fabric’s thermal mass, phase change materials and the like. Even though some mechanical or electrical use may be used to operate or automate shutters, mobile shading systems and mobile insulation may be counted as passive systems. An active system is an energy conversion system requiring electrical or mechanical energy for its operation. Examples include Photovoltaic cells, pump-driven solar collectors and solar tracking systems.¹¹⁷ In energy optimization theory and practice it is generally held that ‘passive’ design should be optimized first, minimizing heating and cooling loads and maximizing daylight, thereby reducing the energy demand, before ‘active’ systems are integrated into the design supplying renewable energy.¹¹⁸

But the active/passive dichotomy is somewhat unsatisfactory as it addresses energy optimization primarily in terms of technical systems, be it building or energy technology. Are the occupants active or passive? How do they interact with the building’s climatic systems, be they electric or mechanical, ‘artificial’ or ‘natural’? More speculatively, we may even ascribe some sort of agency to the building itself, as its design delineates some spatial characteristics that condition the behaviour of the occupants as highlighted by Brand’s reworked quote of Winston Churchill: “First we shape our buildings, then they shape us, then we shape them again—ad infinitum. Function reforms form, perpetually.”¹¹⁹ The agency of buildings become even more pronounced when we think

¹¹⁸ Löhnert, Dalkowski and Sutter; International Energy Agency task 21; Peter Andreas Sattrup, pp. 49–55.
¹¹⁹ Brand, p. 3.
of their service systems, which are increasingly automated and regulated by sensors and
monitoring devices, whose workings and logics may escape personal experience and
control. There is a range of ways that buildings (and built environments) may play
diverse roles of structure and agency in an interplay with human behaviour, from the
long term influence of buildings’ relative permanence - their durability and adaptability -
on the requirements of their occupants to their everyday environmental performance
marked by buildings’ ability to accommodate the occupants’ physiological needs and
desires by offering adaptivity to changing environmental conditions.

**Adaptive Design**

In adaptive comfort theory, the term ‘adaptive’ may be used to describe both the
occupants’ physiological ability to adapt to changing environmental conditions and their
ability to interact with the building and its climatization systems, ‘adapting’ the
environment according to physiological or psychological needs or preferences. We may
elevate that to a design principle, and talk of ‘adaptivity’ and ‘adaptive design’ as a
design strategy focussed on offering adaptive opportunities to the occupants so as to
improve comfort and satisfaction with the environment. This use of the term ‘adaptive
design’ is parallel to the term ‘selective design’ introduced by Hawkes, McDonald and
Steemers, 120 referring to Banham’s three modes of environmental management:
conservative, selective and regenerative.121

Banham’s terms may offer a more suitable terminology for an architectural approach to
energy optimization than the passive/active dichotomy, as they may be redefined to
distinguish between effects caused by building physics, occupancy and the service
system. This semantic distinction is necessary as the role and effects of occupancy and
user behaviour are very different to those caused by building physics and service
technology. While it makes good sense to describe the building/service system in terms
of physics, user behaviour and interaction are essentially based in the realm of

120 Dean Hawkes, Jane McDonald and Koen Steemers, *The Selective Environment: An Approach to
121 Banham, chap. Environmental Management.
psychology and the social sciences, where the physics may only serve minor descriptive aspects. As it is necessary to understand the influence of user behaviour beyond the very reductive occupancy patterns used in energy calculations now, this distinction may open a road to better integration of insights gained from social science approaches to building performance in future research.

The three modes of environmental management - Conservative, Selective and Regenerative - may be used as a step by step procedure in energy and environmental performance optimization, first analyzing the outdoor environment, next understanding the way the building physics modify it in terms of eg. daylight availability, before the comfort needs of the occupants are added, and finally climatization technology driven by energy use. The mode may be redefined as follows:

**Conservative:** The environmental properties of the building fabric with no human intervention nor occupation. The building is described as empty: Windows and doors are closed, ventilation, heating and cooling systems are off, no one is in the building, it just passively receives energy flows: daylight, sunlight and temperature changes. This is an abstraction, as buildings are always serving utilitarian purposes, but it serves an analytical purpose in environmental simulation: It isolates the performance effects caused by building form and physics from the performance influenced by the occupants and service systems. Daylight availability, solar gains and temperature profiles may be adequate analytical tasks to perform at this stage.

**Selective:** In the selective mode, human occupancy is included in the analysis. The activities of the users add internal gains, humidity etc. to the building, and the requirements for energy use develops from the needs of the inhabitants. The occupants may interact with the building, opening and closing doors and windows, drawing blinds or curtains etc, and may interface with the technical service systems, eg. switching on and off light, heating and cooling. **Interfacing** is used as a term in recognition of the increased integration of information technology for building control.
**Regenerative**: This mode describes the effects achieved by the service systems. In terms of environmental simulation this is the setting of the heating, cooling and artificial lighting systems that modify the climate of a building to meet comfort criteria or create desirable environmental conditions. The service system may be integrated with the building fabric through *automation* of building components such as automated louvers, daylight redirection systems, automated opening of windows for hybrid ventilation strategies etc.


**Methodological Framework**

Now several frameworks can be defined that link the different scales surrounding a building project. Within the regulatory layers of the Urban Framework, we can use Brand’s layers to describe the Building Framework, which again frames the Performance Framework. Each of these operate at different time scales: The Urban and building Framework have time scales of centuries, decades or several years, while the Performance Framework works in yearly, seasonal and daily cycles.
By organizing these visually it is made clearer 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 environmentally and culturally sustainable buildings. The important message is that design choices need to be understood in the wider context of how they are conditioned by spatial and temporal scales, and how they condition other design choices.

As was discussed previously, design processes and methods can be structured according to architectural scale, and consequently Brand’s terminology of the shearing layers – Site, Structure, Skin, Services and Spaceplan is used to classify design issues throughout this dissertation, so as to maintain the link between energy and environmental performance optimization, resource management and life cycle considerations.

Each of the frameworks may be read as a guideline to parallel optimization sequences, depending on their relevance for a given design task.

Multi-dimensional framework for architectural energy and environmental performance optimization in a resource management perspective. Each layer frames design decisions on consecutive layers, but is also influenced in return.
Methodological framework including adaptive/selective design parameters.

Schematic representation of the methodological framework with a range of design variables added.
DANISH ARCHITECTURAL RESEARCH CONTEXT

The Danish architectural research literature on energy optimization is limited to relatively few studies which, as a consequence, inform the conceptual point of departure for the dissertation quite directly. The underlying reason for this lies in the history of the architectural education in Denmark which is strongly rooted in the tradition of the Beaux-Arts. This tradition has historically downplayed the technical aspects of architecture somewhat in favour of aesthetic and user-oriented design considerations. Only relatively recently have courses in architecture been offered at technical universities in Denmark.\(^\text{122}\)

This disregard may even be seen as a barrier to technical improvements in sustainable construction, as Lauring notes,\(^\text{123}\) and continues to outline the challenges to the profession: Either the architects will have to allow engineers and other consultants in on the initial design stages, thus assuming a more humble and collaborative role, or architects will have to integrate the necessary technical knowledge into the profession itself, - which in the Danish context could be a considerable shift in identity. The problem is not that the particular Danish breed of architects is without experience in sustainable architecture as Lauring’s account of the political and societal developments related to energy in Denmark since the first oil-crisis in 1973 shows, rather it is the lack of precision in understanding the appropriate technical issues and the misconception of a supposed contradiction between aesthetics and technical performance. Lauring’s subtle advocacy of a return to a Vitruvian model of architectural thinking which reconciles arts and sciences, is shared by many authors including myself,\(^\text{124}\) as elaborated on in chapter 2: Methods and in the paper Architectural Research Paradigms.\(^\text{125}\)

---

\(^{122}\) ‘Architectural Engineering’ at the Technical University of Denmark and ‘Architecture Design & Media Technology’ in civil engineering at the Universtiy of Aalborg.


\(^{124}\) Hawkes, McDonald and Steemers; Steane and Steemers, pp. 3–16.

The Vitruvian virtues Commodity, Firmness and Delight - or, as they also can be translated: usability, durability and beauty is a pivot point in the argumentation for ecology and aesthetics as central to an architectural definition of quality in Beim, Larsen and Mossin’s *Økologi og arkitektonisk kvalitet*. Beauty is here seen as a premise for durability, when durability is understood as a sense of connectedness between people and their dwellings, inviting a behaviour of caring for their maintenance and protecting the resources and collective memories embedded in them. This argument is reminiscent of Stuart Brand’s identification of “the High Road” – high cultural value invested in buildings over long time. But beauty is not the shallow surface appearance of images, Beim *et al.* point out referring to Rasmussen’s *Experiencing Architecture*. Beauty is in the human experience, engaging all the senses and relating sensation to the context of spatial, temporal, functional and symbolic aspects of architecture. Originally *aisthetikos* was the Greek word for *sensing*, and in this sense aesthetics can be seen as an ethical dimension to sustainability in architecture, as it is presumably instrumental in developing resource consciousness. With this framework of architectural philosophy in mind, a number of Danish and International buildings are evaluated qualitatively and discussed critically focussing on the articulation of environmental concerns in scales ranging from urban form to the details of building components. No attempts at quantifying the effect of design choices were made, however, though the building physics are an import aspect of the discussion of the cases’ design qualities. Moving a step closer to the specific effects of architectural design choices Sørensen and Larsen’s *RENARCH sustainable buildings* was organized according to a matrix of architectural scales and the related environmental impacts; whether these were addressing climate and comfort issues, or were part of an effort to minimize material use through efficiency in the construction phase, waste minimization etc.

---

126 Beim, Larsen and Mossin.
127 Rasmussen.
128 Beim, Larsen and Mossin, p. 9.
Danish energy performance research

The balance between embodied energy in materials and the energy performance of typical Danish Housing and construction types were described by Marsh, Lauring and Petersen in *Arkitektur og miljø*¹²⁹. Their report assesses a range of seven environmental impact parameters associated with typical materials used in the Danish construction industry including resource consumption, renewable and non-renewable embodied energy use, carbon, acidification, nitrates and end of life impacts. Assembling the materials in internal and external, light and heavy construction types, reflecting typical design choices, the relative carbon emission and embodied energy associated with each can be compared. At the level of the building, detached, terraced and apartment building types are compared, and the impact of construction choices – construction weight, insulation values, orientation and glazing ratios are calculated.¹³⁰

The choice of housing typologies reflect, in a simple way that allows for easy comparison by analogue, a span of designs typically found in the urban zones from suburb to city center. By choosing to assess low-tech constructions with higher thermal performance than required when the report was published in 2000, the authors achieved that the results are still relevant, now more than a decade later. The findings indicated that building form and construction insulation values were key energy use design parameters, and as a consequence, that the initial design decisions taken by the architect usually without consulting engineers, carry great environmental impacts. Thermal mass did only play a relatively little role, but was increasingly important with higher insulation levels and glazing ratios in order to exploit the increase in solar gains. It was observed that optimization of glazing to benefit from solar gains was a viable strategy, but very high south facing glazing ratios may lead to higher embodied energy use due to increased quality demand on the glazing constructions. A higher degree of use of wooden

¹²⁹ Marsh, Lauring and Petersen.

¹³⁰ The environmental impact calculations were done using the programme BEAT referring to the ISO 14040:1997 standard of Life-cycle assessment, and the heating energy use was calculated using BV95 a predecessor of the later Be06 and Be10 calculation programmes which are mandatory to use for documentation in Danish building regulations.

Marsh, Lauring and Petersen, pp. 12–19 & 118–129.
Construction types were recommended to the Danish building industry due to their low embodied energy and environmental impacts. Possibly a differentiated use of lightweight exterior and heavyweight interior constructions would serve to get the best performance in terms of both operational and embodied energy. In the relatively cold Danish climatic context heating is dominating the energy budget for housing. Cooling has until recently not been considered in energy calculations for housing as it was rarely used in domestic applications, but it is predicted that cooling strategies will increasingly be necessary as a consequence of climate change.

Embodied energy and operational energy use for residential buildings according to building type, glazing ratio and thermal mass parametric variations. Data from Marsh et al. reorganized and visualized according to site, structure and skin. It can be noted that in this study of low density residential buildings the site/structure scale has the greatest impact on energy performance as energy use is almost halved going from detached houses to apartment buildings.

The graph above is constructed on the basis of data from Marsh, Lauring and Petersen and shows the balance of embodied energy and operational energy use (heating only) in various housing designs, that reflect an investigation of the impact of different design parameters. Whereas the embodied energy content is given as a static figure, based on

---

131 Marsh, Lauring and Petersen, p. 11.
133 Marsh, Grupe Larsen and Hacker.
an average over the lifecycle of a building, the operational energy use for heating is shown as a gradient over time. Improving the operational energy performance leads to a flattening of the gradient, but still the embodied energy needs to be taken into account. A tendency towards increased embodied energy coupled with improved operational performance can be noted, but is not necessarily a given as Marsh et al point out, an observation which is reinforced by recent research focussing on recycling and low-embodied energy material strategies.\textsuperscript{134}

In a later report \textit{Arkitektur og Energi} Marsh, Grupe Larsen, Lauring and Christensen shifted the focus to a wider range of operational energy use related parameters, now adding daylight, artificial lighting, building services and renewable energy strategies to further elaborated studies of constructions and glazing. The energy performance of design choices were thematically divided into four themes: Daylight, Solar gains, Building core and Services.\textsuperscript{135} In addition to housing - this time using only two story terraced houses as a type, - offices were included on the basis of a 3 story building slab. As the emphasis was on optimization strategies for operational energy, the number and complexity of design parametric variations increased significantly in comparison with the single parameter energy related variations in \textit{Arkitektur og Miljø}. In each theme a number of design parameter variations are grouped into consistent optimization strategies to establish an overview aimed at architectural practice, which in a few cases makes it hard to distinguish the specific effect of individual design parameter variations.\textsuperscript{136}

Apart from analysing the energy performance of architectural design choices in the Danish climatic context in considerable detail, the report identified energy savings focussed on electricity as an issue for future research, as improved thermal performance of the building envelope were deemed to yield relatively smaller savings as research had until then been focussed on thermal performance. End-user energy savings for electricity

\textsuperscript{134} Berge.

\textsuperscript{135} My translation from Danish: Dagslys, Solvarme, Råhus og Teknik. Marsh and others.

\textsuperscript{136} As for instance when multiple design parameters; increased wall insulation, increased window insulation, increased window glazing ratio are grouped to maintain a constant average Daylight Factor in a housing unit. Marsh and others, pp. 42–43.
have higher associated primary energy savings than savings for heating due to the
efficiency of supply systems and the energy mix in Denmark, for which reason a 2.5
primary energy conversion coefficient were applied to electricity use compared to heating
when primary energy is calculated. The energy performance was calculated using Be06
which was released and made mandatory for documentation of compliance to the Danish
building regulation’s energy performance criteria previous to the report. Based on a
thermal calculation engine, Be06 added functionalities related to the service systems
performance and electricity use to the inventory of simulations.

The emphasis on energy savings for electricity was further reinforced in *Bygninger
Energi Klima: Mod et nyt paradigme.*\(^{137}\) Tracking a consistent and dominant increase in
the use of electricity in new-built housing and offices in the period 1975-2005 driven
mainly by increased use of electrical appliances and information technology, this
development was correlated with a scenario of a warmer future Danish climate reflecting
global climate changes which would lead to a lower demand for heating. A new paradigm
for low-energy buildings is discussed as a reaction to these macro-trends requiring a
holistic approach to spatial design, material selection integrating intelligent services and
renewable energy systems in buildings. The potential energy savings to be achieved by
adopting this paradigm are documented through simulating the cumulative effects of
each of these four strategies mentioned above for housing and offices.

Though the literature on energy performance in Danish architectural research is limited
to relatively few volumes, good understanding of key design issues has been achieved,
which is furthermore well integrated into policy and building regulations. But the
quantitative aspects of environmental performance have not been examined in much
detail in architectural, rather than technical research, and the impact of the urban scale
on energy and environmental performance is limited to a single contemporary study
*Sustainable Compact City*\(^{138}\) which studies and discusses a wide range of dense urban

---

\(^{137}\) Marsh, Grupe Larsen and Hacker.

\(^{138}\) Poul Bæk Pedersen, *Bæredygtig Kompakt By / Sustainable Compact City* (Aarhus: Arkitektskolens
Forlag).
typologies in both qualitative and quantitative terms, but has relatively little detail on the technical aspects of environmental performance and energy use.

**Initial interests and assumptions**

While essential relations between climate, architecture and energy use in the context of Denmark had been covered, many questions were left open for future research. How would the use of digital environmental simulation modelling play into the design process? Could visualization improve understanding and communication of the phenomena behind the energy calculations? How does a building’s form affect its energy use, and what is the impact of it’s urban context in a Danish setting? These questions have remained central throughout the research process.
CHAPTER 4: Observations
COPENHAGEN – THERMAL AND DAYLIGHT STUDIES.

During winter 2008/2009 and following spring and summer several observation studies were made in Copenhagen, using thermography, photography and video to capture and study phenomena of the thermal environment. Since most technical studies of urban environments have been addressing issues in warmer climates with relatively more sun than in Copenhagen,¹³⁹ this was seen as a first step towards understanding the impact of urban environments on buildings’ energy use and environmental performance in this specific context. The assumption was that the thermal images would make it possible to identify the spatial and temporal dimensions of thermal phenomena and therefore make the physics behind them easier to understand to persons with relatively little knowledge of physics.

The places and situations that were recorded were chosen to be representative of diverse areas of the city that have distinct building patterns: the medieval city centre, the modernist district around Vesterport, single family homes in the suburbs, and new urban developments at Ørestaden, Frihavn and Frederiksberg. Both urban environments, building envelopes, indoor environments and social situations were recorded, with the aim of visualizing environmental phenomena and behaviour patterns related to them. The approach is related to the empirical studies of urban spaces and human behaviour made by Gehl in ‘Life between Buildings’¹⁴⁰ though the focus has been changed from documenting social patterns as affected by urban design, to studying the environmental phenomena as results of urban and building design, and their implications for social patterns.

¹³⁹ Which is not surprising due to its position at the northern periphery of Europe. Comprehensive works on urban climate and building energy use such as Matheos Santamouris and Demosthenes N. Asimakopoulos, Energy and Climate in the Urban Built Environment (Earthscan, 2001), have few references addressing the particularities found in this context.

The urban environment is the first layer that mediates the natural environment, the building is the next. Our clothing is the last layer.\textsuperscript{141} As a key strategy in sustainable architectural design is to create high comfort with minimal use of energy it is important to understand the urban microclimate as a context for urban environmental quality and the energy and environmental performance of buildings.\textsuperscript{142} The interpretation of the images is influenced by recent research on urban comfort, which move the attention from physical and physiological factors of comfort to include psychological factors and adaptive behaviour.\textsuperscript{143}

Thermography is based on the principle that energy can be transferred as radiant heat as we know it from sunlight or from the embers of a bonfire. According to the laws of thermodynamics all bodies give off electromagnetic radiation according to their temperature. Human eyesight has evolved to register only a narrow spectrum of radiation which we perceive as light, but most radiation is outside the visible range as either ultraviolet or infrared light\textsuperscript{144}. Our environment and our bodies radiate heat as infrared light, which a thermal camera can detect and process into images. In order to process the images correctly, one has to know the emissivity of materials, as this affects the calculation of temperatures. Emissivity is connected to surface roughness and physical properties of materials which makes it a bit complex to interpret images where several materials are represented. Particularly glass and metal temperatures are difficult to measure. For this reason one should be cautious about reading the surface temperatures of these materials in an image as absolute values, as the image processing is most likely based on the emissivity of less reflective or conductive materials as it is in the thermograms presented here.

\textsuperscript{141} Dahl.
\textsuperscript{142} High Comfort Low Impact: Transsolar ClimateEngineering, ed. by Monika Lauster and Erik Olsen, 1. edn (fmo publishers ohg, 2008).
\textsuperscript{144} Not counting the extremes of electromagnetic radiation eg. x-rays, radio etc.
In the construction industry thermography is usually used as a tool to measure the performance of the building skin in order to find construction errors like lack of insulation and thermal bridges etc. The traditional focus on thermography sees it first of all as a measuring tool, where the focus is on the accuracy of measurement and elimination of possible causes of error. What counts is the absolute value of the measurement. In these studies it is different. In photography it helps to know about the properties of light to make a technically good image. In thermography one needs to have a basic grasp of thermodynamics.

But thermography generates images on many more levels: It allows us to see the invisible, - how our environment and bodies are constantly in a dynamic exchange of energy as heat. It allows us to perceive the physics of energy transfer visually as a spatial and temporal phenomenon. It allows us to record, document, understand and possibly act towards optimize these energy flows in relation to our needs. They show us a picture of our sensed experiences of the world, the space of heat, which we otherwise perceive subliminally through the skin.

The attitude here is that of a photographer which is intent on finding and telling a story and in the process improve understanding of the invisible energy exchanges in our environment. As they become visible they potentially create a culturally significant image of our relationship to energy and climate in the built environment. The studies presented here were exhibited at the ‘Green Architecture for the Future’ exhibition at the Louisiana Museum of Art in 2009 and have been used as instructional material in the education of architects.

In terms of the research process, making these thermograms provided a learning experience in the physics of the environment, and the many ways the built environment affects our social life by offering environmental qualities and opportunities if not challenges when conditions are adverse. The experience gained from making these images and interpreting them have deeply informed the subsequent research process, as they gave an idea of the qualitative assessments, be they conscious or subliminal, which we continuously make of the environment surrounding us, reading it with our own purposes and intents in mind. Understanding energy as environmental opportunities and
qualities with spatial and temporal dimensions provided a key to interpret later simulation studies beyond the technical results of energy efficiency and add a discussion of the relevance of simulation results in terms of quality of life.
The Medieval City

The "Urban Heat Island" is the name for the phenomenon that temperatures in the center of a city can be several degrees warmer than at the periphery and the surrounding countryside. In most parts of the world the main cause of urban heat islands is solar heat trapped in the semi-closed space between buildings - 'urban canyons' as it is called in urban climatology – due to the concentration of heavy, heat absorbing materials used in cities and the low wind speeds at street level. On a cold, overcast, foggy January day in Copenhagen with air temperatures just around 1°C, the main cause is waste heat from buildings. The massive brick walls of the historic houses have low insulation values, and heat continuously seeps through the walls, warming the air in the streets. We see the

---

effect as a reddish haze on the horizon, broken only by waste incineration chimneys and clouds of steam that indicate heating of the moist air in, and just above - the city. Rooftops and the horizon are the dominant elements. Some places the top floors are inhabited in which case they are insulated, elsewhere they are not and remain as empty cold attics. In the dense city where connectivity is high and the cultural scene is most dynamic, insulating and inhabiting these top floors may reduce energy use while increasing the density of the city and thus further reduce energy consumption for transportation.

The greenhouse effect in action
The sky is mirrored in the VM houses' glazed facades. What appears to be an almost uniformly overcast sky turns out to have different temperatures, depending on the thickness of the cloud cover. The water vapour of the clouds is heated from below by heat radiated from the surface of Earth, forming an insulating layer in the atmosphere. What we see is the ‘Greenhouse Effect’ in action.\textsuperscript{146} The image demonstrates the

\textsuperscript{146} Water vapour is in fact a much stronger greenhouse gas than carbon dioxide, but one which is less directly influenced by human activities. Arrhenius, 237–276.
essential physics of heat transfer through glazed facades. The glazing is opaque to the infrared radiation which it reflects, allowing the façade to work as a selective device keeping the absorbed heat inside. The shown surface temperatures of the glazing should not be taken at face value, due to the low emissivity of glass and reflected infrared from the surroundings can’t be detracted from the shown values. The temperature of the window frames are more precise markers of the heat losses through the façade.

The Atrium
The building is shaped around the themes of daylight and heat, presenting a fully glazed façade with distinct vertical louvers for sun protection to the outside and a generous atrium on the inside, where daylight is filtered and modulated through circular openings in the roof. In office and educational buildings like this, the challenge is often to filter the light to avoid overheating while creating visually comfortable light conditions with adequate light levels without glare inside, minimize energy use for cooling and lighting. On a winter’s day with overcast sky, the atrium skylight and the view to the outside street creates a pleasant visual environment, where the bluish cool colour tone of the skylight is supplemented with warmer toned artificial light. The heat from occupants and
their electronic equipment is not sufficient to heat the house on such a day. The thermogram reveals a technical strategy which is almost poetic: Below the stone floor is an underfloor heating system, which appears as a landscape of molten lava radiating heat, warming the air in the atrium. The slowly rising air contributes to keeping uniform, comfortable temperatures on the balconies.

Modernist urban space

The area around Vesterport, Buen and the Scandinavian Airlines hotel is one of Copenhagen's most heroically modernist urban spaces, celebrating traffic and the means of mobility, cars, trains and planes. In the parking garage on the first floor of the Imperial building, commuters leave their cars to cool after the ride into town from a home in the periphery. At street level it is clear that not all the petrol goes to propulsion alone - the heat from the engines, brake friction and air conditioning makes a contribution to cities' warmer climate.

The openness of the railway tracks and the many variations in building form and height creates a local climate which is very different from that of the narrow streets of the historic centre. On windy days the tall buildings and the open structure creates
turbulence which may result in lack of comfort, as the wind chill factor increases body heat loss. The links between city form, climate and energy use is an area to be studied in connection with future transformations of the city.

**Urban life, Comfort**

People walking the commercial centre display very different ways of adapting to the winter cold. Eating a bit of warmth at the sausage stall, wrapped up in full-body snowsuits on a kindergarten excursion, ladies in fur, builders in thin sweatshirts and teens clad in next to nothing, reveal that comfort is individual and can not be reduced to a matter of being hot or cold. With children and the elderly the interest of health is primary. The builders can maintain a comfortable body temperature as physical activity increase their metabolism rate, and allow them to stay warm. The teenager prefers to display attractiveness rather than wearing a heavy coat to keep warm, and that is likely a reason why they can be observed migrating from one store to the next, minimizing the duration of their thermal exposure, while carrying a bit of the heat from inside with them in the surface of their clothes as long as it lasts. Comfort – in the sense of feeling at ease – is dominated by a preference for displaying social identity in this case. Comfort is a
matter of perception, depending on activity and psychology, in addition to a question of maintaining the body’s heat balance.147

Our House – in the middle of our street
This terraced house was built as part of a cooperative workers housing development in 1901 inspired by the English garden city movement as a reaction to the cramped conditions of speculative housing in the centre. While it originally consisted of three apartments, each the home of a family, it has now become a single family home, and the area has become a popular place for families with children. Massive brick wall construction with timber decks and slate roof, the building was recently remodeled and renovated inside, with little attention to energy optimization other than replacing the windows, insulating the roof and installing district heating, which in Copenhagen is mostly based on waste incineration. The residential program of the building is revealed by the different intensities of heat visible on the façade: the bright colour of the ground

147 The observation emphasises the points made on psychological adaptation made by Nikolopoulou and Steemers, 95–101.
floor windows show that the living room and kitchen are the warmest rooms of the building. Above are the children's rooms - a little colder, and the bedroom in the top floor is so cool, but better insulated, that it is represented as a shadow in the masonry below the roof. Craftsmen have been sloppy with the vapor barrier in the roof. The luminous streak across the roof surface shows heat escaping where the attic floor meets the surface of the roof, and the barrier is missing.

On the inside the temperature difference between the bedroom and the kitchen/living room is clearly visible as a difference in background color. In the bedroom local temperature differences on the underside of the roof show thermal bridges in the construction. Sharing stories after coming home from school, doing homework, preparing food - the kitchen/living room is the heart of the home, with a lively and dynamic environment. In winter it can be warmed by lighting a fire in the fireplace, in the summer it has access to the warm front garden facing south and the cool terrace at the back.

My family, whose home it is, migrates from one floor to the other, and from one climatic condition to the next according to the daily and seasonal rituals of life, gradually moving upstairs to the cool bedrooms when it is getting late, moving outside in spring, moving back in when the outdoor season ends in October. The living room has a very dynamic interior climate. Variations in temperature set the air in motion, heat rising from the radiator, cold air falling at the bottom of windows and un-insulated walls. The air movements can be seen as traces of convection particularly along the edges of windows and above the radiators. While the average air temperature may be quite high, this space may still be experienced as slightly uncomfortable on a cold winter’s day.

During winter, a surprising daylight phenomenon may be observed. The House faces directly south, and the low sun angle means that only the top floor receives direct sunlight, while the lower floors are overshadowed. The buildings in front of the house are all of the same type, but behind it is a 5 storey housing block with white painted balconies and a highly glazed, faceted façade. And while the height of this building interferes with the view of the sky to the north and decreases diffuse daylight availability, it is the opposite on sunny days: reflected light enters the house from the
north, and may even be more abundant in the lower floors than light entering from the south façade which is overshadowed from November to the end of March. This phenomenon is examined thoroughly in later simulation modelling studies, as it showed to have a considerable impact on daylight availability in dense urban situations, and had a discernible effect on energy use for lighting.\textsuperscript{148}

\textsuperscript{148} See chapters 5, 6 and 7 and Papers I, II and IV.
Sunspot

Come spring, the mood of the city changes radically as the outdoor season suddenly starts. While the air is still chilly, one may find these sheltered spots in the old city where there is no wind, and the orientation of the street is just perfect for the sun to penetrate to the bottom of the street. The triple thrill of sitting here warmed by the sun, chilled by the air with the knowledge that the summer will be here soon inspires an atmosphere of excitement and inspiration in this place, among these people. The sense of relief after 6 months living inside, enduring the lack of light, is tremendous. Most northern Europeans would probably agree that there is no better place to be than in a sunspot on a spring morning.
What we see is an environmental situation which goes beyond the normal definitions of comfort, where too strong contrasts are avoided both in the visual and thermal environment. The contrast is the whole point, which changes the situation from comfortable to delightful. With air temperatures below 15°C it should be too cold to sit still, but the direct sun in combination with the dark, heavy façade of the café (shining bright with heat in the thermogram), and the little nook in the street which creates shelter from wind creates a microclimatic situation which has strong stimuli and contrasts. Being both too cold and too hot, depending on which side and how much of the body is exposed to the sun, the whole situation is charged with the surprise that it suddenly is spring and the latent expectation of even better times to come. The preciousness of the occasion is marked by the sharp line of the shadow on the floor, marking the precise spatial limit of the attractive zone. No one lingers in the shadow, except if moving. Elsewhere, one may find rare spots like this as street levels are still quite overshadowed in spring, and generally it is too cold to sit still outside with light clothes on like this. A sunspot like this is hot property in more than one sense of the word. The situation demonstrates that urban form and materials may modify the local microclimate by creating shelter and permitting solar access at given times of the day, and thereby prolong the outdoor season significantly at specific places. This is crucial information to the architect who wants to create a building in an attractive site.  

149 The idea of using urban geometry and material selection to create sunspots with a benign urban climate was used in the Carlsberg case study, where a sunspot was created for the central square of a university campus, by arranging urban geometry to allow solar access from early spring to late fall around lunch time for outdoors eating opportunities in an otherwise extremely dense urban setting by Scandinavian standards.
Curved Canyon

Returning to the modernist ensemble at Vesterport, it has now become summer and the whole city has warmed up. On a calm summer day, one may feel at ease sitting anywhere without feeling cold. The design parameters that influence urban comfort are now different, rather than the heat/cold balance it becomes a question of whether one is exposed to wind, noise or pollution. The image from Buen – a street called ‘the Curve’ – shows how solar radiation is converted and dispersed in the urban space as light and heat.

The space between buildings, - the Urban Canyon as it is called in urban climatology,150 plays a crucial role for the energy conversion of solar radiation as light and heat. As the solar radiation hits the façade on the south facing façade of the street, it is either

150 Oke, 237–254; Oke, 103–113.
reflected, absorbed or transmitted depending on the properties of materials in the façade. The reflected component of the radiation may be perceived as light by our eyes, while the absorbed radiation is accumulated as heat in the material and may be reemitted as infrared radiation, conducted through the wall, or may heat the air by convection.

As these buildings are mono-functional office blocks, the image also shows that sun and daylight can be too much. All sun exposed windows have their shades fully drawn, to protect the office workers from overheating and glare, when the incoming sunlight produces too strong visual contrasts inside the building, interfering with the visibility on computer screens. Drawing the blinds on a sunny day may have the ironic effect of blocking out light, and therefore result in higher use of electricity to compensate the resulting lower daylight levels. New methods and metrics have now been introduced that allow the effects of direct sunlight to be included in climate based daylight simulations, drawing on climate data for specific geographic locations.\textsuperscript{151} The reflected light from the sun facing façade may also contribute quite considerably to daylight levels inside the building opposite and distribute it deep into the lower floors.\textsuperscript{152} Linking climate based daylight simulation with thermal simulation and energy calculations is a very recent technological advance in simulation technology that has made the simulation studies in this dissertation possible.


\textsuperscript{152} See chapters 5, 6 and 7 and Papers I, II and IV
Terraced House

As summer has arrived a street sheltered from traffic and wind may become a childrens’ paradise as they can play unhindered and visit each others’ gardens and homes. The microclimate of the sheltered front gardens is significantly warmer than that of a nearby main street where openness to the wind allows for a stronger influence of the urban mesoclimate. On windy days, My family and I often find ourselves wrongly dressed for the weather as we exit the shelter of these tiny streets, and are exposed to the full influence of the urban weather conditions. The local micro climate is generally very benign, and the outdoors season starts sooner and ends later than in less sheltered locations. As temperatures may build in a prolonged period of high pressure, the heat may even be a bit too much in the afternoon, though the plants offer some modification due to evapo-transpiration (plants ‘sweat’) and shading. It is good to have a cool backyard to migrate to, on the northern face of the house.

As the house is facing south it gets the most exposure out of available solar energy, though the traditional windows are smallish and the glazing ratio compared to the area of the façade is only 11%, reducing the passive solar heating effect considerably. The windows were recently replaced and the roof insulated, which most likely is a significant part of the explanation why the energy use for heating in this home is in the lowest quartile of the same type of buildings in the area. The walls are still un-insulated. Since the buildings’ architectural expression is protected by planning regulations, energy optimization strategies are limited to replacement of windows, adding roof and wall insulation and installing efficient service systems and appliances. Occupant behaviour is probably a very significant factor in these buildings’ energy use, as a survey found a very wide range in occupant energy use for heating, which could not be explained by differences in the buildings’ technical state.

---

153 This effect is examined in paper I and III.
154 As found in a survey made by Søren Borch and myself for the energy commission of the owners’ association.
155 Ibid. Same survey supplemented by energy calculations using the Danish regulatory software Be10.
The south facing orientation of the building is good for passive solar heating but bad for daylight, which may come as a surprise. On overcast days, this has no influence as light is evenly diffused by the sky. But on sunny days the living room / kitchen on the ground floor which is the social heart of the home often appears quite dark, and light is turned on to compensate. Why?

The explanation is that most of the weeks days are spent at work or in school, and this space is thus experienced in the early morning and the late afternoon and evening. While it makes no difference in winter, when the outside is dark at these times of the day and light is continually turned on, it makes a great difference once the light is back in the streets. The problem is that in these peak periods of occupancy (7-9am and 3-9pm) the sun rays are almost parallel to the façade, and lights up the streets but do not penetrate deep into the interior. As a result the interior appears dark, as the contrast between outside and inside is strong.
Again, as described for the winter season, where reflected light bouncing off the neighbouring building to the north may contribute more to the daylight levels than the sky to the south, the housing block at the rear of the house comes to our aid. As it is quite reflective and has faceted glazed facades at varying angles to the sun, it reflects light into the ground floor at times when there otherwise would be little light. In the morning, for example, light comes in from the east, but is redirected by the faceted façade and mirrored into the backside of our living room, giving an effect which may be delightful and add something to the daylight levels of that space.

For every 15 degrees change in horizontal orientation the sunlight exposure is shifted one hour and may be better aligned with the daily rituals of life in a building, increasing or decreasing the time interval and radiation intensity as deemed best according to design intentions. Similarly, the effect may be used for seasonal changes, if applied vertically. If this effect is more precisely used, when urban areas and buildings are planned, it may become part of ‘urban daylighting’ strategies in urban and architectural design, just as daylighting is a design strategy when designing buildings’ facades and interiors. The concept of urban daylighting is just beginning to take shape in this dissertation, and should be further developed with future research.

---

156 This idea is used in the Carlsberg case study, and contributed, along with other design principles, to a significant overall increase in daylight availability in the urban space. See chapter 6: Return to Practice.
Approach

This chapter analyses and discusses architectural practice in relation to sustainability and energy optimization through interviews with representatives of two architects’ offices and one engineering office. Through interviews with partners and associates of these offices two themes are investigated: 1) Design philosophies and 2) Design methods related to energy optimization. The interviews are supplemented by literature studies on the work of the offices. Within the theme of Design methods a subtheme related to the use of simulation modelling in the design process were developed. The design philosophy of the three offices emphasizes different aspects of environmental performance, reflecting both the professional divide between architects and engineers, but also different points of departure in design culture. Yet, some common themes emerge as common interests and shared notions underlying the individually articulated projects.

Figure: analytical structure of the interpretation of source data from interviews

While the architects follow different design philosophies, and have different design methods, environmental simulation modelling is used in all three offices to qualify design choices. Some differences can be observed as to the roles of collaboration among
architects and engineers, and as to the understanding of environmental qualities. The architects share a notion, more or less directly expressed and founded on diverse aspects of environmental design, that architectural scale is roughly related to the environmental performance of buildings, in the sense that the bigger the scale, the more impact it has.

Analysing the interviews, it is found that this idea of impact related to scale may form the base of a decision-making hierarchy, as architectural design often, but not necessarily, progresses along a path of increased level of detail – from urban scale decisions such as massing and orientation to building detail decisions such as space-plan layout and façade details. If the relative impacts of each scale on building energy performance can be identified, the information may serve to help designers identify which specific design decisions at different scales have most impact on the energy performance of buildings – a ‘hierarchy of scales’. But does it make sense to identify such a hierarchy of scales? Does it even exist? The idea of a hierarchy of scales is the background for the design of the simulation studies in subsequent chapters, where each simulation study highlights an aspect of the impact of urban scale design decisions on building scale design.

Over the course of the first year and a half of the research project (March 2008 - September 2009), a number of interviews were carried out with practitioners in architecture and engineering whose work demonstrated experience and/or innovation in the field of sustainable design. Following a grounded theory approach to qualitative research, the interviews were intended to probe the state of the art in architectural design practice in order to let new theory emerge from the collected data. As qualitative research the intention is not to prove or disprove a hypothesis but rather to describe the complexities of a dilemma or situation, possibly but not necessarily arriving at a hypothesis. In this sense the research questions guiding this phase of the research are: *How do these experts understand sustainable architecture? Which design methods do they use for energy optimization? Which performance aspects do they consider most important?*
The increased attention to environmental matters in the public debate and the rapid
development of simulation software in the time that has passed since the interviews
were conducted means that the interviews represent a relatively short period in time,
(2008-2009) and the views expressed and practices investigated may have changed to
some degree in the meantime. The practices of integrating environmental considerations
and simulations in the design process, that then were unique capacities of a limited
number of practices, have become much more commonplace, as simulation software has
seen a great increase in availability and user-friendliness and are now marketed directly
at architects. In the Danish context the interviews have been widely disseminated as
they were either published in the Danish Journal *Arkitekten* or as part of the exhibition

**Interviewee profiles**

**Dietmar Eberle** is co-founder and owner of the office Baumschlager Eberle Architekten,
and a Professor in Architectural Design at the ETH Zürich. Baumschlager Eberle
Architekten was founded in 1985 and has received a number of awards for sustainable
and energy efficient design.\(^{158}\) Dietmar Eberle was interviewed in Zürich 16 June 2008.
An edited version of the interview has previously been published in the periodical
*Arkitekten*.\(^{159}\) The interview has since been supplemented by information from a lecture
that Eberle gave in Copenhagen on the use of digital tools in the architectural design
process, as well as literature sources and conversations with former employees of
Baumschlager Eberle.\(^{160}\)

**Matthias Schuler** is founding partner in Transsolar ClimateEngineering in 1992 and co-
author of the TRNSYS environmental simulation software. He is an adjunct professor of

\(^{158}\) Resources and Architecture - Baumschlager-Eberle, ed. by Gert Walden and Gernot Schweigkofler

\(^{159}\) Peter Andreas Sattrup, 42–43.

\(^{160}\) Dietmar Eberle, ‘Sustainable Building Design · Principles and Tools’ (Royal Danish Academy of Fine
Arts School of Architecture Copenhagen, 2009).
Environmental Technology at the Harvard University Graduate School of Design. Transsolar is recognised for its innovative work in environmental engineering design and its collaboration with Foster and Partners on the Masdar City project. Matthias Schuler was interviewed 22 August 2009 in Copenhagen, where he gave a lecture ‘High Comfort Low Impact’. An edited version of the interview has previously been published in the periodical Arkitekten.¹⁶¹

Stefan Behling and Gerard Evenden are both senior partners at Foster & Partners, responsible for sustainability and the design of the Masdar urban masterplan respectively. Irene Gallou and Bruno Moser are associate partners and members of the Specialist Modelling Group (SMG) - an internal unit within the office that is specialized in parametric and simulation modelling and works as consultants to project groups within the office. Foster & Partners was founded in 1992 in continuation of Foster Associates founded in 1967, and is one of the most published and influential offices in sustainable design worldwide. The interview with Behling and Evenden was commissioned by the Louisiana Museum of Modern Art and appeared in the ‘Green Architecture for the Future’ exhibition catalogue in 2009.¹⁶² The interview with Gallou and Moser has not been published previously.

¹⁶¹ Peter Andreas Sattrup, 58–59.
¹⁶² Peter Andreas Sattrup, pp. 49–55.
DESIGN PHILOSOPHY AND SUSTAINABILITY

Social acceptance

While the surface appearance of the work of Foster & partners and Baumschlager-Eberle suggests widely differing design philosophies at first glance, the notions on sustainability in architecture behind it are remarkably similar, yet articulated with emphasis on different aspects of sustainability. The energy use of buildings and built environments is identified as the single most important design parameter to work with to improve the sustainability of architectural design among many other issues.  

However, sustainable architecture is seen as something which goes beyond optimization of technical criteria of resource management and environmental performance, engaging the cultural sphere of architecture. Both offices stress that the key criteria for sustainable architecture is to achieve social acceptance of the design through its cultural contribution to its immediate context and society at large. “It’s the cultural value of the building, the social acceptance, that gives buildings a very long lifetime”, says Eberle, while at Foster and partners Evenden notes that “Many people have an image of sustainable architecture as something to do with plants and solar cells all over it. Lots of doodahs everywhere. But it’s much more important to create a place for people that they can relate to. If that doesn’t succeed, no one will accept it.” Without achieving social acceptance, a building risks being demolished after only a short functional lifetime,

---


164 Resource management is understood here as the consideration of material and economic resources in the architectural design process, and its subsequent implications for the building’s transformation over the course of its lifetime. Resource management encompasses environmental performance through the aspects of energy use and related issues of comfort and productivity.

165 Environmental performance is understood in this context as a building design’s (or a built environment’s) ability to modify the natural environment according to specified design intents and performance standards, in particular daylight metrics, indoor comfort definitions and energy use.


167 Behling and Evenden, note 45.
wasting the considerable resources invested in them, as Eberle states with irony: “I don’t judge them, - history judges them. You know what history does with a lot of these buildings? History tears them down! Because you cannot use them anymore. I think that’s not responsible in relation to the problem with which we are confronted during the next 20 years.”

The above remarks indicate some differences in the approach to sustainability of the two offices. Where Foster and partners are particularly interested in the environmental performance of their designs and take that as a point of departure towards energy optimization, Baumschlager-Eberle are more concerned with resource management as an approach to energy optimization in architecture. Some particularities of their approach to design methods, energy optimization and environmental performance can be discussed by highlighting particular aspects of their approaches. Highlighting aspects such as ‘adaptability’ in the work of Eberle, ‘environmental performance’ with Foster and partners and ‘adaptive comfort’ in Transsolar’s approach, does not imply that the others don’t share the notions expressed, it just means that that it is articulated with particular attention which makes it a suitable starting point for discussion.

Highlighting Durability and Adaptability: Baumschlager-Eberle

A particular emphasis in the approach of Baumschlager-Eberle is a life-cycle oriented concern for resource management expressed as an interest in creating durable, long-lasting design solutions, thus protecting the resources invested in the buildings, - including the embodied energy of the building and its processes of transformation. This is done by designing for generality of use, so that buildings can be easily adapted for many different uses over their lifetime.

“How can we learn to balance this relation of resources and people much more efficiently than we did in the last 30 years? What does it mean to architecture?...

So what can buildings do? They can have a very long lifespan. Because this is the most effective way to reduce the percentage of resources used for buildings.\(^{169}\)

The fundamental condition for a building to have a long functional life is believed by Eberle to be offering beauty, utility and comfort by placing itself into its surroundings and in the collective consciousness, making a functional and cultural contribution in the public domain. To Eberle, working in continuation of an architectural tradition is a way to promote the social acceptance of the building, and to ensure that the resources invested in the building are protected, as buildings are perceived as aesthetically and functionally valuable.

According to Eberle, an important question is how to establish a coherent methodology\(^ {170}\) in architectural design. That is, how to establish a hierarchy of decisions in the design process so that sustainability in architecture is not just applied technical solutions, but is an integrated holistic approach to architecture.\(^ {171}\) A key to this question, in Eberle’s view, is that buildings change over time. By accepting the premise of change, architects can make the most of resources by managing them through material selection and designing for durability and adaptability, thereby allowing clients and future owners the greatest possible freedom of managing the same resources over the lifetime of the building. This notion of the importance of durability and adaptability is shared by Foster and partners, but with a twist towards considering environmental performance and recyclability: “You will have to design the building so it is flexible and can have a long life, and that includes assessing the relationship between materials and energy. You can for example choose materials that have taken a lot of energy to produce, but which extend the life-cycle considerably. It could even happen that after 50 or 100 years these

---


\(^{171}\) Methodology is understood as a design culture but also as a rationalist approach to design decisions. Eberle, ‘Interview, Baumschlager-Eberle - Sattrup 2008-06-16’, pp. 2–6.
materials will have increased in value because they are recyclable... The important thing is the totality, the overall design.”

**Highlighting Environmental Performance: Foster and Partners**

Foster and Partners highlight the use of architectural design in achieving environmental performance, typically directed towards reducing energy use by efficiency of operation. Form is used to make the most of climatic potentials in order to create comfortable and potentially delightful environmental qualities, minimizing adverse effects: redirecting daylight, provide shelter and shading, diverging local wind patterns to drive natural ventilation.

“Today I would call it ‘form follows performance’. The performance of the building is crucial... What should a building’s performance criteria be? Those things have to be defined in terms of energy and sustainability. But buildings are only the top of the iceberg... You have to relate to the city and the infrastructure. You can’t solve the problem with buildings alone.”

In the work of Foster & partners, form is a primary element in achieving design performance to such a degree that it is suggested that ‘form follows performance’ in what appears as a slight twist of the early functionalist credo ‘forms follow function’. But what is implied in this twist? A technical meaning of the word performance is “how

---

172 Behling and Evenden, note 15.
173 Behling and Evenden, p. 27.
174 Peter Andreas Sattrup, pp. 49–55 (p. 51).
175 The phrase was originally conceived in 1896 by Louis Sullivan in his description of the high-rise office building type. In Sullivan’s terms, function is a richer concept than mere utility: “It is the pervading law of all things organic and inorganic, of all things physical and metaphysical, of all things human and all things superhuman, of all true manifestations of the head, of the heart, of the soul, that the life is recognizable in its expression, that form ever follows function. This is the law.” Louis Sullivan, ‘The Tall Office Building Artistically Considered’, Lippincott’s’s Magazine, 1896 <http://academics.triton.edu/faculty/fheitzman/tallofficebuilding.html> [accessed 5 October 2011].
well a person, machine, etc. does a piece of work or an activity”,\textsuperscript{176} indicating that it is not the function itself, - the activity or work, - that is in focus, it is how well or efficiently it is done according to the expectation or standards it is compared with, or measured up against. Whereas the early functionalists would express spatial programme or the process of manufacturing in the design, the introduction of performance instead of function to the statement shifts the attention from the expression of basic functionality to relative functionality, or in another word, efficiency.

With the declared interest in performance and efficiency also comes an interest in the process of optimization, looking at how to improve performance of design which again, in the long run, is likely to create new levels of expectation and higher performance standards.

Form is seen as one of the main instruments in the architectural inventory to achieve environmental performance, from the aerodynamics of the SwissRe building driving a natural ventilation system to the daylight distribution system in the dome of the German Reichstag. But the focus on performance is no mere functionalist exercise, aimed at compliance to a set list of performance criteria,\textsuperscript{177} - it also carries with it an expressive force, which may even become the basis for a project’s identity as a design icon, as Evenden describes:

“The interesting thing about SwissRe, Commerzbank and the Reichstag in Berlin is not that they are iconic buildings because of their form or architectural character. The interesting thing is that everything in them has a function, and that function is driven by studies of the sun, the light, the movements of the air, the place, the way people occupy the building, their needs ... That’s what drives the form of the buildings, and that’s what gives them their iconic nature.”\textsuperscript{178}

\textsuperscript{176} Here, we may substitute building for person or machine - dictionary.cambridge.org, ‘Performance Noun (DO) - Definition in British English Dictionary & Thesaurus - Cambridge Dictionary Online’ <http://dictionary.cambridge.org/dictionary/british/performance_1> [accessed 27 September 2011].

\textsuperscript{177} Such as the varying Green Building assessment systems such as LEED, BREEAM, DGNB etc.

\textsuperscript{178} Peter Andreas Sattrup, pp. 49–55 (pp. 50–51).
Form is both a result of analysis of the environmental context and an instrument which modifies it according to the design intents which include functions that are both utilitarian and, particularly evident in the Reichstag, symbolic. In this sense, form unites architectural articulation and modification of natural and social forces, from the functional aspects of utilitarian purposes to the construction of cultural identities.

Highlighting Adaptive Comfort: Transsolar ClimateEngineering

“It is much better that people understand that they should not submit themselves to a mechanical control system but rather be active themselves!” 179

Transsolar has become an internationally recognized climate engineering office which despite its relatively modest size has won commissions in Europe, Northern America, the Middle East and Asia in collaboration with many different architects. One of the keys to Transsolar’s success seems to be its early shift of attention from designing only building services as conventional mechanical engineers would do, to understanding the whole building and its immediate environment as their design object. In Transsolar’s understanding, the building fabric, rather than its service systems, should do the main work of modifying the natural climate. 180 In order to achieve environmental performance

180 Lauster and Olsen, p. 3.
through architectural design, which Transsolar as an engineering company can only influence indirectly, Transsolar place a strong emphasis on the importance of communication within the design team in the very first design stages.

Referring to a case where Transsolar was involved in the renovation of Mies van der Rohe’s Crown Hall at the Illinois Institute of Technology, an ethics of user involvement is introduced, which seeks to push behavioural change in the future generation of architects under education at the IIT, by exposing them to the bodily experience of volatile climatic situations the iconic glass building offers, - in theory forcing them to act on their experience. This ethics of promoting behavioural change is a critical departure from the HVAC (Heating, Ventilation Air-Conditioning) industry’s commodification of mechanically produced climatization for passive consumption.181

Transsolar follows an adaptive approach to comfort, 182 stressing the influence of physiological, behavioural and psychological aspects of occupants’ sensations of comfort, 183 subscribing to the idea that a building’s occupants are active agents rather than passive recipients 184 of mechanically created comfort conditions in buildings. Transsolar structures their work and design philosophy according to the environmental themes temperature, air, sound and light in addition to materials and the human scale in the book ‘High Comfort, Low Impact’. 185 Each theme links the physics of environmental phenomena to the human physiology and sensory system. Adaptive comfort reconciles the physiology of human sensation and the physics of moderating climate with building fabric and service systems with the psychology of culturally embedded interpretations.

183 Lauster and Olsen, sec. temperature, air, sound and light.
184 As proposed by Brager and de Dear, 83–96 (p. 83).
185 Lauster and Olsen.
experiences and expectations. Psychology and culture is recognized as part of what makes up a person’s physical and mental well-being, - his or her experience of comfort.

Transsolar’s adaptive approach to comfort answers to some degree a sentiment on the definition of comfort expressed by Eberle: “... comfort in a building is not an engineering question, that’s an architectural question... comfort is much more complex. I mean comfort on a thermal level, acoustic level, - in a level of atmosphere, in a level of finding yourself. ... I think this word comfort really is a driving force of what people go for. But comfort not only as a thermal issue, economic issue, - a social issue, a cultural issue. A question of atmosphere. Lots of different levels. So I think we should work much more, and think much more on the issue of comfort.”

Here, Eberle expands the notion of comfort from the technical definitions used in engineering to something more vague, but altogether more encompassing of the psychological and perhaps existential connotations of well-being, which is connected to desirability and quality of life, - perhaps delight and a sense of meaning beyond utility.

**Sustainability beyond resource management and environmental performance**

According to both Baumschlager-Eberle and Foster and partners architecture plays an important role in creating new identities beyond its physical manifestations. Architecture creates new behavioural patterns and may inspire new social cultures, but being able to do so successfully, requires an intimate knowledge of both historical and contemporary social and cultural patterns. The notion of social acceptance as the premise for sustainable architecture is indeed shared, and the design output of both offices is rooted in traditional and modern architecture. But where Eberle seeks to refine an architecture of the ordinary, of the everyday, Foster & partners seek to transform, reinvent or even transgress architectural tradition more radically, often arriving at expressive, iconic solutions. So while resource management and environmental performance are seen as important necessities in creating sustainable architecture they are not the ultimate goals, - that is rather to create spaces that have strong identities while serving the needs

---

and possibly the aspirations of both clients, occupants and a general public audience. Both offices work in continuation of the functional tradition of modernism, and demonstrate attention to architecture’s direct and derived environmental impacts through resource and energy use, while focussing on creating good built environments that are situated in a deeper, cultural understanding of sustainability than mere technological energy performance and resource management efficiency.

A few examples of built works may show how both offices work in continuation of architecture’s ancient legacy of representation and climatic modification.

Baumschlager Eberle: ETH E-Science Building, Zürich, Switzerland. Photo: E. Hueber
Baumschlager Eberle: Boating club house, Fussach, Austria. Photo: E. Hueber

Baumschlager Eberle’s design for the E-Science building in Zürich is a glass house surrounded on all sides by shading panels protecting the windows from excess sun. The repetitive stacking of equally spaced vertical shading fins on horizontal balconies reminds us symbolically of the public loggias of Italian renaissance architecture and the chiaroscuro effect of the classical vitruvian orders. It is an architecture which is both environmentally and historically conscious as it resolves its design issues in continuation of a traditional architectural idiom. Complex shapes can be found in Baumschlager Eberle’s work as the boating clubhouse at the harbour of Fussach demonstrates. Again, the shape of the concrete structure behind the façade and the choice of patterned matte glass is argued on the basis of their environmental performance: The aim is to avoid too
sharp a visual contrast between exterior and interior light conditions\textsuperscript{187} – essentially an argument based on visual comfort criteria.

But the effect achieved goes beyond comfort: The singular position of the clubhouse on the harbour front and the architecture’s celebration of the atmospheric qualities of light and the community of people in the area resonates functionally and symbolically at a deeper level: Instead of countering the contrast between inside and outside as a comfort minded approach to daylighting might suggest, the contrast is cultivated to achieve a sense of delight in the interplay of light and structure highlighting the diversity of the environmental phenomena interacting with the architecture. The clubhouse is a small temple allowing people to engage socially and commune with the forces of nature.

\textsuperscript{187} ‘Dezeen » Blog Archive » Nordwesthaus by Baumschlager Eberle’
temple, while repeating the juxtaposition of vertical and horizontal elements and displaying the technical advances of 20th century construction technology versus the tectonics of stone masonry. As with Baumschlager Eberle’s work, the same elements that are used to engage in a dialogue with architectural history have important environmental uses. The slender steel columns carry a filigreed roof which filters the sunlight and allows daylight to enter the building without excessive solar gains to achieve comfort and delight for the occupants and visitors of this cultural centre, yet the motif of environmental performance remain understated.

The use of complex form to achieve environmental performance is more directly evident in the Greater London Council by Foster and Partners. The pearl-shaped form of the building addresses a context which is not the architecture of the surrounding urban situation, but instead focuses on the environmental conditions of the site, particularly the sun and daylight. Opening up towards the North, looking out on the Thames, the large uninterrupted glass facade of the council chamber allows diffuse daylight to enter the building abundantly, while expressing a symbolic open and transparent connection between people and democratic government. As the back of the building faces south the shape and orientation of the building itself protects the council chamber from overheating which would otherwise occur. This motif of shaping the building according to the movement of the sun is further elaborated by staggering the south facing façade so that the upper levels cast shade on the lower ones according to the time of day and change of seasons.

These examples show that even today’s state of the art, technologically advanced architecture addresses the same conditions of human physiological needs, desires and aspirations as did traditional architecture, and that addressing these conditions are crucial to successfully establishing strong culturally embedded identities of buildings and places that resonate at a deeper level than mere pragmatic problem solutions to functional programmatic demands. While highly conscious of environmental and energy performance, these issues are central but not the essence of design. These buildings operate at multiple levels, uniting functional utility with social aspiration and cultural identity, seeking to expand the notion of comfort by possibly inspiring delight and
affection, if not in extremely rare moments in today’s disenchanted reality: a sense of sacredness.  

HIERARCHY OF SCALES

Analyzing the interviews, it can be noted that Eberle, Behling and Evenden seem to share an idea that there exists something which I would call a ‘Hierarchy of scales’ related to the questions of energy use and environmental impact of buildings, although they arrive at this idea from different directions. It is an important idea because it relates design issues to each other in a hierarchical manner that is easy to communicate and understand and hence use as a designer (or any other stakeholder) who has to navigate great complexity in the design process. The idea of a Hierarchy of scales indicates that issues at larger scales frame and make conditions for the issues at smaller scales, imposing a seemingly linear dependency among scales. Though an important idea, it is vaguely defined and its foundations are only partially explicit as will be seen. The idea is most eloquently expressed in a diagram presented by Foster and partners:

---

188 Referring to Lisa Heschong’s four levels of appreciation of architecture’s mediation between man and the natural environment: necessity, delight, affection and sacredness. Heschong.

189 Behling and Evenden, note 8.
As can be seen the diagram is multidimensional. Several aspects of environmental design, - specific design elements, energy optimization and costs, - are claimed to relate in general ways according to the diagram:

- The greater the scale, the greater the environmental impact.
- The cost implications are inversely proportional to the scale at which design decisions are taken.
- Basic design decisions such as building form and orientation have greater positive environmental effects than optimization of building technology systems and applying integrated renewable energy solutions, and can be achieved at a much lower cost.

Very similar ideas were expressed by Eberle in a presentation in Copenhagen in 2009, based on his experience with low-energy housing projects.¹⁹⁰ Schuler also seem to support the idea, although indirectly, as the design philosophy of Transsolar seeks to minimize service systems by optimizing the environmental performance of the building structure and skin.¹⁹¹

The diagram uses technical terminology describing design in terms of ‘passive’ and ‘active’ solar energy systems. ‘Active’ indicating that solar radiation is converted to electricity or heat feeding the building’s energy service systems, while ‘passive’ indicates building systems or components that redirect, transmit or conserve the energy of the sun as daylight and solar heating (or cooling). This technical terminology is linked to examples of building components, elements and form, making an explicit connection between energy optimization and the discrete elements of an architectural scale progression from the parts to the whole. With Foster and partners’ more than 40 years of accumulated experience in sustainable design the claims have authority, but the diagram opens many questions:

- On what basis, what evidence is it constructed?

¹⁹⁰ Eberle, ‘Sustainable Building Design - Principles and Tools’.
¹⁹¹ Lauster and Olsen, p. 3; Schuler, note 10.
- What are its conditions and limits?
- Does it make sense to impose such a strong hierarchy on such complex matters?
- Would this hierarchy of environmental impacts be applicable as a decision hierarchy regarding specific performance parameters, particularly energy use in buildings?

Foster and partners deliver the outlines of an account for the diagram based on their experience with energy optimization in architectural design, from urban planning to building design. The power of design is great, Behling argues: “... consumption is a question of demand, and demand is dependent on design. Your demand for petrol depends on the design of your car, and your demand for a car depends on the way the city you live in is designed... The same goes for buildings: it applies to all sorts of things. Architecture and planning can reduce the demand for energy through the way buildings, infrastructure and urban development work”.¹⁹² And further: “If you add transportation, a total of 70% of energy consumption depends on buildings, the way people move among buildings, and the way the infrastructure works.”¹⁹³

The belief in the power of design in energy optimization is precisely articulated, as can be noticed: The primary role of design should be to reduce energy demand, through energy optimized planning and building design. Only after reduction and optimization is it possible to cover demand by making buildings part of an urban energy producing infrastructure. The ethics behind this notion implies that the diagram should not just be read as a neutral description of a presumed causality of architectural design’s environmental impact. Rather, the ethics instate the relative impacts of the different scales as a decision-making hierarchy for the design process, in which the accumulated effects of design should be considered in order of importance. Evenden confirms this interpretation of the diagram: “Yes. If you don’t reduce demand, none of the

¹⁹² Behling and Evenden, note 2.
¹⁹³ Behling and Evenden, note 31.
technologies of today can create enough energy to run the building. You have to reduce the energy demand by working with the orientation and with the passive systems.”

Evidence?

Returning to the question of what evidence would support the notion of a hierarchy of scales, Eberle, Evenden and Behling discuss the main aspects of energy use that are particularly influenced by planning and building design, which may be adding up to the relation between architecture and environmental impacts implied in the diagram:

- **The energy use for transportation – urban density.**

  Referring to a study by Newman and Kenworthy, Behling and Evenden note that urban density is directly and dynamically associated with energy use for transport. Urban density should be promoted to lessen the need for transport and hence the energy use for it. This notion has a range of implications to architectural design as it calls for high density, yet attractive building patterns, instead of low density urban sprawl. Particular to Foster and partners’ work with urban planning, this is also connected to the design of new transport systems and a concern for urban climate to promote pedestrian movement instead of motorized transport, as demonstrated in the Masdar City project designed in collaboration with Transsolar. Furthermore it is held that dense cities have advantages of promoting commercial and social life.

---

194 Asked whether form and orientation coupled with the ability of the design to accommodate future changes constitute the most important aspects of a decision-making hierarchy. Behling and Evenden, notes 19–20.


196 *Attractive building patterns* is referring back to the primacy of social acceptance as noted previously. Architectural design carries a responsibility to promote denser building types than the prevalent single family home it is suggested by Behling. Behling and Evenden, notes 38–43.


198 Behling and Evenden, pp. 38–43.
- **The energy used for building operation – environmental performance**

Reducing energy use is perceived as the main technical criterion of sustainable architectural design at present by all three offices.\(^{199}\) While operational energy encompasses the energy used for mechanical and electronic equipment in building operation, what is particularly highlighted is the energy used for climatization of buildings – heating, cooling and lighting – as these aspects of energy use are directly influenced by basic architectural design and its environmental performance.\(^{200}\) A novelty in contemporary architecture is Foster and partners’ introduction of urban design as a first step of reducing energy demand in the process of energy optimization of building design, as demonstrated in the Masdar City project. By optimizing urban design, so as to shade and ventilate streets and lower the temperatures of the urban microclimate, energy demand for climatization in buildings is lessened and better urban comfort achieved.\(^{201}\)

- **The energy embodied in buildings – durability and adaptability**

The importance of considering embodied energy is perceived somewhat differently among the interviewees. The embodied energy of a building refers to the energy used to produce the building, including material extraction and processing, transport and the processes of construction, renovation and demolition for an entire life-cycle of a building.\(^{202}\) Both Eberle, Behling and Evenden subscribe to the idea of designing for durability and adaptability of buildings so as to facilitate the inevitable changes that will happen to a building over its life-cycle with relative ease, a notion introduced by Duffy and Brand through the application of the Shearing Layers

---

\(^{199}\) Calculation methods may vary depending on which standard is referred to.

\(^{200}\) Eberle, ‘Interview, Baumschlager-Eberle - Satrup 2008-06-16’; Schuler; Behling and Evenden.

\(^{201}\) Behling and Evenden, notes 61–65; Schuler, note 20.

theory in architecture. It has its own very strong inherent hierarchy which may support the idea of an Hierarchy of scales: The greater scales change at a much slower rate than the smaller scales, indicating that small scale building components such as windows or service systems may be replaced several times during the lifecycle of a building, while building elements such as the load bearing structure may change very little in the entire lifecycle of the building. The higher rate of turnover will mean that its contribution to overall embodied energy will theoretically be multiplied by a factor equal to the number of life cycles the smaller scale goes through compared to the overall lifecycle of the building, adding considerable embodied energy and costs with each lifecycle. But where Behling and Evenden seem to consider this an important yet minor issue compared to considering operational energy, it has a prominent place in Eberle’s design philosophy, as he builds his design methodology around the issues of durability and adaptability.

Graphic illustration of notions that may support the idea of a hierarchy of scales.

Eberle emphasizes a life cycle oriented approach which is combined with a parametric energy optimization process, while Foster and partners recognize the life cycle approach but highlight energy optimization and environmental performance.

---

203 An idea first expressed by Duffy and Brand applying the shearing layers theory to architecture. Brand, chap. Shearing Layers.

204 Behling and Evenden, notes 14–15.
<table>
<thead>
<tr>
<th><strong>DESIGN PHILOSOPHY</strong></th>
<th>Baumschlager-Eberle</th>
<th>Foster and partners</th>
<th>Transsolar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hierarchy of scale</strong></td>
<td>Hierarchy of scale is an explicit idea informing the design process. Based on durability and lifecycle considerations. It plays a role in energy optimization too.</td>
<td>Hierarchy of scale is an explicit idea informing the design process. Based on environmental performance related to energy use for transportation in urban design and operational energy in building design.</td>
<td>Not expressed (The thermal simulations done for the environmental performance of the urban design (street section) in the Masdar City project may be interpreted as such).</td>
</tr>
<tr>
<td><strong>Focus on sustainable design</strong></td>
<td>Durability and adaptability plays a key role in the design philosophy of the office, informing a decision making hierarchy in the design process. Energy optimization is an integral part of the design methodology.</td>
<td>The main focus is environmental performance including energy performance, while durability and lifecycle considerations are recognised and integrated in design decisions and play a minor role.</td>
<td>The main focus is energy and environmental performance aimed at generating comfort. Lifecycle analyses of materials and resources may be integrated in design.</td>
</tr>
<tr>
<td><strong>Adaptive approach to comfort and Delight</strong></td>
<td>Adaptive approach to comfort understood both in technical terms and within a wider cultural context of the psychology of experiencing architecture.</td>
<td>Adaptive approach to comfort, stressing the influence of physiological, behavioural and psychological aspects of occupants’ sensations of comfort. Architectural design goes beyond a technical understanding of comfort and is aimed at creating diversity and experiential qualities, possibly delight.</td>
<td>Adaptive approach to comfort, stressing the influence of physiological, behavioural and psychological aspects of occupants’ sensations of comfort.</td>
</tr>
</tbody>
</table>

Schematic summary of Design philosophies
Discussion

As can be seen above, all three aspects of energy use may have inherent hierarchies relating energy use to scale: The link between urban density and energy use for transportation is very strong, while the hierarchy inherent in the different rates of turnover of the lifecycles of building elements and components is quite dependent on material specification and fabrication which is not the focus of this dissertation. The impact of larger scales on smaller scales in operational energy use, is however at the very heart of the original research interest of this project, and seems more complex and dependent on specific design choices than the hierarchy of scales would suggest.

- What is the impact of urban design decisions on building energy use and environmental performance in Northern Europe, taking Copenhagen as a case?
- Will the impact of urban design decisions on building energy use support the notion of a hierarchy of scales?

These questions became the key research questions in a subsequent series of simulation studies, investigating the impact of urban design on building energy use and environmental performance.

But before shifting stage to the simulation studies, the design methods of the offices in relation to energy optimization and environmental performance will be discussed.
DESIGN METHODS: ENERGY AND ENVIRONMENTAL SIMULATION

In the everyday of architectural practice, design methods may be applied more or less systematically or intuitively according to the preferences of individual designers and the design cultures of practices. Arguably much of the knowledge applied in design lies inherent in the skill set used to define, analyse and solve design problems, and may be considered tacit knowledge. As architect’s offices range in size from single person consultancies to large enterprises with several hundreds of employees, and design tasks may range from product design to urban planning, the ways that design knowledge and methods are managed vary. In the following the design methods used in energy optimization by Baumschlager-Eberle and Foster and partners are discussed based on an analysis of the interviews.

Design methodology and Energy Optimization: Baumschlager-Eberle

“... when we deal with architecture we should understand that the relation of methodology we use to produce architecture will determine the result much more than the architectural willingness of individual people... first of all, we have to use a different methodology to develop architecture, because only this different methodology will make it possible to integrate this different way of thinking”.

Eberle displays a strong belief in design methodology: Having an explicit design methodology is seen as a guarantee of properly integrating environmental performance and resource management in the design project, managing workflows, knowledge and personnel resources internally in the office, not only to promote efficiency in the office’s design processes, but to be able to achieve the architectural qualities in a project they pursue. “We have to work with knowledge based design. And we have to be very clear

---

205 Referring to Polanyi’s distinction between tacit and explicit knowledge and Nonaka’s concepts of knowledge creation and knowledge management. Polanyi; Nonaka, 14–37.
about what knowledge we really have. So this is also the relation between research and architecture. We have to have a method of integrating knowledge into the design process.”

Eberle believes in breaking down the design process in discrete elements which are analysed both individually and holistically in order to form a synthesis in the architectural project. This explicit process of analysis and synthesis is a guarantee of ensuring the best possible integration of the multiple kinds and sources of knowledge which may be relevant and brought to inform the project. Buildings are understood as metabolic processes, not static objects. Looking at how this metabolism is manifested over time, it can be noted that it happens at different speeds in relation to the various scales of the building’s functional organization. Different layers of the building have different functional lifetimes. The building’s program has a tendency to mutate from the moment a new tenant or owner moves in or takes over. This should be reflected in the design approach, Eberle stresses, and this notion is the foundation of the design methodology he works with, in practice and in teaching. “This is the background and the reason why we speak about design on maybe 5 different levels parallel, you know. It’s on the level of the site, its on the level of structure, its on the level of skin and its on the level of the organisation of the building, of the programme, and on the level of the interiors and the materials. These different elements also relate to different lifetimes.”

---

209 This view has strong similarities to Stuart Brand’s concepts of Shearing Layers in architecture, the ‘high road’ of aesthetical value invested in buildings and the ‘low road’ of functional flexibility and adaptability expressed in Brand.
The build-up of information in the design process is structured according to the permanence of the different layers that constitute the (building) design. Some general assumptions are made of the functional life time of different building layers: ORT: 

**ORT**: (Site) well over 100 years

**STRUKTUR** (Structure, Building massing) over 100 years

**HÜLLE** (Building Skin) 50-100 years

**PROGRAMM** (Programme, spaceplan) 20 years

**MATERIALITÄT** (Surfaces, materiality, Stuff) 10 years

The site and the relation of the building to its site has the highest degree of permanence. The building’s basic organization, its massing and load-bearing structure are the aspects of the building that have the longest functional life and regulate subsequent changes to the building. The building skin and building service systems are assumed to have a lifetime of 50 years. The building's use tends to change over a time horizon of about 20 years. Materials and surfaces (this refers primarily to the interior outfitting) are replaced relatively frequently. The most surprising element is perhaps that the building programme is among the last issues to be considered, but the convention of the primacy of programme in architectural expression is just a modernist convention Eberle argues.

Since the programme is very susceptible to change, it is more appropriate to design for

---

211 The layer names in german are used to structure the design methodology taught in Eberle’s course in architectural design at the ETH Zürich. They are close to Brand’s Shearing Layers (noted in italics), with the exception of the layer **Services** which is left out. In Eberles design practice, services are treated in the context of environmental performance under the label ‘Climate and Comfort’ Dietmar Eberle and Pia Simmendinger, From the City to the House: Eine Entwurfslehre / A Design Theory (Gta verlag, 2007); Pia Simmendinger and Ulrike Schröer, ‘City and House – a Strategy Of Teaching Design’ (presented at the The Complexity of the Ordinary, Copenhagen: Royal Danish Academy of Fine Arts School of Architecture, 2006), pp. 1–6 <http://www.scarch.dk/Sessions/Session%207%20Communicative%20Space/Pia%20Simmendinger%20Ulrike%20Schröer.pdf>; Brand, pp. 19–21; Eberle, ‘Sustainable Building Design - Principles and Tools’; Eberle, ‘Sustainable Building Design - Principles and Tools’.

general rather than specific use patterns.

Ranking these layers according to their degree of permanence or speed of change corresponds to a change in scale from the large scale of urban design to the smaller and more detailed scales of building design. This change of scale can be related to an increment in complexity generally seen in initial design stages when constraints given by the site conditions have to be understood properly as a condition for the building massing to be decided and articulated in further detail. The change of scale reflects a hierarchy of influence of design decisions which may be linked to different stages of the design process: The differences in permanence is seen by Eberle as a framework for a proper decision-making hierarchy in the architectural design process, with the intent to ensure that the decisions taken at each step is qualified in relation to a long-term life-cycle perspective. Differentiating the design according to durability and adaptability is essentially a way of offering freedom of managing the resources invested in the building to its future owners or tenants, by carefully considering the constraints that each layer or scale places on the other. In energy terms, this design effort is directed towards conserving the embodied energy of the building, as it can be modified with relatively little effort, thereby aiming at extending its useful lifetime. It doesn’t call for a full life-cycle calculation of embodied energy, rather it is focussed on how the formal articulation of the architectural detail and the overall design may promote the adaptability and hence durability of the design. Apart from selecting locally produced building materials, minimizing embodied energy for transport, this is arguably the area where architectural design may influence embodied energy the most. This view can be fully integrated with an approach to operational energy optimization, as will be seen. In the interviews Eberle does not explicitly mention applying design principles which are aimed at recycling building materials in industrial ecology loops, but it may well be possible to some extent.

The framework offers a simple decision hierarchy for the design process by which design decisions can be classified and organized according to their influence on the adaptability

213 Such as suggested by Braungart and McDonough; Crowther; Nordby.
of the design. It is held that by designing for adaptability, durability is enhanced, as adaptability is a way to ensure that the building can accommodate the inevitable changes that will happen to it over the course of its lifetime, ultimately prolonging its useful life. In energy terms this consideration is about conserving the embodied energy invested in the building. Moreover, adherence to the principles of this framework is seen as a guarantee for successful integration of knowledge from different fields into the design. The belief in a rational framework guiding design decisions as opposed to a more intuitive view of the architectural design process is expressed in the process of project information build-up in the office. Each project is described in a standardized project book. As a project is developed in iterative stages, information is collected and accumulated in the project book according to preset standards. In this way, the completeness of information is standardized, quality-checked and made available as a pool of transferable explicit knowledge, communicable within the office and to external stakeholders in the project. “When you have this structure, you’re able to implement a lot of different knowledge from different fields into a process. When you always go back to intuition, how do you implement other knowledge? You can say, ok that’s nice. You have a way to implement it into a process, the knowledge of different fields.”

In a certain sense this focus on efficient processes of information and knowledge management within the office, continuously making explicit the experiences accumulated in the design process, can be considered as a way to minimize the ‘energy’ used by the office on the design, either to release more manpower resources on enhancing the quality of the project, or with a more commercial attitude, to minimize effort in order to increase profit. This point is not made in the interviews. But interestingly, it can be related to Tribus and McIrvine’s theory of information and energy: The fraction of energy that goes into creating the design – I would label this the informational energy of

the design – regulates the energy embodied in the design and its future operational energy deeply.216

DESIGN METHODS

<table>
<thead>
<tr>
<th>Baumschlager-Eberle</th>
<th>Foster and partners</th>
<th>Transsolar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Methodology</strong></td>
<td>Explicit design methodology based on durability and lifecycles.</td>
<td>Design culture rather than design methodology</td>
</tr>
<tr>
<td></td>
<td>Explicit methodology of simulation. (one tool)</td>
<td>Explicit and experimental methods of simulation (catalogue of tools)</td>
</tr>
<tr>
<td></td>
<td>Project book as medium of information integration and collection.</td>
<td>Building Information Model (BIM, microstation) as medium of information integration</td>
</tr>
<tr>
<td><strong>Simulation and design process</strong></td>
<td>Simulation is used to examine design performance relating to design decisions at all scales, but the Skin layer has most parametric variation possibilities</td>
<td>Simulation is routinely used in the very first design stages of the Site, Structure and Skin layers, and may include the others</td>
</tr>
<tr>
<td></td>
<td>Energy and (indoor) environmental performance is simulated and documented through energy calculations in the early design process.</td>
<td>Environmental performance is simulated and documented through a wide variety of simulations in the early design process.</td>
</tr>
</tbody>
</table>

The Masdar project introduces simulation for the urban scale.

Schematic summary of Design methods

216 Adapting Tribus and McIrvine’s introduction to Energy and Information to the issues of design processes. “The flow of energy in human societies is regulated by the tiny fraction of the energy that is used for the flow of information. Energy and information are also related at a much deeper level” Tribus and McIrvine, MCMLXXI, p. 179.
THE ROLE OF SIMULATION IN THE DESIGN PROCESS

Energy calculations in the initial design stages: Baumschlager-Eberle

One of the chapters of Baumschlager-Eberle’s Project book is dedicated to environmental performance or Climate and Comfort, as the relevant chapter is called. Within this chapter the climate, comfort and energy performance of the proposed building is documented through simulations. The software used for the simulations has been developed specifically for Baumschlager Eberle by Lars Junghans, as part of a research project. It offers an interface intended for ease of use for architects, calculations of thermal environment and comfort, and recommendations for environmental design strategies. It is sequenced in three parts; data input, passive strategies and passive strategies so as to fit into the architectural design process. Each part allows several design variables to be investigated parametrically, and the software offers suggestions for design choices with each variable.

---

217 Eberle, ‘Sustainable Building Design - Principles and Tools’.
219 Junghans.
Sample screenshot from the energy calculation software developed for Baumschlager-Eberle showing default construction types with different thermal mass. Selecting from default architectural construction ‘types’ makes it easier for architects to navigate the consequences of design choices without having to deal with numerical input values.

Since the software is intended for use by architects, care has been taken in reducing the complexity of input information, by using templates for most inputs. The default values of these templates are connected to images of building types, construction types, shading system types etc. thereby making it possible to navigate design decisions without having to know the numerical values and physics behind the simulations. The output is a set of predefined graphs describing the performance of the design, including a comparison of the improvements achieved relative to a given base case.

If we use Brand’s terms for the Shearing layers to organize the parametric energy optimization design variables that are specified in Baumschlager-Eberle’s software, a framework can be created which may serve to describe the use of software related to specific design issues at given stages of the design process.

Framework: Design variables related to Shearing Layers. The software is focussed on energy optimization rather than environmental simulation. It allows architects to validate and track the impact of every design decision for each parametric design variable in the design process. It establishes complete input by offering the designer a palette of architectural types to use as default input rather than numerical values.

While aiming for ease of use to non-experts in building physics such as the usual architect, the software has some of the limitations: How to deal with more environmental aspects than the thermal environment, how to deal with more complex geometry and the limited possibilities of estimating the impacts of urban scale
As the work of Baumschlager Eberle only occasionally goes beyond cartesian geometry – preferring to refine an architecture of the everyday, - the software seems fit for purpose in the sphere of a vast majority of ordinary commissions, including those that are not even designed by architects.

The environmental performance analysis which can be made with the software is limited to assessing the indoor thermal environment. It does not have the capacity to calculate any wider range of outdoor environmental factors, which may be critical to deal with, in order to have a better point of departure for optimizing indoor environment. The focus of the software is aimed at controlling energy use more or less roughly in the initial design stages, possibly replacing – to some extent – the advice of a consulting mechanical engineer in the beginning of a design process. By integrating software at this stage, Eberle expands the architect’s control of the design into the field of energy optimization traditionally dominated by engineering.

It can be noted that the simulation tool requires a consistent set of initial input data of the geometry of the building. It apparently has little functionality with which to analyse urban design parameters, suggesting that the use of the software is not that adequate when doing a site analysis. It makes more sense to use it when at least one or more design variations on the building mass have been established.

Omitting daylight simulations from the performance assessment seems more critical. Without assessment of daylight, basing design decisions predominantly on thermal performance, the risk of compromising daylight performance increases. While the energy use for electric lighting is usually less than that used on providing thermal comfort, it increases in importance as the thermal performance of building envelopes is improved.

Apart from the lack of calculation of energy use for lighting, it shares these limitations with the Danish software be10 for regulatory compliance, which calculates energy use according to the European norms prEN ISO 13790:2005, prEN 15193-1 (2005) & prEN 15316 (2005). Søren Aggerholm, Karl Grau and Sbi Statens Byggeforskningsinstitut, ‘Bygningers Energibehov. Pc-program Og Beregningsvejledning. Version 1.05.12, Be06’ (Statens Byggeforskningsinstitut, 2005), sec. Beregningsmetode; A+E:3D <apluse.dk>.
Balancing daylight and thermal performance is a complex issue, as the simulation studies presented later in the dissertation demonstrates. But the real problem is that daylight plays such a fundamental role in architectural quality beyond energy and visual comfort. At the state of development of the software that was presented by Eberle in 2009, daylight performance assessment was not integrated in the software.

**Environmental Simulation in the design process: Foster and Partners SMG**

Foster and Partners has invested early in developing specialist competencies and internal research and development which may be unavailable to smaller offices: A unit known as the Specialist Modelling Group (SMG) - a group of employees working with advanced parametric modelling and environmental simulation - acts as internal research and development consultants offering support to the design teams. The SMG uses a variety of simulation tools such as IES Virtual Environment, Ecotect, Daysim and Radiance to ‘map’ the environmental performance of designs at various stages of the design process, and feed back the information to design teams. Visualizations and colourcoded 3D prints are used to make the essentially spatial characteristics of environmental performance communicable to designers who do not have the background knowledge of physics, as do the SMG members.

A range of simulation methods are defined, typically to analyse solar radiation, sky component of window views, daylight levels, wind and others, indicating a highly structured approach to the use of simulation in the design process. A catalogue of simulation tools and methods which can be used at discrete stages in design processes has been produced by the office, offering a methodological framework for the

---

221 Eberle, ‘Sustainable Building Design - Principles and Tools’.
222 When the interviews took place in March 2009, the office had recently been downsized from app. 1200 to 800 employees due to the global economic downturn. The Specialist Modelling Group (SMG) was at that time counting 12 people. Personal conversation, Hugh Whitehead, head of SMG, 20-03-2009.
223 Members of the SMG involved in simulations typically have a Master’s degree in building physics or environmental design. Irene Gallou and Bruno Moser, ‘Interview, Foster & Partners SMG - Sattrup 2009-03-20’, 2009, note 106.
224 Gallou and Moser, notes 52, 54, 70, 72.
integration of simulation and other analytical tools in sustainable design. The methods do not constitute an overall design methodology however, as their proper application will change from project to project, depending on scope of scale of the given project. Bruno Moser, also of the SMG, points out that new software continue to be integrated, and that the use of simulation in these cases is experimental and iterative, allowing the SMG to expand their competencies in new areas of specialization, such as urban connectivity and movement. Generally the use of simulation is aimed at improving the understanding of design performance internally with the design teams and with external consultants, by making sure that teams work on the basis of shared information, models and assumptions. The SMG also create software applications to ensure proper data transfer between different CAD and simulation software, and have developed plug-ins for their main BIM platform Microstation so that designers can perform simple simulations such as daylight factor analysis directly from within the BIM model.

Sketching out the use of simulation in the initial stages of a building design process, Gallou would first analyze site constraints, daylight and solar radiation availability, possibly identifying a maximum envelope within which a given development would not interfere with neighbours’ rights of light, and would itself have adequate daylight and solar access. As a maximum envelope for the possible development has been established, the design team can try out different massing options within the envelope with considerable freedom, as the envelope guarantees a base level of daylight and solar availability. The role of the SMG in the design team is then to guide the attention of designers as to how and where certain environmental qualities may be found on the site which can be integrated in the functional programme of the given project. Once a few

---

225 However the document was not available to outside readers at the time the interviews took place. Gallou and Moser.
226 Gallou and Moser, notes 81, 83.
227 Gallou and Moser, notes 3, 6.
228 Gallou and Moser, note 29.
229 Gallou and Moser, notes 48, 50.
230 Gallou and Moser, notes 83, 84.
design options of building masses has been developed, these are checked in further
detail at specific points, where problems may occur. One of the standard simulations
that are run is a check of the sky-view component for all facades, as it is intricately
connected to the minimum daylight of the interior spaces. In addition sunlight
availability in public spaces created by or surrounding the project may be analysed,
checking how many hours of the day direct sunlight will be available. Once a rough
building mass design has been decided, facades and interiors may be analysed further, to
decide on the appropriate transparency of facades - glazing ratios, glass properties and
possibly shading and daylighting systems – to satisfy the daylight requirements of the
programme.

If we draw up Gallous’s description of how simulation is used to support analysis of the
Site, develop building form and the design of the building Skin in the initial design stages
according to the same framework based on Brand’s shearing layers that was used to
summarize Baumschlager-Eberle’s use of simulation, a schematic representation of the
use of simulation in the design process and the role of the SMG can be made.

Framework: Foster and partners use of simulation related to Shearing Layers. The use of environmental
simulation is focussed on analysing environmental phenomena, eg. solar radiation and daylight,to
understand environmental performance and support formal design choices rather than calculating energy
use. Simulation is used in sketching/conceptual modelling at the very beginning of a design process as an
exploratory tool rather than as a validation tool.

It can be noticed that the sequence of issues addressed using simulations by the SMG,
and the SMG’s communication with the design team follow the definitions of the
shearing layers quite closely. Particular emphasis is made to understand the

---

231 Gallou and Moser, notes 85, 87, 88.
232 Gallou and Moser, notes 91–95.
environmental conditions of the site, defining geometries to regulate the development of
the projects volume, before mapping daylight and solar radiation availability. A key
difference to Eberle’s use of simulation is that the analyses are not directed directly
towards the building’s energy use. Rather the emphasis is on understanding the
phenomena of solar radiation and daylight on the site, as a qualitative dimension which
the project may develop as environmental qualities through its design.

“If it is a museum, for example, what you want is a lot of diffuse light, so you start
analyzing the daylight levels. But before you do that you just try to say: This is a
museum, make sure that your roof has enough light, because you will maybe want
diffuse light, the best place to take diffuse light is from the roof or from a north facing
façade. Then you check: do you have that? (Adequate daylight availability on the site,
sufficient daylight through the roof). And if you don’t have that, then you should go and
do some changes in your design of the roof profile. So as an architect we are trying to
quickly predict what they (the design team) want and then help them with the design
which will comply (to a given functional or programmatic criterion) - so we don’t go after
and say: oh, it’s analyzed, oh, you failed! So we don’t know what to do now and they
have analyzed everything! You have to predict as much as you can, but you cannot
predict all.”

The use of simulation in the design process necessitates and supports a dialogue in
which the specialist knowledge of the SMG members on environmental performance is
informing the design team’s effort of resolving the many other design issues of the
project. Successfully feeding information and knowledge into the design process requires
an intimate understanding of the design process, so as to time the necessary information
when it is needed, without exhausting time and personnel resources on overly
sophisticated and time consuming simulations. Arriving at that level of competence as a
simulationist – where you are both able to simulate correctly and have adequate
understanding of the design issues and the design process to act as an advisor to a

---

233 Irene Gallou, Gallou and Moser, notes 89, 90.
design team - is described as a personal maturing process. As experience is accumulated through working with different types of simulation, it becomes easier to understand complex performance issues, on the basis of simple simulations. And it becomes possible to pinpoint which of these simulations and performance metrics that are best applied to specific issues in the design processes.

As the design team member does not have the same knowledge of environmental performance of design as does the simulationist, the other use of simulation lies within the communicative process of knowledge transfer within the organization of the design practice. In the case of Foster and Partners, this is the collaboration of the SMG and the design team. Addressing specific design problems, simulation is used as a communicative tool to transfer knowledge within the group, through visualizations and colour coded 3D prints analysing different performance aspects.

Having visual and physical feedback on the performance implications of design options allows the designers to learn about not only the specific performance issues of the project but performance in general. However, this is not an automatic process, happening by the mere presentation of simulation visualizations. The role of the simulationist as an active interpreter of results, and an active agent in the transfer of knowledge in the design process, should not be underestimated. In this instance simulation and the

---

234 Gallou and Moser, note 79.
235 Gallou and Moser, notes 81, 83.
various ways knowledge of design performance may be made explicit through visualizations and interpretations is a tool in the processes of knowledge transfer and organizational knowledge creation.

If we apply Nonaka’s SECI model as an analytical framework to Gallou’s description of the role of the SMG in Foster and partners’ design processes, we may interpret the design process as a process of ‘organizational knowledge creation’ directed towards embedding knowledge in an innovative design project. The SMG members have their individual tacit knowledge of building performance and simulation, which is bound in their professional training and experience.

At the onset of the design process, both the design team and the SMG members have socialized, tacit knowledge in their respective fields of specialization. Simulation is making tacit knowledge explicit and specific for the project’s purposes. The knowledge made explicit through simulation visualization is combined with the knowledge of the design team, possible creating new knowledge embedded in the project. Both design team members and SMG members learn from the experience and internalize the knowledge gained in the respective practices and roles as architects.

It can be observed that simulation has two main uses in the design process: Both have to do with the processes of learning about the performance of design solutions. Depending on how systematic an approach the simulationist has towards collecting and comparing the results of design variation simulations, this knowledge may be very precise, or if less systematic, a set of intuitions about how typical design solutions perform. Systematic parametric variation and collection of performance data provides information which may be turned into design knowledge through careful interpretation of implications to design. Going through several iterations of simulation in order to understand a design performance problem provides a potential learning experience, when reflected upon by the simulationist/practitioner, but unless made explicit it resides as tacit, personal knowledge with the simulationist. So, the first use of simulation resides with the [236 Referring to Schön’s argument of ‘reflection in practice’ being a mode of knowledge creation. Donald A. Schön, Den Reflekterende Praktiker. Hvordan Professionelle Tænker, Når De Arbejder (Århus: Klim, 2001), chap. 2.]
simulationist: Simulation is a process of learning through collecting information more or less systematically, more or less tacitly or explicitly, by means of testing design variations and analysing them for given performance criteria.

**Exploration versus Validation – Transsolar Climate Engineering**

The two founders of Transsolar, Matthias Schuler and Thomas Auer wrote the thermal simulation software TRNSYS early in their career, enabling them to simulate the thermal performance of buildings as integrated systems from building fabric to service systems, and to understand the interconnectedness of building geometry, building fabric, comfort and energy use with increased precision. Having collaborated with many architectural practices in his career, Schuler displays an insight in the architectural design process seen from the outside, commenting and offering critical views on architects’ design methods. These comments are used to discuss the role of simulation in the architectural design process as tools of exploration and/or validation.

As an expert in simulation, Schuler is also somewhat cautious if not suspicious of the use of simulation by architects, who are not educated with the same understanding of physics as are engineers. His precautions are based on two reservations: 1) The limitations of the software to adequately represent the simulated physical reality, and 2) the ability of the architects to interpret results properly.

Asked how to qualify the initial design stages, Schuler responds: “- *By letting your consultant work with his gut feelings. That’s the best. Because I’m not convinced of the value of design guidelines and tools where you start with a very rough model and get results based on that. And I am not convinced either, that architects should be as deeply involved in simulation or efficiency as to be able to analyse it from the first moment. If you have a really good energy consultant, then you get advice from someone with the opposite view, - that is the energy relations of the site which is different to the social sphere that architects work with – and then you get the creative brainstorm that you need. That is much more innovative than someone developing an idea, and then using a tool to validate it. Integrated Design, - that’s my advice for the initial design stage.*”
Several issues are at stake here. Behind the reservations regarding the validity and adequacy of architects’ use of simulation, there may be some differences as to the understanding of the purpose of simulation and a hint of territorial demarcation, in the sense that simulation is traditionally engineering territory, while the initial design stages has traditionally been the exclusive territory of the architect. The approach to the design process ‘Integrated Design’ that Schuler mentions, highlights the initial design stage as a collaborative effort by a design team that encompasses many specialist competencies, different to traditional architects’ associations’ descriptions of the initial design stage in which the architects are in control.237 But more important than discussing professional boundaries is Schuler’s notion of collaboration and communication being essential to innovation. This highlights that the design process is a social processes of knowledge creation made manifest in the design, in which combination of different kinds of knowledge is essential to create innovative results.238

The engineer’s concern for precision is not necessarily the architect’s primary concern, as the whole design process is about navigating extreme uncertainties before arriving at the end result, as seen from the viewpoint of the architect. At the beginning of a design process most design issues are quite abstract and imprecise, so rather than validating results with precision, it is important to get feedback that indicates whether a design choice performs better or worse towards fulfilling design intents. That feedback may be given by a person or a piece of software depending on the complexity of the problem. Schuler emphasises that interpreting results necessitates an understanding of the design problem239: “I can’t exclude that the tools and the way people work with them can be improved, so that they can give indications. But the tools are not design consultants!"

---

237 A similar hint at rivalry between architects and engineers for influence in the design process is found in a remark by Eberle of regret that architects have left the issues of comfort to the engineers. Eberle, ‘Interview, Baumschlager-Eberle - Sattrup 2008-06-16’, note 50.
238 Referring to Nonaka’s SECI model of knowledge creation. Nonaka, 14–37.
239 Essentially the definition of design problems as ill-defined or ‘wicked’ problems. Rittel and Webber, 155–169.
Design is something mental that connects many issues. Tools only answer one question at a time.”

Having worked with Foster and partners on more occasions, Schuler confides that his gut feeling for valid results on one occasion got provoked by a peculiar exploratory use of simulation at Foster’s: “They tried to define a form based on a solar radiation analysis, and it just got so…. It seemed like someone who missed an idea for a design, used a solar analysis tool to find an idea for a design. And I was so impolite to ask them: Do you know Niemeyer’s sketches? Three lines are an idea for a church. Is there no one here who can sketch a design idea instead of using a calculation tool to generate forms that just become more and more crazy?” While Schuler seemingly disregards the expressive potential of form derived from environmental performance studies that Behling and Evenden introduced, he does make a point that architectural ideas may come from many other considerations than energy and environmental performance and not all the experimental-generative-environmental-synthetical digital modelling strategies that are very much en vogue in recent years are equally relevant to performance when it comes down to it.

Nevertheless the engineers too, use simulation not just as a tool of validation but as a method of exploration: “(Simulation) allows you to move much closer to the edge of what is possible. It can help you define the limits of your intuition. How far can you go before a function changes?” Simulation is seen as an essential method of learning in their practice, as the results of thousands of simulations keep informing and adjusting the intuition and understanding of environmental performance.

In addition to aiding learning and possibly innovation as a result, simulation also aids the implementation of innovative concepts by offering theoretical evidence to promote the

240 Schuler, note 32.
242 Schuler.
243 Schuler, notes 13, 15.
acceptance of untried concepts by clients who would by not be inclined to risk using untried and unconventional solutions. Simulation offers evidence which is more acceptable as proof to outsiders than professional experience alone. 244 With that in mind, it is a bit surprising that simulations are not used in competitions to promote the qualification of a proposal’s design solutions, as it could be assumed that the evidence created by numerical information would back up its credibility as a quality solution: “We rarely do simulations in competitions. Only if the clients want some ‘graphics’ on energy. If they just want an energy efficient building we usually do it based on experience.” 245 One of the reasons may be that simulations may be time consuming and expensive to produce, and the rapidly developing design may render results irrelevant in the time it takes to produce them.

Decision hierarchies?

Can Schuler add something to the idea of a Hierarchy of scales and whether it may be used as a decision hierarchy in the design process?

Projects may change considerably from conception in a competition to the constructed building. 246 Schuler notes that some architects have a very direct process of going from concept to finished project (as in the methodological approach of Eberle) while others have an approach where radical changes to concept may happen very late in the design process, if the process of learning in the design process implies that a different solution may serve design intents better. “Behnisch may change design concept fundamentally, even in the documentation phase. His attitude is that if he understands a problem very late in the process, he insists on being able to change the design in order to optimize the project. Others, for example Jahn, would never change concept. Design decisions are taken at the beginning and then the machine starts. But changes will always happen.” 247

244 Schuler, p. 15.
245 Schuler, note 7.
246 Schuler, note 9.
247 Schuler, note 9.
This comment highlights that the design process may be seen as both a process of learning and negotiating solutions and as a process of fabrication itself which may be managed emphasizing efficiency of production. The design process is not a linear process though it may be structured so in time, but a process subject to changes that the design team does not control fully. Design processes may develop as evolutionary processes in which concepts are tested and discarded even very late in the design process. Imposing a too rigid design methodology with a strict decision hierarchy that does not respond to changes and insights gained along the way may run the risk of losing potential qualities as the cost of efficient design production management. On the other hand, if a design methodology is able to shift the processing of the design brief, stakeholders’ design intents and technical considerations forward in time by rendering the information as an accessible and explicit pool of information for the design team, it may very well aid the process of learning and innovation, thereby confirming Eberle’s emphasis on design methodology as a framework for knowledge integration and his appropriation of the Shearing layers as its structure.

Working internationally with projects in many countries with very diverse climatic conditions, Schuler uses simulations to get a feel for the local environmental design issues and to identify key points in environmental design strategies, there by saying that the key points that may constitute the backbone of an environmental design strategy in one climate, may not be relevant in another. If hierarchy of scale exists that is useful as a hierarchy of design decision, it is based on regional climatic conditions.

---

Schuler, p. 7.
### Types of simulations

<table>
<thead>
<tr>
<th></th>
<th>Baumschlager-Eberle</th>
<th>Foster and partners</th>
<th>Transsolar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focus: Energy use</td>
<td>self-developed simulation application for energy and thermal comfort</td>
<td>Commercially and experimentally developed daylight, thermal, wind &amp; movement simulations. Self-developed applications for integration of simulation in BIM tools</td>
<td>Simulations of energy use and environmental performance of all comfort parameters using both commercially available and self-developed applications (TRNSYS)</td>
</tr>
<tr>
<td>Focus: environmental performance</td>
<td></td>
<td>Focus: energy use and environmental performance</td>
<td></td>
</tr>
</tbody>
</table>

### Simulationist expertise

<table>
<thead>
<tr>
<th></th>
<th>Baumschlager-Eberle</th>
<th>Foster and partners</th>
<th>Transsolar</th>
</tr>
</thead>
<tbody>
<tr>
<td>The simulations are structured according to simple typologies and parametric variations for ease of use by non-experts (architects)</td>
<td></td>
<td>Most simulations are done by intermediate level experts (SMG: architects with post graduate qualifications in environmental performance) simple daylight simulations are integrated in BIM tools and are available to non-experts (architects)</td>
<td>Simulations are done by experts (engineers)</td>
</tr>
</tbody>
</table>

### Use of simulation

<table>
<thead>
<tr>
<th></th>
<th>Baumschlager-Eberle</th>
<th>Foster and partners</th>
<th>Transsolar</th>
</tr>
</thead>
<tbody>
<tr>
<td>- to validate early decisions roughly</td>
<td>- to explore design performance criteria and learn</td>
<td>- to validate design decisions</td>
<td></td>
</tr>
<tr>
<td>- to explore energy performance criteria and learn</td>
<td>- to aid internal and external communication</td>
<td>- to explore design performance criteria and learn</td>
<td></td>
</tr>
<tr>
<td>- to aid external communication</td>
<td>- to validate early decisions roughly</td>
<td>- to aid external communication</td>
<td></td>
</tr>
</tbody>
</table>

**Schematic summary of Design philosophies**
EMERGING THEORY

If we understand grounded research as a process of making tacit knowledge explicit and combining it with other explicit knowledge (thereby understanding grounded research within Nonaka’s SECI model of knowledge creation as processes of explicitation and combination) we may combine the methodological and typological approach of Eberle based on his version of the shearing layers with Foster’s use of more sophisticated simulation tools in the early design stages, and Schuler’s concern for validation into a coherent approach to energy optimization in the early design stages.

- We have seen Eberle propose a life-cycle approach akin to Brand’s shearing layers as a decision hierarchy in the design process. Large scales with long durability have long lasting impacts and consequences for minor scale decisions, and should therefore be considered most important.
- We have observed that Foster and partner’s SMG would propose a sequence of environmental simulation studies for the initial design stage, analyzing Site conditions and restraints first, then building massing and form (its Structure), before studying the building Skin’s windows and material properties – which can be labelled using Brand’s terminology to distinguish different scale considerations.
- This hierarchy of scales can be used as a guideline to the progress of the design process: Large scale decisions should be taken first as they have consequences for minor scale decisions.
- We can also see this progress of going from larger to smaller scales in the design process as a process of increasing the level of definition of the project by accumulating information and integrating knowledge in design decisions.
- Combining all these observations, we may now apply Brand’s terminology of the shearing layers: Site, Structure, Skin, Services, Spaceplan and Stuff and can now use the same terms to coordinate a life-cycle approach to design for durability and adaptability with energy optimization and environmental performance parameters.
CHAPTER 6: Simulation Modelling Studies
Introduction to simulation modelling studies

This chapter summarizes and discusses results from simulation modelling studies that are more fully described and referenced in four research papers that are appended to the dissertation. The full papers also include additional research background information that is specific to each study.

Having identified the hierarchy of scales as a shared notion in practice and as an idea that can be supported by different strands of literature, it is now a question of how applicable it actually may be at describing energy optimization in a given context. With Foster and partners’ statement that urban design and basic building design are the bottom levels in a hierarchy of environmental gains, we can now transfer that idea to the dimension of operational energy use in buildings and test the hypothesis that urban design and basic building design have the greatest impact on energy optimization in architecture.

But is this true? Can it be observed? And if so, how is it expressed, on which parameters? To test this hypothesis I designed a range of modelling studies that would investigate different aspects of urban and building morphology as parametric studies of discrete design variables, in order to identify their relative impact on energy use, and invited fellow PhD student civil engineer Jakob Strømann-Andersen to collaborate on them, with the intention of qualifying the studies in terms of both architecture and engineering research traditions. To achieve this the research develops along two interconnected quantitative and qualitative tracks, recognizing that most engineers validate research according to (post)positivist research assessment systems while architectural research is often qualitative. The research questions guiding this stage of the research were:

- What is the impact of urban design decisions on building energy use and environmental performance in Northern Europe, taking Copenhagen as a case?
- Will the impact of urban design decisions on building energy use support the notion of a hierarchy of scales?
As the studies progressed we each contributed to the other’s understanding of design challenges in a cross-disciplinary research collaboration. The collaboration was later joined by Anne Iversen who contributed to the research effort by elaborating on the first findings on daylight reflection in the urban canyon, in the paper ‘Urban daylighting’.

Establishing a shared space for knowledge creation through socialization, externalization, combination and internalization of knowledge in tacit and explicit states. Illustration: Nonaka.249

Premises and conditions

The modelling studies are based on some basic assumptions and conditions, which are examined and discussed: The assumption that urban densification is a strategy towards improved sustainability and energy efficiency of cities and buildings, the climatic conditions and urban morphologies of Northern Europe with Copenhagen as the case, and the implementation of low energy construction standards.

It is often assumed that high urban density increases the sustainability of cities, which in energy terms is based on reduced demand for energy use for transportation and more compact and hence energy efficient buildings.250 This assumption is challenged by focussing on the qualitative dimensions of environmental performance in relation to building energy use.

249 Nonaka and Konno, 40–54; Nonaka, 14–37.  
The context conditions for the design of the parametric modelling studies is the historical and contemporary urban morphology and Climate of Copenhagen, which is also representative of other Northern European cities in the North Sea and Baltic area, such as Hamburg, Oslo and Stockholm. The models describe a wide range of densities and are also relevant to less dense urban areas, as in urban peripheries or provincial cities.

Left: Newman and Kenworthy’s study of urban density and transport energy use.
Right: The 1947 ‘Fingerplan’ of the Copenhagen metropolitan area showing typical patterns of dispersed and compact building typologies.

Another condition is the move towards low energy buildings becoming the new regulatory standard in Denmark. By the end of the present decade demands for energy efficacy will be severely tightened. While this in the first place is required for new buildings, the question of what to do with the already existing buildings is also present. For this reason the simulations are based on current Danish construction standards (BR10)\(^{251}\) as a pragmatic reference which offers an adequate base for further optimization in future low energy buildings and a standard which is achievable when renovating existing buildings. As it is the basic urban and building design decisions that are targeted with these studies, - the urban Site conditions, the Structure and form of

\(^{251}\) Erhvervs- og Byggestyrelsen, ‘7.2 Energirammer for Nye Bygninger - BR10’.
buildings, the basic fenestration and material properties of the building Skin, - more sophisticated building technology optimization parameters are not investigated as variables.

Future regulatory and voluntary classes of low energy buildings in Denmark.252

**Focus on energy optimization**

To test the hypothesis, an additional research question is posed, looking at the bottom layers of the hierarchy of scales: Site, Struture and Skin. If we can identify the relative impact of these layers, we may be able to find out whether or how the idea of a hierarchy of scales is supported specifically by operational energy optimization of buildings.

*How do urban density, building form and façade materiality affect building energy use and environmental performance?*

---

This research question is examined in four research papers, examining different relations between urban space and building design. The first paper ‘Urban Canyon’ looks at the space between buildings and how the proportions of this space – typically streets and courtyards – affect building energy use, typically through overshadowing, though it turns out to be more complex. The second paper ‘Urban typologies’ investigates how building form and the resulting urban patterns affect energy performance. The third paper ‘methodology’ develops a framework for environmental simulation in the architectural design process, while the fourth paper elaborates on the first results on reflected daylight in the urban canyon and develops a new urban design concept: ‘Urban Daylighting’.

Building typologies and urban canyons with different Height/Width ratios. The very dispersed building patterns found in the periphery of cities are by far the most prevalent compared to the dense, compact urban typologies of the inner city and local centres. In this study the interest is focussed on the impact of urban form and materiality on building energy use. The bottom left image is a photo/thermogram showing energy conversion in an urban canyon: Solar radiation is reflected and perceived as light, or absorbed and emitted as radiant heat which is heating up the air locally. This connection between thermal and visual environmental aspects of solar acces is crucial knowledge when interpreting the results of simulations in qualitative terms.
Looking specifically at how urban density affects building energy use, these studies conclude that both urban canyons and building typologies have strong impacts, and are therefore important design parameters:

*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.*

*Analysis of urban typologies, from traditional patterns to very recent architectural projects, shows a relative deviation of total energy performance up to 16% 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.*

These findings indicate that the impact of urban and building form are greater than hitherto realized, which is mainly due to the increased performance of the building skin in the low energy construction paradigm that is tested. As the thermal insulation values of the building skin is increased, passive solar gains and daylight contributions to lighting have a much greater relative impact on overall energy demand. As these contributions can be understood as common resources it makes sense to argue that they should be protected.

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.

While considerable energy efficiency is gained by going from dispersed to compact typologies, which is a strong argument for urban densification, the results show that

---

there are limits to densification as a sustainable strategy, since the effect wears off and is actually negated at high densities, compromising solar access and energy savings associated with daylighting. For buildings used in the daytime such as offices electricity use for lighting becomes the dominant energy parameter, increasing the overall building energy use significantly as density is increased. In offices electricity for lighting is increased by 85% compared to an unobstructed building. A climate dependent optimal density range is identified at plot ratios ranging from 100-300% which are both energy efficient and able to maintain and distribute sun and daylight as environmental qualities.

Left: Energy use increase significantly for offices, as electricity is used to compensate for lack of daylight. The same effect is less pronounced for housing as the occupants are less at home in the daytime, and lighting is therefore more constantly switched on. For that reason increased density results in lack of environmental qualities in housing, rather than increased energy use.

Right: An optimal range of densities can be identified as a function of energy use and environmental performance. Great variations in performance among the typologies indicate that there is plenty of design opportunities to increase density while maintaining or improving environmental qualities. The green energy use curve is for housing. For offices where the absence of daylight have a more direct impact on energy use, energy use will increase considerably with increased urban density, as shown on the graph to the left.

These studies show the relative influence of urban design and building form, - the Site and Structure layers in the Hierarchy of scales. When the Skin layer is added as a design variable, looking at the impact of window sizes on building energy use in urban canyons, even greater relative impacts are found. A preliminary study correlating energy use with urban canyon proportions and wall to window ratios found variations of up to +225%
and +85% in energy use in offices depending on orientation when the cumulative effects of Site (canyon H/W ratio) Structure (5 story urban building slab) and Skin (window to wall ratio) are added up. The window to wall ratio of the building Skin alone accounts for variations of up to 175% and 75%, making it an all together more powerful design variable than what was found for the Site and Structure layers.

Cumulative effect of Site, Structure and Skin layers (Urban canyon proportion, building slab typology, window to wall ratio) on energy use for south and north facing offices. The urban horizon angle is a metric describing the proportions of the urban canyon. The range of densities are similar to the urban canyon study.

The results show an impact from urban form on building energy use which is much greater than previous studies, more precisely described and more dynamic in character as daylight is taken into account. This finding could be further enhanced when adding lifecycle and transport analysis to the evaluation of the influence of urban design on the energy use at the urban scale.

If we illustrate the hypothetical hierarchy of scales as a pyramid with the large scale, most permanent layers at the bottom we come to the conclusion that looking at operational energy use in buildings alone, the relative impact of each of the Site, Structure and Skin layers results in a figure that is rather rhomboid than pyramid shaped.
While the diagrams are extremely reductive, they may communicate the finding that in operational energy optimization the building Skin layer has the greatest impact on building operational energy use (as should be expected, as it is the direct barrier between interior and exterior climate) in a low energy scenario in a Northern European setting. But the impacts of urban Site conditions, and the form (Structure) of buildings have significant impacts adding to the overall optimization potential. And it is in fact the relatively high insulation values of the building skin in these models that make these effects discernible. With a less insulated building skin, the effect of the urban design parameters would have been relatively smaller as they are directly attributable to passive solar gains and daylight availability. The variations in energy use on the Site and Structure levels are increased in significance as they are most likely to be permanent properties of the building, as Site conditions change very slowly.

*Can we use the insights into the qualitative dimensions of daylight, solar access and building energy use to redefine their role in urban and building design?*

Shifting the focus from energy to environmental performance associated with daylight and solar access, the relative impact of urban density and building form is much greater in qualitative terms. Within the ‘optimal density range’ Daylight Autonomy - which is a metric describing the percentage of time in a year when daylight levels in a room are
above a certain threshold value, varies from 30-60% which is a huge difference in daylight availability, and solar gains vary from 30-40kWh/m²yr. The quality dimension is critical for a discussion of energy optimization results, as daylight and sun availability is so limited in Northern Europe and is very highly valued. The connection between daylight, human productivity and health are well established. While energy use for heating and lighting is aimed at providing comfort, Daylight and in particular sun are associated with joy, possibly adding a dimension of delight and affection to a space. Only rarely are central heating and electrical lighting associated with the same intensity of pleasure.

Focus on Solar Access

It could be seen that the temporal dimension of adding sunlight to climate based daylight simulation had considerable effect on both thermal and daylight performance of buildings and spaces. But the differences in intensity and duration of solar radiation and daylight were very difficult to visualize as anything else than graphs in the IES-Virtual Environment model that was used for the analysis. While these graphs may very well be crucial to analyzing the separate effects caused by building physics, occupant behaviour and energy systems, they do not communicate very well to most architects, who need visual feedback on spatial phenomena.

Left: Study isolating the thermal performance of facades with different window to wall ratios in relation to outside temperatures and solar gains, without internal gains from occupants. Highly glazed facades may

---

shorten the heating season by 1½ months if not overshadowed, but has a much more volatile interior climate on a daily basis and a tendency to overheat in summer compared to buildings with moderate window to wall ratios.

Right: Same study, but with 40% window to wall ratio, graphs showing accumulated effects of façade performance, internal gains from occupants, and applied energy use for heating and cooling. The terms conservative, selective and regenerative modes are adapted from Banham to isolate effects from building physics, occupant behaviour and energy systems analytically.

The abstraction level of data sets, graphs and in particular energy performance standards which reduce a building’s environmental performance to a single value of yearly energy use per square metre, tends to distance the data from real-life empirical experience of buildings. For anyone who is not initiated or interested in the finer aspects of spreadsheets and graph-making, the chain of causes from energy data to experienced climatic intensities and their impact on energy use, is simply too long. With the experience of using thermograms to analyse, visualize and communicate energy and environmental performance aspects to a wider audience in mind, visualization techniques that would allow a better understanding of the spatial and temporal dimensions of sun and daylight were investigated.

To visualize why the Urban Canyon Study did not show any particular increase in energy use for artificial lighting, seasonal daylight availability was compared to the daily rhythms of time spent at home and at work, drawing the everyday rhythm of a generic occupancy pattern of a family home on a 24 hour clock.
It is then possible to compare the daily rhythm to the seasonal rhythm of changes in daylight availability from winter to summer, and the directionality of sun relative to the time of the day. This is an essential diagram to keep in mind if an architect wants to design homes or workplaces which exploits the daylight and passive heating potential for the benefit of the occupants’ daily lives. The diagram also explains why housing did not increase energy use for lighting when urban density and overshadowing was increased: In the winter season when days have little more than 7 hours of light (marked in orange), the occupants are at work or in school (green) when daylight is available. In other words, when the home is occupied it is nearly always too dark and lights tend to be turned on in the winter half-year, statistically drowning out the energy effect of daylight availability in summer. But in the dense city the main problem is overshadowing, and lack of solar access particularly at the lower levels of buildings and at street level. To understand these phenomena as spatial and temporal dimensions solar radiation studies were made in Ecotect.
Left: Radiation analysis of the seasonal changes in intensity of incident radiation on the facades of a 50x50m north-south oriented urban block (Copenhagen climate data). The changing intensity and directionality of the solar radiation is clearly marked on the facades, as are the impacts of overshadowing from the neighbouring blocks.

Right: While the geometry of a building’s Structure may be locked due to Site constrictions such as street orientation, it may be possible to increase the intensity and duration of available solar radiation by folding the building Skin and maximize passive solar heating as a result of the angle of incidence. A rule of thumb is that an hour’s sun is gained for every 15° a façade element is turned towards the sun (not counting self-shading)
Mapping solar radiation on a number of urban and building figurations with different orientations it can be seen that while we established solar access and daylight availability as common resources that should be protected, there are limits to the feasibility of exclusive pursuing passive solar strategies as an approach to low energy building design. The low sun in the cold season means that only the top floor gets sun throughout the cold season. If passive solar strategies are pursued they should aim at exploiting the sun during spring and autumn to shorten the heating season, where the sun also penetrates deeper into the urban canyons, and more apartments may benefit from it. The basic orientation of the street grid has noticeable impacts on seasonal solar access: it is more evenly distributed in diagonal (NE, NW, SE, SW) rather than cardinal orientations (N, S, E, W) of the street grid. Diagonally oriented buildings for housing have the additional benefit of solar access directly at the façade in the periods of the day where the home is most likely to be occupied (before 9.00 after 15.00).

These observations coincide with the basics of Knowles solar envelope geometries which were applied according to the latitude of Copenhagen (N56, E12). The basic idea of Knowles’ solar envelope is an ethics of ‘avoid overshadowing your neighbour’ so that most will have a share of the solar energy potential. Knowles’ geometric principles define ‘solar envelopes’ which are a basic maximum volume a given building development is allowed to take up. The geometry is defined so as to guarantee solar access for a given period of the day and the year. If a solar envelope is defined to ensure solar access throughout the winter in Denmark the maximum height of any building development will be around 1½ floors, due to the low sun angles. So in order to have higher densities, one will have to accept overshadowing in the depth of winter.
Top. Knowles’ original case studies of solar envelopes. The high end faces the sun so as not to overshadow the street and the facades of the block to the north.

Middle: Solar envelopes for Copenhagen (N56, E12) protecting solar access for neighbouring buildings in the daily interval 9-15hrs, for winter, equinox and summer, equalling maximum eaves heights facing streets at app 1½, 3and 5 stories respectively, when both sides of a building are regulated.

Bottom right: BIG’s W57 project. While the shape of the building is argued for preserving the views of neighbours, it is practically an inverted solar envelope which instead of minimizing its impact on the neighbours, maximizes its own solar access, and overshadows the neighbours. Solar access is partisly ‘privatized’ for the maximum ‘hedonistic sustainability’ of its own occupants.
Above: Seasonal radiation intensity studies of folded façade elements (south facing, 5 storeys, street H/W ratio 1:1). Solar gains and sunlight hours may be increased by folding facades – particularly relevant in spring and autumn.

Below: Reflected light from sunlit surfaces contribute significantly to light levels in opposing buildings yet may cause glare, if the glazing ratio is very high. The temporal dimensions of reflected light patterns may also be used for aesthetic effects, animating otherwise self-shaded surfaces.
Introducing 'Urban Daylighting'

When delving into the qualitative dimension of daylight, it was noted that the reflectivity of facades plays a particular role in the dense city. This realization was made both on the basis of empirical observations in everyday situations in my home and workplace, but did also emerge as a discernible phenomenon in the energy optimization studies of the urban canyon. In a wide canyon (H/W ratio 3.0) the northfacing side of an office building would use less energy for lighting than a southfacing one, which could be attributed to the reflected light from the opposing façade. When the reflectivity of buildings’ facades were investigated as a design variable, it could be seen that it had considerable effects on the daylight levels inside buildings, particularly when using climate based daylight modelling to study Daylight Autonomy and sunlight is included in the calculations.

Reflective bright facades are able to transport daylight deeper into the urban canyon and deeper into the rooms on the lower floors than darker facades that absorp the light and converts it to heat. The basic idea is that any building façade may work as an ‘urban daylighting’ device – improving the daylight availability of its neighbouring buildings, but may on the other hand also contribute to glare, if light levels are too high and contrasts too sharp. A number of geometric and material conditions may influence the dynamic spatial and temporal dimension of reflected light, first of all the overall reflectivity of a façade which is a balance between the colour (reflectivity) of the wall and the glazing ratio. Glass has lower reflectivity than is usually thought of as it transmits most light into the building and reflects only a fraction of it, though the reflected fraction may change with the angle of incidence of the incoming light. So contrary to our usual impression of glass facades as highly ‘reflective’ their reflectivity is quite low (app 15%) but their specularity is relatively high. In this way, the balance between opaque and transparent façade elements is also a question of how diffusely and how directly light is reflected off a façade. The effect is very dynamic, changing intensity with the position of the sun during the day and over the seasons, as it is strongest when sunlight is reflected among the facades.
Daylight Autonomy > 10,000lux in urban canyons H/W ratio 0.33 – 3.0. Range 0-50% DA. Wide canyons have more light from the sky while buildings in narrow urban spaces are very dependent on reflected light from neighbouring buildings.

The impact of façade reflectivity on daylight autonomy inside buildings. Changing the reflectivity of a façade in a dense urban context can have considerable effect on daylight conditions inside buildings. Left: façade reflectivity 0.45 (medium grey) right 0.75 (white). Range 0-100% DA.

Matrix of twelve 5-storey façade patterns organized according to wall reflectivity (grayscale 25-75%) and window to wall ratio (20-80%). The white façade with small windows has an overall reflectivity of 65% while the dark grey, highly glazed façade is at less than 10% not counting the effect of occasional specular reflections due to sun position.

5 urban canyons H/W ratio 1.0: Daylight availability (DA > 10,000lux) as result of façade reflectivity. Facade reflectivities are 25, 45 and 65% total representing a range from medium dark to very bright. Daylight availability depends strongly on the reflective properties of facades, including the glazing ratio.
When acknowledging that the reflectivity of facades have an impact on the distribution of light in the urban space, we can take a closer look at what happens when the facades at either side of the canyon are differentiated according to colour or window to wall ratio. Visualizations show that the reflectivity of facades has a considerable effect on the daylight distribution, and is actually the main source of illumination on the lower levels of neighbouring buildings in dense urban situations where the contribution from the sky is restricted.

This important finding emphasises that buildings are not self reliant entities but play an active role in creating adequate daylight for neighbouring buildings. Since facades with large windows transmit light into the interior of the building, they ‘privatize’ more of the available daylight than a brighter, more reflective but less specular façade would. In dense urban situations where daylight and solar acces can’t be further improved by geometric design, it makes good sense to develop design guidelines for bright facades, protecting the common resource of daylight and bringing it deeper into the space between building so that more people can benefit from it.

Urban Daylighting adds another step to the inventory of planners, urban designers and architects dealing with complex urban situations or very dense building design. If we consider the hierarchy of scales as a three step optimization process at the urban level going from Site to Structure and then Skin design considerations, Then the first step would be to map the temporal and spatial availability of daylight and preferably identifying directionality and intensity patterns across the seasonal and daily rythms, developing solar and daylight envelopes for the site. Once that has been done, building form may be allocated so that solar access and daylight availability is guaranteed according to functional criteria of the brief. The third step would then not just allocate windows to ensure adequate daylight levels on the inside, but consider how the distribution of windows and allocation of materials for the façade may contribute to better daylighting of the overall building ensemble. While working with urban daylighting one should also consider the thermal effects derived from specifying darker or brighter materials as they may contribute to a better urban microclimate too.
Discussion

Having found that design decisions on the urban scale have a bigger and more precisely described impact on building energy use than hitherto found, it is necessary to discuss how that knowledge is put to action in architectural design and planning practice. It is demonstrated that even the most basic design decision – specifying the overall form of a building – has wide ranging, and long lasting effects on both urban environment, building energy use and its environmental performance and quality. In other words – once the architect pulls out his pencil and begins doodling on the napkin at the first meeting with the client – he is fully immersed in laying out the future energy use of the place he is about to design. The problem is that architects most often do not fully realize the responsibility which comes with the power of imaginative specification, which a project is.

From the experience gained through the collaborative effort of developing these simulation studies in a close architect – engineer research collaboration it can be stated that there are new insights to be had when crossing the borders of traditional professional territories – combining the understanding of intricate spatial, temporal and social connections of the architect and the understanding of physics of the engineer. The combination of knowledge inspires new ideas in both, possibly informing their ways of doing and knowing in practice, which may then again be made explicit informing a new cycle of knowledge creation.
Example illustration using a methodological framework based on the hierarchy of scales idea to map the parametric variations studied in paper III: Methodology.

The idea behind the hierarchy of scales is that design decisions at each of its layers should simultaneously be seen as both an energy and environmental performance issue and a life-cycle consideration. If a design decision at a given layer has a specific environmental impact – as could be seen when discussing the differences in daylight availability resulting from choice of urban typology – the impact should considered in lifecycle terms too, and the approximated lifetime be considered as a factor potentially multiplying the impact of the decision.

If we see the hierarchy of scales as a step by step optimization method, first considering Site conditions, then building form and structure before considering the building skin, introducing the concept of urban daylighting has introduced new dimensions to the Site, Structure and Skin layers of scale related design decisions with important connotation for the thermal environment as well. It may be an extremely adaptable way to achieve
considerable environmental impact, as specifying the colour of a façade ill change both the thermal and visual environment of its surroundings.

When the hierarchy of scales is understood in terms of durability and the qualitative dimension of daylight and solar access rather than operational energy use, it is strongly reinforced as a design imperative: Once daylight availability or solar access is diminished due to urban scale developments or Site related design decisions, it is practically an opportunity lost for good. The ‘Urban Typologies’ study show that even within the same urban density of a fixed 200% plot ratio, daylight availability and solar access may change considerably depending on typological design choices. Understanding daylight and solar access on the urban scale should be considered an essential first step in any architectural design process.

The essential next step is to take the observations back to design practice.
CHAPTER 7: Return to Practice
CARLSBERG URBAN DESIGN COMPETITION

Model of Competition entry for Carlsberg. Henning Larsen Architects, Dorte Mandrup Arkitekter, Polyform and Signal.

As part of a larger trend of transformations of former industrial zones seen in Western Europe, the redevelopment of the former Carlsberg Brewery area in the Valby district of central Copenhagen is among the most ambitious urban development efforts in Denmark. The master plan is a result of an open international competition in 2008 which was won by the Danish architects Entasis, proposing a reinterpretation of classic Copenhagen typologies: the dense courtyard blocks, smallish squares and parks, and several scattered towers reminiscent of the historical Copenhagen skyline, ranging in height from 60 to 100 meters.

Invited to participate as a sustainability, energy and daylighting consultant to a design team consisting of Henning Larsen Architects, Dorte Mandrup Arkitekter, Polyform and Signal, this urban design competition for a very dense university campus mixed with housing offices and commercial activities was an ideal case to test how the findings from the simulation modelling studies might be transferred back to practice, as the densities and narrowness of urban spaces would be in the same range.

**Research interests**

How would the theoretical findings inform the design decisions taken by the team? I would have to acknowledge not having any direct executive power over design decisions,
and my role was basically to feed information to the team, informing and challenging their ideas. I was particularly interested in seeing how the team and the jury would respond to visualizations of environmental performance, as I had the assumption that these could ‘pack an argumentative punch’ for the project, and in seeing whether these would add to a process of learning or knowledge creation\textsuperscript{255} in the design team. Through the modelling studies in Chapter 6 explicit knowledge regarding urban design’s influence on energy and environmental performance had been created, and my interest was whether this could now be made tacit knowledge as it was transferred to other architects’ design processes.

I therefore kept track of how and when information was fed to the team and conducted a round of structured interviews with the team leaders immediately after hand-in, but before the result of the competition was known. Except for Henning Larsen Architects who have considerable experience using simulation in the design process as a result of having three architectural engineering PhD students associated with the office, the approach of having simulation modelling and environmental performance consultants integrated in the architectural design team was new to the other team members.\textsuperscript{256}

I joined the design team at the beginning of the design process, and Jakob Strømann-Andersen, whom I had collaborated with on a number of research papers, joined the team a bit later, working on wind simulations and finalizing daylight visualizations before hand-in.

The primary way of extracting explicit knowledge from this process is by ‘reflection in action’ and ‘reflection on action’,\textsuperscript{257} as expressed by the team leaders in interviews and during the design process, and my own reflections informed by the experience gathered from previous research studies. In addition, the design proposal was backed by solar access and daylight simulation modelling, which document a very strong impact of urban design on daylight availability, when using the design principles outlined in chapter 6.

\textsuperscript{255} Using Nonaka’s SECI model as a reference for interpretation. Nonaka, 14–37.
\textsuperscript{256} As opposed to working with consulting engineering firms as in traditional design processes.
\textsuperscript{257} Schon.
Engaged in this design process as both a designer and as a researcher I was exerting influence on the situation studied, and was therefore not a neutral observer, but an active participant, for which reason the events are accounted for in first person when directly related to my own interpretations and influence.

**Brief and Master plan**

As part of the planning effort for the Carlsberg area an extraordinarily detailed local regulatory framework\(^{258}\) had been worked out by Entasis Arkitekter, who had won the commission in an open international competition with several hundred competing proposals. The present competition was a first major step in realizing the ideas presented in the Master-plan.

As the first stage of the transformation process, the competition was a prequalified ‘dialogue’ competition in which four teams each consisting of several architect’s firms would present their ideas at three consecutive workshops, getting feedback from the jury. The brief of the competition called for the design of an urban ensemble of three buildings including a 100m tower surrounding a square at the southernmost end of Carlsberg. The programme was specified as a 54,000 m\(^2\) university campus, 14,000 m\(^2\) housing and approx. 12,000 m\(^2\) of shops, cafes and commercial buildings. In addition to the Masterplan, Carlsberg had commissioned a volumetric study, which prescribed a specific building mass reference within which the brief could be allocated. The design task was to articulate the volumes, by adding detail and expression.

---

As Carlsberg wanted a cultivated diversity of architectural expression, it was an important design issue to develop both individual yet cohesive identities for the overall ensemble of buildings. The design team chose to split the ensemble into separate buildings so that each office would have clearly defined design territories, while trying to come up with a unifying theme. Henning Larsen and Signal were in charge of the majority of university buildings, Dorte Mandrup designed the housing tower, while Polyform designed a mixed-use and an office building.

**Design Process**

The design process developed over four weeks with one or two team meetings per week and three workshop meetings with the jury. At the first team meeting I presented a general introduction to my research verbally and some indications on how it could be relevant to the project. The team was at that point developing massing options which were more based on conservational, perceptual and organizational matters than environmental considerations. After the first workshop which I did not attend I offered a graphic presentation of research findings, to give the team members an idea of how it
would be relevant to the project.\textsuperscript{259}

Research references: Daylight and solar heat in urban spaces for urban comfort and daylight availability. Urban daylighting depending on façade transparency and reflectivity (colour). Impact of urban density on energy use of offices.

The idea of a hierarchy of scales was introduced, both as a method of energy and environmental performance optimization and as a way to relate design decisions to resource management in terms of durability and adaptivity. A site analysis of the incident solar radiation on the facades around the central square in the predefined building volume and a study of overshadowing and reflection for urban daylighting were presented, as a basis for discussion and development.

SITE analysis. Average yearly incident radiation on facades facing the central square. Overshadowing and reflection patterns 8.30 – 11.00 at equinox.

In particular the narrow streets separating buildings from each other were identified as problematic, as they would impede on daylight, which would probably make it very difficult to meet Danish standards on daylight levels in educational rooms.

**Design principles: Hierarchy of scales, solar geometry and urban daylighting**

A number of design principles developed on the basis of the simulation studies were pitched to the design team in the first week of the design process:

**SITE:** Changing the disposition of building massing of the predefined volumes to improve solar access and environmental performance, offering better daylight availability for urban spaces and facades and prolonging the outdoors season.

**STRUCTURE:** Using setbacks in the top floors of the narrowest street sections to increase sky-view components of the facades, improving the Height/Width ratio for the lowest part of facades, and ensuring deep penetration of daylight to interior spaces.

**SKIN:** Using brighter, more reflective materials on the top floors than specified in the masterplan so that these could work as ‘urban daylighting’ surfaces for the lower levels of the project, while differentiating window sizes and position according to daylight availability and solar access. Using heavier and darker materials near the ground floor to create a warmer microclimate in the outdoors season.

**SERVICES:** While service systems were not considered at all due to the scale of the project, mapping the radiation levels on the site offered information on potential integration of renewable energy systems.

**SPACEPLAN:** Shifting the overall disposition of the interior organization to allow the volumetric changes, and to better exploit the microclimatic conditions created in between the buildings for social purposes.

**SOLAR GEOMETRY, INTENSITY AND DURATION OF ENVIRONMENTAL ENERGY INPUT:** Experimenting with the orientation of buildings, facades or façade elements it is possible to increase or decrease solar energy and daylight availability and intensity and to prolong or shorten their duration, using overshadowing, self-shadowing, and reflection patterns as geometric means and reflectivity, absorption and transmissivity as material properties to achieve desired environmental effects.
SOLAR GEOMETRY, BUILDING VOLUME AND SOCIAL PATTERNS: Locating synergy effects between the daily and seasonal changes in solar trajectory and the social life of the campus and housing developments. Practically this meant optimizing the building volumes around the central square so as to prolong the outdoor season by protecting solar access at ground level around lunch time in early spring and late autumn.

SOLAR GEOMETRY AND URBAN DAYLIGHTING: paying attention to the temporal and spatial dimension of sunlight when deciding where to have bright facades, and creating diverse and differentiated lighting situations according to daily and seasonal rhythms.

By using brighter materials for the top floors of buildings light could be reflected deeper into the narrow urban spaces, exploiting the daily and seasonal movement of the sun to bring reflected light to places that would otherwise be dark.

The role of communication within the team

I was invited to do the same presentation at workshop 2 with the jury, seemingly attracting interest from the jury as well, as experienced by the design team members.260 But in workshop 2 three members of the jury, - the urban master-planner, the city architect and Carlsberg Properties’ director, - were absent. The apparent interest spawned in the jury at workshop 2 led the design team to adopt the theme of using daylight, sun and the changing daily and seasonal rhythms of weather and social patterns fully, 261 to such a degree that it became a common reference for architectural and

260 “It seemed to have a quite good effect” Jonas Sangberg, ‘Carlsberg Interviews’, 2011, note A3.
261 ”It seems like daylight was taken very seriously, that it was identified as a key element with which to (challenge) the main volume.” Esben Neander Kristensen, ‘Carlsberg Interviews’, 2011, note B4.
experiential quality\textsuperscript{262} and a common identity marker that united the different approaches of the four firms that constituted the design team.\textsuperscript{263}

Almost all the principles and strategies that were initially offered were, in some way or another, integrated into the final design, with varying degrees of conceptual clarity due to the very limited time for design development.\textsuperscript{264} Only the idea of integrating renewable energy systems in specific facades resulting from the solar radiation site analysis was abandoned as irrelevant at this stage, and the idea of skewing façade elements’ orientation according to solar geometry as seen in the tower, was more of an applied rationalization than an original source of the design idea, which was originally based on a perceptual analysis.\textsuperscript{265} At the final presentation the theme was an important narrative in the team members’ presentations of the project,\textsuperscript{266} and perhaps the most important unifying concept.

\footnotesize
\textsuperscript{262} “It made us talk of the passages... Daylight is of course important when you (want to) create the most pleasant atmospheres” Peer Teglgaard Jeppesen, ‘Carlsberg Interviews’, 2011, note D3.


\textsuperscript{264} “(daylight) was a unifying element in our design development... However it was limited how precisely it could be incorporated due to time pressure.” Sangberg, notes A1, A2 & A7.

\textsuperscript{265} Dorte Mandrup Poulsen, ‘Carlsberg Interviews’, 2011, note C2.

\textsuperscript{266} Mandrup Poulsen, note C3.
Visualizations showing the cumulative effects of following the design principles of the hierarchy of scales and urban daylighting going from Site to Spaceplan: Solar radiation and daylight availability in the central square and daylight in an office/educational space in a narrow street. The effects are very considerable, increasing the time of the year daylight levels above 10,000lux are available at the bottom of the central square, while distributing daylight much deeper into the educational rooms, well above the 2% daylight factor threshold value, which would be impossible to achieve without modifying the masterplan.

The cumulative effects of the design choices were calculated by Jakob Størumann-Andersen: Solar radiation levels are increased from 845 to 1025Wh daily average and Daylight availability is increased from 23 to 38% Daylight Autonomy > 10000lux in the central square, which means both the duration and intensity of available daylight and heat is both prolonged and increased. With careful elaboration in later design stages this increase in availability can be used to improve both indoors and outside environment considerably, when care is taken to avoid glare. Setbacks and brighter facades increase the daylight factor in rooms on the 3rd floor from 1,6% to 2,6%. Since the lower
threshold value is 2% DF the results indicate that the extremely narrow street canyons given by the masterplan will result in insufficient daylight conditions to meet the requirements of the university campus unless design measures are taken.

Zooming out from the specific concerns of the competition to the overall research project of this dissertation, the results show that the accumulated effects of pursuing a hierarchy of scales oriented approach to energy and environmental performance, may give very strong positive relative impacts on environmental performance on both the urban and the building scales.

Endgame
At the final presentation all members of the jury were present. There was a time limit to the overall discussion, so time was very tight considering the wealth of information that had to be conveyed. While all the team leaders addressed the environmental performance aspects relevant to their specific design issues, only a minute was given for my presentation to sum up the concepts related to daylight and thermal environment, which was less than optimal, given that it was a first introduction to three of the jury members. But overall the project seemed to be very well received. All we could do was to wait for the verdict.

Returning to my research interests, I conducted interviews with each of the team leaders a few days after hand-in, in order to analyse the experience and inquire how new knowledge was gained from the design process. As noted previously, introducing environmental simulation visualizations very early in the design process seemed to have had a strong impact on the way the design process developed in the team, which was confirmed by the interviewees. But energy optimization was never really the central issue, it was rather the process of working with shaping the environment of this specific corner of the city that had a strong appeal as a narrative and provided an interesting design challenge. But having adopted the theme of environmental performance as a design motif, - did environmental factors detract attention from other crucial matters? “No – but it is really interesting. Sometimes when you have tough demands it becomes
easier to get to the right expression.” Environmental performance was generally seen as an interesting challenge that could drive architectural expression in an innovative way.

One may speculate whether the visualizations and facts presented to the team members somehow inspired a more or less rational approach to energy optimization, but this was not the case. The evidence offered by the research and the visualizations were effective instruments aiding my communication with the team members, but as some of the interviewees note, the visualizations themselves did not make the impact. Rather it was made through the continuous dialogue, where the access to specialists would keep the environmental issues high on the agenda: “It was a really positive driver... Rather than the visualizations making an impact, I think what made it was that you (PAS) were constantly asked, and constantly advocated some choices, pushing things in a certain direction... The visualizations were of course your tool in a chain of argumentation, but I think it was the argumentation that really made it. It may very well have ended up at the bottom of the stack of design considerations. The difference was that you kept readdressing it” Esben Neander Kristensen remarks. Two points are highlighted here: the importance of communication and that the simulation tools in the very beginning of the design process are instruments supporting a creative act of constructing a new social and physical reality by arguing for particular environmental qualities rather than validating results in terms of achieved performance, as was done at the end.

The human factor of communicating the implications of results and arguing the way effects may be accumulated when observing the overall hierarchy of scales, was the element making the difference. Time was simply too short and the design team too scattered working in their separate offices meeting once a twice a week, to follow a step by step optimization method going from one scale to another. And it is most likely that such a direct application of the hierarchy of scales theory would require an intimate culture of collaboration and shared design philosophy before it can be more effective.

267 Teglgaard Jeppesen, note 7D.
268 Mandrup Poulsen, notes A2, D3, C6 & D6.
269 Kristensen, notes B1 & B2.
The visualizations gave a sense of satisfaction to the designers, as they were seen to verify intuitions they had from personal experience. As Dorte Mandrup Poulsen says: “It has been a process of learning for us in some ways. There are some things we know intuitively because we have observed them empirically for many years. I think it was a learning process in the sense that it confirmed that what one knew, one knew, could be documented. That was just fantastic!”

In terms of knowledge creation this may be interpreted as transferring knowledge from tacit to explicit, clarifying, verifying and perhaps expanding intuited knowledge gained from design experience and observation. And being able to inform design choices by this explicit knowledge, the designers could reinvest it in new processes of design, starting a new iteration of knowledge creation by transferring the explicit knowledge to new tacit ways of designing. Perhaps it is the thrill of turning knowledge to power that explains the excitement Dorte Mandrup expresses. But a certain scepticism of basing qualitative architectural design on quantitative information is also found: “It’s up to us to judge things so precisely that we don’t get so overly excited about measuring, that we allow the design process to become totally controlled by it. I’m not sure you will have better buildings because of that... If you throw everything over board and design (only) according to these parameters, - that will never go very well”. The caution here is directed towards understanding performance in a very technical sense – perhaps as a technical focus that is overly concerned with standards and technical metrics of performance assessment. As Steen Eiler Rasmussen reminded us in ‘Experiencing Architecture’ – the architectural experience involves all senses simultaneously and cannot be reduced to discrete measurable elements.

Now that that the environmental qualities of the project were extremely well documented what would the jury make of it? Would it be appreciated, judging from the

---

270 Mandrup Poulsen, note C5.
271 Organizational learning and knowledge creation works in iterative loops of transferring knowledge between tacit and explicit states. Nonaka, 14–37; Nonaka, 96–104.
272 Mandrup Poulsen, note C7.
273 Rasmussen.
comments received in the final presentation? Dorte Mandrup Poulsen was not sure: “We don’t think they really took it in. Actually there were some really fine and relevant points made... Maybe the discussion, or our argumentation was very influenced by it, but I don’t think the focus on energy (along with daylight and environmental performance) really had the jury’s interest... It’s the usual story. There’s a superficial interest in making things sustainable, but when it comes down to it and it has consequences, people are not that interested anymore”\(^\text{274}\)

Winning proposal by Vilhelm Lauritzen, Christensen & CO, COBE, EFFEKT and Nord Architects, articulating the Skin and Spaceplan layers only.

Another design team led by Vilhelm Lauritzen Arkitekter won the competition on the merits of a strong collaborative effort among the teams’ different member offices, and an architectural concept that articulated the transition zone between the outdoors and the interior as an attractive social space.\(^\text{275}\) Neither the winner nor the other projects had challenged the master-plan and the predefined volume of the building massing.

Not winning the competition, the project was however very well received and the effort of improving daylight and environmental performance acknowledged as a special quality. But the changes to the predefined volume and the proposal to introduce brighter materials at specific places were understood in terms of overdone aesthetic effects,

\(^{274}\) Mandrup Poulsen, note C3.

rather than as essential to achieve the desired environmental qualities, and the project was seen to be somewhat missing an understanding of the established identity given by the master plan.²⁷⁶

The masterplan was in conflict with the future requirements of the university for adequate daylight, as it prescribed narrow dark urban spaces, intending a contemplative, silent atmosphere for this end of the greater Carlsberg area, and though the conflict was acknowledged in the jury’s report,²⁷⁷ the cultural value of social acceptance, identity and aesthetics (as judged by the jury) were deemed more important than the functional aspects of sustainability through energy optimization and environmental performance.

As it turned out, the master-plan and the predefined building volumes given in the competition brief, were not negotiable, or at least not negotiated convincingly enough by the project. In essence the greater scales SITE and STRUCTURE in the hierarchy of scales approach to energy and environmental optimization were practically locked, which effectively ruled out using urban design and building massing as the first two steps to improve daylight availability and reduce energy use. As daylight levels’ connection to health, learning and productivity is well documented, this should be a considerable functional concern for the university, well beyond the question of energy efficiency.

Perhaps a flaw in the design team’s communication with the jury was the absence of three of the five jury members in workshop 2 where these premises for the design strategy were laid out. As documented above, the use of simulations and visualizations contributed to communication within the design team supporting a learning experience which created new knowledge to the team. This loop of knowledge creation may very well have been extended to the jury, had the communication been less unidirectional, and the necessary background knowledge been more effectively transferred, and not least accepted. As the position of power in a competition lies with the jury, and great effort had been put into the planning paradigm that was being challenged by our proposal, the question of which values to use when evaluating the proposal, - the identity established

²⁷⁶ Arkitektforeningens Konkurrenceafdeling, p. 17.
²⁷⁷ Arkitektforeningens Konkurrenceafdeling, p. 6.
by the master-plan or new knowledge on sustainable urban design, - would likely be contested territory, and pursuing a design idea challenging the boundary conditions of the brief a risky but potentially rewarding strategy.

Asked whether the project’s qualitative architectural argumentation was strengthened by quantifying environmental performance, daylight and energy Peer Teglgaard Jeppesen, - before he knew the results of the competition, - sums it up, commenting on the neccessity of educating the client in order to win a competition: “It depends on how you interpret it. If we are going to win some commissions, then the client needs to understand it. If he does, it’s a point of quality... If he doesn’t, it goes to hell. So it is insanely important to communicate what we do, to make sure they understand it. In the present situation Carlsberg can get some interesting new buildings, but the city and the city architect can also get an exciting new story to tell, of how we use this new knowledge of daylight and wind.”

While the project did not make the transition into physical reality, it may still tell that story, serving as a case study in this dissertation.

278 Teglgaard Jeppesen, note D9.
CHAPTER 8: Conclusions
Results and Discussion

Returning to the aims of this research project presented in the introduction, the central ambitions of this dissertation was to reframe energy optimization as a qualitative approach to sustainable architectural design, to advance knowledge on the impact of urban design on buildings’ energy use and environmental performance related to daylight and passive solar gains in Northern Europe and to develop design guidelines within a methodological framework that would aid architects’ and engineers’ (and possibly policy makers’) decision making.

The thesis demonstrates that not just one, but several functional and cultural hierarchies of scales can be found from practical and theoretical studies and combined into a coherent methodological framework, which may be further elaborated with future research. Using Hierarchies of Scale rather than passive or active technical optimization terminology to structure design decisions in the earliest stages of the design process, focuses attention on the impact of form and material choice, and is aligned with the workflow of increasing level of definition found in architectural design processes. It may also serve as a loose-fit guide to lifecycle considerations, as scales are ranked according to their degree of permanence.

But the hierarchies are not unidirectional or linear of nature, - rather they work like ecologies: Each design choice has implications for other design choices, changing their performance effects in subtle or more dramatic ways.279 This strong and dynamic interdependency becomes an important point: As buildings affect their neighbours’ energy use and environmental qualities in both positive and negative ways, it becomes increasingly important to develop guidelines for urban and building design that mediates and protects access to daylight and sun as common resources in a future where low-energy buildings relying on daylighting and passive and active solar energy contributions will increasingly be the standard.

279 The interrelatedness of design choices is also observed Beim, Larsen and Mossin; Steemers, pp. 310–318.
The thesis confirms that the most basic architectural design decisions – urban density and pattern, building form and material choice, window to wall ratio, colour and insulation properties of facades, have great impacts on energy use and environmental performance, which is described with more detail and greater precision than previous studies, by adding climate based daylight analysis to thermal and energy simulations.

This is summarized in these conclusions in the simulation modelling papers:

“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 density is a key factor in energy use in buildings.”

“Analysis of urban typologies, from traditional patterns to very recent architectural projects, shows a relative deviation of total energy performance up to 16% 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.”

“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. What this highlights is that in northern Europe, building facades 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.”

“Further optimization through building technology is typically (more) expensive (than urban and building design solutions to environmental performance) 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.”
“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.”

Understanding the variations in energy use and environmental performance requires an understanding of the relations between climate, building use, form, material, technology and human behaviour. Climate based simulation modelling can become an critical tool in the process of understanding these relations better, as it may offer the architect better understanding and control over the environmental performance of their designs, which is essential in the initial design stages. There are however limitations, as simulations are (for now) more focussed at describing particular aspects of the physics and technology than human behaviour, interaction and psychological experience. Though this is likely to improve with ongoing research and development, it should be recommended that designers working with simulations continuously check results with their empirical experience in mind, and continue to question results and methods in terms of their relevance to design intentions.

If the term ‘scale’ is understood as: “Measurable relations between the built environment and the human body” – in a wider sense than the traditional sense of proportion and geometry – simulation opens up environmental performance aspects as new ‘scales’ to architecture, which are not geometric, but related to environmental phenomena and the way these relate to human physiology and perception.

If we follow Kahn’s statement that architecture “must begin with the unmeasurable, must go through measurable means when it is being designed and in the end must be unmeasurable”, simulation offers new a whole new range of measurability of environmental performance to architects’ inventory. Interestingly, these new scales have ‘soft’ gradient boundaries and are better described by intensity and duration, instead of

the static geometric proportion of the traditional understanding.\textsuperscript{281} Light and heat create architectural spaces per se,\textsuperscript{282} which can now be articulated quite precisely in space and time. This extension of the control architects have on the performance of their design offers exciting new opportunities for architectural expression and invention, new aspects of the ‘unmeasurable’ experiences that architecture may inspire.

But it also carries a responsibility that many architects seem to have forgotten in this closing era of cheap fossil fuels: As the future energy use and environmental performance of a design is founded at the point of conception, all design decisions carry an impact on the overall sustainability of a design.\textsuperscript{283} Architects should rethink their role as advisors not only to individual clients but to society at large, and improve the relevance of the special kind of knowledge which is the architects’: The argumentative production of new realities and environments that may offer comfort, delight, joy and meaning in our lives.

\textsuperscript{281} Which may be interpreted as a re-emergence of a new sensitivity towards environmental phenomena as spaces by themselves as in Banham’s discussion of the tent and the campfire as arche-types of environmental management. Banham, pp. 19–20.

\textsuperscript{282} Merete Madsen, ‘Lysrum : Som Begreb Og Redskab’ (unpublished PhD dissertation, Copenhagen: Royal Danish Academy of Fine Arts School of Architecture, 2004); Heschong.

\textsuperscript{283} Reinforcing Beim et al.’s observation from an energy optimization and environmental performance point of view. Beim, Larsen and Mossin.
REFERENCES
‘Dezeen » Blog Archive » Nordwesthaus by Baumschlager Eberle’

‘Methodology | Define Methodology at Dictionary.com’

‘Technology - Wikipedia, the Free Encyclopedia’

A+E:3D <apluse.dk>

Aggerholm, Søren, Karl Grau, and Sbi Statens Byggeforskningsinstitut, ‘Bygningers Energibehov. Pc-program Og Beregningsvejledning. Version 1.05.12, Be06’ (Statens Byggeforskningsinstitut, 2005)


Auken, Svend, ‘Syv Spildte År Med Fogh - Politiken.dk’, 2009


---, Energy and Environment in Architecture, 1st edn (Taylor & Francis, 1999)


---, ‘Sustainable Building Design - Principles and Tools’ (Royal Danish Academy of Fine Arts School of Architecture Copenhagen, 2009)

Eberle, Dietmar, and Pia Simmendinger, *From the City to the House: Eine Entwurfslehre / A Design Theory* (Gta verlag, 2007)


---, ‘8.4.2 Energirammen for Boliger - BR05’, 2005 <http://www.ebst.dk/bygningsreglementet.dk/br95_10_id163/0/42> [accessed 1 August 2011]

---, ‘8.4.3 Energiramme for Andre Bygninger - BR05’, 2005 <http://www.ebst.dk/bygningsreglementet.dk/br95_10_id164/0/42> [accessed 1 August 2011]


Gallou, Irene, and Bruno Moser, ‘Interview, Foster & Partners SMG - Sattrup 2009-03-20’, 2009

Gehl, Jan, Livet Mellem Husene (Arkitektens Forlag, 2007) 


Gore, Al, An Inconvenient Truth: The Planetary Emergency of Global Warming and What We Can Do About It (Bloomsbury Publishing PLC, 2006)


Hawkes, Dean, The Environmental Imagination, 1st edn (Taylor & Francis, 2006)


Kristensen, Esben Neander, ‘Carlsberg Interviews’, 2011


Københavns Kommune, ‘Lokalplan Nr. 432 Del I’ <http://www.netpublikationer.dk/kk/9628/> [accessed 8 February 2012]


Mandrup Poulsen, Dorte, ‘Carlsberg Interviews’, 2011


Marsh, Rob, Michael Lauring, and Ebbe Holleris Petersen, Arkitektur Og Miljø: Form, Konstruktion, Materialer - Og Miljøbelastning (Aarhus: Arkitektskolens Forlag, 2000)


Pedersen, Poul Bæk, Bæredygtig Kompakt By / Sustainable Compact City (Aarhus: Arkitektskolens Forlag)


Rasmussen, Steen Eiler, Experiencing Architecture (Cambridge, MA: MIT, 1959)


Sangberg, Jonas, ‘Carlsberg Interviews’, 2011

Santamouris, Matheos, and Demosthenes N. Asimakopoulos, *Energy and Climate in the Urban Built Environment* (Earthscan, 2001)


---, ‘DKDM i Radiohuset - En Samtale Mellem Generationer’, *ArkFokus*, 2008, 10–15


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


Schön, Donald A., Den Reflekterende Praktiker. Hvordan Professionelle Tænker, Når De Arbejder (Århus: Klim, 2001)


Sørensen, Peter, and Lena Larsen, Renarch - Ressourceansvarlige Huse (Copenhagen: Royal Danish Academy of Fine Arts School of Architecture, 2006)

Teglggaard Jeppesen, Peer, ‘Carlsberg Interviews’, 2011

Teglggaard Jeppesen, Peer, Jonas Sangberg, Esben Neander Kristensen, and Dorte Mandrup Poulsen, ‘Carlsberg Interviews’, 2011


PAPERS
PAPER I: URBAN CANYON
The urban canyon and building energy use: Urban density versus daylight and passive solar gains

J. Strømann-Andersen\textsuperscript{a},* , P.A. Satrup\textsuperscript{b},
\textsuperscript{a} Department of Civil Engineering, Technical University of Denmark, Building J3, DK-2800 Lyngby, Denmark
\textsuperscript{b} Institute of Building Technology, Royal Danish Academy of Fine Arts School of Architecture,Via della Lungara 189, I-00185 Rome, Italy

\textbf{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 how 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 +15\% for housing, which shows that the geometry of urban canyons is a key factor in energy use in buildings. It was demonstrated how the reflective properties of urban canyons play 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.

© 2011 Elsevier B.V. All rights reserved.

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 maximizing 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
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 inclination mean that the urban geometry affects solar access much more here than in other urban centres around the world. Overheating 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 should have 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 lessons learned on 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 neighboring 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 ≤35 kWh/m²/yr for housing and ≤50 kWh/m²/yr 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 urban 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, the building design process for use by building designers and tend to consider buildings as self-contained entities, neither neglecting or grossly simplifying the importance of phenomena that occur on the urban scale. Nevertheless, there have been some investigations, e.g. LeBlanc et al. [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-meter energy consumption of non-domestic buildings. They demonstrate the effect using a calculation that compares the EDM (Digital Elevation Model) with the LT method (Lighting and Thermal) developed by Buck and Sweeney [8]. The most detailed and complete investigations of urban obstruction affecting energy use are presented by Baker and Sweeney [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), demonstration that daylight is significantly reduced in a heavily obstructed environment. A study of VDF predicted by RADIANCE simulation demonstrates that an upper obstruction (n0) at 60° and a lower obstruction (n1) 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. Few, if any, studies have investigated the results of a combined and fully integrated dynamic energy simulation. An earlier study by Steubing and Scharmann-Andersen [11] 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. 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 pattern associated with buildings. While generic models obviously lack a lot of the variation and diversity that could make them architecturally
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 technologically-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 orientations. The building type has two variations: housing and office linked to the types of use 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 2.0 to 5.0 (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).

![Fig. 1. Contemporary urban redevelopments (A) Offices, Kompagnistræde, Copenhagen, H/W ratio 0.8, (B) Housing, Viborggade, Copenhagen, H/W ratio 1.25.](image)

<table>
<thead>
<tr>
<th>Street width</th>
<th>30 m</th>
<th>20 m</th>
<th>15 m</th>
<th>10 m</th>
<th>7.5 m</th>
<th>5 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height/width ratio (H/W)</td>
<td>0.5</td>
<td>0.75</td>
<td>1.0</td>
<td>1.3</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Plot ratio (R) guideline (5-story uniform pattern)</td>
<td>200</td>
<td>250</td>
<td>285</td>
<td>335</td>
<td>365</td>
<td>400</td>
</tr>
</tbody>
</table>

![Fig. 2. Typical urban patterns and proportions of urban canyons in Copenhagen.](image)
3.2. Urban-canyon simulation, radiative and daylight environment

The radiative environment was studied using Autodesk Ecotec Analysis 2010. Ecotec is a highly visual architectural design and analysis tool that links a comprehensive 3D modelling 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 ('weather'). In addition to standard graphic and table-based reports, analysis results can be mapped over building surfaces or displayed directly in the software. This includes visualisation 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 Shakespear, 1998) and Ward and Ward, 1998) 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 ('weather') file. More detail on the underlying simulation algorithm of DAYSIM can be found in [17,18]. Daylight factors have been used in earlier 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, which in available daylight is quantified combining both direct and diffuse radiation [19,20].

Street canyon surface reflectance varies 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 stories of 50 m² 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 m² apartment or office subdivision, a size that is commonly found, and close to the national average of 110 m² 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.

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, ApacheCalc/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 boundaries surfaces are 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/m²K. Glazing U-values are 1.5 W/m²K. 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 on 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 geometry 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.

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Factor</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas and oil</td>
<td>1.0</td>
<td>Heating and DHW</td>
</tr>
<tr>
<td>District heating</td>
<td>0.8</td>
<td>Heating and DHW</td>
</tr>
<tr>
<td>Electricity</td>
<td>2.5</td>
<td>Cooling, Mech. Vent. and Art. Light.</td>
</tr>
</tbody>
</table>
Energy use for electric appliances other than those 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. 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 at midday winter solstice, 58 in summer (compared to 15°/62° 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 illumination levels (>10,000lx) (Fig. 5) and low illumination (<500lx) (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 illumination levels are pronouncedly asymmetrical, yet not only in terms of 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 (0.15), 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 levels 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 distribution 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 1.5) 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/m²/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 moves at 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 canyon.

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 allow 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 larger 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 2-3 times greater than with other orientations. The largest
Fig. 4. Average daily solar radiation in street canyon. Calculated in ECOTECT (working hours 06–17, contour range 500–2500 Wh in steps of 200 Wh). Weather data, Copenhagen (°Cw).

Fig. 5. Annual illuminance >10000lx in street canyon. Calculated in RADIANCE/DAYSIM (working hours 08–17, contour range 0–50% in steps of 5%). Weather data, Copenhagen (°Cw).

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 (°Cw).

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 5%). Weather data, Copenhagen (°Cw). (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 horizon. 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

Urban density versus total energy consumption

*Office, Window-to-Wall ratio 40%*

<table>
<thead>
<tr>
<th>Street width (m)</th>
<th>Primary energy consumption [kWh/m²/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 m (H/W = 0.5)</td>
<td>70 kWh/m²/year</td>
</tr>
<tr>
<td>20 m (H/W = 0.5)</td>
<td>50 kWh/m²/year</td>
</tr>
<tr>
<td>20 m (H/W = 0.75)</td>
<td>40 kWh/m²/year</td>
</tr>
<tr>
<td>15 m (H/W = 0.5)</td>
<td>30 kWh/m²/year</td>
</tr>
<tr>
<td>10 m (H/W = 0.5)</td>
<td>20 kWh/m²/year</td>
</tr>
<tr>
<td>7.5 m (H/W = 1.5)</td>
<td>10 kWh/m²/year</td>
</tr>
<tr>
<td>5 m (H/W = 3.0)</td>
<td>5 kWh/m²/year</td>
</tr>
</tbody>
</table>

Fig. 8. Total primary energy consumption (kWh/m²/year) for a 5-storey office building 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 2000 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

![Relative deviation of energy consumption for a 5-storey office building as a function of urban density compared to five horizons.](image)

![Urban density versus Solar gain for a 5-storey office building as a function of urban density.](image)

![Urban density versus Artificial light for a 5-storey office building as a function of urban density.](image)
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/m²/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 the light 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 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
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 stories of low energy buildings facing the urban canyon under study on a cloudy day.

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 70% for offices and +15% for housing, not necessarily worse without design appeal, but sometimes. From the given specifications of the building layout, it is possible to design a high-energy office building with an energy consumption of around 50 kWh/m²/year. If the corner around the building and the surrounding buildings into a dense urban area, the energy consumption will increase approximately 70 kWh/m²/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 concept as is, but also an estimate based on the maximum density allowed on neighboring 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 neighboring buildings and the public spaces they participate in creating. As the real 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 offices and 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 very dependent on the reflectivity of the 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 [20] 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 dependencies 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.

<table>
<thead>
<tr>
<th></th>
<th>Office</th>
<th>Housing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Construction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extensive walls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-value</td>
<td>0.2 W/m²K</td>
<td>0.2 W/m²K</td>
</tr>
<tr>
<td>Roof</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-value</td>
<td>0.15 W/m²K</td>
<td>0.15 W/m²K</td>
</tr>
<tr>
<td>Ground-contact</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-value</td>
<td>0.25 W/m²K</td>
<td>0.25 W/m²K</td>
</tr>
<tr>
<td>Internal walls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-value</td>
<td>0.35 W/m²K</td>
<td>0.35 W/m²K</td>
</tr>
<tr>
<td>Internal ceiling/floor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-value</td>
<td>0.32 W/m²K</td>
<td>0.32 W/m²K</td>
</tr>
<tr>
<td>Window</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-value</td>
<td>1.3 W/m²K</td>
<td>1.3 W/m²K</td>
</tr>
<tr>
<td>g-value</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Visible light normal</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Lighting</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting level</td>
<td>200 lx</td>
<td>200 lx</td>
</tr>
<tr>
<td>Maximum power</td>
<td>4 W/m²</td>
<td>4 W/m²</td>
</tr>
<tr>
<td>Installed power density</td>
<td>2 W/m²/100 lx</td>
<td>4 W/m²/100 lx</td>
</tr>
<tr>
<td>Luminous efficacy</td>
<td>56 lm/W</td>
<td>56 lm/W</td>
</tr>
<tr>
<td>Variation probe</td>
<td>4.8 am-5 pm, M-F</td>
<td>4.8 am-5 pm, M-F</td>
</tr>
<tr>
<td>Switched-off percentage</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Dimming profile</td>
<td>Dimming, (200 lx)</td>
<td>Dimming, (200 lx)</td>
</tr>
<tr>
<td><strong>Miscellaneous</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum sensible gain</td>
<td>6 W/m²</td>
<td>6 W/m²</td>
</tr>
<tr>
<td>Variation profile</td>
<td>8 am-5 pm, M-F</td>
<td>8 am-5 pm, M-F</td>
</tr>
<tr>
<td><strong>Air exchanges</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infiltration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min flow</td>
<td>Day: 0.13 l/s m²</td>
<td>Night: 0.09 l/s m²</td>
</tr>
<tr>
<td>Variation profile</td>
<td>Day: 0.13 l/s m²</td>
<td>Night: 0.09 l/s m²</td>
</tr>
<tr>
<td>Air flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variation profile</td>
<td>8.7 am-5 pm, M-F</td>
<td>8.7 am-5 pm, M-F</td>
</tr>
<tr>
<td>Natural ventilation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variation profile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating and cooling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter season (mid-wk 22-28)</td>
<td>20°C (winter hours)</td>
<td>20°C (winter hours)</td>
</tr>
<tr>
<td>Heating set point</td>
<td>20°C (winter hours)</td>
<td>20°C (winter hours)</td>
</tr>
<tr>
<td>Cooling set point</td>
<td>24°C (summer hours)</td>
<td>24°C (summer hours)</td>
</tr>
<tr>
<td>Summer season (mid-wk 32-37)</td>
<td>25°C (summer hours)</td>
<td>25°C (summer hours)</td>
</tr>
<tr>
<td>Heating set point</td>
<td>25°C (summer hours)</td>
<td>25°C (summer hours)</td>
</tr>
<tr>
<td>Cooling set point</td>
<td>26°C (summer hours)</td>
<td>26°C (summer hours)</td>
</tr>
<tr>
<td>Hot water consumption</td>
<td>100 l/day</td>
<td>150 l/day</td>
</tr>
</tbody>
</table>
References

PAPER II: TYPOLOGIES
“Building Typologies in Northern European Cities – Daylight, Solar Access and Building Energy Use”

P.A. Sattrup¹ and J. Stromann-Andersen²

¹P.A. Sattrup (corresponding author)
Institute of Architectural Technology,
Royal Danish Academy of Fine Arts, School of Architecture
Postal address:
Phil. de Langes Alle 10,
14 35 København K
Denmark
E-mail: petersattrup@kdafk.dk
Direct tel: +45 3258 6218
Mobil: +45 2636 3012

²J. Stromann-Andersen
Department of Civil Engineering,
Technical University of Denmark
Brovej Building 110,
2800 Kgs. Lyngby
Denmark

Journal of Architectural and Planning Research
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 16% 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 m² of floor space](image1)

![Figure 2: Energy required for space cooling per m² of floor space](image2)

![Figure 3: Energy required for artificial light per m² of floor space](image3)

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 Paolo, Brazil at 23.5° 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-and climates.

A previous study by the authors (Strømmen-Andersen J. & Sattrop 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 façades 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 2000%, 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 5, 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 (50m² zone, 5 stories of 100m² apartments with 2 rooms each, 500m² 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 m² (1076 ft²) apartment, a common size close to the Danish national average of 110 m² (1184 ft²) per dwelling. 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/m² K (0.04 Btu/hr ft² °F). Window U-values (including frame) are 1.5 W/m² K
(0.32 Btu/hr ft² °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.

![Diagram of analytical field with plot ratio 275% perimeter block](image)
Urban Building Type Patterns

Type A (Courtyards Block)

Type B (Indented Block)

Type C (Perimeter Block)

Type D (Barcode)

Type E (Slab)

Type F (Tower)

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>
<thead>
<tr>
<th>Smoothness</th>
<th>Surface-to-Floor Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>94%</td>
</tr>
<tr>
<td>Type B</td>
<td>101%</td>
</tr>
<tr>
<td>Type C</td>
<td>108%</td>
</tr>
<tr>
<td>Type D</td>
<td>112%</td>
</tr>
<tr>
<td>Type E</td>
<td>108%</td>
</tr>
<tr>
<td>Type F</td>
<td>160%</td>
</tr>
</tbody>
</table>

Table 2: Smoothness. 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.

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 occupations can be very misleading given wide variations in daylight availability under 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 illuminance² 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

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 (16% 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)

² Illuminance is the total luminous flux incident on a surface, per unit area
and New York City at 12.4 °C), which necessitates more energy for heating to achieve thermal comfort.

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 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 on 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 (Typical).

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 lesser 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 16% 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 interface 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.
There is no great variation in energy consumption. Types C and E perform best with a relative saving of -2.3% and -3.6% in relation to Type A. A saving of 3.6% 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 (7 inches). 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.

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**

![Twisted Block Diagram](image1)

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

**STEPPED BLOCK**

![Stepped Block Diagram](image2)

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

Table 10: Perimeter type used as reference

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/m²/year (0.64 kBTu/ ft²/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’ inserted so as to protect the solar access of the buildings behind it. Density 250%. Range 0-2000 Wh/m². View from solar position at equinox 11h34.

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 neighbors to the north, the triangular urban spaces on each side allow sunlight to penetrate deep into the streets and on the opposing facades. The block to the north does lose some solar radiation, but how much compared to what the neighboring 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 facades 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 16%, which correlates with the compactness of the different types’ surface to floor ratio. With well insulated building facades, 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).

![Graph showing the relationship between solar gain, daylight autonomy, and energy use across different densities.](image)

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.

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


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).


Appendix

CALCULATION PARAMETERS, DEFAULT VALUES

<table>
<thead>
<tr>
<th>Construction</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>External Walls</td>
<td>U-value</td>
</tr>
<tr>
<td>Roofs</td>
<td>U-value</td>
</tr>
<tr>
<td>Ground/Exposed Floors</td>
<td>U-value</td>
</tr>
<tr>
<td>Internal Walls</td>
<td>U-value</td>
</tr>
<tr>
<td>Internal ceilings/floor</td>
<td>U-value</td>
</tr>
<tr>
<td>Windows</td>
<td>U-value</td>
</tr>
<tr>
<td>g-value</td>
<td></td>
</tr>
<tr>
<td>Visible light normal properties</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Use of the building

Service, occupants on continuously.

Internal Gains

People

Internal heat gain 1.5 W/m² (0.47 Btu/hr ft²) midnight-9 am & 3 pm-midnight (weekdays) on continuously (weekends)

Lighting

Lighting level 200 lux

Maximum Power 5 W/m² (0.95 Btu/hr ft²)

Variation Profile 0 am-9 am & 3 pm-10 pm (weekdays)

2 am-8 am (weekends)

Switch-on percentage 20%

Dimming profile Manual on/off, (200 lux)

Miscellaneous

Maximum Sensible gain 3.5 W/m² (0.11 Btu/hr ft²)

Variation Profile on continuously

Switch-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

- Natural ventilation
- Max. Flow: 0.94 l/s m², t > 25 °C (0.18 ft²/s, t > 77 °F)
- Variation Profile: (steady 15–37)

### Heating and cooling

- **Heating set point winter**: 20 °C (68 °F)
  - (on continuously)
- **Cooling set point winter**: 25 °C (77 °F)
  - (on continuously)
- **Heating set point summer**: 23 °C (73.4 °F)
  - (on continuously)
- **Cooling set point summer**: 26 °C (78.8 °F)
  - (on continuously)

### Hot water consumption

- 256 l/m² pr. Year (0.64 ft³/m² pr. year)

### Surface reflectance variables

- Ground (Asphalt): 0.20
- External wall: 0.45
- Windows: 0.75

### Primary energy factors

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Factor</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas and oil</td>
<td>1</td>
<td>Heating and DHW</td>
</tr>
<tr>
<td>District heating</td>
<td>0.8</td>
<td>Heating and DHW</td>
</tr>
<tr>
<td>Electricity</td>
<td>2.5</td>
<td>Cooling and Mech. Vent.</td>
</tr>
</tbody>
</table>

List of energy factors as stated in the Danish Building Code and how they are used in the simulations.
PAPER III: METHODOLOGY
A methodological study of environmental simulation in architecture and engineering. Integrating daylight and thermal performance across the urban and building scales.

Peter Andreas Satrup¹, Jakob Strømann-Andersen²

¹Royal Danish Academy of Fine Arts
School of Architecture
Philip de Langes Allé 10.
DK-1435 Copenhagen K, Denmark
peter.sattrup@karch.dk

²Technical University of Denmark
Department of Civil Engineering
Brovej 118.
DK-2800 Kgs. Lyngby, Denmark
jastra@byg.dtu.dk

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, 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.

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 emphasises 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 multidisciplinarity 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), Baumgeschlager & 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 Baumgeschlager 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 (Simmdendinger and Schrör 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 Baumschluger & 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 ‘conservate’ 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, - furnishings 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's 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: Setup: At the urban scale, regulatory layers can be identified on the basis of the spatial, property and planning framework that govern 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 technically. 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 related?

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 defined that link the different scales surrounding a building project (Fig. 5).

Figure 5: Connection of Frameworks: Urban, Building, Operation, Time and Energy. The relative position of layers imply their interrelatedness.

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.
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. Ecopt 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.

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 storey 50x50m urban 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 0-200W/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 45 degrees and North/South faceted façade block. Radiation levels during warm season April-Oct and cold season Oct-April. Radiation levels 0-200W/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 45 degrees and East/West facing buildings.

Surprisingly the rotated block does not get the energy savings for daylight that the high radiation levels would make on 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 when 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 straightforward. 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 rythms 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 ads 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 5th 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 5th 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).

Figure 12 CONSERVATIVE+SELECTIVE+REGENERATIVE: 5th 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).

![SELECTIVE: DAYSIM Daylight autonomy renderings of the yearly percentage of time where daylight levels exceed 200 lux during occupancy hours 6-18.](image)

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 200 lux 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).

![REGENERATIVE: graph showing the temporal dimension of energy use for artificial lighting dependent on window to wall ratio.](image)

7. CONCLUSION

A methodological framework was developed, derived from interviews with leading practitioners and key references from architectural theory. The framework establishes a holistic and integrative approach that emphasizes that the layers, scales, components, materials use 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 climate-based daylighting metrics, and a continual evolution of conceptual clarifications that allows knowledge to be integrated and disseminated across professional borders.

References


### Appendix

<table>
<thead>
<tr>
<th></th>
<th>CONSERVATIVE MODE</th>
<th>SELECTIVE MODE</th>
<th>REGENERATIVE MODE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Opaque Construction</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External Walls</td>
<td>0.2 W/m²K</td>
<td>0.2 W/m²K</td>
<td>0.2 W/m²K</td>
</tr>
<tr>
<td>Roof</td>
<td>0.15 W/m²K</td>
<td>0.15 W/m²K</td>
<td>0.15 W/m²K</td>
</tr>
<tr>
<td>Exposed floors</td>
<td>0.15 W/m²K</td>
<td>0.15 W/m²K</td>
<td>0.15 W/m²K</td>
</tr>
<tr>
<td>Thermal capacity</td>
<td>140 J/(m²·K)</td>
<td>140 J/(m²·K)</td>
<td>140 J/(m²·K)</td>
</tr>
<tr>
<td>Thermal bridging coefficient</td>
<td>0.035 W/m²K</td>
<td>0.035 W/m²K</td>
<td>0.035 W/m²K</td>
</tr>
<tr>
<td><strong>Glazed Construction</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External Windows</td>
<td>1.5 W/m²K</td>
<td>1.5 W/m²K</td>
<td>1.5 W/m²K</td>
</tr>
<tr>
<td>g-value</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Visible light normal transmittance</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>USE OF THE BUILDING</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>People</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal heat gain</td>
<td>-</td>
<td>1.5 W/m²</td>
<td>1.5 W/m²</td>
</tr>
<tr>
<td><strong>Lighting</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting level</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Power</td>
<td>200 lux</td>
<td>200 lux</td>
<td>6 W/m²</td>
</tr>
<tr>
<td>Variation Profile</td>
<td>8am-9am &amp; 3pm-10pm (weekday)</td>
<td>8am-9am &amp; 3pm-10pm (weekend)</td>
<td></td>
</tr>
<tr>
<td>Switched-on-percentage</td>
<td>30 %</td>
<td>30 %</td>
<td>30 %</td>
</tr>
<tr>
<td><strong>Miscellaneous</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Sensible gain</td>
<td>3.5 W/m²</td>
<td></td>
<td>3.5 W/m²</td>
</tr>
<tr>
<td>Variation Profile</td>
<td>on continuously, 50 %</td>
<td>on continuously, 50 %</td>
<td></td>
</tr>
<tr>
<td><strong>AIR EXCHANGES</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infiltiration</td>
<td>0.13 l/s m²</td>
<td>0.13 l/s m²</td>
<td>0.13 l/s m²</td>
</tr>
<tr>
<td>Variation Profile</td>
<td>on continuously</td>
<td>on continuously</td>
<td>on continuously</td>
</tr>
<tr>
<td>Natural ventilation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Flow</td>
<td>0.9 l/s m²</td>
<td>0.9 l/s m²</td>
<td>0.9 l/s m²</td>
</tr>
<tr>
<td>Variation Profile</td>
<td>(week 15 - week 37)</td>
<td>(week 15 - week 37)</td>
<td>(week 15 - week 37)</td>
</tr>
<tr>
<td>Mechanical ventilation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min Flow</td>
<td>0.3 l/s m²</td>
<td>0.3 l/s m²</td>
<td>0.3 l/s m²</td>
</tr>
<tr>
<td>Variation Profile</td>
<td>on continuously</td>
<td>on continuously</td>
<td>on continuously</td>
</tr>
<tr>
<td>System specific fan power (SFP)</td>
<td></td>
<td></td>
<td>1.0 W/m²</td>
</tr>
<tr>
<td>Vent. Heat recovery effectiveness</td>
<td></td>
<td></td>
<td>65%</td>
</tr>
<tr>
<td>Cooling efficiency</td>
<td></td>
<td></td>
<td>COP=4.5</td>
</tr>
<tr>
<td><strong>HEATING AND COOLING</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating set point</td>
<td>winter</td>
<td></td>
<td>20 °C (on continuously)</td>
</tr>
<tr>
<td>Cooling set point</td>
<td></td>
<td></td>
<td>25 °C (on continuously)</td>
</tr>
<tr>
<td>Heating set point</td>
<td>summer</td>
<td></td>
<td>22 °C (on continuously)</td>
</tr>
<tr>
<td>Cooling set point</td>
<td></td>
<td></td>
<td>20 °C (on continuously)</td>
</tr>
</tbody>
</table>

Table 1: Simulation systems settings.
PAPER IV: URBAN DAYLIGHTING
Submitted to Building and Environment

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

A. Iversen*, J. Strømann-Andersen† and P.A. Satrup‡

* A. Iversen (corresponding author)
Department of Civil Engineering, Technical University of Denmark
Postal address:
Brogel Building 118,
DK-2800 Kgs. Lyngby
Denmark
E-mail: ani@byg.dtu.dk
Direct tel.: +45 45285334

† J. Strømann-Andersen
Department of Civil Engineering, Technical University of Denmark

‡ P.A. Satrup
Institute of Building Technology
Royal Danish Academy of Fine Arts School of Architecture

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 illuminance in individual buildings, (2) to investigate how urban geometry, façade reflectance and window-to-wall ratios affect the daylight distribution at multiple levels of buildings and (3) to indicate the need for inclusion of urban daylighting studies in planning and the early stages of building design.

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

Keywords: Urban Design, Daylight Strategies, Indoor Environment
1 Introduction

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

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

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

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

Figure 2: Wall Street Canyon, Facade reflectance approximately equal to 45% - 55%.
The effect of obstructions or urban geometry has been described in various research papers. Previous research on daylight availability has focused on the solar irradiation and illuminance levels on the urban fabric. Compagnon et al. (2004) looked at the solar irradiation on the urban fabric (roofs and facades) in order to assess the potential for active and passive solar heating, photovoltaic electricity production and daylighting [2]. Mardalevic 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, Kämpf and Robinson (2010) applied a hybrid evolutionary algorithm to optimize building and urban geometric form for solar radiation utilization [4]. These studies only investigate the urban design from external environmental impact.

Nevertheless, there have been some investigations that link the exterior radiation/illumination to interior daylight availability. In studies by Li et al. (2009), they introduced the vertical daylight factor (VDF) and demonstrated that daylight is significantly reduced in a heavily obstructed environment [5,6]. A study of VDF predicted by RADIANCE simulation demonstrates that an upper obstruction at 60° compared to a lower obstruction at 10° reduce the daylight level by up to 85%. The results also indicate that the reflection of the obstructive buildings can be significant in heavily obstructed environments, such as rooms on lower floor levels facing high-rise buildings. In another study by Iversen et al. (2011), they looked at the influence of the surroundings on the daylight factor within the room followed by a categorization of the facades according to their daylight performance, with the aim being to facilitate the design process aiding to point out urban areas that are good in terms of daylight inside the buildings and areas that have a poor daylight performance [7]. In a study by Strømann-Andersen and Sallrup (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>
<thead>
<tr>
<th>Ambient bounces</th>
<th>Ambient Division</th>
<th>Ambient sampling</th>
<th>Ambient accuracy</th>
<th>Ambient resolution</th>
<th>Direct threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1000</td>
<td>64</td>
<td>0.1</td>
<td>300</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1: Radiance simulation parameters

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 2: Simulation matrix of different WWR’s (20%, 40% and 60%) and facade reflectances (0.15, 0.45 and 0.75)](image)

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

![Figure 4: Urban street compact simulation setup](image)

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/m² 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.
The influence of orientation is depicted for the 5th floor, in Figure 5b, as expected the southern orientation has a higher DA, whereas the northern orientation is the lower bound. For the 1st and 3rd floor 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 1st floor no difference is observed at WWR of 20 %. However at WWR of 40 % and 60 % the southern orientation has the shortest DA penetration depth. When comparing the East/West orientation for the 5th floor it can be seen that slightly more light enters the space for the western orientation. This is a result of the climatic conditions, when the cloud cover in the afternoons is smaller compared to the mornings.
Figure 6: Distance from facade with DA below 50 % for street width of 15 m. WWR varies from 20 %, 40 % to 60 %. External reflectance 0.4.

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

3.3 Influence of opposing facade reflectance

On Figure 7 the daylight autonomy through the room is depicted for different facade reflectances for the northern and southern orientation for the H/W of 1 and for the 5th floor. As expected the increments in reflectance increase the daylight penetration depth within the room, both for northern and southern orientation.
Figure 7: Daylight Autonomy 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 5th floor in an urban canyon of H/W 1. When looking at the other floor plans in this typology, the DA on the 1st and 3rd floor increases for the northern orientation, and comes to the same level or even higher than for the southern orientation, see Figure 8.

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

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

The green line shows 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 1.8 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.

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 1st floor and 3rd floor respectively. This is a consequence of the direct part of the daylight being reduced when the H/W ratio decreases, because a smaller amount of the sky is visible from the lower floor plans. For the dynamic simulations this has the effect that a higher proportion of the reflected light bounces of the southern façade, and then falls into the northern oriented rooms. Hereby the limit at which a DA threshold of 50% is reached increases.
4 Conclusions

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

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

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

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


SUSTAINABLE CITIES:
DENSITY VERSUS SOLAR ACCESS?
A Study of Digital Design tools in Architectural Design

P.A. Satrup¹ and J. Stromann-Andersen²

¹Institute of Building Technology,
Royal Danish Academy of Fine Arts School of Architecture
Copenhagen, Denmark; email: peter.satrup@karch.dk

²BYG-DTU, Danish Technical University /
Henning Larsen Architects
Copenhagen, Denmark; email: jasta@byg.dtu.dk

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.
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).

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 Modeling (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 modeling with an extensive database, thus controlling geometry, quantities, qualities, time aspects and costs, giving the designers unprecedented
Simulation Modeling

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 modeling interfaces that connect directly to architects software and even offers templates and default values for typical construction and material types, that architects can work with and create simple simulations. The results can even be visualized spatially and temporally (fig 3.) so as to get an impression of how the building physics and climate conditions work together in space and time. There seems to be a potential in exploring these interrelationships for formal and conceptual design ideas, and for using these visualizations to improve communication between architects and engineers.

Fig. 3. Ecotect daylight simulation

The challenge of simulation modeling 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 their end performance 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 shadowcasting 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 (1/2 hectare) is modeled. 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 timespan.

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’s 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?

3. RESULTS

![Fig. 4. Urban morphology. Generic urban patterns reflecting Copenhagen’s evolution from walled city to dispersed metropolis.](image)

![Fig. 5. Overview of energy performance calculation results for pavilion, terrace and courtyard urban patterns.](image)

**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. 2 kWh/m²year 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. 7.)

![Fig. 7. Courtyard type energy performance with increased urban density](image)

**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. Increasing the density of the terrace type urban pattern does result in increased energy use for the lowest levels. (Fig. 8.)

![Fig. 8. Terrace type energy performance with increased urban density](image)

**Pavilion**
The pavilion has the highest energy use due to its high surface to volume ratio, which allows for considerable heat losses. Its open context allows solar gains from more directions and longer durations. 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 dispersed city, which has implications for energy use for transport. Increasing density for a pavilion type urban pattern used for offices will actually reduce energy consumption slightly, as the context will offer shading to the lowest levels, and thus reduce cooling demands. (Fig. 9.)

Fig. 9. Pavilion 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 basic stage. (Fig. 10.) The difference becomes even more pronounced when calculated for primary energy consumption, as electricity is used for both cooling and artificial lighting. (Fig. 11.)

While it is not very time-consuming to set up a basic 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 are 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.

The balance between heating, cooling and daylight is both building type and site specific. 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 important role for both solar gains and daylight and should as a minimum be included in any simulation.

5. REFERENCES

Eberle, D. and Simmendinger, P. (2007) "From City to House – a Design Theory"

6. APPENDIX

Systems settings used for models in IES Virtual Environment:

1 Location
The buildings are located in Copenhagen with facades facing north and south.
Weather data (Aalborg) Copenhagen WEclim.dat
Orientation South, street
Context
Land register 20 m x 25m (500 m2)
Street width 15 m
Ground reflectance 0.20
Context reflectance 0.70
Scenario
Zone
The scenarios are simulated by default as one zone. The zone is defined as a complete floor plan. (Marked with red).

2 Boundary conditions
In IESVE (plug-in SketchUp) all surfaces with no adjacent room are considered to be facing the external environment. In this case only the facades (and ground deck) face the external environment. Therefore, the boundary conditions for the side walls and ceiling have to be changed manually in order for the program to consider these as internal walls.
It is not possible to model all the walls as inner walls in IESVE. Therefore, the inner walls have to be added a temperature profile, which corresponds to the presumed temperature in the adjacent room.
Adjacent Room Temperature (°C): ta, variable for the room temperature
Ground temperature: 10 °C (constant)
Construction
(Standard constructions from IESVE)
Exterior Walls, ASHW1113
Construction thickness 0.5271 m
U-value 0.1849 W/m2 K
Roofs, (ASHRF211)
Construction thickness 0.3588 m
U-value 0.1599 W/m² K

**Ground/Exposed Floors (STD_FLO2)**

Construction thickness 1.1985 m
U-value 0.2999 W/m² K

**Internal Ceilings/Floors (CCS130)**

Construction thickness 0.1800 m
U-value 2.4108 W/m² K

**Window, (GDPI6)**

U-value: 1.97 W/m² K
Visible light properties: 0.76

3

**Use of the building**

**Standard open plan office**

Daily profiles 8am-6pm No Lunch (internal gains)
Heating weekdays (Heating and cooling)
Heating weekend (Heating and cooling)
Weekly profiles 8am-6pm M-F (internal gains)
Heating, week (Heating and cooling)
Annual profiles Heating, year (Heating and cooling)
Heating season (16 September – 14 May)
Outside heating season (14 May – 15 September)

**Thermal template – Internal Gains**

**People**

Occupancy units
Maximum Sensible Gain 90 W/person
Occupancy Density 10 m²/person
Variation Profile 8am-6pm M-F

**Lighting**

Fluorescent Lighting
Maximum Sensible gain 7 W/m²
Minimum Sensible gain 20 % of maximum gain
Radiant Fraction 0.45
Variation Profile 8am-6pm M-F
Dimming profile Dimming, (200 lux)
(The heat is transferred to the room by convection (55 %) and by thermal radiation (45 %)

**Miscellaneous**

Maximum Sensible gain 10 W/m²
Radiant Fraction 0.22
Variation Profile 8am-6pm M-F
(The heat is transferred to the room by convection (78 %) and by thermal radiation (22 %)

**Thermal template – Air exchanges**

**Infiltration**

Infiltration Infiltration

4

Max Flow 0.1 ach (h-1)
Variation Profile on continuously
Adjacent Condition External Air

**Auxiliary ventilation**

Auxiliary ventilation Mechanical ventilation
Max Flow 1.0 l/(s m²)
Variation Profile 8am-6pm M-F (constant air flow)
Adjacent Condition External Air
Note: Mechanical ventilation is set as constant air flow to control a minimum CO2-concentration (1000 ppm ± 25 ppm)

Thermal template – Heating and cooling

Heating
Simulation heating setpoint Timed, Annual profiles
summer, off
Monday-Friday (8am-6pm M-F) 00:00 - 08:00 hr 16 °C
08:00 - 18:00 hr 18 °C
18:00 - 24:00 hr 16 °C
Weekend 00:00 – 24:00 hr 16 °C
Hot water consumption 0 (l/h pers.)

Cooling
Simulation cooling setpoint Timed, Annual profiles
Summer
Monday-Friday (8am-6pm M-F) 00:00 - 08:00 hr off
08:00 - 18:00 hr 26 °C
18:00 - 24:00 hr off
Weekend 00:00 – 24:00 hr off
Winter
Monday-Friday (8am-6pm M-F) 00:00 - 08:00 hr off
08:00 - 18:00 hr 24 °C
18:00 - 24:00 hr off
Weekend 00:00 – 24:00 hr off

Model settings
Solar reflected fraction 0.05
Furnace mass factor 1.00

5
Note: The setpoints are the operative temperatures (weighted mean of air and mean radiant temperatures of the surfaces facing the room)

Thermal template – System
HVAC Central Heating Radiators
Vent. Heat recovery effectiveness 80 %
Cooling/ventilation mechanism Air conditioning
Auxiliary energy method Use SFPs
System specific fan power (SFP) 1.5 W/(l/s)
Supply condition External air

Radiance daylight control
In this part Radiance module is used to control artificial lighting based on daylight.
The lighting system in the office rooms is dimmable and controlled by the illuminance in a reference point.
Reference points are placed 0.85 m above the floor in the middle of the floor plan for each office room.
The lighting is dimmed between full power when no daylight is available and minimum power (20 % of max.
power) when the illuminance from daylight in the reference point is above 200 lux. A linear control is
assumed.
PAPER VI: ARCHITECTURAL RESEARCH PARADIGMS
Architectural Research Paradigms – an overview and a research example

Research Paper presented at the Symposium
'When Architects and Designers Write/Draw/Build a PhD'
Aarhus, May 6 2011

Peter Andreas Sattrup, Architect MAA, PhD student
Royal Danish Academy of Fine Arts School of Architecture
Email: peter.sattrup@karch.dk

Abstract
As Architectural Research is in the process of re-establishing itself as a research discipline according to university standards, it may appear as if the pool of knowledge generated by more than three millennia of experimental research and its internal systems of evaluation are being grossly devalued and colonized by attitudes to research that are imported or even imposed from the outside. Does architectural research have to rely on imported theory from philosophy, the social or the natural sciences in order to meet societal acceptance of its relevance? What constitutes architectural research as a particular research discipline, what are its main characteristics and how can its paradigms, methodologies, strategies and tactics be described? What should be essential aspects of doctoral curricula in architecture?
Discussing Groat and Wang’s Architectural Research Methods1 in the light of Reflected Practice2, and Organizational Knowledge Creation3, a framework is presented that includes evolving paradigms and art in architectural research, and demonstrate how this framework allows one to describe the paradigmatic shifts that happened during the course of a PhD research project involving cross-disciplinary teamwork.

Architectural Research Paradigms – Index

Abstract 1
Architectural Research Characteristics 2
Architectural Research Paradigms 4
Architectural Research Theories, Methods and Strategies 7
Towards a recognition of practice as research 8
A Research Example – architecture engaging engineering 11
Research process – paradigmatic shifts and creation of knowledge 14
Cross-disciplinary collaboration – expanding the borders of each discipline 15
Conclusions 16
Framework illustrations 17

Fig 1: Marcel Duchamp, Three Standard Stoppages 1913-14. MOMA New York

Architectural Research Characteristics
Judged by a notion of classical positivist science emphasizing objectivity, internal and external validity, the normative stance that characterizes most architectural discourse and theory is questionable, disqualified by its inherent bias. In this understanding architecture belongs to the arts, and does not qualify to the high status of science. On the other hand, viewed from a position
in the arts, science is sometimes seen as less creative than the arts including architecture, dealing only with found facts.

But is it really possible to distinguish so sharply between science and art? It depends on what is understood by the terms, and in that respect the subliminal weight that the recent history of the dominant positivist scientific paradigm and the avant-garde in the arts carries in the collective imagination should be realized. Now the traditional dichotomies of arts and sciences are in a process of transformation.

As Kwinter points out, applying a purely positivist notion of science to architectural research would be an extremely difficult position to maintain now. Instead Kwinter’s notion of science is shifting towards a general idea of knowledge: “Science is about model building, not facts. Every experiment is a model, a form imposed on a piece of world to produce an effect, isolate a behavior, generate a fact that can be transposed to another milieu. ... Any practice ... which approaches this place and world with something other than a superstitious and magical attitude, is fundamentally science.” In Kwinter’s view it is the model-building capacity of architecture understood as gedanken-experimente, the creation of ideas, narratives and physical reality that makes it scientific. But can we equate science with qualified knowledge? How should that knowledge be qualified?

If the introductory hypothesis that architectural research is besieged by other research approaches is justified, - assuming that for a moment - What are then the characteristics of architectural research per se? A closer look at the beginnings of architectural theory may surprisingly act to confirm a radical contemporary position like Kwinter’s.

The opening phrases of Vitruvius' first book of architecture remind us of the fundamentally multidisciplinary understanding required by the architect (archi-tekton - from greek: master-builder) which is not only necessary in basic architectural education as Vitruvius argues, but is imperative in architectural research education too, a point which will be argued in this paper.

---

5 Kwinter, pp 11-12.  
A remarkable aspect of the Latin original is the connotations surrounding the concepts of science/knowledge, theory, practice and arts. It is hard for a contemporary reader mentally to dissociate the words science and art from the particular 20th century meanings ascribed to them, which arose from the antithetical positions of positivist science and the avant-garde in the arts, and we may not fully understand how the terms were understood then either. The role of the architect has changed too. The city planning, temple constructing designer of water-clocks and war-machines has fragmented into a wide variety of contemporary professions counting architects, engineers, industrial designers and more.

But the core of the discipline as described by Vitruvius surprisingly similar today:

"The architect should be equipped with knowledge of many branches of study and varied kinds of learning, for it is by his judgement that all work done by the other arts is put to test. This knowledge is the child of practice and theory." 9

Scientia is here translated generally as knowledge, while arts are associated with fabrication and practical skill. The relation to technology is obvious, the Greek roots of the word techne – art, craft or making, and the suffix –logia, meaning study or theory. 90 But what is particularly revealing in a contemporary interpretation is the term that is translated with theory. Ratiocinatio means not only theory but is also a particular figure used in rhetoric, referring to a process of reflective reasoning: one makes a statement, questions it, and answers the question, to achieve rhetorical effect. 91 What is important here is the emphasis on reflection and rhetoric purpose, a point which seems to have been unnoticed in previous readings.

The aspect of rhetorical effect in ratiocinatio can be seen as surprisingly similar to the emerging acceptance of polemical theory in the social sciences, which will be explained in the following. The intricate connection between practice concerned with fabrication and reflective reasoning as the constitutive parts of architectural knowledge, has only recently been reintroduced to research theory as reflective practice. 92 The architectural research community may very well have been

---

9 Vitruvius, "Architecti est scientia pluribus disciplinis et variis studiis omnibus omnibus, quae ab ceteris artibus perducatur. Opera et nascetur et fabrica et ratiocinatio.
blind to this relation, due to the inherited strict distinction between science and art in modern thought. If architectural research is understood as knowledge creation\textsuperscript{13}, rather than in terms of science or art, it is possible to bridge the unproductive separation between science and art in research and accept that it navigates multiple paradigms or systems of inquiry.

**Architectural Research Paradigms**

Very few attempts have been made at describing a comprehensive guide to architectural research methods, possibly owing to the relatively short history of doctoral research in architecture. In 'Architectural Research Methods' Groat and Wang\textsuperscript{14} discuss the limitations of traditional dichotomies that divide research into categories of 'quantitative' or 'qualitative' research, 'hard' or 'soft' science - or even 'science' versus 'myth'.\textsuperscript{15} These dichotomies are, it is argued, overly simplistic and puts the emphasis on the level of research tactics and techniques - that is, different methods for gathering and analysing data. As a result methods are confused with research paradigms. To Groat and Wang it is important to understand research methodologies hierarchically, in terms of strategies and tactics. Research methods, which are at the level of tactics, are too often confused with research methodologies or systems of inquiry, which is the strategic level. The classic example is the distinction between qualitative and quantitative research. Instead of distinguishing research categories at the level of tactics, one should distinguish between different research paradigms which employ different systems of inquiry.

Groat and Wang argue, which may again entail combinations of quantitative and qualitative research methods. As architectural research relates to bordering disciplines in which different paradigms are dominant and thus possibly has to integrate different kinds of knowledge, it becomes imperative to clarify one's paradigmatic stance as an architectural researcher. This is important, not only at the individual level, but at the institutional level too, as the assessment of research quality is likely to judged according to the paradigmatic preferences of the assessors.

As a response to this problem, Groat and Wang proposes a 'cluster of systems of inquiry' as an integrative framework for architectural research, drawing on contributions from methodological studies in architecture and the social sciences\textsuperscript{16}. The cluster integrates knowledge from three main systems of inquiry, which are termed 'postpositivist', 'naturalistic' and 'emancipatory'. Each

\textsuperscript{13} Nonaka, 14–37.
\textsuperscript{14} Groat and Wang.
\textsuperscript{15} Groat and Wang, pp 21-43.
\textsuperscript{16} Groat and Wang, p 32. Referencing various methodologists from the social sciences: Guba & Lincoln, Mertens, Lara.
system has different ontological and epistemological assumptions, and employ different criteria in judging research quality and validity. The terminology employed by Groat and Wang is deliberately chosen in order to integrate insights from different methodological studies, where the terms may differ. By establishing a common terminology the paradigms can be more readily compared though it is noted that the comparisons should not to give preference to the postpositivist paradigm which is the oldest and consequently has a longer and more elaborated theoretical tradition than the others. The paradigms are not in a steady state, as indeed researchers adhering to either paradigm are competing for influence, as could be seen in the so-called Science Wars.

A short summary of three paradigms according to Groat and Wang, synthesised from Mertens, Guba and Lincoln.

Postpositivist - The traditional scientific paradigm, which assumes an objective reality existing independently of the observer. Knowledge should be acquired through 'dispassionate' and 'objective' observations, in which the researcher interferes as little as possible with the subject. A methodological preference for experimental research where results can be measured and quantified. The research assessment criteria are internal and external validity, reliability and objectivity.

Naturalistic - A more recent approach to social science: It acknowledges that knowledge and reality is constructed socially and multiple realities exist. Rather than believing in objectivity it emphasises that knowledge is reliable when backed by 'thick' descriptions giving it credibility and confirmability. Conclusions are transferable rather than reliable or repeatable. Qualitative research methods are used in combination with quantitative methods. The researcher is interacting with the subjects of research, and it is accepted that the researcher has tacit bear on the study. The research does not necessarily seek to prove or disprove a hypothesis. Instead of formulating a hypothesis, the aim is rather to describe the complexities of a dilemma.

---

37 Science Wars refers to a heated debate among natural and social scientists which erupted after Nobel Prize W. Knowledge which is brought to ailing Physicist Alan Sokal had a nonsensical article published in a social science journal and took this as an expression of fallacy of the standards of knowledge. Nick Jardine and Marina Frasca-Spada, ‘Splendours and Miseries of the Science Wars’, 1997 <http://www.math.tohoku.ac.jp/~kuriki/Sokal/science_wars.html> [accessed 28 February 2011].

38 Groat and Wang.

39 Guba and Lincoln outline five paradigms which they rate is an abstraction of several emerging systems of inquiry. Neither are the boundaries of paradigms in any way clear, as new theories are proclaimed continuously at a rapid rate of change. Egon G. Guba and Yvonna S. Lincoln, ‘Controversies, Contradictions, and Emerging Confluences’, in The SAGE Handbook of Qualitative Research (SAGE, 2005), pp. 191-216.
Emancipatory – Is the most recent research paradigm, and covers (as does Naturalistic) several emerging research methodologies. In emancipatory research the researcher is not objective but an active participant who not only seeks to describe the realities of a dilemma, but actively seeks to change the relations of power surrounding it. As the name implies, its validation criteria concerns whether it establishes its historical situatedness and succeeds in eroding ignorance through a transformational impulse. The research is critical, even polemical and seeks to change reality.

Architectural Research – Theories, Methods and Strategies
Groat and Wang distinguish between three types of theory: positive, normative and polemical20. Positive theories are descriptive, causal and explanatory theories that are able to predict future behaviours of the systems they describe, developed from a disinterested position of the researcher. Normative theories describe value judgements related to a discipline of research, possibly to identify desired lines of actions and decisions to assist policy makers or decision takers in achieving identified often utilitarian goals. Polemic theories of design are theories where the theorist is actively involved in promoting a new set of values or a value system that changes the existing one. In polemical theory the theorist is involved with the subject of study from a position of power.

In addition Groat and Wang distinguish theories according to scope. Theories are described as ‘small’, ‘medium’ or ‘big’. Preferably research should be relevant on the level of the research discipline of the profession surrounding it, which Groat and Wang calls the medium range of theory, as different to small theories that apply to a personal level or big worldview size theories. Theories can be brought to bear on research subjects on different levels, whether it is on the strategic or tactical level, and the theories can feed back information to the overarching philosophy framing it.


20 Groat and Wang, pp 78-87.
Within these strategies a preference for certain methods may be observed, whether these are quantitative or qualitative, empirical or constructivist, and methods are presented that are typically used within the conceptual framework of each strategy. It is an important point that all these strategies are available to architectural research, all of them have strengths and weaknesses and, according to Groat and Wang, no strategy has higher intrinsic value than others. A study may even employ more strategies together, as is indicated in the Case Studies and Combined Strategies category.

While Groat and Wang’s attempt at categorizing architectural research methods according to the notion of research paradigms establishes a frame of reference to understand architectural research in terms of recent developments in social science, it does have its blind spots. The autonomous form of knowledge in architecture which is associated with its practice and the influence of art and architecture’s media are neglected. Groat and Wang uphold a distinction between research and design due to the difference between the generative process of designing and the analytical processes of research. As architectural design draws on small scope theories such as personal experiences, emotions etc. associated with art, it is noted that this kind of knowledge is not subordinate to that of research, it is just different. Returning to Kwanten’s position in the introduction, this distinction should not be necessary. - but why?

Towards a recognition of practice as research
In the following it will be argued that research can be understood as knowledge creation, which is a notion that highlights practice and expands the concept of research to include not only the analytical process of making tacit (practical) knowledge explicit, which is the traditional notion of research, but points to a continuous spiralling movement of knowledge between tacit and explicit states, which relies deeply on social processes. This notion is congruent with the deep history of architectural research, but remains to be clearly re-established as a valid notion of research in the wake of the dominance of the positivist paradigm of science. The recognition of the role of social processes and practice in knowledge creation is intricately connected to research in design.

---

21 Groat and Wang, p 118.
23 Nonaka, 14-37.
Kuhn\(^{24}\) was the first to challenge the objectivity of science, by introducing the idea of scientific paradigms that change as new theories are proposed and go through a process of accumulating acceptance before they are considered valid. This process of validation of a new paradigm or theory is essentially social, and the act of constructing theory is creative in the first instance.

**Rittel and Webber\(^{25}\)** dissociated planning and social policy from the belief in positivist science which was then (1974) dominating the approaches to these disciplines. They stated that these disciplines deal with 'wicked problems' – problems that are complex and resist resolution. Solutions to wicked problems depend on the perception of the problem at hand, and because intentionality is inherent in them, they are never true or false but merely better or worse, and thus elude science – in the positivist sense of the word. Wicked problems can’t be resolved without leading to new problems. **Buchanan\(^{26}\)** generalized the problematic of wicked problems to all the design disciplines, including architecture. In Buchanan’s terms, as is apparently common in American design theory, design is the overarching discipline embracing sub-disciplines such as architecture, industrial design, engineering and many others that practice design thinking. (This position of design as the base discipline for architecture is somewhat contrary to the idea of architecture as the original profession of the master builder or – craftsman inherited from Vitruvius\(^{27}\), which spawned engineering and other specialized design disciplines as specialization increased historically.) While Buchanan recognizes an element of design thinking in science, he limits that to the moment of conception when a new scientific theory is formulated. He maintains that science describes universal properties of the world that is, while design deals with the particular properties of a future. This distinction is presumably what Kwanter criticizes, when he states that science is about the creation of ideas not just facts\(^{28}\), accepting the latent instability of ideas over time. **Schön\(^{29}\)** outlines the way that professional knowledge is created as reflection in action and reflection on action. Reflection in action is the immediate analysis and choice of action that a practitioner in any profession takes when handling the problems inherent to his or her profession. It relates both to the practitioner’s previous experience and experience of the situation, and involves a speculation on the probable outcome of the action taken. Reflection on action is a retrospective analysis of experience through discussions, note taking and evaluation. With the accumulation of experience comes professional knowledge that allows better prediction.

---


\(^{27}\) Vitruvius.

\(^{28}\) Kwanter, p 11.

\(^{29}\) Schön.
and reliability of the outcome of actions. These procedures of knowledge creation can be more or less conscious, pointing to the problem of knowledge management: How tacit knowledge is made explicit, or by its nature remains tacit either at a personal or organizational level.

Nonaka describes how knowledge can be created and managed in organizations through a spiralling movement of knowledge conversion from tacit and explicit states. Knowledge creation requires interaction between individuals and groups with different expertises in an organization. The SECI model (Socialization, Externalization, Combination and Internalization) is a framework describing this process. Socialization is the conversion of tacit to tacit knowledge in which practical knowledge and skills are transferred through training. Externalization is the process of making tacit knowledge explicit. Combination is the process of combining different explicit knowledge to new knowledge, while Internalization is the process of learning: adapting explicit knowledge to inform the individual or organization’s practical knowledge and skills. In Nonaka’s view the Western tradition (of science) has “emphasized explicit knowledge”. When applying Nonaka’s concept of knowledge creation and the SECI model to a discussion of research that includes professional practice as a research mode, it may be argued that research is not only the externalization process making tacit knowledge explicit.

Figure 2: Spiral Evolution of Knowledge Conversion and Self-Transcending Process. Nonaka 1998

---

30 Nonaka, 14–37.
Research can be understood as the spiralling movement that moves knowledge from one state to another, regardless of whether this follows a structured or a more serendipitous approach, allowing chance insights and accepting the notion that some knowledge by nature remains tacit and resists explicitation. Nonaka highlights the use of metaphor and analogy, concepts that are traditionally associated with arts and poetic language in the western tradition, but are essential communication devices in the knowledge creation process leading to the formation of models by which Nonaka means operable, instrumental concepts. Knowledge creation is highly dependent on sharing a common conceptual and/or physical space which acknowledges differences and builds trust. It is fuelled by the differences among individuals and groups in the organization and depends on the intentionality, aspirations and ideals of those generating it.

Following Nonaka’s lead, it may well be argued that research always encompasses aspects of generative and analytical thinking, and that the integration of these modes of thought are the prerequisites for innovation, which ensures the originality and possibly the relevance of the knowledge generated. The traditional hard boundaries between science, art and moral philosophy – as well as design, practice and research – can’t be maintained upon closer look. Rather their identity as concepts form gravitational fields informing knowledge as it changes state with its continuous movement. It is the degree of explanatory power and generalized scope of applicability that guarantees the acceptance of theories, and their potential impacts.

While the argument for the recognition of traditional architectural theory based on polemical practice should reinforce its status as a strong field of knowledge in its own right, architecture shouldn’t be content with itself. It should actively seek engagement with related disciplines as a driver for innovation and knowledge creation. Applying methods from related disciplines of thought, possibly in cross-disciplinary team-work, carries with it transformative potentials for innovation, relevance and originality. As demonstrated by Nonaka, difference is a driver for innovation, and knowledge is created by exchanges within a larger social space.

A Research Example – architecture engaging engineering
In the following a summary of the research process of the author’s study Sustainability – Energy Efficiency – Daylight and Passive Solar Gains is presented. It highlights the potential of cross-

---

disciplinary teamwork to inform architectural research, by expanding the range of analysis possible and allowing technology transfer in a learning/knowledge creation process.

With little prior knowledge of sustainability, energy optimization and the physics of daylight and solar radiation, the first phase of this study followed an explorative qualitative strategy akin to grounded theory based on data from a number of sources. To generate a dense base of information for the research and to formulate a hypothesis, data was sought using four principal strategies: 1) literature review, 2) interviews with practitioners, 3) Environmental Simulation Modelling of daylight and thermal performance of spaces, 4) observations of daylight and thermal phenomena in the built environment documenting these in memoes, photography and thermograms. Data collection using each strategy evolved more or less along parallel synchronous tracks, which allowed information to be analysed and synthesised from multiple sources. As information was condensed from these sources thematical patterns emerged that became the basis for the formulation of a hypothesis and a set of research questions.

Grounded Theory is quite different from most other scientific theories (according to some paradigmatic positions it would not be recognised as science) in that it does not seek to validate an existing theory or hypothesis through experimentation or deductive thinking, instead it seeks to develop new theory with explanatory power regarding (social) processes drawing on data and information from multiple and diverse sources. In grounded theory analysis is understood as an interplay between data and researcher, presupposing that either has influence on the other. It emphasises the process of gathering and analysing data in a structured yet creative way, allowing the researcher to consider data from many sources of information independently of media. As the data is collected it is continually coded and checked for thematic connections with data from other sources in a process were the interpretation of data shifts back and forth. Interpretations of new data may shift the interpretative attention towards previously disregarded information from datasets, which advances the process of understanding the problem at hand. The logic of creatively establishing a hypothesis follows Peirce’s principle of logical abduction, in which it (contrary to deduction) is allowed to infer a cause from a consequence as a temporary position. Abduction is a prerequisite for learning, as the proposal of a hypothesis is the necessary first step to test one’s assumptions of reality.

As the process of data gathering went on a hypothesis of the influence of architectural scales and layering on energy use in buildings took form, drawing on the interviews with practitioners and the literature. The hypothesis supposes that:

There is a hierarchical relationship between environmental performance and architectural scale. Design decisions taken at the biggest scales have the greatest impact.

The potential implications of the hypothesis are many as it may be applied to the design process, the operation and everyday quality of the project and its lifecycle assessment. If energy performance is used as the assessment criteria, this idea potentially connects embodied and operational energy concerns while lending itself to an incremental level of definition progress in the design process.

Though the architectural design process is not necessarily linear and design attention may shift back and forth among different scales as varying aspects of the design programme are addressed, the project and its documentation develop a high level of definition over time starting with the largest scales. Increasing the level of definition by adding details make design changes very cumbersome and expensive, and therefore it is extremely useful and important for the designer to have feedback on the basic performance of the design in the first 'rough' stages of development. Knowing which design parameters have the greatest impact on environmental performance allows the architect to navigate the many complexities of the design process with
greater ease and control. But is it true? Can a hierarchy be identified? And how would it be expressed?

To test the hypothesis, a range of simulation studies were designed based on architectural typologies, each with the purpose of identifying and quantifying particular environmental qualities associated with the impact of urban form on daylight, passive solar energy and building energy use.

Overall, the research process can be categorized according to three phases, which to some degree were overlapping each other in time. 'Phase' in this sense refers more to a mode of approach than to a period of time. As the collaboration involved engineering in which a positivist paradigm is more dominant than in architecture, the different phases reflect an active engagement with different paradigmatic positions.

![Paradigmatic shifts according to phases of research. Graphics based on Lara - Groat and Wang](image)

**Research process – paradigmatic shifts and creation of knowledge**

In the first phase, data was gathered freely from the different sources, with the intent of creating a knowledge base of the state of the art in practice, theory and simulation techniques which would be made operative in testing the hypothesis that emerged in the process. The paradigmatic stance of this phase was naturalistic in nature, ontologically presupposing an objective reality subject to individual and social interpretation and negotiation, while epistemologically following a critical approach to practice, theory and simulation modelling techniques.
In the second phase, the qualitative approach encountered an inherently (post)positivist paradigmatic stance as three different aspects of urban form and materiality were investigated in close collaboration with engineering doctoral student Jakob Strømann-Andersen. Studying the energy performance of buildings in dense urban contexts each researcher attempted to understand the other’s disciplinary research methodology, concerns and techniques.

In the third phase, the experience gathered in the first two phases is discussed critically. A theoretical framework emerged by the end of the simulation studies that facilitates a discussion of simulation modelling as a generative tool in architecture as opposed to its use for validation in engineering, centering the focus for optimization on the user of the building and the experience of space. The limitations of simulation modelling applying a reductive deterministic approach to building performance is highlighted in favour of a mixed natural and social sciences approach where architecture as an applied art and science forms its integrative core.

Cross-disciplinary collaboration – expanding the borders of each discipline

The collaboration in Phase two requires some further explanation: The interviews and the research into the state of the art of simulation software had also made it clear that it would be necessary to use emergent software in order to be able to push the boundaries of knowledge significantly. As I did not have the necessary technical expertise personally, neither was it available in the immediate or remote academic environment, it had to be developed. As the most promising pieces of software for these purposes were developed mainly for engineers and had very limited functionalities directly applicable to architectural design, I judged it promising, if not necessary, to engage in a cross-disciplinary collaboration with civil engineering PhD student Jakob Strømann-Andersen, so as to be able to explore the potentials of the software. As better integration of technical performance is demanded by design practices, this research collaboration could very well be understood as integrated design research.

The starting point was a research design covering many architectural scales proposed by myself so as to see if any hierarchy could be observed, by way of analysing the environmental and energy performance of selected architectural typologies, which were simulated by my collaborator Jakob. By collaborating closely through several iterations of studies, tacit and explicit knowledge from either discipline was transferred among either of us, and a common understanding of technical and design considerations emerged. As mutual understanding grew, it became
increasingly difficult to distinguish individual conceptual contributions from those arrived at in common.

Figure 5: "Ba" (shared space) and Knowledge creation, Nonaka 1998

Nonaka's SECI model offers an explanatory model for understanding the process: The first phase's literature review is a process of combination and internalization as theoretical knowledge is slowly grafted into new hypothesis and research questions, the interviews with practitioners inform the research by explicitation of tacit knowledge from practice by externalization and combination of the different positions encountered. By collaborating in the second phase tacit and explicit knowledge was transferred in reciprocal movements between the two disciplinary approaches to environmental simulation through socialization, internalization, externalization and combination. As a result contributions to both architecture and engineering knowledge were achieved. The critical discussion of Phase three may inform future knowledge creation as it becomes accepted socially by the profession and integrated in the discipline.

Conclusions
New paradigms of research are beginning to recognize the validity and value of what architectural theory has done for millennia, which is the polemical production of alternative modes of thinking, living and creating environments by model or built exemplar. The recognition of practice as inseparable from research reaffirms the identity of architectural research that builds on experience and creates new realities.

Architecture relies on its media of representation and fabrication in order to communicate its agency on multiple levels of reality. As architectural research and theory can't be dissociated from architectural practice, doctoral education should recognize the inherent importance of architecture's media and prepare the students for specialization and collaboration at the borders of the discipline.
It is argued that the nature of architecture as a research discipline is essentially integrative and generative, and that the basic education of doctoral students in architecture should have a polyhistoric approach to reflect that, preparing the students to navigate the different research paradigms surrounding the discipline. A variety of methods from the social and natural sciences, philosophy and technology may serve to expand the borders of architectural knowledge.

Certainly, architects should be able to write / draw / build a PhD. - but it is in the application of multiple media and varied methods that architectural research best demonstrates its integrative and generative potential and consequently its value to society.
<table>
<thead>
<tr>
<th>Research Phase</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paradigm</td>
<td>Naturalist</td>
<td>Naturalist (Post-positivist)</td>
<td>Naturalist (Emancipatory)</td>
</tr>
<tr>
<td>Ontology</td>
<td>&quot;Multiple, socially constructed realities&quot;</td>
<td>&quot;Multiple, socially constructed realities&quot;</td>
<td>&quot;Multiple realities shaped by social, political, cultural, economic values&quot;</td>
</tr>
<tr>
<td>Epistemology</td>
<td>&quot;Interactive link between researcher and participants; values are made explicit; created findings&quot;</td>
<td>&quot;Objectivity is important; researcher manipulates and observes in dispassionate, objective manner&quot;</td>
<td>&quot;Interactive link between researcher and participants; knowledge is socially and historically situated&quot;</td>
</tr>
<tr>
<td>Hypothesis</td>
<td>Under development; assuming that environmental simulation may be instrumental to improve sustainability through energy performance for daylight and thermal comfort</td>
<td>Urban density and building Energy use are hierarchically dependent. The urban geometries supporting and regulating a building’s sites have major influences on that building’s energy performance over its lifetime.</td>
<td>The use of environmental simulation tools will change architectural culture. As new techniques offer improved control of design performance.</td>
</tr>
<tr>
<td>Research Question</td>
<td>What is the state of the art of architectural practice, theory, and environmental simulation technology regarding energy performance?</td>
<td>How does urban form relate to building energy, daylight and thermal performance in the context of Copenhagen?</td>
<td>How may environmental simulation change architectural culture?</td>
</tr>
<tr>
<td>Methodology</td>
<td>Qualitative research: grounded theory, modified through -</td>
<td>Qualitative research: mixed Mode Case Studies through -</td>
<td>Critical discussion</td>
</tr>
<tr>
<td></td>
<td>Simulation and Modelling</td>
<td>Simulation and Modelling</td>
<td></td>
</tr>
<tr>
<td>Strategy</td>
<td>Collection of data from multiple sources to produce hypothesis: - Architectural and engineering practice; - Theory; - Environmental simulation tools</td>
<td>Qualitative discussion of environmental simulation results.</td>
<td>Argumentation and critique based on observations and experience ‘grounded theory’ from phases 1 &amp; 2</td>
</tr>
<tr>
<td>Facts</td>
<td>- Literature review - Interviews - Observations of climatic, cultural, physical behavioral phenomena - Review of simulation software types</td>
<td>Environmental Simulation Modelling experiments.</td>
<td>Critical discussion of research process</td>
</tr>
<tr>
<td>Notational media</td>
<td>written language photography, thermography diagrams</td>
<td>written language digital environmental simulation modelling diagrams</td>
<td>written language diagrams</td>
</tr>
<tr>
<td>Interpretive logic</td>
<td>Abductive hermeneutic</td>
<td>Abductive / deductive hermeneutic</td>
<td>Abductive hermeneutic critical</td>
</tr>
</tbody>
</table>

Figure 4: Framework showing paradigmatic shifts in the research process
<table>
<thead>
<tr>
<th>Empirical matter / object of interpretation</th>
<th>State of Art</th>
<th>Design of generic urban environments: - urban canyons - urban pattern - urban envelope</th>
<th>research process: phase 1 and 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research Aims</td>
<td>understand</td>
<td>understand, context and critique</td>
<td>understand, critique and change</td>
</tr>
<tr>
<td>Position of Researcher</td>
<td>Independent</td>
<td>Independent</td>
<td>Participatory</td>
</tr>
<tr>
<td>Type of Theory</td>
<td>descriptive</td>
<td>descriptive / normative</td>
<td>descriptive / critical</td>
</tr>
<tr>
<td>Research assessment criteria</td>
<td>Credibility</td>
<td>Transferability</td>
<td>Dependability</td>
</tr>
<tr>
<td>Theoretical scope</td>
<td>S &amp; M</td>
<td>S &amp; M: from personal experience to professional boundaries</td>
<td>S &amp; M &amp; L: from personal experience to professional boundaries and societal values</td>
</tr>
<tr>
<td>Conclusions (or, following the logic of naturalist inquiry: 'tentative generalised claims' (Roberson 2006))</td>
<td>Experienced practitioners are using and developing environmental simulation tools to control environmental performance of their projects. Both Eberle and Potter's office report a hierarchy of scale influencing energy demand and environmental impact. Emerging practices show ways to express environmental concerns that have previously been only theoretically described. Rich sources of theory on environmental performance has remained untapped in mainstream architecture.</td>
<td>There are some hierarchical relations between scales, but they change in dynamic ways when single parameters are varied. Urban geometries have significant impact on energy performance, but affect in particular the experiential qualities.</td>
<td>Environmental simulation offers control of new scales of energy in architecture. Intensity and Duration. To improve creative and qualitative aspects of the built environment, architects need to inform structure and control of energy performance.</td>
</tr>
<tr>
<td>Sources</td>
<td>Muns 2010, Linnon &amp; Duba 2005, Grof &amp; Wang 2001, Robertson 2006</td>
<td>Architectural theory describes environmental performance in a variety of ways that are not necessarily quantifiable per se, but could be brought to bear on the way environmental performance is quantified and determined in engineering.</td>
<td>Visualization and environmental simulation can aid architects in conceptualizing and achieving desired environmental performance, controlling the qualitative and some of the quantitative aspects of energy performance.</td>
</tr>
</tbody>
</table>

Figure 5: Framework showing paradigmatic shifts in the research process
PAPER VII: MATERIAL EVIDENCE

Contribution to research anthology:
The Role of material evidence in architectural research: Models, Drawings, Experiments. / Ed. Beim, Anne, Ramsgaard Thomsen, Mette. Royal Danish Academy of Fine Arts school of Architecture Design and Conservation 2011
PETER ANDREAS SATTRUP

ENVIRONMENTAL SIMULATION AS MATERIAL EVIDENCE

This research project is an inquiry into the relationship of architecture and energy, with a particular interest in the way environmental simulation tools can inform architectural design decisions. Though environmental simulation software has been around for decades, developed mainly by and for engineers, it has only recently become widely available to architects who are not specialists 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 organisation as means to produce desirable human environments, rather than the singular optimisation of specific technical subsystems.

The studies presented here are investigations of the passive solar energy potentials in dense urban environments. We perceive solar radiation with our eyes as light, while the skin feels it as heat, and one of the important roles of building is to temper the environmental forces to create comfortable, delightful environments, harnessing energy, protecting and accommodating human activities. Urban environments ‘filter’ the solar energy potential before it arrives inside buildings as passive energy contributions. As the sun moves across the sky, buildings receive, reflect and absorb parts of the radiated energy and complex interference patterns emerge that change during the day, the seasons and the year. Environmental simulation software allows architects to analyse spatial patterns dynamically, compressing and extending spatio-temporal energy phenomena based on regional or local meteorological statistics. The influence of form, material specification, programmatic issues and other questions of design can be calculated and quantified fast, offering design performance evaluation simultaneously with the development of the design.

METHOD
The text “Performance-oriented Design from a Material Perspective: Domains of Agency and the Spatial and Material Organisation Complex” was chosen as the reference for a discussion of material evidence in architectural research. In this paper Hensel presents a
diagram as a framework for the concept of performance which is discussed on a theoretical phenomenological background, and illustrated by results created through experimental practice. Hensel’s work prompted me to develop a series of diagrams to explain different aspects of performativity related to my own studies. The new diagrams have clarified the theoretical framework of my project, though the most important ones were developed after the seminar and have been presented in a research paper. The diagrams work in multiple ways: They are a research result (a clarification of a theoretical framework in their own right). They are instruments in creating synthesis (with the framework it is possible to map the research studies in terms of their position within the overall field of research). And the diagrams can act as projective devices (the uncharted territories of the framework point out potential fields of future research). Elaborating a poster and a presentation for the seminar, I presented material evidence and used it to develop my argumentation in three different ways: RESEARCH PROCESS: Visualisations of simulation research processes. The experiments are shown in four stages of development, each relating to different scales at the intersection between urban planning and building design. The visualisations unite spatial geometry and temporal analysis of the changing intensities of the passive solar energy potential for daylight and solar gains: 1) Site conditions and planning: maximum density geometries, solar access and yearly radiation levels. 2) Building form and urban pattern: seasonal and monthly distribution of solar energy potential on a fixed geometry, high density urban pattern/building form, the perimeter block. 3) Building skin: folded façade geometries as a design parameter to increase/decrease solar gain according to demand. Building programme: the temporal distribution of internal energy gains and their influence on thermal energy loads. RESEARCH RESULTS: Visualisation of design principles. Each visualisation can be seen as an example of an abstract generic design principle with minimal geometric articulation. Diagrams as research results. Clarification of theoretical framework developed through research process. Theoretical framework as a device to create synthesis between individual research studies. FUTURE RESEARCH: Diagrams as projective analytical devices pointing to future research. Unmapped fields of research become evident when research results are mapped using the theoretical framework.
As architectural research is evolving as an academic discipline, there are many discussions of what constitutes and qualifies architectural research, and what its particular methods and research quality criteria are or may be. Architecture operates within a diversity of research paradigms, requiring architects to navigate successfully among these, while applying both quantitative and qualitative methods. As architecture is both applied science and applied art, the issues of whether architectural research can include ‘research in the Arts’, ‘art practice as research’, or ‘research in and through the arts’ become increasingly important when trying to define the particular field of knowledge that is architecture.

In my view, the seminar on material evidence takes on part of that discussion, focusing on the issue of representation in and of architectural research. One peculiar aspect of architecture is its dependency on visual and plastic media. Architects engage the world through their drawings and models, as much or even more than with their words. Rarely are they directly building their own work, and much of the analytical and projective design process is executed via the symbolic representations of space through geometry. In that sense drawings and models can be likened to language as in “Spoken words are the symbols of mental experience and written words are the symbols of spoken words” — from the opening of De Interpretatione, the volume that laid the foundation of formal logic and its hegemony in the scientific traditions. There is therefore nothing new in understanding architectural representations as a matter and media of architectural research. Rather the problem lies in understanding the shortcomings of representations — language, drawing or model — in expressing the mental experience of the physical world. Environmental simulation models dress spatial geometries in simplified representations of atmospheric and human behaviours, opening up new architectural scales of environmental intensities, offering new modes of control and possible delight. It extends the complexity and possibility in architectural imagination.

Perhaps we should remind ourselves that Aristotle chronicled many more aspects of the knowledge of his day, and that his formal logic was but a part of his writings. In my mind architectural research is about the gaps between representation, experience and the environment. It has both agency and structure. Our research methodologies and standards should reflect the fact that the field of knowledge particular to architecture is multi-faceted, attempting to bridge science and art.
PAPER VIII: CAN ARCHITECTS CHANGE THE WEATHER?

Essay commissioned for Daylight & Architecture, issue 12, 2009
MICROCLIMATES CAN ARCHITECTS CHANGE THE WEATHER?

By the year 2100, the world will be at least two degrees warmer than today. Add to this the effect of the 'urban heat island effect', with city centres being several degrees hotter than their rural hinterlands, and it becomes evident that city planning has to devise new methods to cope with overheating. A new approach is called for – one that not only considers the thermal conditions inside buildings, but also the urban climate as a whole.

By Peter Andreas Sattrup

WHY?
The extreme heat wave in the summer of 2003 was only a foreshadowing of the weather events that will be experiencing increasingly frequently in European cities in the future. The fact is that temperatures are going to rise all over the world – by at least two degrees by 2100. Cities are disproportionately affected by this, their usually dark surfaces store heat, and there are often no green areas and corridors to enable air to circulate. And of course the waste heat from people, buildings, cars and industrial plants also contribute to the fact that cities warm up much more than the surrounding areas.

WHAT?
Cities contribute to climate change, but they are also affected by it to a considerable extent. The urban heat effect is responsible for urban areas getting up to ten degrees warmer than the surrounding countryside, and not just in southern climates. Heat is literally 'held captive' in the canyons between the tall buildings. There is no evaporative cooling to alleviate the heat – there are few trees in our cities, and rainwater is taken away in the sewers, rather than being stored in the ground.

HOW?
Climate comfort will also become a key feature of town planning in the future. Urban climates have to be planned in just the same way as interior air conditioning. Cities cannot be artificially cooled down from the heat island. Using a mix of co-tech solutions (vegetation, shading, operable windows, etc.) and renewable energy sources for cooling purposes is a strategy crucial to handling summer overheating. Above all, the structures of buildings and cities must be much more thoroughly adapted to local climatic conditions (that are also getting warmer).
The Urban Heat Island effect changes wind patterns, humidity levels, precipitation and temperatures. It even prolongs the growing seasons of agriculture in the immediate vicinity of cities.

In August 2003, Western Europe experienced a heat wave. As temperatures climbed, they reached levels up to 10 degrees higher than they did in the same period two years previously. It is estimated that more than 35,000 people lost their lives due to excess mortality caused by heat-related illnesses, mostly among the elderly. France in particular was severely hit but the heat wave influenced all north-western European countries. Many of these deaths were blamed on the lack of emergency procedures for an event of this severity in some of the societies.

Along the Mediterranean, more forest fires were recorded, and agriculture experienced a drought condition. In the same year, harvests were excellent in Northern Europe. In 2002, Central Europe experienced severe flooding after heavy rains in the Alps caused the Danube and Elbe rivers to swell. Several thousand people were evacuated and several cities, among them Prague and Dresden, were severely damaged.

As temperatures increase, the warmer air can contain more humidity. Water that has evaporated from the surface of the earth somewhere in the world condenses, and is carried and dropped somewhere else. Global warming will change the patterns of precipitation too. Dry areas will likely get drier and wet areas wetter. Global moisture distribution will probably change, shifting and expanding and contracting zones of drought and rainfall. Extreme conditions of rain and drought are expected.

When trying to imagine what the climate of 2050 will be like, events like the heat wave and flooding can provide some clues, as such weather conditions will become increasingly normal. Our cities will have to change in order to adapt to climate changes and to mitigate them.

**URBAN HEAT ISLANDS – CITY GENERATED WEATHER**

But we can also look to our cities, since cities create local weather conditions that are significantly warmer than those of the surrounding landscapes. This phenomenon is known as the Urban Heat Island effect. Since urban growth occupies land that was once forest or used for agriculture, the cooling capacities of vegetation is replaced by the heat storage capacity of urban materials – tarmacs, concrete, brick etc.

Heat from solar radiation is trapped in what is imaginatively called the “urban canyons” – the narrow streets and gaps between buildings, from where it can only slowly be ventilated or radiated away. Humidity that would have been soaked up in the soil and could have cooled the air by evaporation is now under ground sewers and carried away. Another minor source of urban heat islands is waste heat from human energy use – transport, building services and industry – and pollution. Pollutants increase as photochemical reactions between pollutants increase with rising temperatures and create smog, causing health problems.

The Urban Heat Island effect changes wind patterns, humidity levels, precipitation and temperatures. It even prolongs the growing seasons of agriculture in the immediate vicinity of cities. Recent research commissioned by the Greater London Authority for the 2033 events indicates that the intensity of the Urban Heat Island effect in London – famous for its evercast skies – can reach 8 degrees Celsius in the city centre, with peak occurrences even reaching 9 degrees. It is not just a phenomenon of southern cities.

**LOCAL WARMING INCREASES ENERGY DEMAND FOR COOLING**

While temperatures rise – the current goal of the European Union is to limit temperatures increase at 2 degrees in 2100 – Urban Heat Islands intensify the local consequences of global warming. It will increase the demand for cooling in the future, which is already accounting for a big share of the estimated 40% of the world’s total energy use that is consumed in buildings. And you cannot air-condition your city out of the heat island. For every cubic metre of cooled air you produce indoors, you will add the same heat outdoors and big carbon emissions to top it off. The direct contribution of Urban Heat Islands to global warming as a result of change of land cover is small, however, compared to the consequences of greenhouse gas emissions. It can be argued that heat islands reduce the need for heating buildings dur-
ing the winter season. The balance of heating and cooling demands will have to be considered locally, as it depends on latitude and local solar radiation levels. For the majority of cities worldwide, heat is a problem.

WHAT CAN WE DO TO REDUCE THE EFFECTS AND MITIGATE THE LOCAL WARMING TRENDS?

Paint your roof white and plant some more trees seems to be the popular answer today. Or growing green roofs and painting the town white. High albedo surfaces reflect much of the incoming solar energy without absorbing it as heat, and plants cool their surroundings by evapotranspiration—they "sweat." These ideas promote cities and buildings that are not just metaphorically but literally green, taking advantage of the capacity of vegetation to clean air and soil, and keep moisture levels balanced overall that are predicted to have more extreme precipitation changes than we knew currently. This also addresses the need for considering moisture as a climatic factor, and developing ways to handle water as a quality of urban spaces. As weather patterns will get more extreme, urban spaces can be developed to work as a way of regulating and balancing moisture. Working with reflective surfaces takes careful consideration, as it may affect visual comfort adversely and does have implications for the thermal environment if used indiscriminately. "Solar dumping," for instance, is what happens when you build a highly reflective building facade on the shadow side of an existing building in a hot climate—solar radiation bouncing off the facade creates a heat overload in the previously cool side of the neighboring building. This has implications for design methodology for urban master planning and building design.

UNDERSTANDING URBAN COMFORT

When designing master plans for new urban developments or intervening in already existing urban areas, it is a primary concern to establish a set of climatic and urban outdoor comfort criteria that are suited to the local climate of the city. There is no universal standard for urban comfort. Urban comfort is quite different from the standards of indoor climate, as it is more influenced by cultural perceptions, expectations and tolerances of local weather conditions. If we wish to change the carbon footprint of transport in our cities during the next few decades by promoting public transport, personal rapid transport systems, biking and pedestrianization, we will have to consider how urban spaces and interventions create shelter, and how urban comfort can be created as a function of distances, travel times, programmes, activities, and tolerances to climatic conditions, be they hot or cold. This is a field that requires further studies of local patterns.

BUILDING PHYSICS FOR THE OUTDOOR ENVIRONMENT

Getting the physics right is crucial. Mainstream architectural thinking, rapidly adapting to the idea that low-energy design must deal with local climatic conditions and use form and materials intelligently to achieve comfort strategies that not only are sustainable but actually improve the environment. The days of the air-conditioned glass-box skyscraper built anywhere from Vancouver to Dubai are over. Getting the balance right between daylighting and heat gains is basic in the new generation of architecture. But we can no longer focus on the indoors alone; we also have to consider what buildings contribute to their immediate urban environment, and what kind of urban spaces they create, not only in social, cultural and economic terms, but also in climatic terms. Sustainable buildings and urban spaces offer open possibilities and situations of choice. Urban life and activity is influenced by the microclimatic conditions created by the architecture of a city.

NEW TOOLS FOR FUTURE URBAN DEVELOPMENTS

Architects and engineers will have to work closely together to evaluate both quantitative and qualitative aspects of design decisions, both for the design of the building itself and
At the end of May 2009, the US Secretary of Energy, Steven Chu, went public with an unusual idea. If all roof and road surfaces in the world’s cities were painted white, it would compensate 44 gigatonnes of CO₂ emissions. That would be equivalent to the projected world-wide increase in emissions for the next 13 years.
Even if mankind stopped all CO₂ emissions tomorrow, the global warming would continue. The inertia of our climatic system is one of the reasons why the fight against climate change is a very urgent one.

For the space that surrounds it. Planners will have to identify criteria for urban qualities to be developed for new areas of expanding cities and for changes to existing ones.

Much can be done by reinventing and developing traditional models. Think of Greek island cities - they are both white and dense and cooled by shadows, and their surfaces reflect the light away. Made for pedestrians, they provide all your basic needs within walking distance. Or think of the Islamic garden, a cool paradise of running water and lush greenery. Or the seasonal waterscapes of Venetian Mogul architecture. What could be future developments of these models? And how could they be integrated into the increasingly complex metropolitan conditions that will soon be the living environment of the vast majority of the earth's population? How do they relate to scale, where one single building can house thousands of people, or even entire communities?

The future of urbanism requires negotiation of unprecedented complexity. As more buildings become dependent on passive and active solar energy to meet future energy requirements, the form of cities and urban spaces will become directly linked to the energy potential of the specific sites that the buildings tap into. Conditions of shade and solar exposure translate directly into the energy balance of a particular site. Since every new development will alter the energy balance and the urban microclimate of its site, new methods of evaluation and new regulatory instruments will have to be developed to deal with future rights of energy disputes, much as the traditional British 'right to light' legislation has tried to do. These will have to fit the properties and patterns of individual cities and building cultures. Simulation Modelling, Building Information Modelling - even City Information Modelling - will be the tools of tomorrow to quantify and qualify our visions of how to create sustainable places for enjoyable living.

**METABOLISM – CHANGE**

Cities change with time. Societies change. Populations change. Perceptions change. Too. Architecture is often seen as static, as something that lasts a long time. If not forever. But architecture is dynamic, albeit changing at a very slow pace. I am not thinking of dynamism in terms of formal expression, or flow management of traffic or the like. I am thinking of the exchange of matter and of the changes in the pattern of materials and activities that constitute buildings and cities. We sometimes forget that we continuously update our surroundings according to our changing needs. The schools of thought that tie together considerations of time, space and material properties in ways that enhance qualities of life might, therefore, hold the key for dealing with the climatic changes we face.

As designers we will have to deal with the long term implications of the choices we make at every level, from the chemical properties of materials to the climatic conditions we create in cities. This requires extensive collaboration across professional and cultural borders. We will also have to realise how powerful we actually are, making decisions every day that change the physical reality of the world. Last but not least, as visionaries of space and good life, we may be able to change the dominating cultural paradigm of wasteful consumption that is leading us in the wrong direction. We will have to grow cities that are adapted and integrated in technical and natural cycles.

Peter Andreas Søstrup is an architect and educator. Since graduating in 1997, he has been involved in the design and construction of a number of housing and cultural building projects in Denmark and abroad. He is currently a PhD student at the Royal Danish Academy of Fine Arts, School of Architecture, studying how daylight and solar heat contribute to energy-optimised sustainable architecture. He is an expert consultant to the curator and a contributor to the exhibition Green Architecture for the Future at the Louisiana Museum of Modern Art in Denmark opening in summer 2009.
12GW and PV 15 solar thermal fall 110 fast with projects totaling sever-

8. The Alamosa Project,
EXHIBITION: GREEN ARCHITECTURE FOR THE FUTURE

Louisiana Museum of Modern Art 2009
Green Architecture for the Future
Louisiana Museum of Modern Art
29 May - 18 December 2009

Exhibited thermographic studies of urban microclimates.

“A sustainable future calls for new inventions, materials, processes and complex architectural methods in the built-up environment. For sustainable architecture is a far more complex matter than rainwater collection and solar cells. That is why the architecture of tomorrow is inextricably bound up with the exploration of new scientific and technological frontiers.

The new requirements for the composition of the materials are reflected in the final architectural product, and this expands and transforms the framework of what we understand by a house. Perhaps the materials of the house change with the seasons, or courtyard gardens are built up with green recycled glass from wine bottles.

If architecture is to be sustainable throughout, from the smallest screw to the roof of a skyscraper, it is not possible to reproduce a particular style and spread it all over the world like modernism’s white cubes and quadratic spaces. The exhibition will show how some of these changes are manifested in both down-to-earth and more sophisticated projects that together fulfill the human and technological visions of society.

Architectural sustainability means taking one’s point of departure in the environment to such an extent that the buildings are created for the specific environment, with due allowances for specific climatic conditions like sun, wind and compass orientation.

The thematic exhibition was divided into three sections – The City, Climate & Comfort and Metabolism – also reflected in the Louisiana Sculpture Park with structures that physically and tangibly underscored the individual themes.
URBAN MICROCLIMATES
Thermographic studies, exhibition contribution
Peter Andreas Sattrup

The exhibition Green Architecture for the Future is part of the Louisiana’s exhibition series Frontiers of Architecture I-IV, which is being shown in the years up to 2011; a series of exhibitions that shed light on new and alternative architectural movements in the force-field between science and architecture. When it comes to the development of sustainable cities, landscapes and environments the architect does not stand alone, and the growing cross-disciplinary approach to architectural practice is pushing forward what we regard as the frontiers of architecture.”


“Large-scale and highly acclaimed exhibition focusing on new departures in architecture that meet the need for sustainable development. Highlighting potentials and possibilities relevant to the current debate.”

EXHIBITION CATALOGUE
Interviews with Foster and partners, Philippe Rahm Architecetcs and Ecosistema Urbano by Peter Andreas Sattrup
LIST OF PUBLICATIONS

2012

Urban Daylighting: The impact of urban geometry and fabric on daylight availability in buildings. / Iversen, Anne, Strømann-Andersen, Jakob ; Sattrup, Peter Andreas.


Urban Building Type Patterns in Northern European Cities: Daylight, Solar Access and Building Energy Use. / Strømann-Andersen, Jakob ; Sattrup, Peter Andreas.


2011

A methodological study of environmental simulation in architecture and engineering: Integrating daylight and thermal performance across the urban and building scales. / Sattrup, Peter Andreas ; Strømann-Andersen, Jakob.

SimAUD 2011 Symposium on Simulation in Architecture and Urban Design, conference proceedings, 04.04.2011, s. 115-123.

Architectural Research Paradigms: - an overview and an example. / Sattrup, Peter Andreas.

Symposium 2011 When Architects and Designers Write / Draw / Build a PhD... Papers, 06.04.2011, s. 1-19.

Going Low Energy - Full Scale. / Sattrup, Peter Andreas ; Strømann-Andersen, Jakob Bjørn.


The Urban Canyon and Building Energy Use: Urban Density versus Daylight and Passive Solar Gains. / Strømann-Andersen, Jakob ; Sattrup, Peter Andreas.

Energy and Buildings, Vol. 43, Nr. 8, 08.2011.

Environmental Simulation as Material Evidence / Sattrup, Peter Andreas

The Role of material evidence in architectural research: Models, Drawings, Experiments. / Ed. Beim, Anne, Ramsgaard Thomsen, Mette. Royal Danish Academy of Fine Arts school of Architecture Design and Conservation 2011

2010
Integrating Environmental Performance across Spatial and Temporal Scales: Material Evidence using Simulation Modeling in Architecture. / Sattrup, Peter Andreas.

2010. Poster session presented at The Role of Material Evidence in Architectural Research - drawings, models, experiments., Copenhagen, Danmark.

2009

Sustainable cities: Density versus Solar Access? A study of digital design tools in architectural design. / Sattrup, Peter Andreas; Strømann-Andersen, Jakob.


Building sustainable communities. A few traits, spaces and moments of Danish experiences in architecture and planning. / Sattrup, Peter Andreas.


Ecosystema Urbano: interview med José Luis Vallejo og Belinda Tato. / Sattrup, Peter Andreas.

Fremtidens arkitektur er grøn. red. / Kjeld Kjeldsen; Michael Juul Holm. Humlebæk, Louisiana : Louisiana, 2009. s. 12-17 (Arkitekturens grænser, 2).

Ecosystema Urbano: interview with José Luis Vallejo og Belinda Tato. / Sattrup, Peter Andreas.


Foster + Partners: interview med Stefan Behling og Gerard Evenden. / Sattrup, Peter Andreas.


Foster + Partners: Interview with Stefan Behling and Gerard Evenden. / Sattrup, Peter Andreas.


Microclimates. Can Architects Change the Weather?. / Sattrup, Peter Andreas.


Philippe Rahm Architects: interview with Philippe Rahm. / Sattrup, Peter Andreas.

Philippe Rahm Arkitekter: interview med Philippe Rahm. / Sattrup, Peter Andreas.

Fremtidens arkitektur er grøn. Humlebæk, Louisiana : Louisiana, 2009. s. 88-93
(Arkitekturens grænser; 2).

2008

Arkitekter, arkitektur og ressourcer: interview med Dietmar Eberle. / Sattrup, Peter Andreas.

Arkitekten, Nr. 11, 2008, s. 42-43.

Broadcasting house: The music of change. / Sattrup, Peter Andreas.


Bæredygtighed i et arkitektonisk helhedssyn: introduktion af Dietmar Eberles arkitekturteorier. / Sattrup, Peter Andreas.

Arkitekten, Nr. 11, 2008.

Bæredygtighed, energioptimering, dagslys og solvarme. / Sattrup, Peter Andreas.

Arkitekten, Nr. 8, 2008, s. 65-67.

DKDM i Radiohuset: en samtale mellem generationer. / Sattrup, Peter Andreas.

ARKFOKUS, Nr. 2, 2008, s. 10-15.

Paven af integreret design. / Sattrup, Peter Andreas.

Arkitekten, Nr. 12, 2008, s. 58-59.

The Music of Change: Transforming Radiohuset into the Royal Danish Academy of Music. / Sattrup, Peter Andreas; Ammundsen, Jens; Agger, Flemming.

PROFILE

Peter Andreas Sattrup
Architect MAA, Ph.D. Student
Royal Danish Academy of Fine Arts
School of Architecture Design and Conservation
Institute of Architectural Technology

Peter Andreas Sattrup is a Danish registered architect (MAA) and PhD student with the research subject ‘Sustainability – Energy Optimization – Daylight and Solar Gains.

Drawing on his experience in architectural practice, he is focussing on the use of environmental simulation to enhance design processes towards sustainability and energy efficiency in the built environment, discussing energy optimization a wider cultural context of sustainability. His research approach is decidedly cross-disciplinary in order to expand the field of architecture in collaboration with bordering disciplines.

Peter Andreas is a skilled and dedicated communicator with experience in academic and professional education from bachelor to master levels, as well as open lectures to audiences generally interested in architecture and sustainability. He was a curating consultant to the exhibition ‘Green Architecture for the Future’ at the Louisiana Museum of Modern Art, which was seen by more than 250,000 visitors in the period leading up to the UN COP15 in Copenhagen 2009, and exhibited his own works under the title ‘Urban Microclimates’.

Peter Andreas has 14 years of experience as a professional architect in Danish and international contexts working for David Chipperfield Architects in London and Vilhelm Lauritzen Arkitekter in Copenhagen among others, and has a long record of cultural, commercial, housing and infrastructural projects. He is a versatile designer with in-depth experience from all design stages at all scales of architecture ranging from urban master-planning to product design. Among the best known projects he has been working on are the Cimiterio San Michele in Venice, The River and Rowing Museum in Henley on Thames, the Museumsinsel Master-plan in Berlin, and Radiohuset in Copenhagen.