SENSITIVITY ANALYSIS as a methodical approach to the development of design strategies for environmentally sustainable buildings

Hansen, Hanne Tine Ring

SENSITIVITY ANALYSIS as a Methodical Approach to the Development of Design Strategies for Environmentally Sustainable Buildings
By Hanne Tine Ring Hansen

PhD Thesis
Department of Architecture and Design and Department of Civil Engineering
Faculty of Engineering, Science and Medicine
Aalborg University
Denmark
October 2007

SENSITIVITY ANALYSIS as a Methodical Approach to the Development of Design Strategies for Environmentally Sustainable Buildings

By Hanne Tine Ring Hansen

SENSITIVITY ANALYSIS as a Methodical Approach to the Development of Design Strategies for Environmentally Sustainable Buildings

PhD Thesis

By Hanne Tine Ring Hansen

October 2007

Department of Architecture and Design and Department of Civil Engineering
Faculty of Engineering, Science and Medicine
Aalborg University
Denmark
e-mail: htrh@aod.aau.dk

1 PREFACE

Synopsis

The field of environmentally sustainable architecture has been under development since the late 1960's when mankind first started to notice the consequences of industrialisation and modern lifestyle. Energy crises in 1973 and 1979, and global climatic changes ascribed to global warming have caused an increase in scientific and political awareness, which has lead to an escalation in the number of research publications in the field, as well as, legislative demands for the energy consumption of buildings.
The publications in the field refer to many different approaches to environmentally sustainable architecture, such as: ecological, green, bio-climatic, sustainable, passive, low-energy and environmental architecture.

This PhD project sets out to gain a better understanding of environmentally sustainable architecture and the methodical approaches applied in the development of this type of architecture.
The research methodology applied in the project combines a literature study of descriptions of methodical approaches and built examples with a sensitivity analysis and a qualitative interview with two designers from a best practice example of a practice that has achieved environmentally sustainable architecture through an integrated design approach.
The findings of the literature study and the qualitative interview have directed the PhD project towards the importance of project specific design strategies and an integrated and multi-professional approach to environmentally sustainable building design.
The project therefore focuses on the issue of design strategy development in an experimental application of sensitivity analysis as a methodical approach to the development of a design strategy for a new energy-efficient residential building in Denmark. The outset of the analysis is a single family reference building through which the sensitivity of parameters relating to energy and residential building design are analysed.
In conclusion the PhD project discusses the strengths and weaknesses of sensitivity analysis as a methodical approach to design strategy development, and makes a suggestion for the development of a tool that supports project specific design strategy development.

Readers Guide

This PhD thesis, entitled 'Sensitivity Analysis as a Methodical Approach to the Development of Design Strategies for Environmentally Sustainable Buildings' presents a study performed in a inter-disciplinary field of Architecture and Building Engineering co-funded by the Department of Architecture and Design, and the Department of Civil Engineering at Aalborg University, Denmark.

The aim of the PhD project has been to gain a better methodical understanding of the development of environmentally sustainable buildings and enable a methodical approach to strategy selection for their environmentally sustainable building projects.

The target group of the PhD project and the design strategy support tool has been mainstream[1] architects and engineers who require simple but adequate tools for selecting design strategies to apply in their environmentally sustainable building projects.

The PhD project has developed through a process-oriented approach in which an intuitive search for knowledge was anchored around existing research methodologies in a headline based structure.

The thesis is part of the requirement for acquiring a PhD degree at Aalborg University, Denmark. Aside from writing a thesis PhD students need to acquire 30 ECTS worth of e.g. PhD courses, conference, network and workshop participation.

Apart from the introductory, concluding and perspective chapters, in respectively the beginning and the end of the thesis, the thesis is divided into two parts; Part 1: Methodical approaches to sustainable architecture and Part 2: Design strategy development.

Part 1 presents an analysis of the state of the art of publications about methodical approaches to sustainable architecture as well as a profession analysis of the architecture and engineering professions.
Part 2 presents an analysis of the state of the art of design strategies applied in examples of residential building projects and the tools available to designers of Danish environmentally sustainable buildings, as well as, a design strategy development experiment in which sensitivity analysis is applied as the methodical approach for design strategy development, and a suggestion for the development of a design strategy development support tool.

Notes are situated at the end of each chapter, and references are stated in brackets after the Harvard method; [Author's last name - Year of publication:Pages]. A list of the references is provided in the 'Bibliography' chapter, along with a short discussion of the selection of sources.

Illustrations are numbered after which page they are situated on and their location on the page and a list of the illustration references is provided in the end of the thesis in the 'illustrations' chapter.

Tables are numbered after the chapter they are situated in and in relation to their order of appearance within the chapter.

[1] 'Mainstream architects and engineers' are understood here, as architects or engineers with little or no experience with environmental sustainability.

2 ACKNOWLEDGEMENTS

Access to other researchers, locally at the university, nationally via networks, and internationally at conferences, other universities and international research projects, has taught me a lot about what it means to do research and how researchers work. This access has also been a great source of information about previous and present research in the field of study and in fields relating to the field of study.

Insight into relating research areas has been achieved through conference participation, a stay abroad at the Martin Centre at the University of Cambridge (UK) and through participation in the ECBCS IEA Annex 44 project entitled 'Integrating Environmentally Responsive Elements in Buildings', as well as sporadic participation in other networks such as the Danish passive house network (Erhvervsnetværk Passivhus Danmark), a regional low-energy network in East Jutland (Midt-jydsk Lavenergi) at Energy Service Denmark and a Danish network focusing on the use of natural and artificial lighting in buildings (LYSnET).

Aalborg University (Denmark)
First and foremost I would like to thank my supervisors; Associate Professor Mary-Ann Knudstrup at the Department of Architecture and Design and Professor Per Heiselberg at the Department of Civil Engineering for guiding me through the process and providing critique.

Furthermore, I would like to thank my fellow PhD students at the Department of Architecture and Design and the coordinator of the ADPL (Architecture & Design PhD Lab) group, Professor Ole B. Jensen for providing a discussion forum for research methodology and theories of science.

Finally, I would like to thank Master student Jasper Nielsen (now M.Sc.Eng. in Civil Engineering) at the Department of Civil Engineering at Aalborg University for insight into his master project and a discussion about the project, and Professor Henrik Brohus at the Department of Civil Engineering at Aalborg University for enabling participation in his 'Stochastic Modelling' course and for engaging in a discussion of my project in relation to the methods presented in the course.

Arup Associates
I would like to extend my gratitude to designers Peter Warburton and Michael Beaven with Arup Associates, London, for their participation in an interview about Arup Associates' approach to integrated, and environmental and sustainable building design.

ECBCS IEA Annex 44
I would like to thank the other participants in the IEA Annex 44 project for providing information about their research and practical experiences and applicable feedback to presentations given at the meetings. This source of information and feedback has made a difference in the way this project has evolved and especially in the way it is communicated

The participants in the annex come from different backgrounds: researchers in engineering or architecture, consultants and practitioners, which has enabled me to experience first hand some of the communicative difficulties faced in multi-professional team work.

The objectives of the annex project are:

- 'To improve and optimise responsive building elements
- To develop and optimise new building concepts with integration of responsive building elements, HVAC-systems as well as natural and renewable energy strategies
- To develop guidelines and procedures for estimation of environmental performance of responsive building elements and integrated building concepts'

[Annex 44 Brochure]

The results of the annex project will be a state-of-the-art report, a designers' guide, a general booklet, a manufacturers' guide and an expert's guide.

This PhD project has participated in subtask B about ‘Integrated Building Concepts’. The contributions made to the annex have primarily been for the state of the art report (activity B1). The conclusions of this project will furthermore contribute to the evaluation and development of tools (activity B3).

The University of Cambridge
I would like to thank the people at the Martin Centre at the Department of Architecture at the University of Cambridge (UK), especially Director of the Martin Centre and Professor of Sustainable Design Koen Steemers for facilitating my stay at the Martin Centre and my participation in MPhil courses at the Departments of Architecture and Engineering, as well as for participating in an interview about his research and teaching.

I would furthermore like to extend my gratitude to Professor Nick Baker at the Martin Centre for participating in an interview about his research and teaching, as well as, PhD candidates Fernanda Sá Oliveira, Vicky Cheng, Nardia Chow and Maryléne Montavon for participating in discussions about research methods and issues relating to environmentally sustainable architecture.

Lastly, I would like to thank PhD candidate Henriette Steiner and ‘Scroope 18’ editor Tommy Chung from the Department of Architecture for facilitating an article in the annual journal (Scroope) from the department in 2006.

3 TABLE OF CONTENT

4 INTRODUCTION

This PhD thesis reports the findings of a PhD project with the work title ‘Methodical Approaches to Environmentally Sustainable Architecture’.

The thesis is divided into two parts; Part 1: Methodical approaches to sustainable architecture and Part 2: Design strategy development; Part 1 presents an analysis of the methodical approaches to sustainable architecture identified via studies of the terminology used in existing publications and methodical process descriptions associated with sustainable architecture, as well as, a profession analysis of the professional differences between the architecture and building engineering disciplines. The profession analysis also presents the conclusions of an interview with two designers from Arup Associates about the methodical approach applied by the practice for the creation of environmental and sustainable building design.
Part 2 presents an analysis of design strategies applied in residential building projects in temperate climate zones in Europe, and an analysis of the tools available to designers of Danish environmentally sustainable buildings. Part 2 furthermore presents an experimental design strategy development for an environmentally sustainable residential building in Denmark in which sensitivity analysis is applied as a methodical approach for design strategy development. This experiment leads to a suggestion for how sensitivity analysis can be used as a methodical approach to design strategy development through the development of tools that support design strategy development.

Methodical approaches
The interest in methodical approaches is the result of exposure to many different approaches to sustainability available in publications and practices that all stress the importance of early integration of environmental consideration in the architectural design process [e.g. Baker and Steemers 2000, Hawkes, McDonald and Steemers 2002, Owen Lewis 1999, http://www.iea-shc.org/task23/ 2006, and Knudstrup 2001 and 2004 etc.]. Only a few of these publications actually discuss what this means in relation to the design process [Owen Lewis 1999, http://www.iea-shc.org/task23/ 2006, and Knudstrup 2001 and 2004]. The interest in methodical approaches to sustainable architecture was, furthermore, fuelled by a frustration associated with how to distinguish between the terms associated with different approaches to sustainable architecture and choose the ‘correct’ approach in relation to a specific project.

Environmentally sustainable architecture
Environmentally sustainable architecture is still an issue because of the global climatic changes over the past decades. This has placed the environmental impact of our lifestyles on the political agenda and agreements, like Agenda 21(1992) and the Kyoto-protocol (1997), have been signed by numerous nations and Denmark is amongst the signing nations. Some of the signing nations plan to buy CO_2-quotas from other nations or pay penalties to the European Union [www.hydro.com 2005, www.dong.dk 2005, http://ing.dk 2007], which, in my opinion, is very unfortunate, because this will diminish the effect of the Kyoto agreement and reduce the environmental concerns to an economic concern. So far the Kyoto protocol has not proved to be very effective[1], and another international political summit was recently planned to take place in Denmark in 2009.

The primary environmental concern in relation to building legislation in Denmark has so far been energy; either as reduction in energy consumption through the building design and appliances or, at bests, the introduction and development of renewable energy sources such as Photovoltaics (PVs) and Solar panels.
A study of the legislative development of the Danish building regulations around the time of the energy crises in 1973 and 1979 has revealed that these have had a major impact on past developments of low-energy buildings in Denmark through the introduction of stricter demands and new ways of calculating the energy consumption in buildings to the Danish building regulations.
Other environmental concerns, such as the pollution, scarcity and human toxicity of materials, are also apparent in Danish building legislation. The legislation about pollution and human toxicity of materials is, however, complicated by the availability of production data and empirical testing of products, which usually means that it takes longer to determine whether the production

of a material pollutes the environment or whether it is toxic to humans or other species. The past two decades have seen scary discussions about the toxicity of e.g. Phthalates, solvents and Freon used in building materials, which in my opinion indicates that this is an area of the Danish building legislation that is under constant development.

Today, we seem to be balancing on the ledge of another energy crisis which will have a great impact on the economic situation of an average family household and our future climate. The decisions we make today with respect to building design will have a major impact on the climatic conditions on both a global level and the political stability of nations worldwide. This is also apparent in the public debate in the Danish media; in 2004 when this PhD project began the Danish media headlines focused on the increasing petrol prices, but since then the focus has shifted to include other areas of energy consumption, such as governmental plans for investments in renewable energy sources and newspaper articles about how Danish consumers can reduce their $C0_2$-emissions.
The energy crises of the past have proved to be a great driving force in the development of energy technology and low-energy buildings, but today the public and political attention seems to have shifted towards the global climatic consequences of human lifestyle. The fact that we need to face these climatic consequences immediately and effectively means that environmental sustainability is still very much an issue that designers of architecture need to face.

With the recent introduction of new energy requirements in Danish building legislation (as of 2006) the Danish building legislation has been adjusted to meet the demands set in the European Directive for the Energy Performance of Buildings [Cox and Fischer Boel 2002]. The preconditions of building design have therefore changed, which has forced architects and engineers to adopt low-energy considerations as a build-in part of their projects. This has brought on demands of simple and applicable design strategies and tools, as well as demands for more detailed process descriptions of methodical approaches to environmentally sustainable architecture.
In the end of 2005 a new energy assessment programme Be06 (Building Energy 2006) was released by the Danish Building Research Institute, which is applied in this PhD thesis for the experimental development of a design strategy for a residential building in Denmark. The application of the Be06 programme as a design strategy development support tool will be evaluated in the ‘Suggestions for development of design strategy support tool’ chapter in this thesis.

The rest of this chapter contains introductions to environmental sustainability, the legislative development of energy and indoor climate requirements in Danish building regulations since 1961 and publications about methodical approaches to sustainable architecture, as well as the problem and demarcation of the project.

4.1 Environmental Sustainability

There are many different terms associated with the field of environmentally sustainable architecture, such as green, ecological, environmental, low-energy and solar architecture. The decision of which term is the ‘correct’ for this PhD project was therefore difficult.
The term sustainable is in this thesis found to be a good umbrella term for the terminology. There are, however, many different kinds of sustainability (e.g. environmental, economic, social and static), which is why the term for this PhD project is specified to concern environmental sustainability. (Please refer to chapter 6.1 for further details).

Environmental sustainability has been an issue since the energy crises in 1973 and 79 [Wigginton and Harris 2002:7]. Before 1973 the environmental concerns were related to how to achieve comfort inside buildings and how to deal with habitation of the developing countries or of desolate areas in industrialised countries [Olgyay 1963 and Steele 2005]. Today in the post-energy crises era the indoor related issues of environmental sustainability are concerned with the increase in illnesses related to the quality of the indoor climate, such as allergies and asthma [allergi.astma-allergi.dk 2005]. More and more time is spent indoors, in the workplace and at home, which increases the problems related to the quality of the indoor climate in buildings. The current energy related issues are motivated by a concern for the scarcity of fossil fuels and natural gas, and the impact on the climatic and ecological conditions of the earth which have changed significantly during the past decades.

A study of the terminology, design strategies and dominant concerns relating to the different approaches to sustainability has resulted in the conclusion that environmentally sustainable architecture covers a lot of bases; from reductions in the energy consumption during the operation phase through the design of the building envelope, the layout of the building and the selection of appliances for the building, to reductions in the energy consumption during the production phase and the life cycle profile of the building and the integration of renewable energy sources and strategies for the flora and fauna preservation and development on the site or in an area.
These issues are all regarded as important in this thesis in relation to environmentally sustainable architecture. Of these issues the reduction of the energy consumption of the building during the operation, and the flora and fauna preservation and development are regarded as a fundamental issue for environmentally sustainable architecture that must be considered, whereas the selection of appliances, the energy consumption during the production phase and the life cycle profile of the building, the integration of renewable energy sources are regarded as issues that might be considered as supplements to the issue of the energy consumption during operation and the preservation and development of flora and fauna. This prioritisation is caused by previous experiences with LCA studies which showed that the energy consumption for operation of buildings is a lot greater than the energy consumption for the production and disassembly of buildings.
Ideally these issues should all be considered together in a joint evaluation of the environmental sustainability of projects, but this is not feasible in relation to the Danish tools that are currently available for assessment of the environmental performance of buildings.
The design strategy development experiment conducted in this PhD project therefore addresses the part of environmental sustainability which has to do with the energy consumption during the operation phase in relation to the design of the building envelope. The issue of preservation and development of the flora and fauna relate to the site selection and the site development, which are therefore site specific unlike the study conducted in the experiment.

4.2 Legislative development of energy and indoor climate requirements in Danish building regulations since 1961

Through a study of the Danish building regulations dating back to 1961 the conclusions presented in the following paragraph can be made with respect to energy and indoor climate.[2]

Energy

In the 1961 and 66 building regulations the construction of the building envelope was to live up to a list of specified k-values (kcal/m^{2}h.°C). The building regulations were focused on 'heat insulation' and contained examples of constructions which lived up to the specified k-values.
The only differences between the 1961 and 66 k-values were for the windows and doors, for which k-values were specified in 1966.[3]

In 1972 the building regulations the unit for the k-values were revised to W/m^2°C, and the 1966 requirements were changed to match the new unit. Besides the introduction of a new unit the k-values were the same as in the preceding building regulations, except for the windows for which the k-value was increased from 3.00 to 3.10 kcal/m^{2}h.°C (3.10kcal/m^{2}h.°C = 3.60 W/m^2°C).
The 1972 building regulations were the last to include construction examples corresponding to the k-values. After 1972 the building regulations referred to the Danish Standard no. 418 for calculation of the k-values (and to SBi direction 147 in 1985).

In 1977 the building regulations were revised again which specified significant changes as of February 1st 1979. The k-values were reduced (in some cases by more than half of the 1972

values) and they were specified with respect to two room temperatures (10 and 18°C). This introduction of temperature specific k-values meant a differentiation in constructions depending on the indoor temperature of the rooms.
The 1977 building regulations introduced a new type of requirement about the window to floor area ratio, which stated that the total window area of the building (excl. shops and the like) should maximum be 15% of the gross floor area (except unutilised loft and basement spaces).

In 1982 another revision of the building regulations was released. This did, however, only contain small changes to the heat insulation requirements, and demands for closed entrance spaces in buildings of more than two to four storeys.

In the 1985 revision of the building regulations the k-values were specified further for heavy wall constructions, basement walls, partition walls facing unheated spaces and for windows. The k-values were not changed much and the maximum permitted window area of 15% of the floor area was unchanged.
The 1985 building regulations did, however, open up to a more flexible approach to the heat insulation of buildings through the introduction of a heat loss calculation and a calculation of the net energy requirement of buildings for space heating. Both calculations opened up to the possibility of changing the k-values and the window area of the building as long as the changes were proved not to cause an increase in the heat loss of the building or a maximum permitted net energy requirement for heating and ventilation (7.2GJ + 0.252GJ/(m^2 gross floor area)*Gross floor area m^2.
The 1985 building regulations also introduced the notion of low energy houses, which had a net energy requirement for heating and ventilation smaller or equal to 50% of the permitted net energy requirement for heating and ventilation.

The 1995 revision of the building regulations introduced significant reductions in the k-values (which were renamed to U-values - the unit was still $W/m^2°C$). The revision of the building regulations changed the minimum temperature for buildings which had to live up to the U-values from 10 to 5°C.
The 1995 building regulations elaborated on the energy requirement calculation, introduced in the 1985 building regulations, and stipulated energy frames for different building types. The energy frames are used to determine the maximum permitted energy requirement of the building for heating and ventilation depending on the heated floor area of the building and the area of the ground floor. With the introduction of these energy frames the maximum window to floor area ratio of 15% was eliminated from the building regulations and unfortunately so was the notion of low-energy houses.

In 2001 a supplement to the 1995 building regulations in which the U-values were reduced slightly and new U-value requirements were introduced for thermal bridges at the fundament, at the joints around the windows, doors and in the building and around floors with floor heating.

In 2006 another supplement was made to the energy consumption chapter in the 1995 building regulations. This revision was the result of the EU Directive for the Energy Performance of Buildings [Cox and Fischer Boel 2002]. The revision had, however, been anticipated since the release of the 1995 building regulations.
The 2006 supplement differs between U-values for buildings heated to 5 and 15°C. The requirements for buildings heated to minimum 5°C are similar to the ones in the 2001 supplement. The requirements for buildings heated to minimum 15°C are significantly lower than in the 2001 supplement.
The 2006 supplement introduced a significant reduction in the energy frame and a distinction between two classes of low energy buildings, as well as a change in the requirements from net energy consumption to primary energy consumption.
Until 2006 the energy requirement calculation had focused on the heating of buildings (incl. passive solar heating and internal heat gains), whereas it from 2006 and onwards also includes the energy required for hot water, cooling, artificial lighting and removing overheating. The 2006

primary energy requirement calculation also includes the possibility of including untraditional energy sources in the building design, such as solar panels, photo voltaic cells, heat pumps, wood burning ovens and electrical radiators.
The 2006 supplement also included a maximum permitted transmission loss through the façade of 6W per m^2 building envelope (excl. windows and doors) for buildings with up to 3 stories and 8W/m^2 for buildings with more than 3 stories, as well as, demands for an effective U-value of the windows that does not exceed 1.20 + n*0.30 W/m^2K (+ 0.20 if the building has window bars). This effective U-value for the windows will be reduced on January 1st 2008 to: 0.50+n*0.30W/m^2K (+ 0.20 if the building has window bars).

To summarise this means that since the 1960's the maximum U-values have been reduced with up to approx. 85% for wall and roof constructions, up to approx. 80% for ground floor constructions and up to approx. 60% for windows and doors.
The building regulations have moved from stating maximum U-values and constructions fulfilling these values to requiring complex calculations of the net energy requirements of buildings (which provided a more flexible approach to fulfilling the building regulations' demands for the energy requirement of buildings).
The calculation of the energy requirement of buildings has changed from focusing on space heating and passive heat gains from solar radiation and internal heat gains in 1985 and 1995 to including more energy sources and focusing on the energy requirements for space heating, cooling, removing overheating, artificial lighting[4] and hot water in 2006.

Indoor climate
Today indoor climate is an important consideration in building design. In the current building regulation the indoor climate chapter focuses on ventilation, pollution from building materials, pollution from other sources, pollution from underground and temperatures. The requirements of the building regulations are supplemented by legislative demands set in Danish Standards for the estimation of e.g. thermal and acoustic comfort in buildings, and demands set for the work environment by The Danish Working Environment Service, which contain a lot of details relating to the human-toxicity of materials and the comfort requirements of work environments.

A study of the Danish building regulations as of 1961 reveals that the notion of indoor climate and comfort was introduced in the building regulations for the first time in 1995. Until 1995 the headline for the indoor climate chapter had been ventilation, which was included in the building regulations for the first time in 1972, and the concern with the pollution from building materials were introduced in the 1985 building regulations in the construction chapter, which back then primarily focused on formaldehyde. Today the chapter about pollution from building materials also include asbestos, mineral wool, fly ash and cinder.

From an ecological point of view, and in light of the recent public debate about the toxicity of e.g. plastic paints and phthalates, one might argue that the chapter about pollution from building materials is in its infancy and that it should be detailed further, not only with respect to the impact the building materials have on human beings but also with respect to how the building materials pollute the environment. This is an interesting perspective in relation to the development of how the understanding of the relationship between the environment and the human race; Publications and projects from the pre-energy crises era focused on how the climate effected human habitation and the relationship between the climatic conditions in a region and the building design, whereas publications and projects in the current the post-energy crises era focus on how human habitation influences the environment and how buildings and lifestyles can be changed to reduce the negative consequences of human habitation. Maybe future versions of the Danish building regulation will see a similar development in the legislation for indoor climate and building materials.

The main problem with the issue of healthy materials is that it often takes a long time to before the health effects of materials can be determined, which makes the process of assessing the human-toxicity, as well as the environmental toxicity, of materials complicated and time dependent, and the fact that new hybrid and artificial materials are developed consistently does

not make this assessment process any easier.
In response to this the Nordic Swan Label for non-edible products has been extended to include building components and building materials and the indoor climate of houses [http://www.miljoeogsundhed.dk/default.aspx?node=5245 2007].

The increased focus on comfortable indoor climates has caused changes in e.g. the required dimensioning room temperatures and maximum airspeeds of the ventilation in relation to the air temperature, as well as requirements for maximum reverberation times for spaces and ventilation rates for buildings in relation to what function the spaces and buildings are used for.

The impact of legislation on architecture

Energy

The changes in the energy regulations have influenced the architectural expression of buildings in Denmark, especially in the period between 1977/79 to 1985 when the maximum permitted window area was 15% of the gross floor area of the building. The obvious results of this were deep plan buildings or very small windows, which are quite typical for this period.
When the 1985 building regulation opened up for the possibility of increasing the window area of the buildings by the considering the heat balance in the building, this possibility lead to the infamous highly glazed office buildings of the 1990's.
With the recent introduction of the inclusion of energy requirement for removing overheating, hot water and electrical energy for lighting and appliances the number of highly glazed buildings will probably decrease.

Besides the window design the reduction in the permitted U-values has also caused an increase in the thickness of the construction of the building envelope, which has caused architects and builders to consider wood constructions over brick constructions in order to reduce the wall thickness and/or to improve the life cycle assessment of the building.

Furthermore the reduction of the energy frames has caused an increase in the application of mechanical ventilation in residential buildings, because this enables a large reduction in the energy consumption for space heating without having to redesign the houses predating the 2006 supplement to the building regulations.

Indoor climate

The increased awareness of comfort has not effected the architectural expression of buildings directly. It has however led to a noticeable increase in the number of buildings with e.g. floor and wall heating.

The increased information of human-toxicity and environmental toxicity of materials has influenced the building industry in relation to e.g. the production of asbestos-free materials and the search for new production techniques that are more energy-efficient and healthy. The information of toxicity of materials made available to the Danish public by newspaper stories and The National Consumer Agency (www.forbrug.dk 2007) has also increased the public awareness and fear of what impact materials have on our health and thus an increase in the demand for healthy buildings produced with healthy materials.

Currently the Danish building regulations only require a dimensioning room temperature of 20°C in buildings, which in most cases causes inconsistencies between the predicted energy consumption of buildings and the measured energy consumption of buildings. This is a problem needs to be solved in Danish building regulations if we are to achieve an actual reduction in the energy consumption of buildings, because there is currently no legislative way of reducing the actual energy consumption of buildings; our buildings may be designed to be more energy-efficient but this has only caused the users of buildings to increase their comfort levels with respect to room temperatures and thus an increase in the actual energy consumption in buildings.
A further issue that adds to the increase in the actual energy consumption in Danish buildings is

an increase in the wealth of the average Dane, which has caused an increase in the introduction of luxury items in new and renovated buildings, such as large flat screen TVs, computers and TVs in every room of the house, extra outdoor lighting, towel heaters, tumble dryers, and heated indoor and outdoor spas.
This means that the efforts of improving the energy-efficiency of buildings might end up balancing out the increase in the energy consumption of the users of buildings due to changes in lifestyles and increases in comfort levels made possible by the improved energy-efficiency of buildings.

I do not personally believe that the Danes are willing to change their lifestyle and give up e.g. their flat screen TVs and their floor heating, which means that we need to find ways of improving the energy-efficiency of these luxury items and account for the increases in the comfort temperatures of the users in our assessments of the energy consumption of buildings e.g. by increasing the dimensioning room temperature of residential buildings to 22°C or change the way the energy performance of buildings is evaluated in relation to the building regulations from assessment of the estimated energy consumption to actual measurement of the energy consumption.

4.3 Publications about methodical approaches to sustainable architecture

Within the last decade a number of design strategies and methodical process descriptions have been developed for different approaches to sustainable architecture. Amongst these the Passive House Standard is one of the design strategies which has received a lot of attention in Denmark during the duration of this PhD project (2004-2007).

After going through the vast amount of publications available about sustainable architecture I found that some publications contain abstract descriptions of the design process and detailed descriptions of a specific design strategy, whereas other publications primarily contain on detailed process descriptions of the design process involved in sustainable design. Lastly there are publications discussing the historical development or current examples of building projects.
The publications included in this PhD project were selected based on literature studies of the available publications about sustainable architecture. A large number of publications were studied for the two state of the art chapters and those presenting methodological process descriptions, definitions of terms associated with specific approaches to sustainable architecture, design strategies and built examples were included the state of the art of this thesis.

When comparing publications aimed at architecture and engineering practitioners I found that many of the same terms and design principles are in play in the publications, but that the understandings of the different design principles seem to vary a great deal from publication to publication. These variations can be traced back to differences in professional language[5], and interests of the authors and target groups of these publications.
General variations in the understandings of design principles can also be found in the publications in relation to the selected approach to sustainability and the scale of focus (e.g. urban design, architectural design and component design).

Most of the methodical approaches found in publications do not yet resonate in Danish practices, but they taught to future generations of architects and engineers, and work as inspiration for architects already experienced in the field of environmentally sustainable architecture, who then develop their own strategies in relation to the trademark architectural expression of their respective offices.
It would however be incorrect to claim that environmental sustainability is non-existent in Danish buildings, as maximum energy requirements and the notion of low-energy buildings have been part of the Danish building regulations since 1985. The notion of low-energy houses were unfortunately removed from the 1995 building regulations, which might explain the relatively low interest in low-energy housing in the Danish public debate and in architectural practice in

the period of 1995 to 2006. (Please refer to chapter 4.2 for details).
The legislative development of the energy requirements in Danish building regulations have caused a kind of environmental sustainability which is invisible in the public mindset and thus also in the mindset of clients of architectural and engineering practices. This invisibility has also caused a political pretext for doing as little as possible because Denmark is already on the forefront when it comes to integration of energy efficiency in buildings. This was reflected in the political environmental debate, which until recently (2006) focused on waste management, and forestry and water conservation.

Environmentally sustainable buildings can still be considered a rarity in Denmark when it comes to going beyond the legislative demands e.g. to achieve low-energy status of a building or the creation of ecological buildings made of recycled or naturally procured materials. Most of these projects are self-build projects, competition projects or projects implementing only a few environmental considerations like the introduction of PVs, heat pumps or unheated spaces.
Projects implementing environmental considerations from the beginning of the design stage have become more recent in the last decade, but they are still a rarity and still the focus is on the implementation of a few environmental considerations, which more often than not cause an amputation of the environmental profile of the building. This is always a risk when narrowing the scope of environmental considerations, but it is also necessary to choose a focus, or it will be impossible to finish a project within the economic boundaries and on schedule without support tools for design strategy development, which are currently not available in Denmark.
After the recent re-introduction of the notion of low-energy buildings in the 2006 Danish building regulations and the increased public awareness about climate change Denmark has seen an increase in the demand for low-energy and healthy buildings, which has created an attractive outlet for low-energy buildings for Danish architects and engineers.

This PhD project addresses the issue of design strategy development where it explores sensitivity analysis as a methodical approach for locating design parameters that are sensitive and robust in relation to the building envelope design and the energy requirement of specific building projects. This exploration of sensitivity analysis as a methodical approach is applied in a design strategy development experiment for a fictional residential building situated in a Danish context. This has resulted in a suggestion for how tools can be developed to support design strategy development. A suggestion that will hopefully inspire the future development of design support tools which will enable integration of a wider range of environmental design principles in the architectural design of buildings.

4.4 Problem and demarcation

Research question

The initial problem formulation for this PhD project focused on methodical approaches to the creation of environmentally sustainable architecture, this was later specified into an aim of developing a methodical design strategy for the design of new environmentally sustainable residential buildings in relation to the following research question:

> ‘When is it best to solve which tasks and implement which design parameters in the design process, if the aim is to achieve an environmentally sustainable residential building?’

This research question turned out to be difficult to answer satisfactory because the answer to this question was concluded to be: that it is best to implement environmental design parameters in the beginning of a project, but that the selection of which design parameters to implement depends on the possibilities in the specific project.
Furthermore, ‘Part 1: Methdocial approaches to sustainable architecture’ of the thesis led to the realisation that the development a stationary and analogue design strategy for a residential building might not enable a better integration of design strategies in architectural practice. The scope of the project therefore turned towards the development of a dynamic and digital support tool for design strategy development, and the research question was, therefore, revised to:

> ‘How can existing design evaluation tools be adapted to support the development of design strategies for environmentally sustainable buildings?’

The revision of the research questions and problems were regarded as the natural progression corresponding to the explorative and open-ended research strategy applied in this PhD project (please refer to chapter 5 for more information about the methodical approach applied in this PhD project).

A number of subsidiary questions have been answered throughout the project;

- Which methodical approaches have been developed for sustainable architecture and what is the difference between these methodical approaches?
- What is the difference between the conventional approach to architectural design and the approaches to the design of sustainable architecture?
- Is there a difference between how architects and engineers work? And does this influence the development of sustainable architecture and tools for design strategy development?
- Arup Associates is one of the international engineering companies who have worked with a lot of the environmentally sustainable buildings reported in publications. What is significant about their approach to environmentally sustainable building design? And how does this relate to the methodical process descriptions found in publications?
- Which design strategies are applied in existing environmentally sustainable residential buildings?
- Which tools are available for designers of Danish environmentally sustainable buildings?
- Is it possible to apply sensitivity analysis as a methodical approach to design strategy development? If so, how can it be implemented in a tool?

How these subsidiary questions fit within the PhD project is described in further detail in the ‘methodology’ chapter of this thesis.

Methodical approaches to environmentally sustainable architecture

Environmentally sustainable architecture

My interest in environmentally sustainable architecture originates in an idealistic and personal conviction that buildings should have as little impact on their surrounding environment as possible, while still being able to keep up with the current lifestyle of the information age, as well as, with future lifestyle developments. This means that my purpose of dealing with environmentally sustainable architecture is not to force lifestyle changes, but rather to reduce the impact of lifestyles on the environment through a more efficient use of resources. This is motivated by a concern for the state of the global environment in relation to preservation of biodiversity, the survival of the human race and political stability[6].

Methodical approaches

My interest in methodical approaches is motivated by the emphasis placed on design strategies and methodical approaches in existing publications in the field of sustainable architecture, as well as my encounters with environmental design during my master level studies at the Department of Architecture and Design at Aalborg University. The interest in methodical approaches is furthermore a natural fixation in relation to a study situation where one has to learn something.

Energy and comfort

Environmentally sustainable architecture embraces a lot of different aspects, as mentioned in the beginning of this chapter. The experimental development of a design strategy described in this PhD thesis primarily considers the relationship between the design of the building envelope and the energy consumption of the building, while other parameters relating to the comfort inside and the use of the building are included in the setup of the experiment in order to ensure that reductions in the energy consumption are not achieved by compromising the comfort conditions inside the building.

Energy is, however, not the only important issue to consider when working on environmental sustainability. Other issues involved in environmentally sustainable architecture are concerned with transportation, the flora and fauna on the site and the life cycle profile of the materials applied in the building. These issues need to be considered in relation to the site selection, the site development plans, the selection of materials and transportation of building components: The issues do, however, fall outside the scope of the experimental development of a design strategy for environmentally sustainable residential buildings in chapter 9[7].

Target group
Some architects and engineers have already achieved a combination of a high level of environmental sustainability and architectural quality, while 'mainstream'[8] architects and engineers still have not achieved this combination of environmentally sustainable buildings and architectural quality. This is a motivating factor for the development of a design strategy development support tool for environmentally sustainable buildings.
The design strategy support tool should ease the development of design strategies that integrate environmental and architectural concerns in one joint design strategy. The tool thereby creates an interface for inter-disciplinary integration in a marketplace that, in my experience, is currently not well-equipped to deal with this type of integration.

Context
There are three types of context to consider in this project; there is the scientific, the physical and the political context in relation to environmentally sustainable architecture.

Scientific
The scientific context of this PhD project lies in a cross-field between engineering and architecture, which makes way for a critical theoretical approach to science. In some cases decisions are based on data developed in the empirical analytical tradition of science, while in other cases decisions will be based on hermeneutic or phenomenological approaches to science. The most important issue in relation to this is awareness of method; the decision-makers must always be aware of what they base their decisions on, how they prioritize and why. The theory of science applied in this project will be discussed in further detail in the chapter 5.

Physical
The physical context of this PhD thesis is Danish which means: a temperate climate, Danish building traditions, Danish building regulations etc. This is important to acknowledge if one has a contextual approach to architecture, which is the case in this PhD thesis (please refer to the 'methodology' chapter for more information about the understanding of architecture applied in this PhD project).

Political
The political context is important when dealing with environmentally sustainable architecture, as there is a lot of political debate about issues relating to environmental sustainability. This PhD project does not aim at changing or influencing the political debate, it merely deals with the legislative results of this debate. Not that influencing the political agenda is not of interest to the author, but it would call for a completely different type of project, that would steal away from the focus on buildings.

Building
This PhD thesis does not claim to develop design strategies for environmentally sustainable *architecture*. This is done to clarify the aim in relation to the discussion amongst architectural critiques of architecture vs. 'mere' building (please refer to chapter 5.5 for further details). In other words the methodical approach to design strategy development presented in this thesis does not ensure that architectural quality is achieved, but the methodical approach can enable an easier integration of environmental considerations in the design process, thereby, enabling better conditions for actually moving from 'mere' building to a status of 'architecture'.
It is furthermore my opinion that early an integration of environmental and architectural

considerations of a project in one joint design strategy can improve both the architectural and the environmental quality of a project.

Residential Buildings

The project focuses on residential buildings, which will be reflected in the design strategy development part of the thesis (Part 2). Residential buildings were chosen as a way of narrowing the scope of the project. This does, however, not mean that the methodical approach cannot be applied in the design of other building types.

New Buildings

The choice of new building projects as the focus of this project instead of renovation projects was made due to the degree of both architectural and engineering freedom to choose solutions in new buildings, and due to the fact that new buildings are subjected to stricter demands than buildings subjected to renovation.
Another reason for working with new buildings is that most research in the field of environmentally sustainable architecture, as well as in the field of integrated design methodology, concludes that environmental considerations must be integrated from early on in the design process to ensure a good solution [e.g. Baker and Steemers 2000, www.iea-shc.org/task23/, Knudstrup 2000 and 2004, and Owen Lewis 1999], which means that the possibilities of early integration of environmental and architectural issues in one joint design strategy are best in new buildings.
Furthermore, the process description for renovation projects differs from the process applied for new buildings and the development of design strategies (i.e. the selection of design principles) would differ from the design strategies described in this thesis. Design strategy development support tools can, however, also be used for renovation projects. The only difference in application would relate to the selection of variable design parameters (i.e. the combinations of the calculation parameters made available by analogue and digital tools[9] and the design principles that are of interest in the project), where the design parameters applied in the design strategy development would limit the possibilities of changing certain parameters in the building (e.g. the number of stories in the building and the construction materials etc.).

The choice to focus on new building projects was, however, not made to belittle the important fact, that there is a lot of potential to introduce energy saving measures in the existing Danish building stock through renovation.

Development of design strategies

There are many different approaches to environmentally sustainable architecture, and there are, thus, a lot of different strategies to choose from. Generally all design strategies applied in environmentally sustainable building design are created by merging environmental strategies with the strategy for the architectural design (based on e.g. logistics, architectural expression, context and site analysis etc.).

The merge of environmental strategies and architectural design strategies into one joint design strategy can be quite a time-consuming process, especially if one wishes to base this decision on precise calculations where one practically has to test every possible combination of the variable design parameters in order to make sure that the best possible combination of variable the design parameters for e.g. the ventilation, heating, cooling, orientation, shape and façade design of the building is achieved. This process is also complicated by the fact that a lot of these issues are rarely be covered by one person or one profession, which means that an inter-disciplinary approach is necessary to ensure all the bases are covered from the initial stages of the project.

Another way of approaching this problem is a more intuitive approach, which is not necessarily based on finding an 'optimum' combination of the variable design parameters. This approach consists of setting up different scenarios or design alternatives, evaluating these design alternatives and choosing the one with the best rating as the design strategy for the building (the rating should be based on both environmental and architectural considerations).
The only problem with this approach is that one might not be able to identify any significant

differences in the evaluation of the design alternatives, unless one has a lot of experience from previous projects. Problems with identifying significant changes in the evaluation criteria for the evaluation of the design alternatives can be due to the fact, that the selected design parameters are robust and therefore do not cause changes in e.g. the energy consumption of the building, or that the selected design parameters are sensitive when changed individually but the effect of a simultaneous variation of the parameters cancel each other out. A tool is, therefore, needed for the development of design strategies for people who are inexperienced with environmentally sustainable buildings.

The project behind this PhD thesis addresses the issue of how to develop project specific design strategies for environmentally sustainable buildings in Denmark, through an experimental sensitivity analysis of the design parameters associated with the relationship between the energy consumption during the operation phase of the building and the design of the building envelope.
The conclusions of this sensitivity analysis will be applied a suggestion for how existing energy evaluation tools can be transformed into tools which support the development of project specific design strategies based on the introduction of sensitivity analyses as the methodical approach to design strategy development.

---

[1] This is partly because the achieved energy savings approximates the increases in the energy consumption caused by economic growth in Denmark, which means that the effects of the Kyoto protocol appear non-existent, which might not be the case.

[2] The old building codes are available in Danish on http://www.ebst.dk/bygningsreglementer/0/91/0 (June 18th 2007)

[3] In the 1961 building codes windows were specified to be two layered with minimum 12 mm distance between the layers. In 1966 k-values were specified for the windows and doors (the construction examples of the k-values corresponded with the 1961 requirements).

[4] The electrical energy required for artificial lighting is, however, not included in energy calculations for residential buildings.

[5] The term professional language refers to the fact that some professions apply the same terms, e.g. concept, with completely different meaning. To an architect a concept can be a conceptual idea for the composition of the building volumes or the design of the building envelope or just the layout on the site, whereas it has been by experience (through participation in the ECBCS IEA Annex 44) that engineers apply the term concept for what to me are strategies for e.g. the ventilation of a building or the structural system.
The term concept might have the same basic definition in both professions (e.g. a rough sketch of something) but the application is different, which leads to problems of miscommunication if the term concept is used without attaching another noun to it (e.g. architectural concept or ventilation concept).

[6] With respect to political stability it is my main concern that climate changes will cause a sense of desperation in the nations suffering from draught and flooding that will lead to climatic refugees, which if not handled correctly by the nations receiving these refugees can lead to a sense of desperation and ultimately war as a last resort.

[7] The reason why the design strategy development experiment presented in chapter 9 is limited to issues relating to the energy consumption of buildings and comfort of the user is threefold;

1. There is currently no programme available in Denmark that supports the legislative requirements in the Danish building regulations as well as life-cycle and urban design assessments in one programme.
2. If I were to include more than one programme in the experiment the analysis would become more complicated and the methodical approach applied in the experiment would become less transparent.
3. I believe that ultimately a tool should be developed that considers multiple aspects of sustainability in performance assessment studies, which can also be used for design strategy development through a sensitivity analysis interface embedded in the programme, and I therefore did not want to support a complicated study that would require application of multiple programmes and import of results in e.g. SimLab.

[8] The term ‘mainstream’ often has a negative association. In this project the term is used in relation to the majority of the architectural and engineering professions which at the start of this PhD project were inexperienced with environmentally sustainable building design. This may have changed during the project with the 2006 introduction of new energy requirement in the Danish building codes.

[9] Examples of analogue tools are guidelines and calculation methods available in e.g. Danish Standards, while examples of digital tools are computer programmes applicable for e.g. assessment and/or simulation of building performances (e.g. thermal, energy consumption, life cycle assessment).

5 METHODOLOGY

This chapter contains a description of the methodical approach applied in the PhD project, the understanding of architecture and the understanding of the design process involved in the creation of architecture applied in this PhD project.

5.1 Project structure

The scientific method applied in this project has evolved around a research question formulated within the first year of the project [Andrews 2003].

The project was built around a structure consisting of the basic elements of a 'traditional' research project (in natural and social science); it is based on an initial problem formulation, followed by a state-of-the-art review of the knowledge relating to the initial problem, the initial problem is then detailed and demarked in relation to the findings in the state-of-the-art and a research question is formulated. The state of the art and review of the research question is followed by an experiment and/or empirical information collection, followed by a conclusion for the research question.

In spite of this seemingly well-structured approach to the PhD project the process has been explorative, which means that the approach has been open-ended with respect to the final outcomes of the project and the results of each part of the structure. This is also reflected in the research questions described in chapter 4.4.
This open-ended approach to the results of the PhD project has been the result of an intuitive approach of keeping an open mind to each part of the structure and trying not to formulate deterministic expectations for the outcomes. This can be quite difficult to do, as one is always asked what the expected outcomes of each part of the structure are and how these fit within the red thread of the project. It has therefore been a balancing act of creating a flexible structure which could thrive within these intuitive and at times fumbling formulations of the expected outcomes.
This intuitive approach to research has also meant that the project might not seem as effective as it could have been with respect to the evaluation of tools and development of a design strategy support tool. It is, however, important to acknowledge that the conclusions with respect to the need for a development of a dynamic and interactive design strategy support tool is a result of this intuitive process, and that the outcome probably would have been different if the project had only focused on tools from the beginning.

The research process has evolved around a basic structure organised via the following phases:

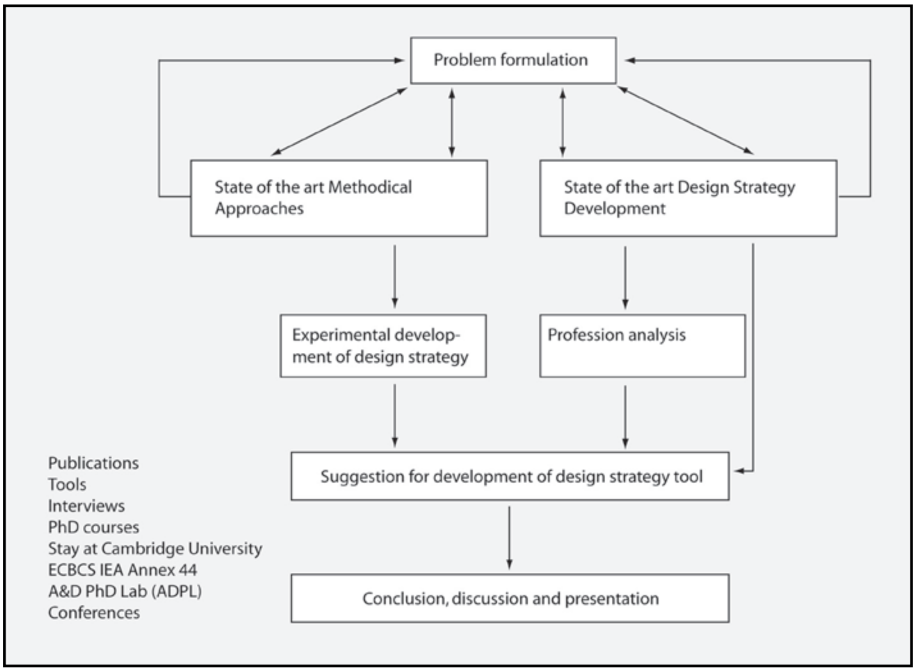


Illustration 22.1: The diagram shows the organisation of the different phases in the PhD project, as well as the external elements which have influenced the project. Some of the phases were iterative within the phase and some phases caused iterations between the phases.

Table 5.1: Summation of the aims, subsidiary questions, analyses and experiments, research methods and results of each phase of the structure

Phase	*Aim*	*Subsidiary question(s)*	*Analyses and experiments*	*Research methods*	*Results*
Problem formulation	Formulation of initial problem and research question		Analyses of the state of the art in methodical approaches Analyses of structures of completed PhD projects Profession analysis and Design strategy development experiment	Literature study, PhD courses, Conferences	Research question; 'How can existing design evaluation tools be adapted to support the development of design strategies for environmentally sustainable buildings?' The overall structure of the projects in relation to the formulation of a set of subsidiary questions
State of the art	Study terminology, process descriptions, design strategies and tools	Which methodical approaches have been developed for sustainable architecture and what is the difference between these methodical approaches? What is the difference between the conventional approach to architectural design and the approaches to the design of sustainable architecture? Which design strategies are applied in existing environmentally sustainable residential buildings? Which tools are available for designers of Danish environmentally sustainable buildings?	Analyses of the topics, terms, design strategies, process descriptions and building examples found primarily in literature and research-based publications and secondarily via web pages relating to the building examples	Literature study, Study trips Application of tools	Discussion of the terminology and the approaches relating to sustainable architecture, of the design strategies applied in building projects, of the methodical process descriptions published about integrated design and environmentally sustainable architecture, and of the tools available in Denmark and a few European tools. Formulation of research question

Table 5.1: Summation of the aims, subsidiary questions, analyses and experiments, research methods and results of each phase of the structure (continued)

Phase	*Aim*	*Subsidiary question(s)*	*Analyses and experiments*	*Research methods*	*Results*
Profession analysis	Study the professional differences between architects and engineers, and a best practice example of a practice that applies integrated design and a multi-disciplinary approach to the design process.	Is there a difference between how architects and engineers work? And does this influence the development of sustainable architecture and tools for design strategy development? Arup Associates is one of the international engineering companies who have worked with a lot of the environmentally sustainable buildings reported in publications. What is significant about their approach to environmentally sustainable building design? And how does this relate to the methodical process descriptions found in publications?	A literature study of existing empirical research relating to observation experiments about how engineers and architects work and an interview with the engineering company Arup Associates about their methodical approach to environmental and integrated design	Literature study, Interview	Identification of the significant differences in the way engineers and architects work and how this influences an integrated design process, the formation of multi-disciplinary work teams and the development of tools.
Design strategy development	Experimental design strategy development through application of sensitivity analysis as a methodical approach. The purpose of the sensitivity analysis is to identify the robust and sensitive parameters in relation to a specified reference building.	Is it possible to apply sensitivity analysis as a methodical approach to design strategy development?	Sensitivity analysis of selected design parameters deducted from the state of the art phase of the project. The input data applied in the analysis were based on the conditions of a comfortable indoor climate, and the analysis focused on design parameters relating to the interdependency between the energy consumption of a building and the design of the building envelope.	Literature study, Master course participation, Calculations in Be06 and Simulations in SimLAB	A design strategy for a new residential building project and a discussion of the sensitivity analysis as a methodical approach to project-specific design strategy development. Revision of research question

Table 5.1: Summation of the aims, subsidiary questions, analyses and experiments, research methods and results of each phase of the structure (continued)

Phase	*Aim*	*Subsidiary question(s)*	*Analyses and experiments*	*Research methods*	*Results*
Suggestion for development of design strategy support tool	Suggestion for how to adapt an existing tool into a project-specific design strategy development support tool.	how can sensitivity analysis be implemented in a tool?	Analyses of the conclusions of the profession analysis and the design strategy development experiment. Experiences with the application of the Be06 tool.	Application of Be06 and SimLAB and Understanding of design process	suggestion of how to improve the interface of the Be06 programme and how to integrate sensitivity analysis as a methodical approach that supports project-specific design strategy development
Conclusion and perspectives and presentation	Summation of conclusions, discussion of research perspectives and presentation of the PhD project.		Different structures were developed for the thesis throughout the project, from approximately three months into the project until approx. one week before submission of the thesis.		Conclusions and perspectives for the project Editing of PhD thesis and defence. Conference papers, journal articles and submission of materials to the ECBCS IEA Annex 44 project (subtask B).

5.2 Inter-disciplinarity

As mentioned in chapter 4.3 the research available through publications indicate that successful architects and engineers in the field of environmentally sustainable architecture cooperate from early on in design teams. This approach is often referred to as a multi-, inter- or trans-disciplinary process. This project was conducted in an inter-disciplinary field that combines the skills of the disciplines of architecture and building engineering, which has increased the interest in the difference between multi-, inter- and trans-disciplinary approaches, which can be described as:[1]

The approaches all involve work teams of people representing different disciplines; the difference between the terms is embedded in the methods applied for the problem-solving process:

Multi-disciplinarity

In a multi-disciplinary process the people representing different disciplines are involved in the process where they work side by side on different areas of expertise from early on in the design process, thus ensuring the involvement of the necessary competencies in all stages of the process. In spite of the different backgrounds of the people in the work team only one method is used which belongs to one of the represented disciplines. This means that the multi-disciplinary approach can be applied for projects of a non-explorative nature which aim for a specifically defined solution. [www.reference.com/search?q=multidisciplinary 2007]

Inter-disciplinarity

An inter-disciplinary process involves approaching a problem from various angles by applying methods from two or more disciplines and eventually coming up with a new way of understanding the problem. This approach therefore differentiates itself from the multi-disciplinary by embracing many different methods of investigation and by having an explorative purpose. The methodical approaches applied in the investigation of a problem can eventually merge into a new method. [www.reference.com/search?q=multidisciplinary 2007]

Trans-disciplinarity
A trans-disciplinary process is applied if the problem lies outside the boundaries of a single discipline.
In this case the team members work together on the different tasks involved in the process, enabling the formation of new 'hybrid' competencies and innovation in the design process. Trans-disciplinary processes can result in the formation of new hybrid professions that build on the methods from a range of existing professions. [www.reference.com/search?q=multidisciplinary 2007]

Differences
The main differences between the multi-, inter- and trans-disciplinary approaches are therefore in this PhD thesis concluded to relate to how many methods are applied, whether the methods merge into new methods and whether new professions emerge from the process; The inter-disciplinary and trans-disciplinary approaches seem very similar the only difference between the two appears to be that the inter-disciplinary approach stops at the method level while the trans-disciplinary approach transcends the professional boundaries and enables the creation of a new profession. It therefore seems that what starts out as an inter-disciplinary approach can at some point in the process cross over and become trans-disciplinary. This point can be defined as the point in the process when it is no longer possible to determine which methods enabled the solution; when it is the summation of the applied methods that enable the solution and when the merged method no longer fits within the existing professional boundaries of the inter-disciplinary team.

5.3 Application of theories of science

This PhD project has evolved in an inter-disciplinary field of science that combines skills from architecture and building engineering. These two professions are traditionally rooted in two different types of science; social science and natural science. The social scientific contribution to the project is related to the architecture profession, while the natural scientific contribution is related to building engineering profession.
Natural science and social science have very different approaches to knowledge and the two sciences investigate very different types of data. The same is true for architecture and building engineering even though both professions operate within the field of building design. Engineering traditionally belongs to the empirical-analytical tradition of natural science while architecture traditionally can belong to different theories of science, such as hermeneutics, phenomenology and structuralism, depending on the approach taken to the creation of architecture.

The educational background for this PhD project also borrows from both the architecture and engineering professions as a result of a 'new'[2] type of inter-disciplinary education at the Department of Architecture and Design at Aalborg University (Denmark). This educational background has resulted in a critical approach to different kinds of knowledge and values associated with these different kinds of knowledge. The project thus applies a critical theory[3] of science based on Jürgen Habermas' writings about knowledge and human interests. It is, therefore, a fundamental presumption of this project that there is no such thing as pure positivism in engineering, as engineers traditionally perform calculations and simulations with a specific intent, thereby applying a degree of subjectivity to their calculations and they interpret their results in order to evaluate a presumed result.
Furthermore, the project presumes that most scientists, whether they belong to natural science or social science, are carriers of specific interests and values and thus set up their experiments/investigations and regard the results of these experiments/investigations in relation to these interests and values. This project, therefore, relies on the assumption that one uses different theories of science when making different investigations and conclusions; sometimes one relies on qualitative approaches based on subjective sources of information, such as hermeneutic or phenomenological approaches, while one in other situations relies on a qualitative approach based on objective sources of information, such as the positivistic or empirical-analytical. This is acceptable as long as one is aware of which approach is applied, which requires an increased method awareness and reflectivity in relation to the applied epistemology[4] and human interest. [Outhwaite 1996:96-104]

The investigation-related approach to theories of science corresponds with the structure applied in the project in which the phases of the project have applied different theories of science in relation to different investigations, specifically in relation to the sensitivity analysis, the literature studies and the interview. The sensitivity analysis is based on an empirical-analytical approach to science via a calculation experiment, while the literature studies and the interview are based on a hermeneutic approach to science which focuses on the interpretation of text available in literature and the interpretation of the interview through a transcription of the interview into text. The methodical approaches applied for each of these investigations are shortly described in the introduction to the chapters containing the investigations, or in a separate part of the chapter, with respect to the purpose and interests of the investigation and the characteristics of the applied method (e.g. whether the approach is qualitative or quantitative).

Criteria of truth

As a result of the focus on epistemology one of the fundamental quests of science is a definition of what the right kind of knowledge is and how it relates to truth [http://en.wikipedia.org/wiki/Epistemology 2007]. This is particularly interesting when dealing with two different kinds of science that deal with very different types of investigation.

A scientific field which has focused on this is social science where criteria of truth are discussed in relation to the discussion of whether social science should strive for objectivity (e.g. through production of quantitative results) and how this can be achieved in a field consisting of primarily qualitative results.

In the book 'INTRODUCTION Theory of Science and Methodology' by Andersen [Andersen 2002] the following criterions of truth are introduced:

Table 5.2: Definitions of different criterions of truth [Andersen 2002:Chapter 11]

Criterion of truth	*Definition*
The criterion of consistency	The basis of the criterion of consistency is the belief that logic and mathematics can ensure truth through application to empirical data.
The criterion of correspondence	The essence of the criterion of correspondence is that theoretical predictions about reality turn out to be true, which means that there is correspondence between terms and empirical phenomenon or between hypothesis and results of investigations.
The criterion of consensus	The criterion of consensus is tied to the epistemological understanding of conversational dialogue as proof of existence. Truth is born in the self-reflective conversation that the participants of the dialogue can agree on.
The criterion of coherence	The criterion of coherence (the narrative criterion of truth) coheres with a narrative (a story). Truth can only be presented in relation to a concurrent and often metaphorical story, which is always subjective, which means that what is truth at one point in time might not be at another point in time. When combined with the criterions of consensus and correspondence the true narrative becomes the narrative which is most accepted because it provides the best description of the world.
The criterion of evidence	Truth is what one chooses to believe – or what one feels obliged to believe. Truth is thus very subjective and individual. The question about truth is transformed to a question about what it is possible to know.
The criterion of pragmatism	A statement is true if it proves effective or if it is useful. Theory is permitted to influence the reality it describes in order to enable that the theory becomes true through correspondence.

Most of the criterions of truth can be found in all professions, but one or more of these will dominate the decision-making process of the different professions.

This project deals with the criterions of truth in relation to the architecture and building engineering professions and it is next to impossible to generalise which criteria engineers

and architects apply in their work, as this depends on their educational backgrounds, work experiences and personal preferences with respect to approaches to architectural styles and building design.
The opinion taken in this PhD project is that the application of the criterions of truth relates to the specific problems solved by different professions and the type of investigation associated with the problems, where architects and building engineers simply have to deal with very different types of problems that relate to different criterions of truth. This means that one might find different traditions within respectively the architecture and building engineering profession due to differences in methodical approaches e.g. if the problems an architect or a building engineer solves simply differ from the traditional problems of his or her profession or if he or she applies a methodical approach to his or her work process that differs from the traditional methodical approach of his or her profession.

These differences in the criterions of truth within the profession make the issue of establishing the criterions of truth even more important, especially when it comes to inter-disciplinary or multi-disciplinary design teams, because the team members need to agree on the criterions of truth of the problem-solving exercises, or at least have an understanding of which criterions of truth they apply themselves and which criterions of truth their team members apply.

The dominant criterions of truth in this thesis

Table 5.3: The criterions of truth applied in this PhD thesis

Research method	*Dominant criterion of truth*
Literature studies – methodical approaches and tools	The criterion of coherence and the criterion of consensus
Literature studies – applied design strategies in residential buildings	The criterion of coherence and the criterion of consensus and the criterion of correspondence
Interview	The criterion of consensus and the criterion of coherence
Sensitivity analysis	The criterion of consistency

Validity

The issue of validity relates to the issue of the quality of the research results presented in this PhD thesis and to the specific theories of science applied for different investigations. The project is primarily based on qualitative research methods, which means that it has not focused on repetition of e.g. experiments but rather on single experiments and interviews. The following will discuss the issue of validity in relation to the applied research methods.

Literature studies and interview

The study of the state of the art of terminology, methodical process descriptions and the design strategies applied in residential buildings are based on comparative studies of e.g. different definitions, descriptions of design strategies and methodical process descriptions available in publications. While only a small part of the study of the state of the art of available tools is based on literature studies (the LT-method [Baker and Steemers 2000]).

The conclusions made through literature studies are based on my interpretation of the written material. This interpretation is sensitive to e.g. the educational background and experiences of the reader, linguistic skills and the reader’s interest at a particular point in time. The relevant parts of the publications were therefore re-read in the end of the PhD process because my frame of reference had changed after reading all the publications. Because of this sensitivity of the interpretation a lot of quotes are used in the thesis as a form of documentation of the interpretation, which should enable the reader of the thesis to form his or her own opinion about the interpretation of the quotes. The texts are supplied with references when quotes are not used for documentation.

The profession analysis chapter is based on a literature study and an interview with a best practice example of an integrated and multi-professional approach to building design. The interview was transcribed and analysed via a qualitative text-analysis with great similarity to the methodical approach applied in the literature studies, where the recurring issues and quotes relating to the methodical approach applied by Arup Associates were filtered and presented in chapter 7 with references to the transcribed interview. The transcribed interview is confidential. It is therefore only made available to the assessment committee of this PhD project in Enclosure B along with a CD with the audio file and the files received from Arup Associates after the interview for verification purposes.

The interview cannot be repeated for verification because the interview was made at a certain point in time of the interviewees' lives and the interviewees did not know the questions in advance, which means that if the interview was repeated with the same questions the interviewees might respond differently. Differences in responses could be due to the fact that the interviewees have reached a new sense of understanding as a result of time, new experiences since the interview and via the questions asked in the interview. The transcribed interview and the main conclusions were, therefore, sent to the interviewees for verification with positive confirmation.

Demonstration and application
The state of the art study of the tools available to designers of Danish environmentally sustainable buildings is primarily based on a demonstration of the LT-method by one of its developers (Professor Nick Baker, Dept. of Architecture, Cambridge University, UK), a literature study of the LT-method [Baker and Steemers 2000], the interview with two designers from Arup Associates (chapter 7.4) and personal application of the programmes.

The demonstration by Professor Nick Baker was recorded, which means that the audio file can be made available upon request, while the descriptions based on personal applications reflect my personal interaction with the tools which cannot be verified, and which is subject to change over time. The descriptions based on personal application are, however, supported by references to web based or programme based tool descriptions, which were written by the developers of the programmes.

Sensitivity analysis
The qualitative sensitivity analysis performed in chapter 9 can be verified if the calculations are repeated in the exact same way, which means that the calculations have to apply the same reference buildings, the same input parameters, the same ranges distribution functions for the input parameters.
The application of SimLab would also have to be repeated in exactly the same way, which means that the sample file generated by the programme would need to be exactly the same as the one applied in this project. If the sample file is not exactly the same but the input parameters are, then the results are subject to change slightly. The Morris Method applied for the Monte Carlo simulation should, however, be fairly precise in spite of changes in the sample file, which means that the analysis can be verified with conclusions that are very close to the ones achieved in this study.
The purpose of the sensitivity analysis was not to develop a stationary design strategy; it was merely to test how sensitivity analyses perform as a methodical approach to design strategy development. The conclusions made about the strengths and weaknesses can be verified through a similar experiment or by reading the SimLab manual, which describes the abilities of the Morris Method, or one of the references made to research publications about sensitivity analyses in the introduction to chapter 9.

5.4 Interview

Methodical approach applied in interview
The methodical approach applied in the interview is based on the writings of Professor Steinar Kvale at Aarhus University (Denmark) [Kvale 1997] in which an approach to qualitative research interviews is described.
The approach is divided into seven stages;

1. The Theme
2. Design of interview
3. Interview
4. Transcription of interviews

5. Analysis
6. Verification
7. Reporting

[Kvale 1997:Part 3]

The Theme

The purpose of the interview was to gain an understanding of the methodical approach to integrated and environmental design applied by Arup Associates.

The reason for this interest in Arup Associates' approach is that the practice has been involved in a lot of the environmental and sustainable projects reported in publications within the last decade. The practice is, furthermore, interesting in relation to the integrated design process and multi-disciplinary design teams;

> 'Arup associates integrates architecture, structural engineering, environmental engineering, cost consultancy, urban design and product design within one studio.
> Every project expresses the multi-disciplinary philosophy that is at the heart of the practice' [www.arup.com/associates/AA_Intro.html 2007]

Design of interview

A semi-structured interview[5] with narrative and focused elements was selected for the interview, and the intention was to also use discursive elements in the end of the interview depending on how the interview evolved.

An interview guide[6] was developed for the interview in which a series of questions were formulated before the interview with support questions if it was difficult to keep the conversation going, but the general approach to the interview was to get the interviewees to talk as much as possible and as freely as possible.

The interview guide was therefore not sent to the interviewees beforehand, as this could unintentionally cause the interviewees to answer the questions in relation to the issues reflected in the support questions instead of the issues they think should be associated with the questions. The decision not to provide the interviewees with the interview guide was therefore a conscious decision in an attempt of ensuring that the interviewees would speak freely.

Instead of the interview guide the purpose of the interview was discussed via email correspondence before the interview with respect to what I was interested in learning more about; 'the Arup approach to environmental architecture (or multi-disciplinary design) and a project you think presents this approach successfully' [quote from the first I sent email to Peter Warburton]. This initial email correspondence also touched upon the subject of the different types of sustainability and how differences in sustainable profiles of buildings were a result of the clients and the brief involved in projects. In the email correspondence preceding the interview Michael Beaven referred to information available on Arup Associate's webpage which is why I decided to start the interview with two quotes from the webpage that I thought reflected the aims of the company and the approach taken to the design process.

Changes were made to the formulation of the questions in the interview guide during the interview in response to what the interviews were saying, and most of the questions were answered implicitly and clarifying questions were formulated during the interview in response to the answers made by the interviewees.

The theoretical presumptions behind the interview were that the interviewees are experts in their field and that their answers would be based on years of experiences with the design of environmental and integrated design. The interviewees were therefore expected to possess valuable knowledge about the methodical approach developed by Arup Associates and have an opinion about some of the issues relating to environmental and sustainable design. Statements made by the interviewees are therefore considered reliable.

Language was identified as a possible barrier of communication with respect to differences in technical language and the fact that the interview was conducted in English. The interview was therefore recorded and the transcript and the conclusions were sent to the interviewees for verification of the conclusions of the interview as a way of eliminating possible misunderstandings.

Interview
The interview took place on February 20th 2006 at the offices of Arup Associates in London.

Analysis
The transcribed interview was analysed to uncover which themes were discussed by the interviewees in relation to the questions, and the themes of interest in relation to the integrated design approach and sustainable design were analysed for their content. The views presented in the interview were condensed and reported in chapter 7.4.

Verification
The transcribed interview (in Enclosure B) and chapter 7 were sent to the interviewees for commentary, as a way of verifying the conclusions made on the basis of the interview.
This process of verification can be a bit difficult because the interviewees have had time to reflect on the questions and answers in the interview which may have changed their perspectives on the matter. This turned out to not be a problem in connection in this particular interview.

Reporting
The main conclusions of the interview are presented in chapter 7 with references to the transcribed interview in Enclosure B. The audio file from the interview and the files received after the interview are available to the assessment committee on a CD. Enclosure B and the material on the CD contain confidential information and they are therefore only available at the discretion of the PhD judging committee.

5.5 My understanding of architecture

The following description of my understanding of architecture is the result of a study of publications about what architecture is and how it can be analysed [e.g. Ballantyne 2001:1-52 and Eiler Rasmussen 1989], as well as my educational background as an architecture candidate from the Department of Architecture at Aalborg University (Denmark)[7].

Usually a distinction is made between architecture and 'mere' building, where architecture can described as the relationship between building and culture:

> 'Buildings are solid objects, there is no doubt about that, but they are never in themselves architecture. Architecture is dependent on the observer's culture, and the ideas of that are brought to bear on the building.' [Ballantyne 2001:49]

In his commentary introduction to the anthropology entitled 'What is architecture?' Balantyne [Ballantyne 2001] argues that a distinction between architecture and mere building should not be made. It is, however, my experience that not all buildings provide an improved quality of life; sometimes a building just serves as a shelter from exterior conditions without adding to the user's quality of life – in fact it might even worsen the quality of life; e.g. if the building is very uncomfortable because of the indoor climate, if there is no daylight in the building or no windows one can look out of, if the dimensions of the space provoke a claustrophobic reaction or if the building attracts socially unstable families and thus create uncomfortable living conditions for an entire neighbourhood through the formation of ghettos.
It is therefore my opinion that we still need to distinguish between architecture and 'mere' building, where the label of architecture should only be given to buildings that improve the quality of life of its users. This quality of life is often culturally[8] dependant and architecture therefore needs to be evaluated in relation to the cultural context of the building, as well as the cultural background of the users and the designer(s) of the building.

The importance of synthesis and surprise

There are many different approaches to architecture depending on aesthetic preferences and the sensitivity or indifference to e.g. the architectural, cultural or climatic context.

As a student of architecture it has been my experience that great architecture is determined by whether the decisions made for the building cause a synthesis between e.g. the use of the building, the construction of the building, the light conditions and the materials inside the building, the indoor environment in the building etc., rather than by what the aesthetic preferences of the designer were. If a synthesis is reached that challenges what the users expected the building to be like it will inspire a sense of surprise or wonder in the user, which will ensure that he or she remembers visiting the building.

The importance of details

Someone once said 'beauty is in the detail' which corresponds with my personal experiences with perception of architecture. Detail does not in this case equal ornament, but merely that the architect has thought about every single detail in the building, e.g. the design of the corners in a window, the way the daylight enters a space or hits a wall, the placement of artificial light, the correspondence between the dimensions of the space and the materials in the space, the acoustic conditions inside the space and the structural elements of the space etc. Details can in other words be regarded as a way of ensuring synthesis in the architectural design.

One way of achieving this amazement is to always push the boundaries of technology, e.g. in relation to the slenderness of constructions, or by challenging the materials applied in the building or the shapes and angles of the walls that define spaces.

Comfort and functionality – architecture as art and architecture as a profession

With respect to comfort and functionality there are two types of architecture which need consideration; architecture as art and architecture as a profession, where architecture as art aims to provoke our habits and architecture as a profession aims to accommodate the habits of the user, whilst trying to improve and challenge these habits without alienating the inhabitant [Ballantyne 2001:39-41].

Architecture as art is not particularly interested in achieving a comfortable or a functional environment inside the building. Discomfort has, actually, been a design criterion in some examples of architecture as art (e.g. Peter Eisenman's Convention Centre in Columbus, Ohio (USA) which was designed to make people sea-sick and his 'House VI' which was designed to make people notice their habits by making the performance of ordinary habits impossible [Ballantyne 2001:14]).

Inhabitable architecture does not make sense to most people, but this does not take away from the fact that architecture as art achieves a lot of publicity and its designers gain a special status in architectural history because they inspire other architects to push the boundaries and think outside the box.

Comfort is one of the primary issues in this PhD project, and architecture as a profession is, therefore, the preferred approach to architecture in this particular project.

Context

The interest in environmentally sustainable architecture taken in the PhD project causes an interest in a contextual approach to architecture that considers both the climatic and cultural contexts of buildings.

The issue of climatic and cultural context has become increasingly important over the past decades where our means of transportation and where globalisation has made the world smaller in a metaphorical sense, which has enabled architects to do projects all over the world. Architects therefore more often tend work in regions that differ from their native, both climatically and culturally, which means that architects need to apply a methodical approach that enables them to gain an understanding of the climatic context they are working in.

Architecture and theories of science

The issue of the perception of architecture fits well within a phenomenological approach to science, the issue of comfort fits within both a phenomenological and an empirical-analytical approach to science and the issue of culture fits within a hermeneutic approach to science. This shows that different issues relating to architecture require different approaches to the theories of science. This becomes even more important when the issue of environmental sustainability is introduced to architecture, because it in itself embodies many different professional disciplines, such as biology, building engineering and planning, which traditionally belong to an empirical-analytical approach to science.

5.6 My understanding of the design process for creating architecture

The understanding of the design process for the creation of architecture which is applied in this PhD thesis relates to the Integrated Design Process (IDP) by Knudstrup [Knudstrup 2000, 2004], as this is part of the educational background that this PhD project builds on. (Please refer to chapter 6.3.2 of this thesis for more information about the IDP).
This understanding of the design process was furthermore solidified by the publications available about environmentally sustainable architecture that conclude a need for an approach which considers technical strategies and solutions early on in the design process in order to ensure solutions which live up to the aim of achieving environmentally sustainable architecture [e.g. Baker and Steemers 2000, www.iea-shc.org/task23/, Knudstrup 2000and 2004, and Owen Lewis 1999].

Distinction between process descriptions and design strategies
Initially the literature study of publications describing methodical approaches left me a bit puzzled with respect to what the different publications focused on; where some publications would contain (1) descriptions of phases, tasks, design principles, actors and issues involved in design processes and others (2) would focus on examples of buildings and description of the design strategies that went into the selection of the design principles applied the buildings, different approaches to sustainable architecture and issues and design principles associated with these approaches to sustainable architecture.
After a lot of consideration, I came to the realisation that the first type of descriptions could be classified as process descriptions and the latter type could be classified as design strategies.
This means that this project distinguishes between process descriptions, which describe the phases, tasks, design principles, actors and issues, and design strategies, which relate to the selection of design principles and issues in relation to a specific approach to sustainable architecture or a specific design project.

The distinction between process description and design strategy led to the realisation that it is the selected design strategy that determines which design principles are applied in a design project, and thus the approach taken to sustainability in the specific project. And that the understanding of the process and the importance of integration and inter-disciplinarity is fundamental to the realisation of the project specific design strategy.

This realisation might explain why the minority of publications in the field of sustainable architecture focus on process description and why the majority of publications in the field focus on design strategies.

The outset of this PhD project has been a study of both process descriptions and design strategies, where the study of the process has enabled a deeper understanding of what part of the design process enables a successful integration of environmental considerations, such as energy performance and comfort, in the architectural design process, and the study of design strategies has enabled an understanding and appreciation of the strategic differences found in the field of sustainable architecture, the relationship between design strategy and approach to sustainability, and an explanation as to why the theoretical design strategies found in publications rarely correspond with the strategies applied in design projects.

Structure of the design process
The design process consists of a series of phases which for time efficiency purposes should

succeed each other preferably in a linear manor. Each phase contains a series of iterations relating to the tasks which need solving in the different phases of the process.
These iterations also relate to the application of the design principles selected in the design strategy for the project and the analogue or digital tools available for solving the specific tasks.
The design strategy for a project is selected in the program phase of the process e.g. in the formulation of the design brief, in the analysis phase or in early in the sketching phase where the schematic design is developed (the phases marked with a dark grey background in the following table of the different phase descriptions available in publications).

Table 5.4: Summation of the different phase descriptions found in the State of the art 1: Methodical approaches, process descriptions (The phases marked with a dark grey background are the phases in which the design strategy is or should be decided depending on which phase description one applies).

<table>
<tr><th>Publications</th><th>Traditional Design Process, ECBCS IEA Task 23 2001</th><th>Integrated Design Process, ECBCS IEA Task 23 2001</th><th>Integrated Design Process (IDP), Knudstrup 2000 and 2004</th><th>A Green Vitruvius, Owen Lewis 1999</th></tr>
<tr><td rowspan="14">Phases</td><td rowspan="2">Investigation of basics</td><td rowspan="2">Basics</td><td>Problem / Idea</td><td>Inception</td></tr>
<tr><td>Analysis</td><td>Preliminary Studies</td></tr>
<tr><td>Schematic Design</td><td>Pre-design</td><td rowspan="2">Sketching</td><td>Sketch Studies</td></tr>
<tr><td rowspan="2">Design Proposal</td><td rowspan="2">Concept Development</td><td rowspan="2">Pre-project</td></tr>
<tr><td rowspan="2">Synthesis</td></tr>
<tr><td>Preliminary Design</td><td>Design Development</td><td rowspan="2">Basic Project</td></tr>
<tr><td>Building Documents</td><td rowspan="2">Building documents</td><td>Presentation</td></tr>
<tr><td>Mass Records and Advertising</td><td rowspan="7"></td><td>Execution of project</td></tr>
<tr><td>Negotiation Contracting</td><td>Negotiation Contracting</td><td>Tender Procedure</td></tr>
<tr><td>Construction Management</td><td rowspan="3">Execution and commissioning</td><td rowspan="2">Construction Supervision</td></tr>
<tr><td>Construction Supervision</td></tr>
<tr><td>Building Documentation</td><td>Acceptance</td></tr>
<tr><td>Supervision after 1 year of operation</td><td rowspan="2">Operation</td><td>Defects Period</td></tr>
<tr><td></td><td>Maintenance and Refurbishments</td></tr>
</table>

Design parameters
As a result of the inter-disciplinary educational background of this PhD project a parametric approach to design was selected as the way of working in the interface between the architectural and building engineering professions. This parametric approach was developed as 'the Integrated Design Process (IDP)' by associate professor Mary-Ann Knudstrup at the Department of Architecture and Design at Aalborg University (Denmark) [Knudstrup 2000 and 2004]

The analogue or digital tools available for solving the tasks specified in a selected process description determine a set of possible calculation parameters which are basically the variables inserted in the calculation conducted by the tool.
If one has a parametric approach to design these calculation parameters are regarded as having a relation to a set of variable design parameters (e.g. the area, orientation and dimensions of windows, the dimensions of a space, the colour of a material etc.), which are determined by the design principles selected in the design strategy and the calculation parameters available in the tool.

This means that the design process in a parametric approach is regarded as a series of variable design parameters which can take different quantitative and qualitative values for different design solutions, and the possible space of design solutions is defined by the design parameters and the range selected for these parameters in the specific project.
In some cases one might not want a large range for a specific design parameter, e.g. if the window

area in the building needs to be fixed in a different direction in relation to a view or the height of an adjacent building, or if the number of stories in the building is limited by municipal plans for the specific area.

---

[1] The discussion of the three terms is based on www.reference.com/search?q=multidisciplinary 2007, which refers to: Newell, W.H. (2001). A theory of interdisciplinary studies. *Issues in Integrative Studies*, 19, 1-25, available at: http://www.units.muohio.edu/aisorg/pubs/issues1/restricted/042/paper.pdf 2007.

[2] The first students started in September 1997.

[3] Comparison of paradigm characteristics of empirical-analytical theory of science, Interpretation knowledge and Critical theory by Andersen [Andersen 2000:190]

	Empirical-analytical theory of science	Interpretation of knowledge	Critical theory
Scientific ideal	Testing of empirical observation Objectification Value-neutral	Hermeneutic interpretation Subjectivization Value-neutral	Interpretation and empirical testing Subjectivization and Objectification Critical (to value-freedom)
Reality frame	System-mechanisms Laws of causation	Lifeworld What if motives Typifications Legitimations	Relation between system and lifeworld

[4] According to the Bretannica Online Dicrionary epistemology can be explained as: 'the study of the nature, origin, and limits of human knowledge. The term is derived from the Greek *episteme* ("knowledge") and *logos* ("reason"), and accordingly the field is sometimes referred to as the theory of knowledge. Epistemology has a long history, beginning with the ancient Greeks and continuing to the present. Along with metaphysics, logic, and ethics, it is one of the four main branches of philosophy, and nearly every great philosopher has contributed to it.' [http://www.britannica.com/eb/article-9106052/epistemology 2007]

[5] Description of three different types of interviews by Jansen and Johnsen [translated from Jansen and Johnsen 2000:11-13]:

The semi-structured interview	The narrative interview	The discursive interview
The interviewer prepares some themes before the interview that he or she wants the interview to concern. The questions are often listed in an interview guide that contains the main questions and a suggestion for the order of the questions. The formulation of the questions is not that important because the purpose of the questions is to get the interviewees to talk about the themes identified beforehand. The order of the questions is usually also unimportant and no attempt is made to fit the answers into predefined categories.	The interviewer tries to get the interviewee to tell a story about an event the interviewee has participated in as coherently as possible. The interview does not follow a classic question – answer structure. The interview has no time limit the story is important and the interviewer does not disrupt the story by asking questions. A good narrative starts by setting the scene e.g. the time, place and social context that the story takes place in. After this it describes the sequence of events leading to the plot of the story. Aside from this, stories also usually contain assignment of roles (villain, hero, victims etc.) direct and indirect value statements, perceptions of causes. The purpose of a narrative interview is to find out how the interviewee sees the world and how he or she interprets the world.	The interviewee is regarded as a theorist and an expert on himself or herself, his or her own story and character. Interviews often contain discursive elements because most well educated people tend to apply theoretical terms when they describe themselves and their situation. The interview usually discusses what the interviewee thinks about specific phenomena that he or she is an expert on.

[6] The interview guide is available to the assessment committee in Enclosure B.

[7] The educational background for this PhD project is a master from the architecture specialty from the Department of Architecture and Design at Aalborg University. A theoretical and a practical understanding of architecture were achieved through courses and lectures about architecture and building engineering, study trips and design projects.

[8] The understanding of the term 'culture' in this PhD thesis relates to the anthropological application of the term, where culture is determined by a study of the social values, beliefs and rules of conduct that defines the acceptable behaviour in a society.[www.reference.com 2007]

PART 1: Methodical approaches to sustainable architecture

The work title of this PhD project has been 'Methoical Approaches to Environmentally Sustainable Architecture'. The interest in methodical approaches is, as mentioned in chapter 4, motivated by exposure to the vast amount of publications available about Self-sufficient, Ecological, Green, Sustainable, Bioclimatic, Environmental, Low energy, and Solar Architecture. The fact that the publications address many of the same issues with, what appears to be, very different architectural results served as a motivating factor to the part of the thesis. The first part of this thesis therefore presents analyses of existing methodical approaches to sustainable architecture and the professional differences behind the methodical approaches applied by architects and engineers.

The analysis of existing approaches is presented in chapter 6 entitled 'State of the art 1: Methodical approaches to environmentally sustainable architecture' which contains presentations and discussions of 1) the terminology associated with sustainable architecture and the different approaches to sustainable architecture reflected in this terminology, 2) the visibility of approaches to sustainable architecture and 3) the methodical process descriptions available in existing publications.

The analysis of the professional differences behind the methodical approaches applied by architects and engineers is presented in chapter 7 entitled 'Profession Analysis' which contains a discussion of 1) how designers think 2) the professional differences between architects and engineering designers, 3) the development of the marketplace and 4) integrated design in practice.

This part of the thesis addresses the following subsidiary questions:

1. Which methodical approaches have been developed for sustainable architecture and what is the difference between these methodical approaches?
2. What is the difference between the conventional approach to architectural design and the approaches to the design of sustainable architecture?
3. Is there a difference between how architects and engineers work? And does this influence the development of sustainable architecture and tools for design strategy development?
4. Arup Associates is one of the international engineering companies who have worked with a lot of the environmentally sustainable buildings reported in publications. What is significant about their approach to environmentally sustainable building design? And how does this relate to the methodical process descriptions found in publications?

Questions 1 and 2 are addressed in chapter 6 and questions 3 and 4 are addressed in chapter 7.

6 State of the Art 1: Methodical approaches to sustainable architecture

Introduction
This chapter entitled 'State of the Art 1: Methodical approaches to sustainable architecture' contains a presentation of the methodical approaches to sustainable architecture available in publications.

Within the last decade or so the number of publications and research projects about sustainable architecture (e.g. self-sufficient, ecological, green, bioclimatic, environmental, low-energy and solar architecture) has escalated to enormous proportions. The publications referred to in this PhD thesis are therefore the publications available in Denmark through libraries and online bookshops.
The publications about sustainable architecture found via literature search has been through a screening process and the publications found to be relevant to this PhD project were the ones describing the methodical approaches applied by primarily professional practitioners and the historical development of the terminology associated with sustainable architecture.

This chapter will discuss 1) the terminology of and approaches to sustainable architecture 2) the visibility of approaches to sustainable architecture and 3) methodical process descriptions

Terminology and approaches to sustainable architecture
The purpose of the study of the terminology and the approaches to sustainable architecture has been to gain a better understanding of the different terms presented by publications dealing with approaches to sustainable architecture. Another purpose of this part of the state of the art has been to determine the terminology in relation to the formulation of the scope of the project.

Through a study of the publications about sustainable architecture I came to the conclusion that the terms applied in the terminology of sustainable architecture in reality are distinguishable by the design strategies associated with the respective terms. This has led me to conclude that these design strategies are in fact what defines the different approaches to sustainable architecture.

The publications of interest to this part of the chapter primarily deal with aims or issues of motivation, definitions of the terms applied in the terminology and the design strategies described by the publications applying the respective terms in the terminology.

Methodical process descriptions
The purpose of the study of the methodical process descriptions has been to gain a better understanding of the design process applied for environmentally sustainable buildings, as well as, to uncover which actors and tasks are involved in the creation of environmentally sustainable architecture.

The publications of interest to this part of the chapter are publications containing methodical process descriptions which focus on how to structure, and in some cases also, how to manage the design process in relation to an iterative design process. These publications therefore primarily focus on describing the phases of the process, the tasks involved in the phases and in some cases the actors involved in solving the tasks.

6.1 Terminology and theoretical design strategies

There are many different terms associated with 'environmentally sustainable' buildings. This can be quite confusing at first glance because the terms seem to be referring to the same thing.
Upon a closer study of definitions associated with the terms, one finds that the definitions are motivated by concerns for many of the same issues. Some terms do, however, focus more on specific issues than others, and the issues seem to be treated at different conceptual levels of scale (e.g. in relation to the site, building envelope or building fabric).

In the publication 'Understanding Sustainable Architecture'[1] Williamson, Radford and Bennetts (2003) argue that the practice of a discipline, concepts and strategies develop as a result of small shifts, fundamental transformations or replacement of issues affected by institutional settings (e.g. due to political events, technological development, economic development etc.). This argument can be used explain why many of the terms[2] seem to relate to the same issues[3]:

Table 6.1: the issues and concepts associated with different terms/labels [Based on Williamson, Radford and Bennetts 2003:1]

Terms/labels	*Issues/concept*
Green, ecological and environmental	'are labels that embody the notion that the design of buildings should fundamentally take account of their relationship with and the impact on the natural environment'
Low energy, solar and passive	'are used to denote approaches to designing concerned with the concept of reducing reliance on fossil fuels to operate a building'

The question is whether or not the definitions of the terms contain differences which separate them from each other in spite the fact that they target the same issues:

> 'In general, the labels refer to a particular strategy employed to achieve the conceptual outcome, and the strategies that occur in a discourse must be understood as instances from a range of theoretical possibilities. The promotion of a restricted range of strategic options regulates the discourse and the ways of practising the discipline. An examination of sustainable design discourse and practice will reveal something of this regulation.[4]' [Williamson, Radford and Bennetts 2003:1]

In other words; what distinguishes the terms are the strategy they employ to achieve the issues and how these strategies are applied by practitioners. With this in mind the following terms[5] were studied for their definitions, issues of focus and design strategies:

1. *Self-sufficient*
2. *Ecological*
3. *Green*
4. *Sustainable*
5. *Bioclimatic*
6. *Environmental*
7. *Low energy, and*
8. *Solar*

The following descriptions of the terms will include definitions by their main advocates, design strategies and design principles applied in relation to the term. The publications associated with the terms in the following descriptions are publications that apply the terms in their title or inside the publications.

6.1.1 Self-sufficient architecture

Most of the areas we focus on today in relation to sustainable architecture were initiated in the late 1960s and early 70s [Steele 2005:7, Williamson, Radford and Bennetts 2003:1] where the environmental impact of the industries became apparent through pollution and through the energy crises in 1973 and 1979. But one might argue that sustainable architecture was a focus long before then in the form of Self-sufficient buildings devised by Sir Richard Buckminster Fuller[6] and Paolo Soleri[7].

Examples of self-sufficient building projects

Buckminster Fuller

Fuller had a socio-cultural approach to self-sufficiency motivated by the notion, that everyone should have access to food and shelter. This idea of social responsibility to not just his fellow country men but to the entire world resulted in the idea of self-sufficiency in order to design housing which could be placed anywhere in the world.

> 'A home, like a person, must be as completely as possible be independent and self-supporting, have its own character, dignity and beauty or harmony.' [Krausse and Lichtenstein 1999:127]

The self-sufficient buildings were derived from the notion of getting 'more for less', and Fuller saw quantity production of light weight structures as a way of achieving cheap housing for easy distribution. This shows that Fuller was influenced by the technological development of his time, which is also apparent in his regard of the dwelling as a machine:

> 'The dwelling, after all, should be a machine for the efficient and comfortable conduct of family life under shelter.' [Krausse and Lichtenstein 1999:135]

The products of Fuller's ideas of the self-sufficient dwelling were the Dymaxion House and his Geodesic Domes.

The drawing for the Dymaxion house was published in 1929 and a prototype of the building completed in 1946 in Wichita, Kansas.
The house was constructed in Aluminium in an abandoned military plane factory. Aluminium was selected as the construction material due to its low maintenance and low density, which meant that the entire house weighted approximately the same as a car after assembly (approx. 2.7 tonnes). The parts were transported to the site in parts and assembled on site by inexperienced workers in two days, and the expenses of the prototype was approximately that of an expensive car at the time (in America).
The house had two stories; one for living and one for observation, and it was equipped with climate control which distributed heat evenly throughout the house.
The artificial light in the house originated from only one light bulb, which through mirrors and prisms supplied the entire house with artificial light. Due to its circular shape the house had really good daylight conditions, and a wind cowl was integrated in the architectural expression of the building, which enabled a naturally ventilated building.
After completion the company behind the prototype received about 3500 inquiries about the house, but Fuller believed that the house was not ready for mass production. The Wichita house is, thus, the only example of the Dymaxion house.
After the termination of the project the house was sold to a board member for US$1 who reassembled the house on his land. The house was deconstructed in 1992 to be reassembled in 'The Henry Ford Museum and Greenfield Village Museum' in Dearborn.

The idea behind the Geodesic dome is similar to that of the Dymaxion house. The project was initially called the Garden of Eden and consisted of two components; a trailer-sized living unit which could be transported and unfolded upon arrival and a dome which would provide shelter for the living unit. The dome was collapsible and, thus, transportable.
Approximately 350.000 domes were erected in the period of 1954 to 1983. The first design was erected by Fuller and his students at a summer workshop in 1948 at Blackmountain College. In the experimental stages of the project the domes were constructed with a lot of different materials (e.g. cardboard, magnesium, plywood, aluminium plates, inflatable plastic etc.).
One of Fuller's domes was the U.S. pavilion erected for the 1967 world exhibition in Montreal Canada constructed with a steel structure and acrylic cells. The pavilion was damaged in 1976 by a fire which only the steel construction survived. In 1990 the building was reopened as the Biosphere Environmental Museum. The domes were also erected as residential buildings, one of which was Fuller's home.

Soleri
Another influential person dealing with self-sufficiency was Paolo Soleri. Soleri was interested in making the desert habitable, due to a concern for extreme growth in population (inspired by Frank Lloyd Wright). Soleri emphasized low-tech solutions for self-sufficient urban communities in arid or semi-arid regions. Soleri's 'Omega Seed Hypothesis', in which he referred to the earth as Biosphere 1, can be ascribed the value of a great instigator of some of the larger self-sufficient projects of the past 15 years, such as the 'Biosphere II' project by Edward P. Bass in 1992. [Steele 2005:135-141] and the design of the Eden project in Cornwall (UK) by Nicholas Grimshaw from 2001, which is also good example of a project that shows close relations to Fuller's Garden of Eden project.

Current application
Today self-sufficient buildings are usually built in ecological communities by self-builders. Other types of self-sufficient buildings are the energy plus buildings, which produce energy and are self-sufficient with respect to e.g. the energy consumption in the building. The energy plus buildings are, however, not necessarily self-sufficient with respect to e.g. cleaning and collecting water or the utilisation of onsite materials for the construction of the building.

Design strategies
The use of the term self-sufficient buildings has decreased during the last decades, and this project has, thus, not come across publications describing design strategies for self-sufficient buildings. The closest one comes to design strategies for self-sufficient buildings are those applied by self-builders in ecological communities, which is described in the next paragraph.

6.1.2 Ecological Architecture
Ecological Architecture is usually associated with self-builders and self-sufficient buildings. The term has associations to the hippie culture of the late 1960's and 1970s and people living in tune with nature. Ecological buildings are rarely taken seriously by Danish architects and architecturally designed ecological projects are therefore rare in Denmark.

Definitions
Bech-Danielsen
In 1998 Claus Bech-Danielsen[8] published his PhD thesis entitled 'Urban ecology and aesthetics[9]', since then he has written a number of publications about urban ecology and ecological architecture. One of these is "Ecological Reflections in Architecture" from 2005 in which Bech-Danielsen describes different approaches to ecological architecture.

Bech-Danielsen addresses a core issue in Danish ecological architecture; the relationship between the ecological achievements of grass root movements and architects. He describes how the grass root movements in Scandinavia 'base their dwellings on environmental considerations and urban ecological commitment', while architects work with an ecological construction which 'makes its appearance in the from of choice materials and with an exiting design'. [Bech-Danielsen 2005:11]

The differences in the environmental commitment are quite eloquently described as:

> 'it can be said that the architects are concocting an image of ecology and that their work with the environment accordingly plays itself out on the façade – on 'the surface'. (…) the architects can conversely be criticized for creating form without meaning. The grassroots create meaning, but are missing the words. The architects have the words, but are missing the meaning.' [Bech-Danielsen 2005:12]

This quote is very interesting because it describes the key dilemma of ecological architecture in Denmark.

The publication discusses three ways of navigating the world; The Place, The Space and The Interface. The different ways of navigation refer to three views of reality; The Space refers to 'the senses' domain', The Place refers to 'the intellect's domain and The Interface refers to 'the creative domain'. [Bech-Danielsen 2005:Ch. 3]

Architecture created in The Place's view of reality is described as:

> 'At the place, the designer orients himself primarily with the aid of his senses and he has no insight into any elevated notion through the agency of which he can make an imprint on the surroundings. (…) This articulates itself in site-specific cities and buildings that come into being on the basis of a sympathetic understanding about specific conditions at a certain locality. When this is the case, the area's character and the place's salient features – its *genius loci* – can be perceived in an architecture that differs from one place to another' [Bech-Danielsen 2005:30].

The architecture created in The Space's view of reality is described as:

> 'a form of architecture is created where cities and buildings are planned as expressions of ideal conceptions rather than being conceived on the basis of impressions of specific localities. Inside the space, all places are held to be equal and the architecture is created against the backdrop of a uniform set of rules' [Bech-Danielsen 2005:34].

The architecture of The Interface's view of reality is described as:

> 'It is neither at the expense of the place or the space that the interface supervenes. It arises as a direct outcome of their interplay. The architect does not articulate an idealized conception at the expense of the place, and the empathy with the place's character – the genius loci – does not transpire at the expense of the space's perspectival overview. At the interface, the universal idea of the space merges with the primordial quality of the place, and what arises is an image that is not an invention of the intellect without any roots' [Bech-Danielsen 2005:40-41].

The last quote indicates that the author clearly believes that the design of ecological architecture should happen in The Interface in an approach that applies the views of both The Place and The Space.

Table 6.2: The characteristics of the three views [Bech-Danielsen 2005:41]

THE PLACE	*THE SPACE*	*THE INTERFACE*
The sense's domain	The intellects domain	Creativity's domain
Holistic	Dualistic	Contextual
Distance-less	Distance-engendering	Building up and breaking down of distance
Concrete	Abstract	Coupling between concrete and abstract
People have no creative powers	The artist is the free-handed creator	The individual is his/her own Master
Non-intentional	Intentional	Intentionally non-intentional
Icon – image is reality	Representation – image reproduces reality	Creation – reality is created in the image
Topological order	Geometric order	The encounter between topological and geometric order
'Primitive' culture	Linguistic culture	Image-oriented culture

Based on this description of the three views of reality and the quote about the differences in the environmental commitment ([Bech-Danielsen 2005:12]) it is my conclusion that the approach to ecological architecture applied by self-builders corresponds to the 'The Place' view of reality, while the approach applied by architects corresponds with the 'The Space' view of reality.

Steele
The following quotation is from a book entitled 'Ecological Architecture – a critical history' by James Steele[10] [Steele 2005]. In the book Steele describes ecological architecture as architecture that responds to the issues of pollution, toxic waste and population growth:

> "Ecology itself is easy enough to understand, as it is the science of the relationship between living organisms and their surroundings, but things get murky when the term is applied to building. Nevertheless it implies a connection to the global environmental movement that began to coalesce in the late 1960s as part of the social upheavals associated with that period. In the United States the focus began to shift away from social injustice *toward pollution, toxic waste and population growth*." [Steele 2005:7]

Through his account for the historical development of ecological projects in the USA he argues that the development of ecological architecture has occurred through a web of inter-relationships between architects, and he identifies three constant determinants of an ecological aesthetics; tradition (learning from vernacular architecture and rituals related to nature), technology (technological development – intertwined with tradition) and urbanism (urban development, positive and negative effects of migration to cities). [Steele 2005:6-7]

Examples of ecological architecture in Denmark
There are several ecological communities scattered all over Denmark e.g. in Hundested, Hjortshøj, Torup and Feldballe. These ecological communities are funded by self-builders in rural areas of Denmark, where the houses are built by the residents. The fact that these eco-communities are built in rural areas correspond well with the fact that most of the inhabitants of the communities wish to lead a lifestyle different from the lifestyle associated with urban areas, but it is also a result of the fact that the Danish Planning Law (Planloven) enables Danish municipalities to demand that all buildings in urban areas connect to e.g. the public district heating system and district power plants. This removes the incentive of creating self-sufficient ecological homes in urban areas because of the expenses associated with the connection duty to the public heat and power plants.
Of the eco-community projects in Denmark one has achieved a lot of public exposure in the Danish media; the 'Friland' project in Feldballe.

Friland
'Friland' was founded in 1992 by a group of producers of ecological products (primarily food stuffs), who were looking for a sales outlet of their ecological products. In 2002 a community of self-builders was officially founded at Friland, with the aim of building low-cost homes which were to be unencumbered, waste free and built from natural materials [www.friland.dk/,www.dr.dk/DR2/Friland/ 2007].
14 houses have been completed of which one is a communal house and one is the result of a summer workshop for approximately 400 European architectural students in 2003[www.dr.dk/DR2/Friland/ 2007].

The development of the 'Friland' community was covered by a national TV station (DR2) which broadcasts educational programmes. The purpose of the 'Friland' programmes was to inspire ecological awareness in Denmark. The project has facilitated an interesting debate about ecological building materials vs. traditional building materials, and the project has resulted in a lot of debate in the architectural community (as indicated by Bech-Danielsen) and the aesthetic judgement made by architects has not been positive. This negative attitude in the Danish architectural communities can be explained by the fact that because the projects in most cases are self-build projects they do not necessarily live up to the norms of architectural quality. This does not mean that these projects do not contain other qualities such as selection of local and natural materials, and social sustainability due to low prices and a communal spirit.

The materials used in the buildings vary a lot from building to building; some of the designers of the buildings have chosen a very literal approach to the material selection, where they only

use natural materials (e.g. straw bale and clay), while others combine the natural materials with recycled materials (e.g. brick and steel). [www.dr.dk/DR2/Friland/ 2007]. The designers of the buildings combine the selection of natural materials with rules of thumb about passive and active solar heat gains, as well as local heat sources such as straw-bale or wood. The buildings reflect their creator's way of life which some might argue is not easily transferred to the lifestyle of the majority of the Danish population.
More information about the project is available (primarily in Danish) at www.dr.dk/DR2/Friland/

Design strategies
The 'Friland' webpage contains guidelines for self-builders on how to apply different natural materials for constructions, as well as, on how to select windows, heating etc. The webpage primarily focuses on the utilisation of natural materials and not so much on energy and fire requirements from the Danish building regulations, which are instead embedded in the descriptions of construction materials and the building documentation process.

There are furthermore a number of self-build books about ecological building e.g. how to design eco-homes (e.g. Roaf 2003). These books do, however, not focus on methodical approaches to the design of architectural projects; instead they contain very detailed and specific information about how to build e.g. a straw-bale single family house in a specific climatic context.

6.1.3 Green Architecture
The term green architecture seems closely related to the image of nature as being green, it is however, also closely related to a political agenda, as described by Steele in the following definition.

Definitions
Steele
Steele describes how the term green architecture is closely associated with political organisations and political parties (leftwing) and that the term is closely related to ecological architecture as it is concerned with the human impact on ecosystems and the materials applied in buildings;

> 'the term 'green' (…) can be traced back to the Grüne Aktion Zukunft (Green Action Campaign for the Future), and the Grüne Listen (Green List), which was used to identify political candidates with environmental sensibilities in West Germany in the 1970s, primarily in their opposition to nuclear power stations. In France, meanwhile, a Green Party was established in 1984, described by the press at the time as being 'in the front line of ecological movement'. Greenpeace, the international organisation that aggressively pursues issues related to environmental conservation and protection, was founded in Vancouver in 1971.' [Steele 2005:8]

Wines
In the book 'Green Architecture' James Wines[11] uses the terms 'green', 'ecological', 'environmental' and 'sustainable' interchangeably, but this quotation from the book cover indicates that he does distinguish between the terms, and that the main issues addressed by ecological architecture focus on technological solutions and a reconciliation between man and nature:

> 'What makes a "green" house? Are ecological materials and solar panels on roof tops the only signs of an environmental architecture? Or were the designs of Antoni Gaudi and Frank Lloyd Wright even "greener" than the buildings of most contemporary architects, whose energy-efficient houses do not differ visibly from traditional modernist architecture? In his book, James Wines discusses the various – and often irreconcilable – concepts of ecological architecture, and pleads for a design that not only calls for technological solutions but also longs to reconcile man and nature by aesthetic means' [Wines 2000:cover]

The projects presented in Wines's book all display a visual relationship with nature either via vegetation on the roof or facades, through the application of reused materials or materials found in nature, or through 'naturally' inspired building shapes.
Seen in this scope green architecture can be concluded to have a close correlation with ecological architecture – in fact it seems to be the image 'concocted by architects' that Bech-Danielsen refers to in 'Ecological Reflections in Architecture'.

Architecture.about.com
The following quotation found on architecture.about.com also identifies a green architecture as the link between architecture and ecology:

> 'Green Architecture is a term used to describe economical, energy-saving, environmentally-friendly, sustainable development. These resources explore the relationship between architecture and ecology, and show how you can use concepts of green design in your own home.' [http://architecture.about.com/od/greenarchitecture/Ecology_and_Green_Architecture.htm February 2007]

Edwards
Another take on green buildings is presented by Brian Edwards[12] in the book 'Green Buildings Pay' from 2003. Here Edwards presents an illustration, which indicates that green design is a result of a relationship between energy, ecology and environment:

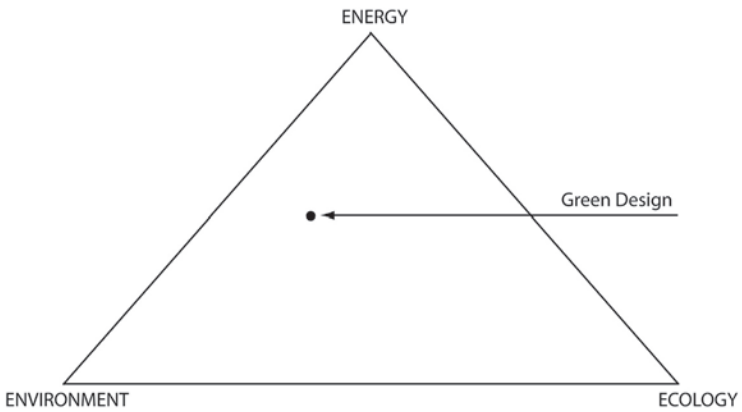


Illustration 45.1: Green design is a result of the relationship between energy, ecology and environment [reproduction of Edwards 2003:10]

Edwards argues that:

> 'Green design is not a matter of addressing the environmental problems society faces as a bolt-on addition to existing practice, but of evolving design from the starting point of these three perspectives. (…) Within the triangle formed by Energy, Environment and Ecology, green design can take its precise position depending upon local circumstance.' [Edwards 2003:9]

Discrepancies between definitions
There are large discrepancies between the architectural expression of the projects presented by Edwards and the projects presented by Wines and, thus, probably also in the strategies applied in the projects.
While all the projects presented by Wines have a green element integrated in the architectural expression the projects presented by Edwards hardly have any visual relations to nature, which makes me question:

- Whether either Wines or Edwards has chosen the wrong title for his publication?
- Whether they just represent different ends of a spectrum?
- Or whether the publications present two very different approaches which coincidentally refer to the same term (i.e. Green)?

The definition of green architecture in the publication entitled ‘A Green Vitruvius- principles and practice of sustainable architectural design’ by Owen Lewis [Owen Lewis 1999] might help answer this;

> ‘Environmentally friendly, environmentally conscious, energy conscious, sustainable, greener of simply green architecture? Identifying our subject was not straightforward. There is no internationally-agreed definition for green architecture. This book offers advice in the areas of energy and water inputs, materials, indoor air quality and wastes.’ [Owen Lewis 1999: foreword]

This quote indicates that the differences in Wines’ and Edwards’ understanding of green architecture might be due to the fact that there is no ‘internationally-agreed’ definition available.

Design strategies

Owen Lewis (1999)

The publication ‘A Green Vitruvius- principles and practice of sustainable architectural design’ was co-authored by a number of people involved in a project within the Thermie programme. The editor of the publication was J. Owen Lewis and the major contributors were: the Energy Research Group at the University College Dublin, The Architects’ Council of Europe, Softtech Turin and the Finnish Association of Architects Helsinki.

The publication contains descriptions of process, issues, strategies, elements and evaluation. The described strategies relate to different scales; from urban neighbourhood scale to finishes, and services, equipment and controls:

Table 6.3: Different strategies for different scales [Owen Lewis 1999:47-94]

Scale	*Strategies*
Urban and neighbourhood scale	Microclimate, Land use, Density, Transportation, Green space, Water and waste, Energy
Site selection and analysis	
Site planning	Microclimate, Density, Transportation, Green space, Water and waste, Energy
Building form	
Envelope	Opaque/solid elements, Translucent elements, Transparent elements, Energy production elements, Sunspaces, Atria
Finishes	Building energy performance, Indoor air quality
Services, equipment and controls	Heating, Cooling, Ventilation, Lighting
Renovation	To retrofit or not?, Building envelope, Hazards, Construction and completion’

Besides describing strategies for each of these issues the publication describes the following green strategies for the different stages of the project:

Table 6.4: Strategies applied at different stages of the project [Owen Lewis 1999:8]

Inception	Inception	• Briefing: identify green design as an issue to be considered • Agree environmental performance targets for the building • Prefer brownfield to greenfield sites
Design	Preliminary studies	• Analyse sites for sunlight, shelter and available shading • Research the building type and analyse good practice examples • Consider what is achievable given the cost constraints
	Sketch studies	• Site layout: use passive solar strategies, including daylight • Provide solar access to residential living spaces • Use thermal mass to dampen the temperature fluctuations • Maximise daylight penetration using plan and section • Consider water supply and waste handling methods • Use locally produced materials • Make iterative studies of design concepts and assess performance
	Pre-project	• Consider room heights for heating, cooling and daylighting • Consider thermal mass for building use pattern: intermittent or continuous • Optimise proportion and distribution of external envelope openings with heating and lighting in mind • Specify design criteria for services • Calculate predicted building performances and assess against targets
	Basic project	• Finalise layout (plans, sections, elevations) for statutory approvals: implications for daylight/ventilation/passive and active systems • Select materials and construction methods having regard to thermal mass, openings and shading, sourcing of materials
	Execution of project	• Develop specifications for good workmanship and site management • Detail for thermal performance, daylight, controlled ventilation • Specify window and external door frames for environmental performance • Consider internal and external finishes for environmental friendliness • Consider environmental performance in selection for heating and cooling plant, radiators, controls • Specify electrical lighting equipment and controls for lowest consumption • Specify sanitary fittings for low water consumption
Construction	Tender procedure	• Explain the requirements of green design to tendering contractors • Specify more demanding construction practices and tolerances
	Supervision	• Protect the natural landscape of the site as much as possible • Ensure completeness of insulation coverings and no thermal bridging at openings • Contractor should not substitute materials or components without architect's approval • Ensure acceptable methods for waste disposal
	Acceptance	• Make sure client and users understand building concepts and systems (provide maintenance manuals) • Show how to get the maximum value from the active systems controls
	Defects period	• Monitor active systems for actual as against projected performance
Maintenance and refurbishment	Maintenance and refurbishment	• Use green finishes materials where these were originally applied • Use the environmentally-acceptable cleaning and sanitation materials • Undertake energy audit prior to commencing project • Survey the potential for upgrading active services • Survey the potential for upgrading the envelope • Consider indoor air quality and healthy building environment

6.1.4 Sustainable Architecture

Sustainability has been the preferred term in the late 80s and the 90s and the Brundtland definition of the term sustainable from 1987 is often the one authors refer to when trying to explain what it means, as this is a definition known and accepted worldwide.
Sustainability is, however, a term used for many other things than architecture and the built environment e.g. in relation to socio-economics. It is even used for different things within the world of architecture for instance in relation to construction being sustainable, which makes the term seem unspecific when it stands alone.
Today the term sustainability no longer seems to be the preferred term. This is probably due to the fact that it is used in too many different contexts and people therefore feel a need to use more specific terms. These days, people, thus, tend to be more precise in their selection of terms and they will usually associate one of the other terms in the terminology with sustainability, where sustainability is used as an umbrella term, or come up with new versions of the terms (e.g. Behling 2000).

Definitions

Dictionary.reference.com

According to dictionary.reference.com the word sustainable originates from the (Latin) word 'sustinére to uphold, equiv. to sus + -tinére, comb. form of tenére to hold' (from the period 1250 to 1300). The term sustainable, thus, simply means to uphold something and the fact that sustainability is applied in many different relations for instance in relation to construction or economics [Hagan 2001:3] shows that the term has a very embraceable meaning.

Brundtland

In connection with sustainability and architecture the primary reference is the definition expressed in the proceedings of the Brundtland Commission's report from 1987 entitled 'Our Common Future'.
The Brundtland report marked a significant change in the world of politics by bringing awareness to the issues of man's impact on nature. The Brundtland report, thus, initiated a lot of the legislations and plans seen today.

In 'Our Common Future' sustainable development is described as: 'sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future' [Brundtland et. al. 1987:51]. This quotation states what the aim of sustainability is, rather than what sustainability means, which might explain why there are so many different understandings of the term – even today twenty years later.

When combining the Brundtland definition and the dictionary definition of the word sustainable one can conclude that the aim is to enable a development which *upholds* the ability to meet the needs and aspirations of future generations.

Williamson, Radford and Bennetts

In the publication 'Understanding Sustainable Architecture' Williamson, Radford and Benntts [Williamson, Radford and Benntts 2003] have defined what sustainable architecture is in extension to their discussion of what they refer to as different labels of sustainable architecture (see page X):

> 'Sustainable architecture (…) is a revised conceptualisation of architecture in response to a myriad of contemporary concerns about the effects of human activity. The label "sustainable" is used to differentiate this conceptualisation from others that do not respond so clearly to these concerns.' [Williamson, Radford and Bennetts 2003:1]

According to this quote the term sustainable should be used to differentiate between architecture which is concerned with the effects of human activity on the natural environment and architecture which is not.

Steele
In the book 'Ecological Architecture – A Critical History' [Steele (2005)] the following quotation indicates a connection between the terms sustainable, ecological and green:

> 'The terms sustainable, ecological and green are often used interchangeably to describe environmentally responsive architecture (…). But at a deeper level each term is also heavily freighted with social and political implications.
> Sustainability seems to be the most ubiquitous of the three terms today (…). It has resulted from a long series of institutional initiatives, primarily guided by the United Nations, that may be characterized as a compromise between the 'growth' and 'no-growth' factions of the environmental movement of the late 1960s and early 70s. It represents the middle ground that has allowed development, as well as global funding of international development projects by large-scale financial institutions, to continue while pacifying the critics of such development.
> Because of its institutional roots, sustainability is easier to trace and define than are the terms 'ecological' and 'green', and there has been a concerted attempt in each of the conferences that have been held since the term was first introduced in the 1970s to eliminate vague connotations.' [Steele 2005:6]

According to Steele sustainability embraces eight issues; 1) Resource equity, 2) Embodied energy of a material or a resource, 3) Socio-economic awareness of global responsibility, 4) Exploration of socio-economic issues, 5) Replace non-renewable with renewable materials, 6) Respect for the traditional wisdom of vernacular architecture, 7) Responsibility to induce institutional change, and 8) a more critical attitude towards technology. [Steele 2005:6-7].

Sustainability as an umbrella term
It is my conclusion of the study of the different definitions of sustainable architecture that they verify that the term sustainable is often used as the overlapping term between different environmental approaches, such as ecological, green and environmental, and that sustainability focuses on the effect of human activity on the natural and social environment. The term sustainable architecture, thus, seems to be an appropriate umbrella term for the terminology.

Design strategies
Williamson, Radford and Bennetts
The publication 'Understanding Sustainable Architecture' [Williamson, Radford and Bennetts 2003] provides a checklist which addresses a number of discourse issues (such as environmental impact, pollution, comfort, longevity, biodiversity etc.) in relation to the stakeholders, objectives, principal active stakeholders, architects possible process means, aspects of possible product means and notes. [Williamson, Radford and Bennetts 2003: appendix] The checklist is primarily focused on urban developments, but it also considers a number of interesting aspects for architects as well, especially in the sketching stage of a project, when the site plan is developed.
The checklist does not discuss the stakeholders (active or passive) in relation to the stages of the process, but to the issues involved in the design and understanding of sustainable architecture.

Table 6.5: Reproduction of part of the checklist; objectives, architects possible process means and possible product means [Williamson, Radford and Bennetts:Appendiks A]

Discourse issue	**Objectives**	**Architects possible process means**	**Aspects of possible product means**
Environmental impact			
Climate change	▪ Reduce life cycle greenhouse gas emissions ▪ Create carbon sinks ▪ Mitigate effects of possible climate change	▪ Life cycle green house gas analysis ▪ Work with client and future occupiers of the building ▪ Work with client in considering the wider system of which the building is part ▪ Work with builders and product manufacturers on production sources and processes	Consider: ▪ Reducing the need for heating and cooling through the building form, materials and control systems ▪ Using forms of energy in the operation of the building that do not produce greenhouse gases ▪ Using highly energy efficient appliances and cooling systems ▪ Using materials and equipment where the use of fuels producing greenhouse gases in their extraction, manufacture and transport is low ▪ Allowing for uncertain future climate ▪ Planting trees
Pollution	▪ Reduce acid rain ▪ Reduce air pollution ▪ Reduce water pollution ▪ Reduce land pollution	▪ Life cycle pollution impact analysis ▪ Work with client and occupiers on future operation of the building ▪ Work with client in considering the wider system of which the building is part ▪ Work with builders and product manufacturers on production sources and processes	Consider reducing pollution during construction by: ▪ Reducing waste materials ▪ Using components that have caused little pollution in extraction, manufacture and transport Consider reducing pollution during building operation by: ▪ Using non-polluting energy sources ▪ Avoiding potential polluted surface water run-off ▪ Recycling water Consider reducing pollution at end of building or component life by: ▪ Using long-life materials ▪ Using biodegradable materials ▪ Using recyclable materials
Resource depletion	▪ Use resources wisely	▪ Determine renewability and rarity of resources	Consider: ▪ Using renewable resources (e.g. plantation timber, managed regrowth timber, solar energy ▪ Using plentiful resources (e.g. many building stones, clays, silicon, iron ore) ▪ Very careful appropriate use of rare and non-renewable resources ▪ Building small
Biodiversity	▪ Avoid actions that lead to reduction of biodiversity	▪ Determine what ecosystems are effected by the project, and how	Consider: ▪ Avoiding building in places that are particularly significant for biodiversity ▪ Using timber with an authoritative certificate of origin ▪ Shifting use of rainforest timbers to low-volume, high value applications ▪ Creating landscapes rich in biodiversity
Indigenous flora and fauna	▪ Minimise disturbance to local flora and fauna ▪ Maintain viability of local ecosystems	▪ Analyse existing local ecosystems	Consider: ▪ Minimal building footprint ▪ Minimal disturbance to surrounding vegetation ▪ Leaving wildlife movement corridors ▪ Designing to avoid bird strikes on windows, wind turbines etc.

Table 6.5: Reproduction of part of the checklist; objectives, architects possible process means and possible product means [Williamson, Radford and Bennetts:Appendiks A] (Continued)

Discourse issue	Objectives	Architects possible process means	Aspects of possible product means
Social and cultural relevance			
Society and culture	▪ Reflect and express culture ▪ Relate built form to social and economic activity ▪ Maintain significant building heritage values ▪ Create future heritage value	▪ Consult with local community about buildings and urban patterns that are socially and culturally relevant to it ▪ Work with government on the development of appropriate development and heritage guidelines ▪ Invite peer and public review	Consider: ▪ Using locally sourced materials ▪ Designing to enable the use of locally-sourced skills for construction and future maintenance ▪ Adapting existing buildings ▪ Maintaining existing mix of spaces for living, trade and social activities ▪ Maintaining existing scale and typologies of buildings ▪ Emphasizing public space ▪ Respecting existing built context ▪ Using pre-used 'blighted' sites rather than green field sites.
Occupants			
Health	▪ Healthy people	▪ Assess potential health impacts of design decisions	Consider: ▪ Designing for fresh air change rate (above minimum requirements) ▪ Using materials with authoritative guarantees of non-toxicity ▪ Designing for easy cleaning and maintenance
Comfort	▪ Thermal comfort ▪ Visual comfort ▪ Aural comfort	▪ Determine context-related preferences for comfort	Consider: ▪ Designing so that the building itself offers internal conditions that are within or approach culturally acceptable limits ▪ Using energy-using systems only when appropriate in relation to other sustainability issues
Economic performance			
Cost effectiveness	▪ Net benefit ▪ Return on investment	▪ Determine life cycle costs ▪ Work with the client in considering wider objectives and whether building is the best way to meet those objectives ▪ Recognize expertise of builder in cost-effective design ▪ Consider how uncertainty in economic conditions may effect the building use and life ▪ Cost planning and control	Consider: ▪ Designing for low imported energy use ▪ Design for low maintenance
The building			
Longevity	▪ Durability ▪ Adaptability ▪ Serviceability ▪ Maintainability	▪ Consult possible future users ▪ Seek flexibility in interpretation of fit between use and building ▪ Work with client on asset management plan	Consider: ▪ Adapting and using existing building stock rather than building new ▪ Designing for adaptability of future change of use ▪ Using long-life materials ▪ Allowing provision for possible future services ▪ Using measures to protect from place-dependant risks such as bush fires and corrosive seaside air ▪ Designing for low maintenance and easy serviceability ▪ Allowing for uncertainty in future climate

6.1.5 Bioclimatic Architecture

Bioclimatic architecture can be traced back to the 1963 to the writings of Victor Olgyay[13], and the term has had a revival in the mid 1990's due to the writings and designs of Ken Yeang[14].
There is, however, a significant difference in the issues treated by Olgyay and Yeang, which can be ascribed to the fact that the two publications are from respectively the pre energy crises and post energy crises eras.
The two publications, thus, also exemplify the difference in the approach to climate before and after the energy crises; Olgyay talks about 'the effects of climate on human environment' instead of the effects the human environment has on climate, which is the focus of Yeang's work.
Olgyay and Yeang both have an urban outset for their work but they also reach the level of building design.

Definitions

Victor Olgyay

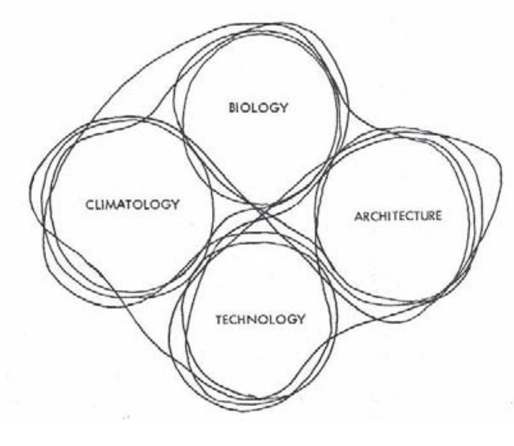
In 1963 the publication entitled 'Design with Climate – a bioclimatic approach to architectural regionalism' was published. It was written by Victor Olgyay, who was the first to introduce the term 'regionalism' in relation to climatic architecture. [Hawkes, McDonald and Steemers 2002]

Olgyay was concerned with the effects of climate on human environment:

> "With the widening spread of communications and populations, a new principle of architecture is called for, to blend past solutions of the problems of shelter with new technologies and insights into the effects of climate on human environment." [Olgyay 1963:v]

This resulted in a new approach to architectural design in which the architectural expression came after the registration of the climatic conditions and the development of physiological criteria and strategies for orientation, shade, ventilation, preferable building heights and compactness etc.

Olgyay focused on what he described as four interlocking fields of climate balance:



'The process of building a climate-balanced house can be divided into four steps, of which the last is the architectural expression. Architectural expression must be preceded by study of the variables in climate, biology, and technology' [Olgyay 1964:11]

Illustration 52.1: The four interlocking fields of climate balance [Olgyay 1963:12]

The book presents the results of Olgyay's analyses of sites in four different climatic zones for which he developed strategies for the orientation of the building, the compactness of the shape, the roof type, volumes of the buildings, insulation of the different elements of the building envelope etc.

Ken yeang

The Malaysian architect Ken Yeang has been engaged in bioclimatic design in connection to Skyscrapers since 1981. Like Olgyay, he is interesting because of his methodological view on bioclimatic design which he has reported in several publications. He is, thus, one of the few people who combine the development of theories with an architectural practice.

Initially Yeang's work was focused on the development of a modern architectural tradition in Malaysia. This presented him with other problems than one is faced with when working in a Scandinavian context; he was faced with a tropical climate which meant small variations in temperature over the day and year, and a large cooling-load due to high external temperatures and high humidity. Yeang has, thus, tried to establish a modern architectural tradition based on the Malaysian culture and climate throughout his work. [Yeang 1994:8]

Yeang's motivation for dealing with bioclimatic architecture is fuelled by a wish to transform architectural design from a whimsical craft into a confident science [Yeang 1994:17], the possibility of lowering costs for operation and enhance the user's sense of well-being and reduce the overall energy consumption. [Yeang 1994: 21-22]

To develop his designs Yeang insists on doing research to update his knowledge during every project thereby improving the architecture. Over time he, thus, integrates more and more sustainable measures in his architecture, which also enables him to reflect on the effectiveness of his solutions. He calls this method RD+D (Research Design and Development). The application of this method has over the years resulted in the development of more and more design principles [Yeang 1994:28-31]. The application of these design principles has resulted in an increase in the complexity of the bioclimatic principles applied in Yeang's buildings.

The following quote was recently found on the webpage of T. R. Hamzah & Yeang's:

> 'The firm's design expertise is in their ecological approach for the design of large projects and buildings that include consideration given to their impacts on the site's ecology and the building's use of energy and materials over its life-cycle. Much of the firm's early work pioneers the passive low-energy design of skyscrapers, as the "bioclimatic skyscraper".' [www.trhamzahyeang.com February 2007]

This quote links the 'Bioclimatic skyscraper' with low-energy design of skyscrapers, whereas it links the more current projects to an ecological design approach which combines strategies for site ecology, energy consumption of buildings and building materials.

The Manchester School of Architecture
This quote from the webpage of the Manchester School of Architecture (UK) contains a nice summation of what bioclimatic architecture is regarded as today:

> "Bioclimatic architecture is a way of designing buildings and manipulating the environment within buildings by working with natural forces around the building rather than against them. Thus it concerns itself with climate (or perception of climate) as a major contextual generator, and with benign environments using minimal energy as its target." [www.msa.mmu.ac.uk February 2006]

The notion of designing with the natural forces rather than against them is essential to the bioclimatic approach to architecture, and the formulation can be traced back to Olgyay's 'Design with Climate – a bioclimatic approach to architectural regionalism' [Olgyay 1963].

Design strategies
Olgyay
The approach presented in 'Design with Climate – a bioclimatic approach to architectural regionalism' [Olgyay 1963] primarily focuses on the climate and physiology and not as much on the resources used in the building process, which is probably due to the fact that this method was developed prior to the energy crises in 1973 and 1979. Therefore it deals with the needs which were present at the time; comfort in relation to climate. It also focuses on the cultural influences on the site, which is very much a part of the regionalistic tradition.

In his book Olgyay performs analyses on sites in four different climatic zones and evaluate preferable guidelines for the orientation of the building, the compactness of the shape, the roof type, volumes of the buildings and which elements of the façade should be insulated etc. The design strategies for the climatic zones were based on his model of the four interlocking fields of climate balance applied in the following order:

1. CLIMATIC DATA is analyzed which leads to an understanding of the climate and how the microclimate surrounding the building works.
    a. Temperature
    b. Relative Humidity
    c. Radiation
    d. Wind effects
2. A BIOLOGICAL EVALUATION is made based on human sensations. The evaluation leads to a number of problems which needs to be solved in relation to climate.
    a. Measures needed to restore comfort conditions (such as physiological and psychological comfort)
3. TECHNOLOGICAL SOLUTIONS are sought which accommodate the climate and solves some of the problems caused by the climatic conditions.
    a. Site selection
    b. Orientation
    c. Shading
    d. Housing form
    e. Air movements
    f. Indoor temperature balance
4. ARCHITECTURAL APPLICATION of the findings of the first three steps are developed and balanced according to the importance of the different elements.
    a. Rotation of houses
    b. Considerations according to plans, shapes, volumes, sections etc.

[Olgyay 1963:chapter 3]

Table 6.6: The overall objectives for each climatic region

Cold regions	*Temperate regions*	*Hot and arid regions*	*Hot and humid regions*
'General objectives in the cool region: Increase heat production, increase radiation absorption, and decrease heat loss. Reduce conduction and evaporation loss' [Olgyay 1963:155]	'General objectives in the temperate region: As both underheated and overheated periods are represented in substantial part during the year a balance should be established by reducing or promoting on a seasonal basis the heat production, radiation and convection' [Olgyay 1963:161]	'General objectives in the hot and arid region: Reduce heat production. Reduce and promote loss of radiation. Reduce conduction gain. Promote evaporation' [Olgyay 1963:167]	'General objectives in the hot and humid region: Reduce heat production. Reduce radiation gain. Promote evaporative loss' [Olgyay 1963:155]

Table 6.7: The issues addressed by the strategies for each temperate zone [Olgyay 1963:155-185]

Housing layout	*Shelter design*	*Building elements*
• Site selection • Town structure • Public spaces • Landscape • Vegetation	• House types • General arrangement • Plan • Form and volume • Orientation • Interior • Colour	• Openings and windows • Walls • Roof • Materials • Shading devices • Foundation and basement • Mechanical equipment • Other

Yeang
Based on the appendix presented in the publication ‘Bioclimatic Skyscrapers’ from 1994 it seems that Yeang’s strategic approach to the selection of design principles is inspired by Olgyay’s findings.
The book ‘Bioclimatic Skyscrapers’ presents a number of design principles applied in Yeang’s bioclimatic projects up to 1995. The principles are the result of the RD+D approach Yeang applies to his work, and they have, thus, evolved throughout his career.

Ken Yeang has used Solar and wind diagrams in his designs from the beginning of his work with bioclimatic buildings. He has developed different principles for how to distribute thermal mass according to the need for heat and shadow. Furthermore, he has kept a vision of external spaces in relation to dwellings and offices in spite of the use of high-rise buildings. This way a natural element comes into play in his work; as he works with a concept he calls ‘vertical greening’ which is a concept of substituting the piece of land that the footprint of the building occupies, with a vertical landscape, thereby diminishing the impact of the building on the site’s ecological systems, while achieving a close connection with nature despite being inside a skyscraper.
Yeang’s projects have developed and he now also uses aspects of urban ecology in his projects, such as decreasing the need for private transportation (cars), collecting rainwater, alternative energy, life cycle assessment etc. He has developed a palette of design principles for how to place service cores, balconies, windows, thermal mass, shading, ventilation, vegetation (vertical greening) and photovoltaic cells can influence the shape of the building and how these principles can be utilized in a given situation.

Yeang uses the design principles not to achieve shape in his designs, but more as a way of programming the project:

> ‘The overall arrangement abandons traditional geometry and responds to the dynamics of climate, sunpath, wind direction and the issue of lifestyle: openness – including breezeways, verandahways, transitional spaces that relate to the society they serve’ [Yeang 1994:s.15]

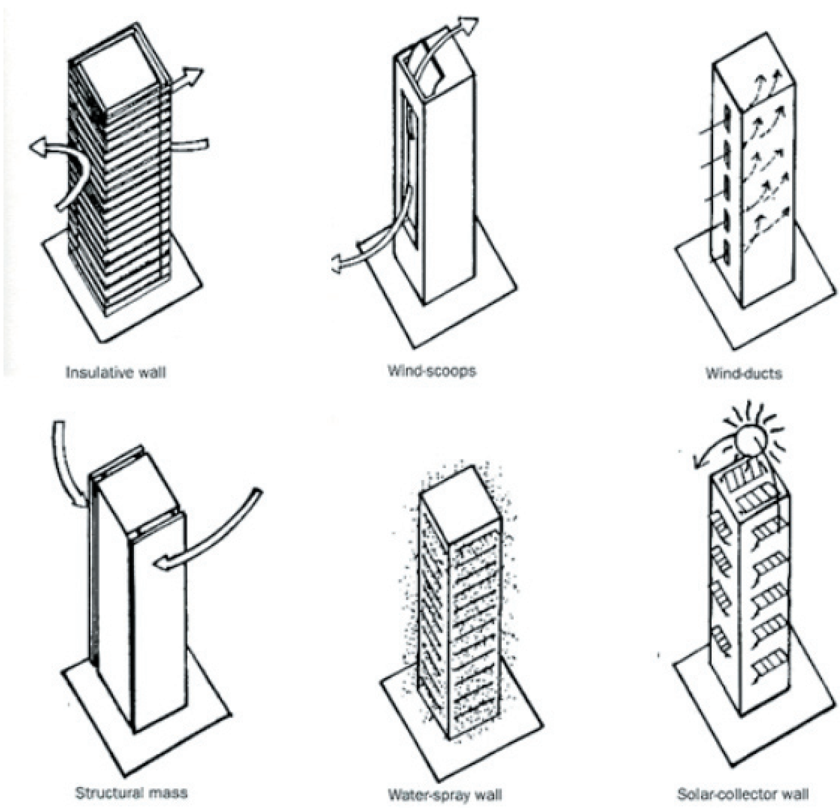


Illustration 55.1: Examples of design principles applied by TH Hamzah and Yeang [Yeang 1994:28-31]

The application of the principles is concerned with energy reduction and the interactive relationship between the inside and outside of the building in relation to the seasonal changes of the climatic context [Yeang 1994:14].

6.1.6 Environmental Design

The term environmental design is used in a lot of different connections, and Environmental Design is currently a preferred term to many.

Publications from the Martin Centre, University of Cambridge (UK)

Most of the publications about environmental design are authored by people with connection to the Martin Centre at the Department of Architecture at the University of Cambridge, UK. For instance:

- 'The Environmental Tradition – studies in the architecture of the environment' by D. Hawkes, 1995
- 'Energy and Environment in Architecture' by N. Baker and K. Steemers, 2000
- 'Energy Efficient Buildings: Architecture, Engineering and Environment' by D. Hawkes and W. Forster, 2002
- 'The selective environment – An approach to environmentally responsive architecture' by D. Hawkes, J. McDonald and K. Steemers, 2002
- 'Environmental Diversity in Architecture' by M. A. Steane and K. Steemers, 2004

These publications discuss what environmental design is, the historical development of environmental architecture, presentations of design principles and issues of interest relating to environmental design of buildings, a selective design strategy, a computerised tool for application during the design process, and a discussion of the importance of environmental diversity in architecture.

According to Hawkes [Hawkes 1995] the idea of environmental design was first initiated by the Electricity Council in Britain in the 1970's as the IED (Integrated Environmental Design) under the pretend of a way of obtaining the benefits of 'full air conditioning at lower capital costs than a conventional building'. The hidden agenda was however to 'obtain a larger share of the office environment market' and to distribute the energy consumption over the entire year. In 1979 Arup Associates redefined and refined the IED principles in the headquarters building for the Central Electricity Generating Board by designing a building in which the building envelope and the mechanical systems worked together harmoniously, but where the nature and function of the building envelope was redefined and refined to enable natural light and ventilation in the building. [Hawkes 1995:20-21]

The origin and revision of the term has lead to two different branches of environmental design, which Hawkes and Forster [Hawkes and Forster 2002] present in a taxonomy with exclusive vs. selective on one axis and concealed vs. exposed on the other axis.

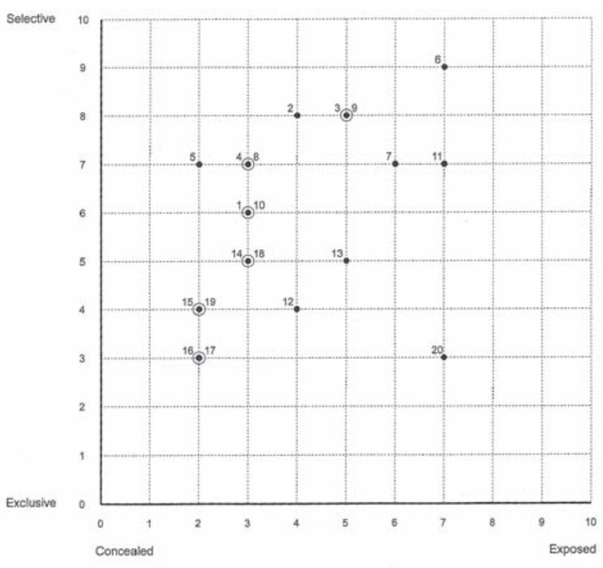


Illustration 56.1: Selective vs. exclusive environmental design and the visibility of analysed projects

Selective/ Exclusive:

"This classification distinguishes between designs that, in selective mode, selectively accommodate and filter the ambient environment as their primary strategy and those that, in exclusive mode, configure and construct the building enclosure to achieve maximum exclusion of the external climate in order to minimize the demands placed on environmental plant. Such a distinction broadly characterizes the predominant environmental options, but the richness and complexity of modern practice demands a more refined taxonomy" [Hawkes and Forster 2002:40]

Concealed / Exposed:

"We propose a descriptive scheme that extends the distinction between selective and exclusive by taking note of the way in which the environmental systems of a building are (…) either concealed or exposed." [Hawkes and Forster 2002:40-41]

Architecturally and environmentally these two branches have very different outcomes which Hawkes and Forster [Hawkes and Forster 2002] refer to as exclusive or selective environmental design.

In the publication entitled 'The selective environment – an approach to environmentally responsive architecture' [Hawkes, McDonald and Steemers 2002] Hawkes, McDonald and Steemers describe the differences between the exclusive and selective mode as:

Table 6.8: The general characteristics of exclusive and selective mode buildings [Hawkes, McDonald and Steemers 2002:7]

Exclusive mode	*Selective mode*
• Environment is automatically controlled and is predominantly artificial • Shape is compact and aims to minimise the interaction between the internal and external environments • Orientation is relatively unimportant • Windows are restricted in size and are fixed • Energy is primarily from generated sources and is used constantly throughout the season	• Environment is controlled by a combination of automatic and manual means and is a variable mixture of natural and artificial elements • Shape is dispersed and aims to maximise the collection of ambient energy • Orientation is a crucial consideration • Windows are of variable size depending on orientation, room size and function. Solar controls are incorporated on exposed facades • Energy is primarily ambient supplemented by generated sources when essential. Use varies from season to season

This means that environmental architecture can either be used as an expression for architecture which considers the environment in which it is placed and, thus, applies passive or active strategies to reduce the energy consumed in the buildings, or it can be used as an expression for buildings with their own artificial environment, such as air-conditioned buildings with artificial lighting.

It is therefore my conclusion that the 'correct' approach to environmental design from an environmentally sustainable way of thinking is the selective approach, which focuses on how the building enables the internal environment to respond to the external environment in order to reduce the energy consumption for artificial lighting, mechanical ventilation etc.

The approach described in 'The selective environment – an approach to environmentally responsive architecture' [Hawkes, McDonald and Steemers 2002] does not place much emphasis on whether or not the materials used in the buildings are natural or renewable in the definition of the selective approach to environmentally responsive architecture. The embodied energy and toxicity of materials is, however, addressed in the publication's checklist.

Design strategies and principles

Baker and Steemers

The publication 'Energy and Environment in Architecture' contains a discussion of energy use in non-domestic buildings, a description of the LT-method developed at the Martin Centre and some case studies of existing buildings.
Since publication the LT-method has been developed into a computer programme which is also applicable for residential buildings. This electronic version of the LT-method will be discussed in the 'Tool' part of the state of the art.

The objective of the publication was to:

> 'to fill the gap between the prescriptive design guide and the building science text-book. Prescriptive guidelines are vulnerable in a field as broad as non-domestic building design, becoming unwieldy if every guideline carries too many qualifications and limitations.' [Baker and Steemers 2000:vii].

The first part of the publication discusses the use of energy in buildings, and the design strategies associated with the different types of energy use in relation to:

- Provision of comfort
- Heating
- Prevention of overheating
- Daylighting
- Ventilation
- The passive zone concept
- Atria and sunspaces
- Energy Systems

[Baker and Steemers 2000:vii]

The second part presents the LT-method (LT stands for Light and Thermal) as a means of quantifying 'the potential energy performance of non-domestic buildings at an early design stage'. [Baker and Steemers 2000:vii]

The LT-method applies a strategy of differing between passive (which are daylit, naturally ventilated and utilise the passive solar heat gains) and non-passive zones (which need artificial lighting, mechanical ventilation and in some cases cooling) [Baker and Steemers 2000:96].

In 2000 the LT-method consisted of pre-computed graphs which together with a small data set of building parameters (such as plan areas and façade glazing ratios) could enable a prediction of the annual energy use for heating, lighting, ventilation and cooling [Baker and Steemers 2000:vii]. Since 2000 the LT-method has been developed into an interactive computerised design tool, which will be discussed in chapter 8.2.

The last part of the publication discusses a case study of completed buildings, which are used to exemplify good energy design practices. [Baker and Steemers 2000:vii]

Hawkes, McDonalds and Steemers
The publication 'The Selective Environment – An approach to environmentally responsive architecture' discusses the issue of exclusive vs. selective environmental design. A discussion which is paralleled in the Hawkes and Forster publication from 2002 entitled 'Energy Efficient Buildings: Architecture, Engineering and Environment'

The outsets of 'The Selective Environment' are the theoretical works of Olgyay and Rayner Banham as well as case studies of existing building stock in the UK and in the rest of the world. [Hawkes, McDonald and Steemers 2002:4-6]:

> 'The principles of 'selective' environmental design have their origins in the work of both Banham and Olgyay. Two important ideas come from Banham. First, the conviction that the problems of the present must be illuminated by a historical sense, that solutions in architecture cannot be fashioned only by the application of pragmatic, analytical process. Second, the notion of 'modes' of environmental control and, in particular, the term' selective' itself. From Olgyay, the greatest lesson is the fundamental principle that architecture is at its best when it is working *with* and not *against* nature. That the severance of historical symbiosis with climate was achieved at a cost to both architecture and climate.'
> [Hawkes, McDonald and Steemers 2002:6]

The strategy presented in the publication is to limit the negative environmental impact of buildings by minimising the dependence upon mechanical systems of environmental control. This is to be achieved through a selective organisation of the form and construction of the building which enables an adaptation between the building and the natural environment surrounding the building. [Hawkes, McDonald and Steemers 2002:vii].

Table 6.9:The global characteristics of environmental design [Hawkes, McDonalds and Steemers 2002:13]

Internal environment	• Standards are related to the local climate • Emphasis is on the maximisation of natural light • Primary temperature control is by the building fabric • There is spatial and temporal diversity of conditions • Control is by the occupant
Built form	• Related to the specific climate • Cross-section is a key element of the environmental response
Orientation	• Related to the specific climate • There is reference to a sunpath diagram
Fenestration	• Related to specific climate • The window area should balance the relationship between the thermal and luminous environments in relation to local climate
Energy sources	• Should be primarily from ambient sources: Natural lighting, exploiting passive solar gains and natural ventilation when appropriate • Mechanical systems for heating, cooling, ventilation and lighting should be regarded as supplementary to the primary control provided by the 'selective' built form • Direct use of renewable energy sources through photovoltaic and water-heating systems should be considered

The process of the design of a selective building is divided into these steps:

1. Construct a description of the climate at its location (e.g. temperature and solar geometry).
2. Examine the temperature data and estimate the need for heating and/or cooling. Based on this examination strategies for collecting or excluding solar radiation can be selected as well as strategies for the thermal insulation of the building envelope and the use of thermal mass in the building.
3. Apply the data on solar geometry as the basis for the development of build forms that admit or exclude solar radiation, as well as the fenestration and possibly shading systems applied in the building.

Based on [Hawkes, McDonald and Steemers 2002:13]

The publication, furthermore, presents a checklist for environmental design where these issues are emphasized in relation to tasks which need solving in the design of a selective building:

Table 6.10: The issues addressed in the checklist [Hawkes, McDonald and Steemers 2002:122-150]

Tasks	*Issues*
Site analysis	Climate, Microclimate, Topography, Urbanisation, Vegetation, Sunpath, Wind, Pollution
Site planning	Spacing, Microclimate, Mixed uses and movement of people
Building form	Passive and non-passive zones, Orientation and Internal planning
Courts and atria	Thermal buffer, Daylight and Ventilation
Building use	Occupancy patterns and behaviour, Environmental requirements, Internal gains and light levels
Building fabric	Insulation and U values, Thermal mass and surface resistance, Embodied energy and surface resistance, Embodied energy and toxicity of materials
Daylighting	Natural light and the daylight factor, Light distribution, Glazing distribution, Views, glare, privacy and thermal balance
Passive solar gains	Useful solar gains, Distribution, Control and comfort
Natural ventilation	Wind and stack-effect, Night-time cooling, Noise and atmospheric pollution
Overheating and comfort	Window sizing, Shading devices, Ventilation strategies, Thermal mass
Artificial lighting	Controls: manual or automated, Lamps and luminaries, Efficacy and internal gains
Heating	Fuel and plant, Emitters, Distribution and Location
Services	Need for air-conditioning, Mechanical Ventilation, Mixed-mode and zoning, Integration

In some cases the description of the issues is also concerned with design strategies, design principles and/or tools associated with the different issues.

6.1.7 Low-energy

Low-energy buildings are also often referred to as energy-efficient buildings. The term low energy building is pretty self-explanatory; it refers to buildings with low energy consumptions.

Definition

The notion of low-energy was introduced to the Danish building regulations in 1985, as buildings for which the net energy requirement was 50% of the maximum permitted net energy requirement of regular buildings. A number of low energy buildings were, however, already constructed in 1978 as part of a research project [HVAC 2004:32-36].

Today the Danish building regulations distinguish between two types of low-energy buildings; low-energy class 1 and 2, where low-energy class 1 buildings have the lowest primary energy consumption, which is 50% of the maximum permitted primary energy consumption in Danish buildings.

Most low energy projects focus on the energy consumed by the building during its operation, but there is no hindrance to the inclusion of the energy consumed for the production and demolition of the house.

Design strategies

Strategies

There are no clearly defined low-energy design strategies available in publications. This means that the following description of the design strategies is based on the development responding to changes in the Danish building regulations. This approach has, at least from a Danish perspective, focused on the issues of reducing the energy consumption in buildings (especially in residential buildings). Initially the strategic focus was on insulation of the building envelope and the internal heat gains from people, appliances and the passive heat gain from the sun with the aim of reducing the energy required for space heating.

Later the strategic focus has changed slightly to also include the air-tightness of the building envelope and the energy requirement for the hot water consumption, the electrical energy consumed by appliances and an issue of summer comfort has been added by the addition of concerns with overheating and, thus, energy required for cooling the building or removing the excess heat through passive strategies.

[www.ebst.dk July 2007]

6.1.8 Solar Architecture

Solar architecture was one of the most popular terms of the 1990s, where it was used as a label for practically any building utilising passive solar heat gains or any building with a solar panel or photovoltaics on the roof. Today the understanding of solar architecture has developed towards renewable energy. It is no longer enough to apply passive solar heating or small solar panels, and the dominant market in Europe for solar architecture is currently Germany, Austria and Switzerland [Schnittich 2003:9-11].

Definitions

Schnittich

In the book ‘Solar Architecture – strategies, visions and concepts’ [Schnittich 2003] Schnittich describes solar architecture as buildings which are total energy concepts which utilises passive and active measures:

> ‘solar architecture cannot be reduced to isolated measures such as collectors or photovoltaic installations on the roof. Rather, a building must be understood as a complex configuration – a total energy concept – that makes the best possible use of locally available natural resources such as solar energy, wind and geothermal energy from a variety of requirements. Passive and active measures complement one another in this approach, from the orientation and division of the building to the integration of systems

for the generation of warm water or power. Flexible envelopes, regulated by intelligent control systems and capable of reacting to varying influences and weather contributions. It goes without saying that such a complex configuration calls for comprehensive interdisciplinary concepts, integrated planning, in other words, where all participating experts are involved at an early stage.' [Schnittich 2003:9]

The projects presented in the book as exemplification of solar architecture are projects that are presented in other publications as environmental design, passive houses or low-energy buildings. Most of the presented projects have either solar panels or photovoltaics integrated in their building design.

Passive house
The first passive houses were built in 1991 and passive houses are very popular approaches today within central and northern Europe.
The most significant source of information about passive houses is the definition from the Passive House Institute in Germany. The institute was started by Dr. Wolfgang Feist who fathered the passive house standard inspired by Professor Bo Adamson from Lund University (Sweden). [www.dcue.dk 2005]:

> 'A passive house is a building in which a comfortable interior climate can be maintained without active heating and cooling systems (Adamson 1987 and Feist 1988). The house heats and cools itself, hence "passive".' [www.passiv.de 2007]
>
> "A passive house is cost-effective when the combined capitalized costs (construction, including design and installed equipment, plus operating costs for 30 years) do not exceed those of an average new home."
> [www.passiv.de 2005]

The passive house standard finds its strength in the precise formulation of the demands a building has to live up to in order to achieve the passive house classification.

Design strategies
Schnittich
In 'Solar Architecture – strategies, visions and concepts' [Schnittich 2003] the following design principles are described by Manfred Hegger:

Location and microclimate; the microclimate is influenced by the topology, plants and groundcover, trees, location near open bodies of water on the site.

- *Topography and vegetation* is used to protect the building from cold-air pressure.
- *Wind protection* to reduce the transmission losses in the building
- *Form*; optimised, energy-conscious building forms that take climate concerns into considerations
- *Indigenous building forms as models*; traditional building types are excellent indicators of suitable building forms
- *Bionics – nature as a model*; study the local wildlife for inspiration of how to design the building in response to the local climate
- *Area/Volume ration*; prefer large and compact buildings to small and compartmentalised buildings
- *Embedding* the building in the ground to reduce transmission losses and temperature fluctuations
- *Orientation, isolation and shade* to utilise or avoid passive solar heat gains
- *Zoning* in relation to the temperature requirements and the internal heat gains of the different rooms in the house

Building skin as a dynamic envelope that provides weather protection and is the source of a comfortable interior through daylight penetration and visual contact with the outside

- *Insulation* for storage of the solar energy *and wind protection* to control unwanted ventilation heat losses
- *Openings* offer the greatest opportunities and the greatest risks for use of passive solar energy; needs to enable heat and daylight penetration during the day while diminishing the thermal heat loss during the night.
- *Glazed buffer zones / winter gardens* work as warm-air collectors for pre-heating of ventilation air if they are unheated spaces.
- *Transparent insulating materials* as solar wall heating systems
- *Storage masses* to stabilise the temperature inside the building
- *Massive storage component* through large firm or liquid surfaces with high thermal mass that are exposed to direct solar radiation
- *Latent thermal storage* in phase change materials, which utilise the phase transition in the material for efficient thermal storage (e.g. paraffin)

Additional technologies on the road toward interactive comprehensive systems

- *Ground ducts for pre-warming and cooling* as passive heat-exchangers that pre-warms or pre-cools the ventilation air before it enters the building
- *Adiabic cooling*; the air is cooled slightly though water evaporation which humidifies the surrounding air and cools it a few degrees
- *Night-cooling*; the combination of night ventilation and thermal storage mass to remove the excess heat stored in the thermal storage mass during the day in order to reset the thermal storage mass
- *Light-directing elements* that guide daylight deep into rooms and reduce the need for artificial lighting
- *Switchable glass*; glass that changes from transparent to translucent by being charged with a current or injected with a gas
- *Switchable film / film cushions*; synthetic materials that offer light-weight solutions usually in the form of pneumatic cushions
- *Vacuum insulating panels* were primarily used for refrigerating appliances; the panels can be used in buildings to minimise the thickness of the building insulation; e.g. 20 mm compacted silicic acid vacuum packed in plastic film can replace 200 mm mineral wool insulation.

[Schnittich 2003:13-25]

The Passive House Standard

For a building to be regarded as a passive house an annual heating requirement that is less than 15 kWh/m² pr year is required. This must not be achieved at the cost of an increase in use of energy for other purposes (e.g., electricity). Furthermore, the combined primary energy consumption of living area of a European passive house may not exceed 120 kWh/m² pr year for heat, hot water and household electricity. Additional energy requirements can be covered using renewable energy sources.
[www.passiv.de 2007].

In order to achieve this, the following principles can be applied:

- *Orientation of the rooms and windows*, where the primary rooms are placed in the building so they have large facades with large window openings with a south orientation. Secondary rooms are orientated towards a north orientation, with very little window openings i.e. the use of *temperate zones*.
- *Thermal mass* used to store excessive energy during the day and releasing it over night.
- *Air-tightness* minimal amount of thermal bridges, preferably none.
- *Mechanical ventilation* to ensure a minimal heating loss to the ventilation during the winter season.
- *Low-emission windows* U-value for the entire window (including frame) must not exceed 0,8W/(m^2K).
- *User manual* to ensure that the passive initiatives in the building have the best conditions
- *Surface to volume ratio* the smaller the better
- The U-value for *none transparent building parts* must not exceed 0,15 W/(m^2K), preferably 0,10 W/(m^2K)

- *Materials* are chosen for their life cycle profile and their thermal abilities.

[Pregizer 2002, www.passiv.de 2007]

Available from the www.passiv.de webpage is furthermore a very detailed checklist for each stage of the building project.

The target of an energy requirement for space heating of 15 kWh/m² pr year is not selected at random. It is based on a study of the economical expenses for space heating and construction, which showed a large reduction in the construction costs when the energy requirement for space heating is 15 kWh/m² pr year. If the energy requirement for space heating is less than 15 kWh/m² pr year there is an increase in the construction. [http://passivhus.aau.dk 2005]. The reduction in construction costs achieved when the energy requirement for space heating is 15 kWh/m² pr year or less is because when the energy requirement for space heating reaches this particular value it is possible to heat the building via heat-recovery in the ventilation system, which means that the construction costs are reduced by eliminating the need for radiators.

To achieve the passive house 'label' the energy consumption of the building must be calculated via a spreadsheet tool developed by the Passive House Institute entitled PHPP (Passivhaus Projektierungs Paket) [www.passiv.de 2007].

6.1.9 Conclusions

Based on the study of the definitions of the terms found in the terminology, and the design strategies associated with the different terms it is my conclusion that the terms represent different approaches to sustainable architecture, and that environmental sustainability is the appropriate term for this project. The following conclusions can be made about the dominating concerns and design principles found in the different approaches to sustainable architecture.

Dominant concerns and design principles

When comparing the design strategies applied by the different approaches to sustainable architecture one finds that the approaches share many of the same concerns of environmental sustainability, but that this happens at different conceptual levels of scale (e.g. urban, building or component).

The following diagram was developed in an attempt to create an overview of the design principles the dominant concerns[15] presented by the different approaches to sustainable architecture. The dashed lines are used where a design principle or concern is implied in only one or some of the definitions, design strategies or projects found in publications applying the different approaches to sustainable architecture.

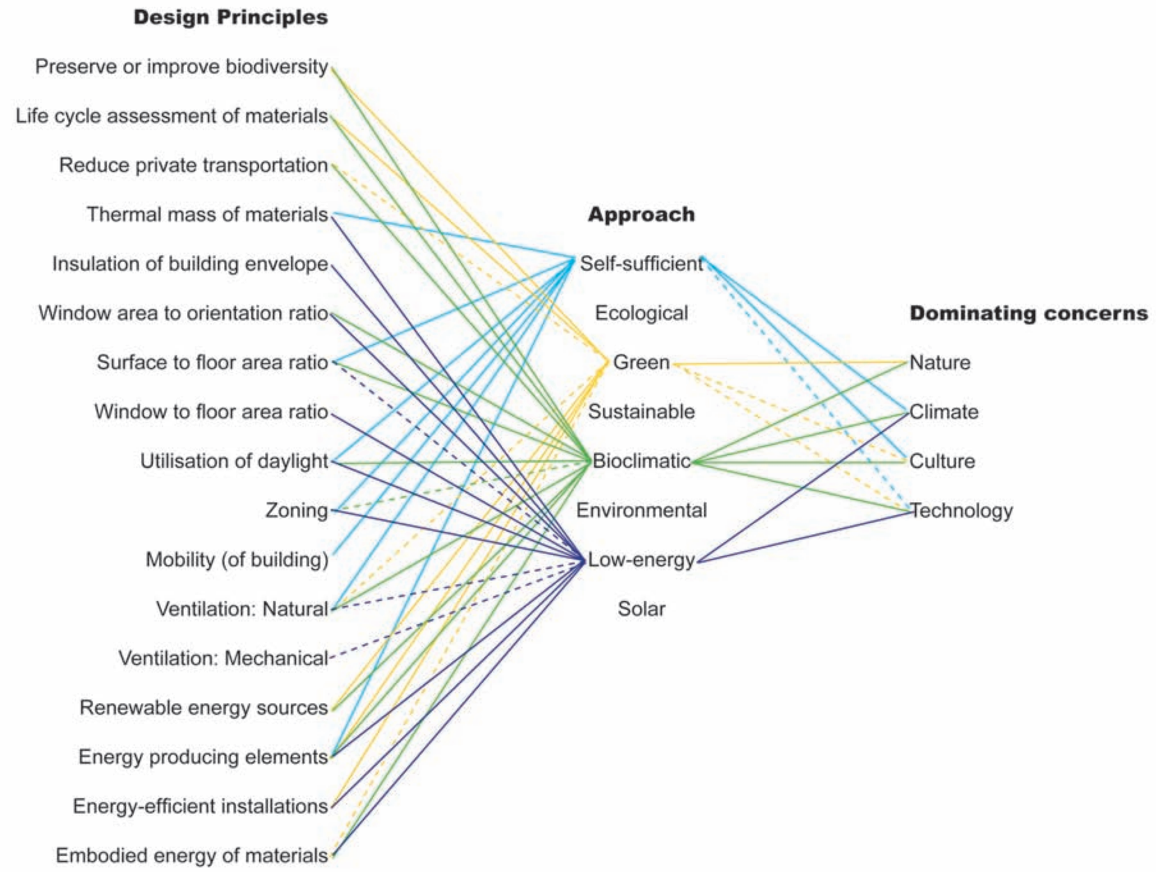


Illustration 64.1: Overviews of the design principles applied in design strategies for different approaches to sustainable architecture and the dominant concerns addressed in the approaches.

Dominant concerns
It is apparent that some of the approaches consider all four of the dominant concerns while others primarily focus on one or two of these; Some approaches do not consider technology (ecological and green). These approaches primarily focus on nature and culture. Other approaches do not focus on nature (self-sufficient, low-energy, environmental and solar). These approaches are instead motivated by climatic concerns as well as technological and/or cultural concerns. Only two approaches embody all four concerns (sustainable and bioclimatic).

Design principles
Some of the dominant concerns applied in the approaches correspond to application of specific design principles: Approaches concerned with nature prioritise biodiversity, life cycle profiles and toxicity of materials, reduction of transportation and renewable power sources over reducing the energy consumption in the building through the building shape.
Approaches concerned with climate prioritise reduction of energy loss through the building envelope (insulation, window area to orientation ratio, window to floor area ratio, surface to floor area ratio, zoning, thermal mass, mechanical ventilation) and reduction of electrical energy (utilisation of daylight, natural ventilation and energy efficient appliances) over lifecycle profile and human toxicity of materials, biodiversity and reduction of transportation.

This corresponds well with the distinction made by Williamson, Radford and Bennetts [Williamson, Radford and Bennetts 2003:1] between approaches concerned with the human impact on nature vs. approaches concerned with energy. (see page 39)

Appropriate term for PhD project
Environmentally Sustainable Architecture
Environmentally sustainable architecture was chosen as the appropriate term for this PhD project was a way of specifying that the project focuses on environmental sustainability and not the other aspects of sustainability, such as economical and socio-cultural sustainability, which in this project are regarded as being of equal importance as environmental sustainability. The choice to focus on environmental sustainability was therefore simply a way of narrowing the scope of the project.

The understanding of environmental sustainability applied in this project is related to the following understanding of environmental design; where 'environmental' means the relationship between the indoor environment and the outdoor environment in a selective approach to environmental design.

A study of the terminology, design strategies and dominant concerns relating to the different approaches to sustainability have resulted in the conclusion that environmentally sustainable architecture covers a lot of bases; from reductions in the energy consumption during the operation phase through the design of the building envelope, the layout of the building and the selection of appliances for the building, to reductions in the energy consumption during the production phase and the life cycle profile of the building and the integration of renewable energy sources and strategies for the flora and fauna development on the site or in an area.
These issues are all regarded as important in this thesis in relation to environmentally sustainable architecture, of these the reduction of the energy consumption of the building during the operation, and the flora and fauna preservation and development are regarded as a fundamental issue for environmentally sustainable architecture that must be considered, whereas the selection of appliances, the energy consumption during the production phase and the life cycle profile of the building, the integration of renewable energy sources are regarded as issues that might be considered as supplements to the issue of the energy consumption during operation and the preservation and development of flora and fauna. This prioritisation is caused by experiences with LCA studies that showed that the energy consumption for operation of buildings is greater than the energy consumption for the production and disassembly of buildings.
Ideally these issues should all be considered together in a joint evaluation of the environmental sustainability of projects, but this is not feasible in relation to the Danish tools that are currently

available for assessment of the environmental performance of buildings.

The approach taken in this project is focused on methodical approaches for development of design strategies in the early stages of a project, and the methodical approach tested in this project takes it outset in the energy calculations and the link between energy and building design. The project does, therefore, not include all the aspects of environmental sustainability.

6.2 Visual translations of approaches to sustainable architecture

The visual translation of the approaches to sustainable architecture is interesting in relation to how the design principles selected in the design strategies are integrated in the architectural expression of buildings. There are many different classifications associated with the visual translation of sustainability. Some projects are easily associated with a specific approach e.g. green architecture (by Wines' definition) and ecological architecture (by the approaches of self-builders [www.dr.dk/dr2/friland] and [Bech-Danielsen 2005]), while others are more difficult to place via visual interpretation e.g. passive houses and low-energy buildings, which can be difficult to recognise because the energy optimisation usually is in tune with local building traditions. It can therefore be difficult to distinguish between e.g. a low-energy or a passive building and a traditional building.

Through a literature study of the available publications about sustainable architecture I have found the following categorisations of the visual translation of environmentally sustainable architecture:

- High-tech, light-tech and low-tech [Daniels 1998, Mostaedi 2003 and 2002]
- Nature, culture and technology [Williamson, Radford and Bettetts 2003:chapter2]
- Symbiosis, Climatic and Cultural differentiation [Hagan 2001:chapter 7]
- Selective / Exclusive and Concealed / Exposed [Hawkes and Forster 2002:40-41]

6.2.1 Existing approaches to analysis of visual translation of sustainable architecture

High-tech, Light-tech and Low-tech

The approaches to high-tech and low-tech architecture presented by Daniels and Mostaedi seem a little different, where Daniels primarily discusses an approach to the technological strategies applied in a building:

> 'Low-tech – Light-tech – High-tech, the title of this book, expresses with confidence that architecture in the information age must be an integrated art. We must search for and discover, investigate and utilize for each individual building, the synergy between these three approaches of vastly different complexities. (…). Low-tech means designing buildings simply and harnessing the specific environment. Light-tech is a challenge to use raw materials sparingly and, whenever possible, 100 % recyclable material. When these are met, High-tech elements and devices can be integrated to create optimal working and living conditions with minimal energy consumption' [Daniels 1998:227]

Mostaedi primarily discusses projects which present the high-tech and low-tech approaches in the architectural expression and, thus, the visualisation and materiality of high-tech and low-tech sustainability:

Table 6.11: Mostaedi's definitions of high-tech and low-tech

High-tech	*Low-tech*
'the latest avant-garde movement in architecture. And it is what it says: the use of cutting-edge technology to maintain sustainability. Industrial materials such as steel and glass are used to make the most efficient use of resources and to create self-sufficient energy supply systems — that's what sustainable architecture is all about.' www.gingkopress.com/_cata/_arch/susthigh.htm	'Architecture is one of the disciplines in which the ecological spirit reaches its maximum expression. Sustainable Architecture is a vibrant new title in which several of the world's leading architects present houses they have designed with the health of the planet in mind. Each one is a brilliant example of originality and ingenuity and all are constructed of ecological or recycled materials and feature self-sufficient energy systems. Includes houses made of adobe, rammed earth, bales of straw, wood, bamboo and recycled materials such as tires and paper' www.gingkopress.com/_cata/_arch/sustarc.htm

Table 6.12: Visual exemplification from the two publications

Examples of high-tech projects	*Examples of low-tech projects*
 Koh Kitayama + architecture WORKSHOP: Omni Quarter (Tokyo Japan)	 Nader Khalili: Hesperia Museum and Nature Center (Hesperia, California, USA). www.gingkopress.com/_cata/ima2/sustar-0.htm
 Architecture Studio: Retirement residence (Paris, France)	 Shigeru Ban: Paper House (Yamanakako, Japan). www.gingkopress.com/_cata/ima2/sustar-0.htm

Daniels and Mostaedi both agree about the technological categorisation of the high- and low-tech projects. The difference is that Mostaedi furthermore focuses on the technological profile of the building materials, where the low-tech buildings apply materials with little embodied energy (e.g. wood and cardboard) and the high-tech buildings apply materials with a lot of embodied energy (e.g. glass and steel).

Nature, Culture and Technology

In 'Understanding Sustainable Architecture' Williamson, Radford and Bennetts have identified three images in the architectural discourse and practise associated with sustainable architecture [Williamson, Radford and Bennetts 2003:24]. These three images are Nature, culture and technology.

The following definitions were found in the publication for the three terms:

Nature:

> "In the natural image, the key to architectural sustainability is to work *with*, not *against*, nature; to understand, sensitively exploit and simultaneously avoid damaging natural systems. (…) 'Design with nature' at the building level is a code for recognizing sun paths, breezes, shade trees and

rock formations as natural features that can be 'worked with' in making somewhere for people to inhabit, while recognizing significant trees, animal tracks, habitats and natural drainage systems as natural features that must be 'protected'. (…) The archetypical visual image is the remote and isolated self-sufficient building dominated by its surrounding landscape. (…) The symbolic and 'eco-aesthetic' manifestations of this image reinforce identification with nature and natural systems. Materials are those of nature with little human modification: straw bale, rammed earth and pressed mud brick (…) Soft, organic, sensuous curves may be favoured over hard mechanical angles, and 'earth colours' over brighter hues. Neither does the building dominate its natural setting. Rather it expresses humility in the face of nature, its character coming as much from the play of sunlight and shade over its surface as from its own form" [Williamson, Radford and Bennetts 2003:27-29]

Culture:

"In *Architecture: Meaning and place*, (…). The cultural image portrays a distinct and meaningful *genius loci* of which architecture is a part. It mirrors an anthropological view that promotes keeping people culturally in place, combined with a belief that 'the logical culture knows best'. Sustainability means protecting and continuing this *genius loci*, and working within the limitations and possibilities that this requires. (…) The image embraces a concern for the way local people live and interact with their buildings, and an expectation that this will be different from other places. (…) Materials, colours and building forms draw on this local vernacular. Buildings are highly contextual (…) the new building is expected to rework rather than reproduce the vernacular, to be identifiably contemporary while eminently respectful of the past. (…) The impression that it would be difficult to expand this architectural language to accommodate the diversity and scale of contemporary requirements is a part of the cultural image. In it we have to accept that sustaining culture may mean limiting what is accommodated (the insertion of new activities into the community) as well as how buildings look. [Williamson, Radford and Bennetts 2003:29-31]

Technology:

"The technical image of sustainability portrays technical innovation in the solution of social, economic and environmental problems. In this image sustainability is a matter of developing technical devices that neutralize or make benefits out of what may temporarily appear to be problems. The track record of architects over the centuries in finding technical solutions to innumerable problems inspires confidence that the same will happen in the future. Success is seen as a matter of applying the tools of the social, economic and physical sciences to analyse the situation and discover a range of answers. But neither applying these tools nor implementing the answers is easy. The prerequisite for success is professional expertise. (…) The key is rationality and efficiency in planning, material use and systems. (…) The archetypical visual image is the high-tech corporate office in a city of similar offices: efficient people in efficient buildings, both in control, both responding to challenges through innovation. [Williamson, Radford and Bennetts 2003:31-32]

The images are caricatures, as most projects tend to apply more than one and sometimes all the images.

The images have been presented as corners of a triangle in which the specific approach of a project can be defined [Williamson, Radford and Bennetts 2003:31-33].

The images Nature and Technology also seem to embody close relations to the Low-tech and High-tech categories, where the nature image relates to the low-tech image presented by Mostaedi and the technology image relates to the high-tech image presented by Mostaedi.

Symbiosis, Climatic and Cultural differentiation
In the publication 'Taking shape – A new contact between architecture and nature' [Hagan 2001: chapter 7] Hagan identifies three themes in her study of architectural practises of environmental sustainability;

- Symbiosis between the built environment and the natural environment
- Climatic differentiation
- Cultural differentiation

The symbiosis between the built environment and the natural environment occurs when the architect steps out of his safe zone and embraces nature and/or climate and culture in his designs and, thus, changes his trademark signature as an architect in relation to the natural, climatic and/or cultural context. [Hagan 2001:147 and 155]

Climatic and/or cultural differentiation occurs when the architect adapts his design in accordance with the climatic and/or cultural conditions of the site. [Hagan 2001:156-161]

Selective / Exclusive and Concealed / Exposed
This approach to visual categorisation was introduced in chapter 6.1.6. The categorisation happens through a placement of the projects in the selective/exclusive vs. concealed/exposed taxonomy in illustration 56.1
The taxonomy provides a way of framing environmental design in relation to the selective and exclusive approaches to environmental design, while also placing the projects with respect to the visibility of the environmental profile of the building.

Because the taxonomy was developed for classification of environmental design projects its primary focus it whether or not the approach taken in the project is selective or exclusive. The taxonomy does, therefore, not discuss whether or not the projects take a natural, cultural, technological or climatic approach to achieving the environmental profile of the projects. However, one might argue that these approaches are embedded in the selective and exclusive approaches to environmental design.
Through a study of the publications placed in the taxonomy (these are represented by the dots and numbers in the taxonomy) it becomes apparent that the selective mode includes project which have cultural, climatic, natural, low-tech and light-tech approaches to environmental design, while the projects in the exclusive category primarily have a light-tech or high-tech approach to environmental design that may include cultural or natural elements, but not climatic, as an exclusive building by definition excludes itself from the climatic context.
The taxonomy does not provide a distinction between the cultural, natural and climatic projects, which to some extend makes sense, as the projects may have applied more than one of these approaches to environmental architecture. This is, however, still a bit problematic, as the approaches found in chapter 6.1 showed, that there are great differences between how the different approaches to sustainable architecture prioritise and include the natural, cultural, climatic and technological considerations.

6.2.2 Conclusions

Based on the preceding discussion of images and categorisations found in the investigated publications the following images were concluded to relate to the visual translation of approaches to sustainable architecture:

- Nature
- Climate
- Culture
- Technology

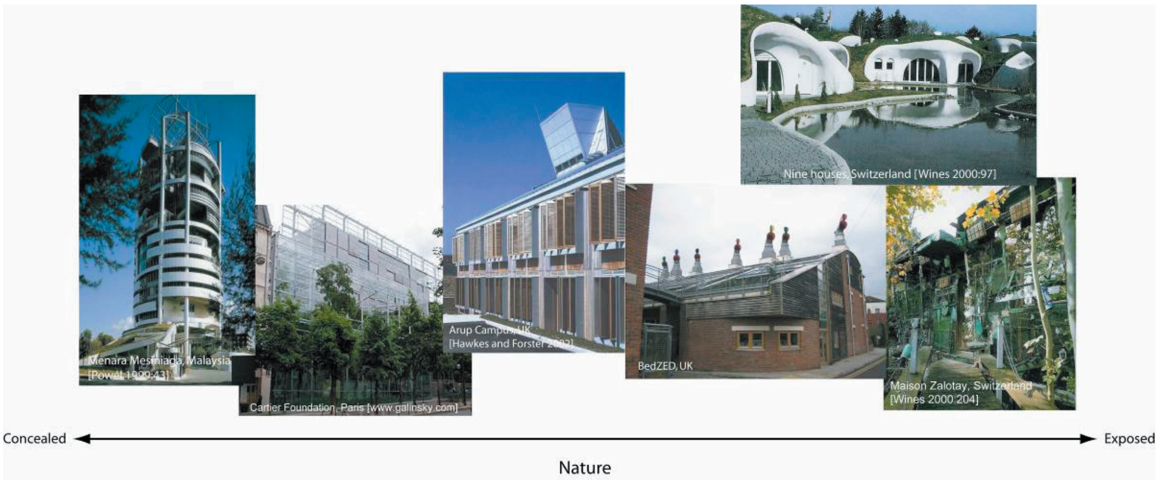
The images are the same as the dominant concerns listed in the conclusion of the previous discussion of the terminology and approaches to sustainable architecture, because they are also the main motivators presented in the approaches.

The nature 'image' by Williamson, Radford and Bennetts and the symbiosis (between the built environment and the natural environment) category by Hagan have similar qualities aiming at the integration or consideration of nature in the architectural expression of the building.

Climate and culture was identified by Hagan as a way of differentiating environmentally sustainable architecture from non-sustainable architecture. Culture was also represented in the three 'images' by Williamson, Radford and Bennetts, while climate was identified as a motivator for dealing with environmentally sustainable architecture [Williamson, Radford and Bennetts:1].

Technology was also represented in the three images by Williamson, Radford and Bennetts, as well as in the high-tech, light-tech and low-tech categorization by Daniels and Mostaedi.

The images can be evaluated on a concealed/exposed axis inspired by the 'Selective / Exclusive and Concealed / Exposed' taxonomy developed by Hawkes and Forster [Hawkes and Forster 2002:41]:



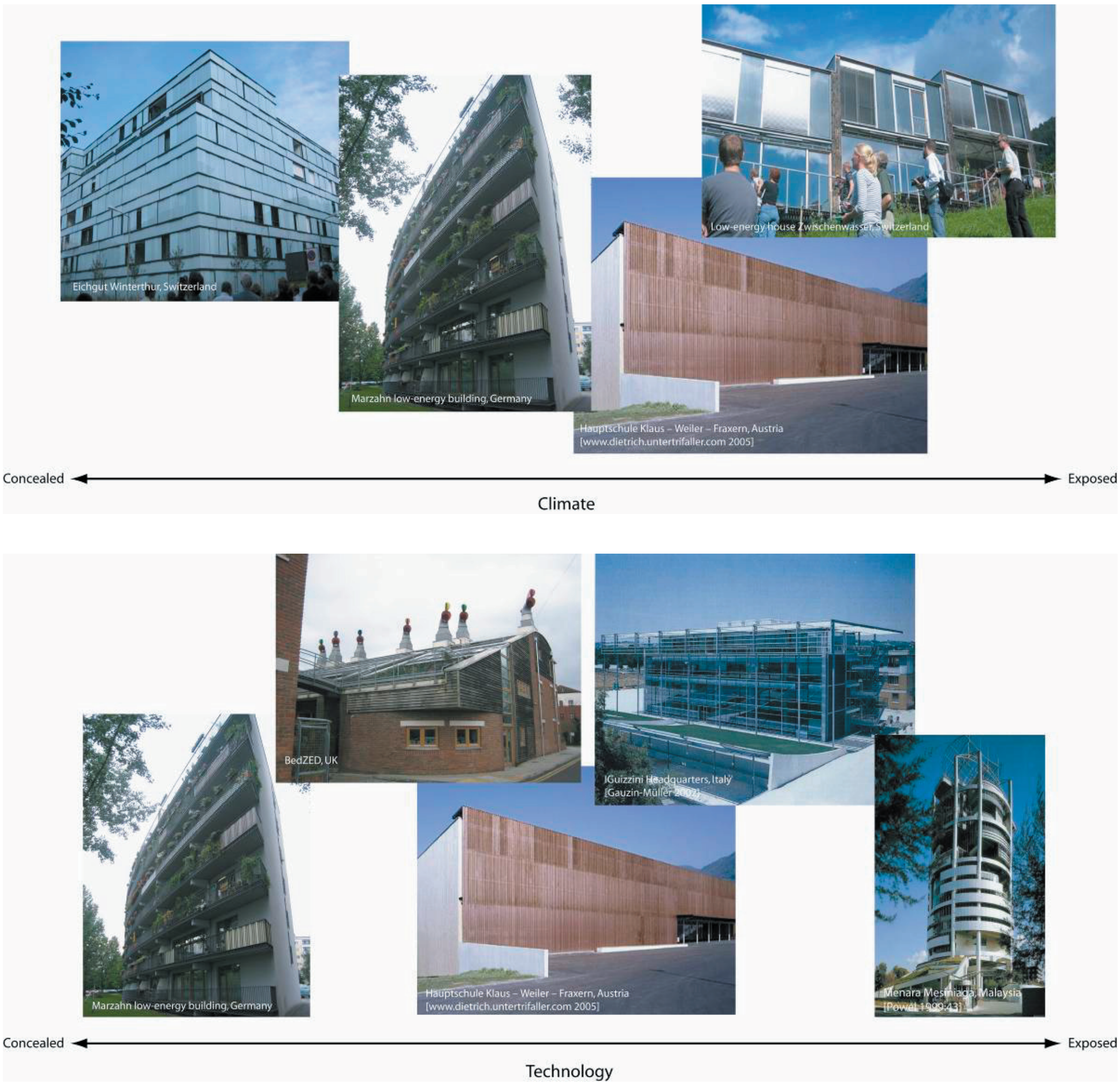


Illustration 71.1: Placement of projects in relation to the degree with the images of Nature, Climate, Culture and Technology are exposed or concealed in the architectural expression of the projects.

6.3 Methodical process descriptions

Methodical process descriptions are included in this state of the art because process awareness is often stressed as being important by publications in the field of environmentally sustainable architecture. The following paragraph contains process descriptions found in some of these publications.

What characterises the methodical process descriptions is that they primarily focus on the phases, actors and tasks involved in the design process, and not so much on design strategies.

6.3.1 IEA Task 23

The IEA Task 23 project was located within the Solar Heating and Cooling (SHC) programme of the International Energy Agency (IEA), and the title of the project was “Optimisation of Solar Energy Use in Large Buildings”.

Researchers and practitioners from twelve countries participated in the project (Austria, Canada, Denmark, Finland, Germany, Japan, Netherlands, Norway, Spain, Sweden, Switzerland and USA), which primarily focused on exploring the nature of the integrated design process (IDP).

Besides investigating the traditional design processes in nine European countries, the IEA Task 23 also deals with integrated design in relation to the development of a guideline for sustainable and solar-optimised building design.

The project consisted of four subtasks;

- Subtask A: Case stories
- Subtask B: Design process guidelines
- Subtask C: Methods and tools
- Subtask D: Dissemination and demonstration

It is especially the results of subtask B, which are interesting to this project, as this subtask deals with both the traditional design process in the participating countries and the notion of the Integrated Design Process.

The traditional design process

In the IEA Task 23 a survey was carried out in order to find out what the traditional design process looks like in nine different countries. The investigation was carried out, respectively, in relation to the work of an architect and an engineer.

Table 6.13: The Danish results of the survey; the building process is divided into eleven phases. The investigation of the traditional design process, furthermore, registered how the workload was distributed for respectively architects and engineers (the percentages shown in the table). [www.iea-shc.org/task23/:Guideline:TDP: 13 and 25]

Phases	*Architect's tasks*		*Engineer's tasks*	
Investigation of basics	3%	• Summary of clients needs (design objectives) • Information on primary requirements from authorities • Set up requirements for room layout, areas etc. • Set up economical frame and over all time schedule with the client • Set up organisation of participants and decision making procedure • Summary report	5%	• Summary of clients needs (design objectives) • Information on primary requirements from authorities • Set up requirements for room layout, areas etc. • Set up economical frame and over all time schedule with the client • Set up organisation of participants and decision making procedure • Summary report
Schematic design	7%	• Conceptual design mentioning different alternatives • Describe environmental, aesthetic, functional, technical and economical factors • First floor plans and façade sketches • Set up principle plan for constructions and systems with the engineers • Estimate economy • Summary report		
Design proposal	10%	• Extension of schematic design • Building description • Drawings (plans, cross sections and facades dependent of building size) • Propose materials • Propose type of tender • All principal investigations should be finalised • Time schedule for planning and construction • The client's approval is the basis for the final economy		

Table 6.13: The Danish results of the survey; the building process is divided into eleven phases. The investigation of the traditional design process, furthermore, registered how the workload was distributed for respectively architects and engineers (the percentages shown in the table). [www.iea-shc.org/task23/:Guideline:TDP: 13 and 25] (Continued)

Phases	*Architect's tasks*		*Engineer's tasks*	
Preliminary design	10%	• Extension of design proposal to get a principal approval from authorities • Site plan, plans, cross sections and facades according to building regulations • Update of time schedule • Update of economy • Report: technical part of application for construction permission	15%	• Extension of design proposal to get a principal approval from authorities • Drawings of typical systems • Update of building descriptions • Update time schedule • Update of economy • Report: technical part of application for construction permission
Building documents	30%	• Elaboration of building documents and drawings according to building codes, regulations, approval by authorities, tender, contract and construction • Final documents for tender • Final approval from authorities	45%	• Elaboration of building documents and drawings according to building codes, regulations, approval by authorities, tender, contract and construction • Final documents for tender • Final approval from authorities
Mass records and advertising	2%	• Detailed description of materials used in the building • Advertising tender procedure	5%	• Detailed description of materials used in the building
Negotiation / contracting	3%	• Management of tender procedure • Contract negotiations with cheapest contractor • Contracting	5%	• Contract negotiations with cheapest HVAC contractor • Contracting
Construction management	10%	• The construction management is often carried out under the command of the leader of the design phase • The construction manager represents the client towards the contractor • Responsible for coordination meetings for the contractors • Coordination of construction supervision, time schedule and economy • Control of budget, checking final invoices		
Construction supervision	15%	• Supervision of building construction according to building documents • Inspection of construction, quality, timing and economy • Participation in coordination meetings for the contractors	20%	• Supervision of building construction according to building documents • Inspection of construction, quality, timing and economy • Participation in coordination meetings for the contractors
Building documentation	5%	• Elaboration of building documents according to the final building construction		
Supervision after 1 year of operation	5%	• Inspection of the building construction • Management of repair of defects	5%	• Inspection of the building construction • Management of repair of defects

When studying the results of the survey, the segregation of the work areas of architects and engineers in the traditional design process become very clear; the engineer comes in very late in the design process and is only briefly involved in the beginning of the design project when setting up the basics for the project.
It is also sticking that the architect more or less is involved in all the phases of the traditional design process, whilst the engineer only is involved in about 60% of the phases.

Integrated design process

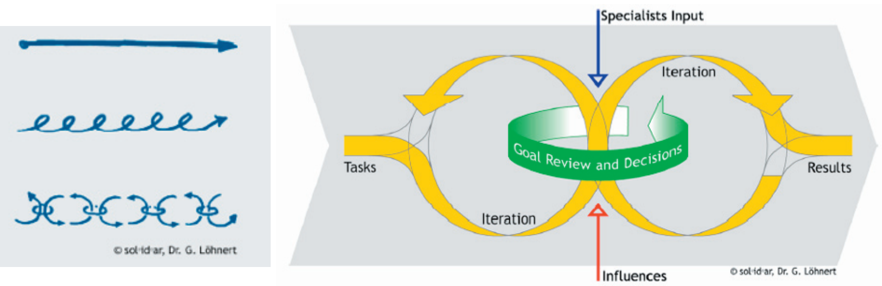
The work done in relation to the integrated design process has concentrated on these elements:

- "Inter-disciplinary work between architects, engineers, costing specialists, operations people and other relevant actors right from the beginning of the design process;
- Discussion of the relative importance of various performance issues and the establishment of a consensus on this matter between client and designers;
- Budget restrictions are applied at the whole-building level, and there is no strict separation of budgets for individual building systems, such as HVAC or the building structure. This reflects the experience that extra expenditures for one system, e.g. for sun shading devices, may reduce costs in other systems, e.g. capital and operating costs for a cooling system.
- The addition of a specialist in the field of energy, comfort or sustainability;
- The testing of various design assumptions through the use of energy simulations throughout the process, to provide relatively objective information on this key aspect of performance;
- The addition of subject specialists (e.g. for daylighting, thermal storage etc.) for short consultations with the design team;
- A clear articulation of performance targets and strategies, to be updated throughout the process by the design team.
- In some cases, a Design Facilitator may be added to the team, to raise performance issues throughout the process and to bring specialised knowledge to the table."

[www.iea-shc.org/task23/www.iea-shc.org/task23/:Guideline:introduction:9]

Phases

The Integrated Design Process presented in Task 23 contains seven phases; Basics, Pre-design, Concept development, Design development, Building Documentation, Execution and commissioning, and Building operation. The process is iterative with transitory stages in between the iterations. These transitory stages are used to review the results of the preceding stage, and they are in the IEA Task 23 considered as the key to integration (Illustration 74.1).



llustration 74.1: Left: linear vs. iterative vs. integrated process. Right: focus on transitory stages which are regarded as the key to the integrated design process. [www.iea-shc.org/task23/: Guideline:IDP date: June 9th 2006:18]

Workflow and tasks

The IEA task 23 has resulted in a work-flow diagram that shows the main activities, formal results and the transmission decision steps of the client in relation to the phases and loops of the process. The activities emphasised in the work-flow diagram are of a technical nature and they focus on the products of the process and the involvement of the different actors in relation to the iterations performed in the design process.

Table 6.14: The tasks presented in this iterative workflow diagram [www.iea-shc.org/task23/: navigator]

Stage	*Tasks*
Basics	• Project brief, objectives, background and influences • Site inspection, site analysis • Programme demand and requirements • Feasibility studies • First design advice • Contracts and safeguard financing • Project definition report • First project initiative • Design start up decision
Pre-design	• Building programme requirement profile • General approach for energy supply and systems • Set up design team • Call in expert (e.g. jury) • Investigation on urban integration, proportion and site development • Rough cost estimate • Consider building codes, regulations and industry standards • General Dispositions (mass/functions), horizontal/vertical development, building periphery • Design alternatives • Preliminary design approach • Pre-design report • Pre-design decisions
Concept design	• Renewed/specified building programme performance profile • Set up/complete design team • Call in expert • Check interfaces; proportions, multi-functionality, flexibility • Review goals and requirements, • Qualified cost estimation • Calculations, simulations, quantifications • Design and gross design of system solutions • Building and energy system, spatial structure and construction, envelope, Daylighting, solar, Traffic and HVAC systems • Concept design approach • Concept design report • Concept design decisions
Design development	• Centred requirements performance profiles • Complete design team • Call in expert • Modular tuning of space use, construction elements • Life cycle cost analysis, cost calculation • Detailed constructions, Simulation • Optimise system solutions, final sizing, system operation • System integration, selection of building components and materials • Design development approach • Design development report, building documents • Definitive design decisions
Building Documents	• Confirmed performance profiles • Construction documents • Environmental criteria and specs for tender • Construction strategies
Negotiating and contracting	• Requirements upon builders and suppliers. • Call for tender • Bidding • Negotiation • Building contracts • Building contract decisions • Contracting

Table 6.14: The tasks presented in this iterative workflow diagram [www.iea-shc.org/task23/: navigator] (Continued)

Stage	*Tasks*
Execution and commissioning	• Commissioning plan for energy related • Construction works • Operational, functional and energy performance checks • Analyse and assess impact caused by project change • Implementation of necessary changes • Construction supervision, cost control, quality assurance • Identify and eliminate deficiencies • Final commissioning • Commiss. report certificate of build. • Building use/rent decisions
Operation	• Lease/use contract • Occupation • Operation strategies • Management and maintenance plan • Operation manuals • Management, control, optimisation • User/operation staff information and training • Operation • Energy checks, monitoring • Adjust energy performance to user demand • Changes in building use • Basics for retrofit design

Navigator

The navigator is designed as an excel file containing the flow chart, a list of actors, issues relating to the different tasks presented in the flow chart and a discussion of available methods and tools.

The navigator tool is designed as a process management tool, and the workflow diagram and the navigator can be applied throughout a project to structure the teamwork and delegate tasks. It also provides a good insight into the interdependence of different tasks performed throughout the design process.

Actors

The navigator provides the following list of actors, from which one can read which actors the different abbreviations refer to, as well as the role of each actor.

Table 6.15: The list of actors presented in the navigator [www.iea-shc.org/task23/: Navigator,Actors]

Name	Nr	Actor	Role
CL	1	**Client**	
IN	2	Investor	Provide all or part of financing
DV	3	Developer	Manage the process of site acquisition, project development, design & construction
O	4	Owner	Own all or part of the building; could also be investor or developer or buy later.
PM	5	Project manager	Retained by developer to organize whole process, incl. site and project development, design & construction
RO	6	Regulatory officer	Represents local authority in interpretation of regulations
DT	7	**Design Team**	
AR	8	Architect	Professional architect, usually in charge of overall design process
EP	9	Energy planner	Supports improved energy performance by proposing design approaches to design team
SE	10	Structural engineer	Designs the building structure

Table 6.15: The list of actors presented in the navigator [www.iea-shc.org/task23/: Navigator,Actors] (Continued)

Name	Nr	Actor	Role
ME	11	Mechanical engineer (HVAC)	Designs HVAC and plumbing systems
EL	12	Electrical engineer	Designs electrical systems
BS	13	Building envelope specialist	Assesses features & proposes measures to improve building envelope performance
CE	14	Civil / Services engineer	Designs infrastructure, such as sewers & roads on site
GE	15	Soils Engineer / Geologist	Assesses site for soil and foundation issues, undertakes remedial action
LD	16	Landscape designer	Designs site improvements and landscaping
ID	17	Interior designer	Designs interiors, especially in retail or office buildings; usually directly for tenants
DF	18	Design facilitator	Facilitates the design process through management techniques
QS	19	Quantity surveyor / Cost consultant	Calculates quantitities and costs
ES	20	Energy simulator	Undertakes energy simulations
DS	21	Daylighting specialist	Assesses features & proposes measures to improve daylighting performance
LS	22	Lighting specialist	Designs artificial lighting systems, for architect and/or for tenants
AS	23	Acoustic specialist	Assesses features & proposes measures to improve acoustics & reduce noise
CS	24	Controls specialist	Designs automated building control systems
TS	25	Telecom specialist	Designs building telecom systems
MS	26	Eco / materials specialist	Assesses features & proposes measures to improve environmental performance of building materials
ELE	27	Elevator / escalator specialist	Designs building elevator and/or escalator systems
FS	28	Fire specialist	Assesses features & proposes measures to improve building fire safety performance
OS	29	Other specialist	Could include specialists in retail, hotel, hospital design etc., or other specialized technical system.
AS	30	Architect site supervisor	Supervises construction on behalf of architect
SS	31	Specialist site supervisor	Supervises construction / installation of a specialized system
CS	32	Construction site supervisor	Supervises construction on behalf of contractor
GC	33	General contractor	Main contractor, who uses sub-contractors
C	34	Contractor	
SC	35	Sub-contractor	Specialized contractors retained by general contractor
PM	36	Building products manufacturer	Producer and vendor of building materials or manufactured products
CA	37	Commissioning agent	Designs and executes commissioning plan, to ensure that design intent is fulfilled
BO	38	Building operator	Responsible for overall operation of the building, on behalf of the owner
BM	39	Building operating & maintenance staff	Responsible for routine operations and maintenance
T	40	Tenant	Responsible for lease for all or part of a building
UO	41	User / Occupant	Uses the spaces within a building, either as a worker, resident or visitor

Design team
The navigator operates with what it calls the core team consisting of the architect, structural engineer, energy engineer, mechanical engineer and lighting specialist:

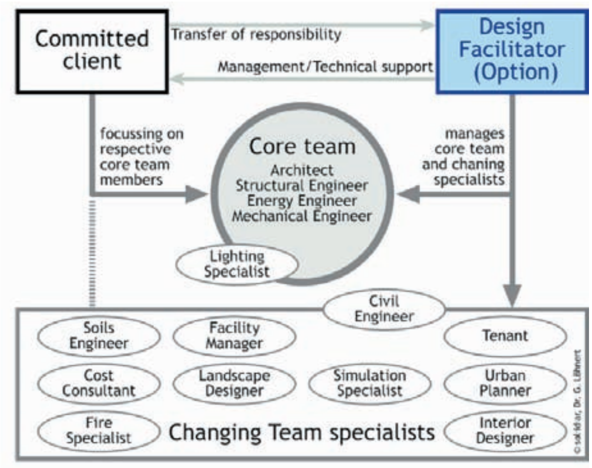


Illustration 78.1: The core team is multi-disciplinary, in this case via actors representing different disciplines. [www.iea-shc.org/task23/:Guideline: IDP:13]

6.3.2 The Integrated Design Process (IDP) by Knudstrup

In 1997 a new type of engineering education was started at Aalborg University (Denmark), which focused on the development of a new inter-disciplinary profile at Aalborg University which deals with the inter-disciplinary field between architecture and building engineering. Today this education is located at the Department of Architecture and Design at the Faculty of Engineering, Science and Medicine at Aalborg University (Denmark). [Knudstrup 2006:2, www.aod.aau.dk 2007]

In 2000 the first environmental design project was made on the education's 6th semester on the architecture specialisation. In the study guide for the semester Associate professor Mary-Ann Knudstrup formulated a methodical approach to the design of environmental design entitled The Integrated Design Process (IDP) [Knudstrup 2001]. Today the IDP used by staff members and students as a fundamental methodical approach taught at the master level at the department.

Knudstrup formulated the description of an integrated design process which could enable the link between the architectural design of buildings and the energy and comfort calculations associated with environmental design. The process description in the study guide consisted of a phase description and a strategy for which tasks to solve in the different phases of an environmental design of an office building. [Knudstrup 2004:3-4]

This illustration shows the issues Knudstrup described in the study guide for the first environmental design project at the education in 2000;

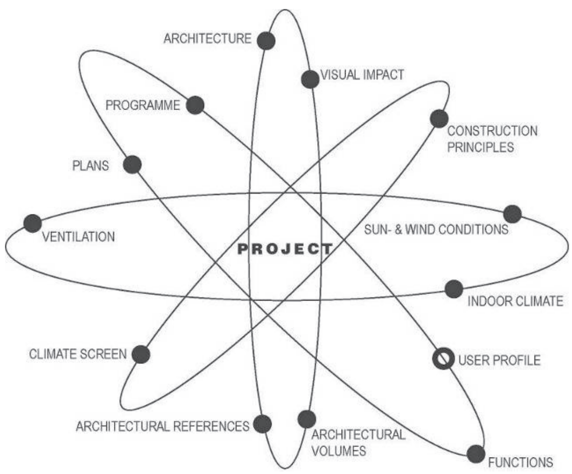


Illustration 78.2: The project is depicted as the nuclear core of an atom and the issues as the electrons orbiting the core. The idea is that all the issues are to some extend needed to define projects. The user profile is emphasised because it is especially important in Danish architectural traditions [Knudstrup 2004:8]. The issues that are of special interest in a design project are identified in the atom and used in the generation of ideas for the architectural design of the building.

The Integrated Design Process was designed to be flexible, which means that one can implement about as many design issues in the process as necessary for a project. The IDP, thus, varies according to the type of project it is applied to, and it can therefore be applied with a different focus than what it was originally designed for.

The teaching form at Aalborg University focuses on problem based learning and the students therefore work in teams of tree to seven students. As Illustration 74.2 indicates the approach focuses on inter-disciplinarity, and the students, thus, have to integrate different types of engineering skills in their building design process. This situation creates a new type of inter-disciplinary team consisting of actors with a similar educational background, but these actors might have different strengths e.g. in architectural scale and environmental, acoustic or construction engineering.

Inter-disciplinarity

The Department of Architecture and Design has a close cooperation with a number of polytechnics at different departments of the university which enables the multi-disciplinary teaching needed in order to enable the students to work in an inter-disciplinary field such as environmental architecture or tectonic architecture.

The intention of the IDP was to find a way of enabling the implementation of technical discussions and calculations early in the architectural design process for varies reasons, such as for enabling environmental architecture or simply just to ensure better integration of the construction and systems in the building in the aesthetic expression of a building. [Knudstrup 2006:2]

Through the inter-disciplinary approach the Integrated Design Process enables the designer to control and integrate the many tasks, design strategies and issues that must be considered when creating good environmentally sustainable architecture [Knudstrup and Hansen 2005:7].

During my PhD studies I have participated in the teaching staff at the architectural specialisation at the master level at the Department of Architecture and Design at Aalborg University (Denmark). Through this participation I have experienced first hand that it makes a difference that the staff involved in the inter-disciplinary field created by the teaching staff on the 8th semester are consistent from year to year. When this is not the case the teaching agenda for the semester changes and the integration of architecture and building engineering courses and supervision becomes more difficult because the staff members are unfamiliar with each others professional language and preferences. This does not mean that it is impossible to reach the integration; it just means that the integration is most effective when the staff members on the semester have worked together before.

Phases

The process is divided into five phases (shown here chronologically); a project-formulation phase, an analysis phase, a sketching phase, a synthesis phase and a presentation phase. The phases may be performed by one person or a team of students.

The problem-formulation phase, which is also called the project idea phase, is where the brief is formulated, based on discussions with the client and preferably all the parties involved in the project.
The analysis phase is where analyses, such as a site analysis, a climate analysis, function analysis, analysis of the user profile, comfort analyses etc., are performed. [Knudstrup 2004:5]

The sketching phase involves the solution of the problems, target values and aims found through the varies analyses in relation to the project idea and the brief. The sketching takes place on several levels and with different degrees of detail. In this phase technical calculations and discussions based on the sketches and the aesthetic ideas are implemented in order to find solutions to the technical parameters of the project which are in harmony with the architectural expression desired in the project. Furthermore, the technical considerations and discussions are implemented in order to ensure the legality of the solutions and the comfort conditions in the building, as well as for instance the sustainability of the building. [Knudstrup 2004:6-7]

The synthesis phase in when the different aesthetic and technical parameters of the project unite into an architectural expression which, hopefully, contains many qualities. This is in other words where the generation of good architectural solutions may happen. This phase also involves technical calculations and discussions and all the loose threads of the project are gathered and the relations between the different solutions are evaluated. [Knudstrup 2004:7-8]

The presentation phase is where the project is presented to the client and the other parties involved in the project .This can be done differently depending on the type of project, for instance, there is a big difference in the choice of communication between competition projects, commissioned projects and student projects. [Knudstrup 2004:8]

In relation to teaching the IDP focuses up until the presentation of the pre-project, i.e. before the projecting phase. It should, however, make the projecting phase run smoothly, as many of the technical solutions are already considered during the sketching phase and analysis phase.
In relation to research the IDP should also be applicable in relation to the later phases of the design process.

Iterations

As indicated in the illustrations below iterations occur within each phase, as well as, between the phases:

Illustration 80.1: Examples of iterations within the phases [Knudstrup 2004:7]

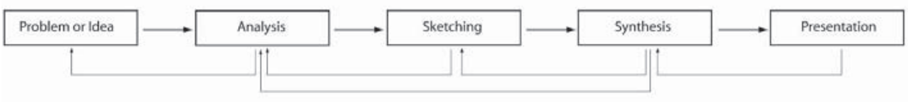


Illustration 80.2: The phases and iterations between the phases in the integrated design process [Knudstrup 2004:5]

Tasks

In her description of the Integrated Design Process Knudstrup describes the different tasks involved in the student projects in relation to each phase of the project:

Table 6.16: The tasks described for the different phases of the IDP [Knudstrup 2004:4 and Knudstrup 2006:2-3]

Phase	*General phase description*
Problem formulation	• Formulation of problem; discussion with (fictive) client about programme and design brief, description of the project idea for an environmental or sustainable building.
Analysis	• Analysis of site; wind, sun and landscape, architecture in the neighbourhood, topography, vegetation, light and shadow, access to the site and size of the area and neighbouring buildings, the sense of the place (Genius Loci), • Urban development plans (regional plans, municipal and local plans) • Client (and user) profiles; demands for space and logistics etc., • Chart of functions • Architectural expression (iconic or adaptive to context?) • Principles and targets of energy consumption (for heating, cooling, ventilation and lighting), indoor environment (thermal comfort, air quality, acoustics and lighting qualities) and construction. • Criteria for application of passive technology; natural ventilation, daylighting, passive heating and passive cooling, developed in consideration of the local climatic context and local energy distribution facilities. • Other criteria or wishes stated by client (LCA of materials, Solar panels or PVs) • Aim and programme collected in an architectural programme.
Sketching	• Professional knowledge of engineers and architects is combined for mutual inspiration to ensure that the demands and wishes for the building are met • The demands for architecture, design, working or living environment • Visual impact and demands for functions, construction, energy consumption, indoor environment, and other quality criteria such as architectural quality, thermal comfort, views to the outside, lighting quality. • Consideration of the defined criteria and target values (incl. the ones defined in the architectural programme from the analysis phase) in the development and evaluation of design solutions though continuously estimation of how sketches meet the defined criteria and target values (e.g. how the choices made for building form, the plans, the architectural programme, the orientation of the building, the construction and the climate screen influence the energy consumption of the building for heating, cooling, ventilation and daylight, and how these choices inspire each other).
Synthesis	• The final decisions are made for the design of the building, so the design meets the demands made in the architectural programme and the project reaches a synthesis between e.g. the architecture, plans, visual impact, functionality, client and user profile, aesthetics, the space design, working environment, room programme, principles of construction, energy solutions and targets and indoor environment technology. • The building performance is documented detailed calculation models • The project finds its final form and expression in which, hopefully, the architecture, architectural volumes, aesthetic, visual impacts, functional and technical solutions and qualities have been created.
Presentation	• Presentation of the final a report, drawings, a cardboard model and computer visualisations in a way that displays the qualities of the project and how the aims, design criteria and target values have been fulfilled.

6.3.3 Owen Lewis

The publication “A Green Vitruvius – principles and practice of sustainable architectural design” is a compilation of experiences, design practices and rules of thumb gathered from different practices and research institutions. The publication is funded and developed by the European Commission, the Architects’ Council of Europe, the Energy Research Group, SOFTTECH Energia Technologia Ambiente and Suomen Arkkitehtiliitto. This means that the publication has a wide range of contributors and, thus, contains a lot of knowledge, which is easily accessed by reading this publication.

The publication contains a very detailed process description, which embraces most if not all the key-issues and systems involved in green architecture on a need to know basis. This means that this publication contains a lot of information beneficial for new-comers to the field of environmentally sustainable architecture, but not as much beneficial information to people who are experienced in the design environmentally sustainable buildings. The publication is, thus, a good read for professionals or students embarking on the sustainable adventure. This might rule out the news value to people already working within the field of sustainable architecture, but because of the holistic approach applied in the publication these people will also acquire new knowledge by reading chapters in this book which lie outside their area of expertise, unless, of course, they are familiar with every aspect of environmentally sustainable architecture.

The publication focuses on the technical and communication aspects of green architecture and can, thus, be regarded as a technical guide to green architecture. The issue of architectural expression is embedded in the titles applied to the different stages, but it is not discussed further in any parts of the publication.

The publication is divided into 5 sections, which respectively focus on; Process, Issues, Strategies, Elements and Evaluation and one can use it as an encyclopaedia of environmentally sustainable design.
The publication also contains lists of strategies, key areas and tasks, as well as issues for each stage of the design process. The strategies were presented in chapter 6.1.3, while the issues, tasks and key areas for specialist advice are described in this chapter.

Stages of the design process
The process is in this publication described, as consisting of these stages:

- Inception
- Design;
    - Preliminary studies
    - Sketch Studies
    - Pre-project
    - Basic project
    - Execution of project
- Construction;
    - Tender procedure
    - Supervision
    - Acceptance
    - Defects Period
- Maintenance and Refurbishment

The very thorough description of the issues relating to each stage of the process deals with both the product related issues as well as communication related issues (i.e. the communication between the different actors involved in the project). [Owen Lewis 1999: 7-23]

The thoroughness of the stage description, as well as in the rest of the publication, is what in this PhD thesis, lands this publication the merits of being regarded one of the most complete methodical process descriptions in the field, as it really does consider all the actors and stages involved in the project. It equips the reader with a thorough understanding of the process of ‘green architecture’ and with rules of thumb on how to approach the different issues stated in relation to the different stages of the process.
However, one should, as always, be cautious when applying these rules of thumb, as their application will have different results when applied in different projects.

Table 6.17: Issues at the Briefing stage [Owen Lewis 1999:12-13]

General	• Will the client actively manage the environmental control systems on a day-to-day basis? • If there is a choice between refurbishment and new build, explore client preconceptions and see whether lower standards are acceptable in structural capacity and environmental control, to retain the existing fabric • Review and agree design comfort standards with a view to reducing energy demand • Explain the need for climatic data on the site: macro-climate; material from meteorological stations and micro-climate: survey work might be necessary
Building use	• Use patterns (diurnal, weekly and seasonal) affect environmental requirements and choice of structure and systems. Construct a use profile of the building: occupants and activities at different times of day and week.
Architect	• What green expertise does the architect have? Don't pretend expert knowledge without dedicated training and/or substantial experience. • Explain that the subject is not yet definitively researched and that much remains to be done in researching green urban planning and materials for example
Consultants	• Do you recommend that environmental, daylighting or energy consultants be appointed? • Who will pay for these? • Can this cost be offset against 'normal' consultants? Does the client intend to nominate consultants? If so, do they have 'green' expertise or do they need to be supplemented by specialists? • Ensure that the scope of appointments includes the requisite environmental advise.
Heating	• Explain the possibility of passive measures; their contribution to performance • Can the client use sunspaces if these are provided? • How does the client feel about draught lobbies? About zoning the plan? • Are weather compensating controls justified? • Will the client use 7-day programmable controls? • Would the client consider a CHP installation?
Cooling	• Will the client countenance passive cooling measures if these are judged useful? • How precise is the level of environmental control required? (Can temperatures go above comfort levels, say, 5 days per year? Or never?)
Lighting	• Is daylight maximisation a desirable goal? • Will the client pay for passive infrared switching? For individual light switching? For photoelectric override of active systems?
Ventilation	• Will the occupant operate manually operated trickle vents in windows? • Is passive stack ventilation an option (it may be in apartment buildings)? • In what areas is mechanically assisted ventilation required? • Identify the possibilities of heat exchangers, discuss the capital against life cycle costs
Water	• Would the client pay for low-water WC cisterns and lavatory controls, spray taps? (depends on water tariffs, explain that these are subject to gradual increase). Similar issues surround domestic appliances (dishwasher, washing machines)
Waste	• Discuss disposing of surface water run-off on site and advise on the need for treating run-off from car parks • Is composting of domestic refuse on site acceptable? • What provision might be made for recycling of paper, of packaging? Extra storage space needed?
Site works	• Identify existing vegetation to be conserved and discuss how this affects the design • Discuss the provision of sheltered and secure bicycle storage on site
Materials	• Explore the possibility of alternative structural systems and materials, which might influence load-bearing capacity • Discuss performance of finishes, especially internal wall and floor finishes, and of window and external door materials, in connection with improved indoor air quality, as against ongoing maintenance requirements
Cost	• To what extent is the client concerned with life-cycle issues? Explain life-cycle costing: investigate the client's intention for the building: short or long-life investment? It is not yet easy to demonstrate against that of comparable non-sustainable buildings • Try to obtain agreement that a measure of life-cycle costing may be factored into all design and specification decisions
Timescale	• Does the design team require more time at any stage in the process to explore design issues? For example: alternative site studies, daylighting studies, and heating and cooling calculations at sketch design stage, particularly if few persons are available to undertake specialist tasks
Contractor	• Discuss the steps needed to select the contractor and how the green design will impact on the construction process

Table 6.18: Issues at Preliminary Studies stage [Owen Lewis 1999:14]

Site	• Obtain environmental information about the site • Examine the environmental impact of alternative strategies • Examine a number of alternative sites if this option is available • Incorporate green issues into the feasibility studies reports

Table 6.19: Issues at sketch studies stage [Owen Lewis 1999:15]

Site plan	• Protection and use of pre-existing site characteristics: vegetation, landscaping, topography, water; site disposition for insolation, shading and shelter; proportion of hard landscaping for water run-off or conservation; vegetation and shelter; cold air drainage • Orientation, zoning and general disposition, with impact on energy consumption
Building plan	• Section height and depth, number of floors and orientation to optimise daylighting, to enable passive ventilation using the stack effect and to reduce heat loss. Which factors can be optimised through shallow plans, high floor to ceiling heights, and roof lighting via the ceiling or an atrium
Elevation	• Broad proportions of fenestration, with effects on daylighting, ventilation, overheating on east, west and south facades, which can be passively controlled by the use of external shading devices
Materials	• Structural system (concrete, steel or timber) and external envelope, and their environmental impact

Table 6.20: Issues at pre-project stage [Owen Lewis 1999:16]

Site plan and external landscaping	• Consider layout and orientation of building groups in relation to insolation and overshadowing • Consider size and location of hard surfaces in relation to desired sunlight and shelter • Use earth berms and shelter planting to create protected and sheltered areas
Building plan and section	• Provide draught lobbies at entrances where necessary • Optimise use of daylight in habitable spaces • In northern latitudes, zone areas such as sanitary, circulation and storage to the north • Include air flow paths for natural ventilation in plan [if the building is swallow] and section [perhaps employing the stack effect]
Elevation	• Consider proportions of glazing to opaque façade for daylight distribution and passive heating and cooling • Control glare and overheating, particularly on east and west facades: consider shading devices [external louvers or set backs, blinds]
Materials	• Consider use of structural thermal inertia to dampen internal temperature fluctuations • Consider sustainability and environmental impact of materials, embodied energy, impact on habitats, toxic emissions and ease of recycling or re-use
Specialist consultants	• Presentations should indicate how environmental principles will be developed at detailed design stage, and how proposals will be evaluated, with maximum use of passive systems
Technical principles	• Consider combined heat and power to reduce primary energy use • Provide outline illustration of environmental performance, particularly through plan and section diagrams for passive and active energy flows: heating season – day; heating season – night; cooling season – night and Sankey diagrams of energy flows

Cost	• Consider factoring environmental and life cycle costs into initial estimates
	• Where higher initial costs is proposed this may be for better performance, improved environmental quality, and/or lower life cycle energy and environmental cost, e.g.,
	  • High quality as against poor quality timber window frames
	  • Linoleum floor finishes as against petrol chemical based sheet floor finishes – more acceptable emissions and smell
	  • Compact fluorescent light bulbs as opposed to tungsten, passive infra red switching
	• Design for re-cycling

Administrative authorities	• Consult about innovative propositions for fresh water supply, rain water disposal or reuse, grey and black water disposal • Discuss advantageous tariffs for low consumption with utilities • If the building generates electricity [photo-voltaic panels, wind] discuss buy-back with the utility company as necessary

Table 6.21: Issues at basic project stage [Owen Lewis 1999:17]

Site and building plans	• Confirm earlier decisions on site and building plans: siting and positioning for insolation and shelter; form for overshadowing; layout and extent of hard and soft landscaping • Consider disposal of surface water within the site • Consider treatment of polluted water from vehicle hard standings
Section and elevation	• Confirm floor to floor heights to maximise daylight and natural ventilation and avoid overheating • Confirm façade proportions, and provision and design of external shading to prevent overheating • Consider opening sections in windows for passive ventilation • Confirm previous decisions on sustainable materials
Specialist consultants	• Consider long life and loose fit building structure and the adaptability of structure and services for different building use • Long-term adequacy of load-bearing capacity • Ensure accessibility to ductwork, pipes and wires, with removable covers, demountable trunking • Size conduit drops in walls for easy rewiring
Technical principles	• Develop design of building services systems from the principles previously enunciated • Make calculations of building energy performance

Table 6.22: Issues at project stage [Owen Lewis 1999:18]

Site plan	• Specify rainwater soak-aways and ponds • Closed sewage treatment systems
Section and elevation	• Select glazing frames for best performance • Glazing to incorporate low emissivity coatings • Use trickle ventilators, and/or passive ventilation strategies • Use heat recovery where appropriate • Insulate beyond building regulation requirements in sustainable materials • Detail to avoid cold bridging
Materials	• Specify for long life and low embodied energy • Masonry components of local origin, roof finishes for long life, greater thickness of sheet flooring, timber boards of low formaldehyde content, lime-based plaster mixes and acrylic and/or water paints are healthier • Monitor consultants to ensure strategy agreed at earlier stages is implemented
Technical principles and application	• Specify mechanical services components for good energy performance over long life: gas fired condensing boilers, best available thermostatic radiator valves, weather compensating heating system controls, underfloor low pressure hot water central heating, mechanical ventilation systems to include heat recovery components, low energy lift installations, passive infrared light switching and compact fluorescent lighting, dual flushing WC cisterns, photoelectric cell operated urinals and washbasins, energy and resource efficient domestic appliances • Minimise hot water pipe lengths from storage to point of use

Table 6.23: Issues at tender stage [Owen Lewis 1999:19]

Site plan	• Limit contractors' working space to protect pre-existing natural features and vegetation • Specify to conserve and re-use top soil • Give directions on material handling and storage to minimise waste
Specialist contractors	• Make green requirements explicit in all tender packages, especially in specialist packages for design and construct works. These requirements will include directives on the use of as-found material; on construction waste minimisation, handling and disposal; and on the use of environmentally-friendly cleaning materials

Table 6.24: Issues at inspection stage [Owen Lewis:20]

Check proper procedure	• Gathering and storage on site of topsoil for subsequent re-use • Specified components and materials are provided • Adequate protection of existing landscape, water, vegetation and other site features • Correct handling and storage of materials • Use of any as-found elements such as hardcore or earth • Storage for recycling of polythene and cardboard packaging • Use of environmentally friendly cleaning agents
Check construction standards	• Correct installation of insulation • Correct working of materials for health: cutting, spraying • Quality of external facing masonry • Weather tightness of opening elements • Sealing of openings around pipes penetrating the external envelope • Vapour controls membranes • Low emissivity coatings on glazing • Correct disposal of toxic waste • Housekeeping regarding waste materials and recycling of packaging

Table 6.25: Issues at acceptance stage [Owen Lewis 1999:21]

Advice on building operation and maintenance	
Correct building maintenance	• Maintaining and renewing floor and wall finishes selected for health and environmental performance • Regular cleaning of windows and luminaries • Maintaining sanitary components to minimise water consumption • Maintaining internal and external planting • Use of sustainable, non-toxic, biodegradable cleaning agents • Application of paint and thin film coatings in properly ventilated spaces • Annual inspection of active systems to check continued efficiency of boilers, cooling equipment, radiator valves, infrared switching, heating and cooling controls
Operating energy management systems	• Operating systems to prevent overheating in summer: moveable shading, nigh-time cooling • Operating ventilation systems: both mechanically assisted and passive: fans, natural ventilation, to optimise balance of ventilation, heating and cooling demand • Operating the building to maximise heat gain in the heating season: control night-time ventilation, operating blinds to maximise insolation, closing internal doors to retain captured heat, opening shutters to promote desired ventilation • Illustrating the mechanical system controls such as programming time clocks, operating weather compensating controls, setting thermostatic radiator valves, seasonal manipulation of flow temperature in heating system • Operating electrical installations: correct replacement of fittings, discussion of switching on lighting and power, lighting sensors, power zoning • Operating to maximise the use of daylight and minimise use of artificial lighting • Avoid peak electricity costs [typically at 7.30 and 17.30] by periodically shutting down large plant
Monitoring environmental performance	
	• Check for infiltration as a result of drying out and shrinkage leading to poor air tightness • Investigate energy consumption through an entire heating and cooling season, by reference to utilities invoices or electricity, gas, other. These can be totalled over a year and consumption in kWh/m^2 readily derived. This can be compared with reference figures for an assessment of the overall performance of the building users' comfort, particularly in relation to overheating in the cooling season, where air conditioning is not provided and natural cooling methods are employed; and user satisfaction in relation to daylight availability. Questionnaires can be helpful in this regard • Monitor room temperatures, either by simple maximum/minimum thermometers or by thermometer linked to computerised recording system, to establish the effectiveness of heating and cooling installations and help determine whether active installations are over-utilised • Water consumption, by monthly and yearly meter readings and a daily consumption in litres per heat calculated from the number of building users. Data may be checked with reference to established bench marks to establish the level of performance.

Table 6.26: Issues at refurbishment stage [Owen Lewis 1999:23]

Before fixing the brief for the work	• Undertake an energy audit of the building
Identify the building's potential for environmental improvement, including	• Increasing daylighting through roof lighting • Reducing overheating through the use of external louvers or blinds • Reducing the heating demand through installation of draught lobbies and by adding insulation to external walls and roof • Envelope performance by better windows and doors • Natural ventilation by adding opening sections to windows and roof lights • Controlling ventilation and causal infiltration • Performance of active systems through better controls: time clocks, thermoststs, building energy management systems, and ore efficient fittings: lights, heat emitters • Indoor air quality by substituting natural for synthetic finishes: linoleum, water based paints

Consider the following when refurbishing	• Improved controls on active service systems. The following will often be cost-effective:
	  • Solid state programmable controllers for heating and cooling
	  • Automatic switching systems for lighting
	  • Individual thermostatic room and/or radiator control
	  • Weather compensating controls
	• Improved air tightness in the external envelope
	• Improved thermal insulation: not always easy, but where roof finishes are being replaced it may be possible at modest extra cost to significantly upgrade thermal insulation. External wall insulation can enormously enhance thermal performance and increase internal comfort
	• If windows or external door sets are to be renewed, the best performing models available will generally be worth installing
	• Secondary glazing can create small sunspaces, pre-heat ventilation air and reduce transmission of external noise.
	• The best available floor and wall finishes will increase service life out of proportion to cost
	• Passive climate control devices, including draught lobbies at external entrances, external shading devices such as fixed or moveable louvers, and sun spaces, can be undertaken in conjunction with façade refurbishments
	• Retrofitting sustainable components such as roof-mounted solar water heaters and photovoltaic cells, and low-energy lifts

Actors

The publication describes the following actors in relation to the respective stages:

Table 6.27: The actors involved in the different stages[Owen Lewis 1999:8-23]

Stage	*Actors*
Inception	Client and Design team
Preliminary studies	Design team
Sketch studies	Primarily Architect + Input from Consultants
Pre-project	Architect and Consultants
Basic project	Primarily Technical Consultants + Architect and Client
Execution of project	Engineering Consultants
Tender procedure	Contractors, Architect and Client
Construction supervision	Contractor and Architect
Acceptance	Client and Architect
Defects period	
Maintenance and refurbishments	

Green tasks in client-architect contract

Furthermore the publication describes the following green tasks which could be identified in the client-architect contract:

Table 6.28: Indentification of green tasks in the client-architect contract [Owen Lewis 1999:9]

Stage	*Tasks*
Preliminary studies	• Advising on sustainability issues (environmental and life cycle cost, goal setting for the project • Interviewing consultants for competence in sustainability • Making topographical models to study shelter and insolation • Analysing site microclimate • Above-normal levels of inter-disciplinary work
Sketch-studies and Pre-project	• Calculations of environmental performance objectives for heating and cooling • Special research on sustainable systems, materials and components • Advising inexpert consultants on environmental issues and holistic performance • Studying alternative methods for complying with building regulations, particularly with regard to thermal insulation, heating, cooling and ventilation standards, water supply and consumption and waste disposal and treatment
Basic project	• Studies of room interiors to optimise daylighting and minimise glare • Redesign work and detail studies of building facades to optimise energy performance
Tender procedure	• Pre-qualifying contractors in relation to special requirements • Checking to avoid uncompetitive loading of tenders • Preparing advice to contractors on site production
Acceptance, defects period and maintenance	• Preparing special manuals with life cycle costing advice • Advising clients on use of passive and active environmental features in the building
Refurbishment	• Making comparative life cycle cost analyses of new build as against refurbishment costs • Environmentally auditing of existing buildings

Table 6.29: Key areas for green specialist advice [Owen Lewis 1999:10]

Building structure	• Re-use of demolition spoil and use of as-found materials • Embodied energy: use of composite structures to maximise use of low embodied energy materials and systems • Structural systems using sustainable materials (timber, earth, straw) • Ease demolition and recycling • Long-life, loose fit design (good load bearing capacity, generous floor to ceiling heights • Relationship between mass and thermal performance
Envelope design	• Relationship of openable area to lighting and thermal performance • Sustainable materials (finishes, paints, floor coverings; external wall openings; framing, glazing types; insulation)
Lighting services	• Maximisation of available daylight use: daylighting studies including daylight factor studies, daylighting simulations • Selection and location of lighting components: task lighting, high efficiency fittings • Lighting management: controls to integrate natural and artificial light
Electrical power	• Minimisation of electricity consumption: isolation of electrical circuits at night-time, optimised cable sizing, low-energy lifts • Combined heat and power generation systems to maximise total energy efficiency
Heating engineering	• Maximisation of passive heating techniques: Advice on building planning and on façade design to maximise useful solar gain, comparative U-value calculations to ensure effective passive contribution, modelling of heat flows through the building in different temperature situations at different times of the year • Maximum efficiency of active heating measures: Selection of heating method and fuel, combined heat and power, high efficiency heat emitters for the smaller quantities of heat involved, air and water plant size optimisation, optimisation of controls including Building Energy Management systems (BEMs), VAV air heating systems and fully ducted systems – with optional free cooling • Input on life cycle costing calculations • Energy calculations to take account of passive gains • Combined heat and power on larger projects

Table 6.29: Key areas for green specialist advice [Owen Lewis 1999:10] (Continued)

Cooling engineering	• Maximisation of passive cooling techniques: Thermal mass and ventilation to promote passive cooling measures Modelling of temperature changes to predict internal in relation to ambient temperatures, advice on façade design and modelling of shading and daylight/solar gain • Active systems to minimise energy consumption including optional free cooling in ventilation systems
Water services	• Minimisation of water consumption through component selection for water conservation, and by re-use of grey water • Small scale self-contained waste treatment systems
Ventilation	• Building modelling to maximise through ventilation and stack effect ventilation for cooling
Cost estimation	• Comparative life cycle cost studies, for individual components and alternative systems, to incorporate initial cost, cost in use, cost for demolition and re-use including recycling • Environmental cost accounting
Baumeister / Bureau d'etudes	• Inspection of construction quality but particularly for air tightness of envelope, efficiency of active systems, particularly heating
Landscaping	• Site assessment, including land contamination, methane, radon and landfill gas, hydrology • Environmental assessment, including ecological issues • Soft landscaping for life cycle winter solar access (height of vegetation, shading, light reflection, sunlight penetration) and shelter (prevailing wind directions and intensity, modelling of earth berms) • Passive cooling and urban design • Indigenous vegetation: conservation and propagation • Waste treatment plants (reed beds)

6.3.4 Williamson, Radford and Bennetts

The publication 'understanding sustainable architecture' contains a checklist discussing the key-issues involved in sustainable architecture in relation to; stakeholders, objectives, active stakeholders, architect's possible process means, aspects of possible product means and notes.

The publication does not discuss the stakeholders (active or passive) in relation to the stages of the process, but to the issues involved in the design and understanding of sustainable architecture.

This part of the state of the art describes the stakeholders, objectives and principal active stakeholders in relation to the discourse issues, while the rest of the checklist is discussed in the terminology part of this state of the art chapter.

Stakeholders

The publication presents the general stakeholders and the principal active stakeholders in relation to the discourse issues presented in the publication checklist.

Table 6.30: Part of the checklist; description of the stakeholders, objectives and principal active stakeholders of the different discourse issues [Williamson, Radford and Bennetts:Appendix A]

Discourse issue	Stakeholders	Objectives	Principal active stakeholders
Environmental impact			
Climate change	Many existing ecosystems, present and future generations of people	▪ Reduce life cycle greenhouse gas emissions ▪ Create carbon sinks ▪ Mitigate effects of possible climate change	Designers, clients, occupiers, government, builders, product manufacturers
Pollution	Many existing ecosystems, present and future generations of people	▪ Reduce acid rain ▪ Reduce air pollution ▪ Reduce water pollution ▪ Reduce land pollution	Designers, clients, occupiers, government, builders, product manufacturers
Resource depletion	Present and future generations of people	Use resources wisely	Designers, clients, occupiers, government, builders, product manufacturers
Biodiversity	Many existing ecosystems, present and future generations of people	Avoid actions that lead to reduction of biodiversity	Designers, clients, government, product manufacturers
Indigenous flora and fauna	Local non-human ecosystems	▪ Minimise disturbance to local flora and fauna ▪ Maintain viability of local ecosystems	Designers, owners, government
Social and cultural relevance			
Society and culture	People	▪ Reflect and express culture ▪ Relate built form to social and economic activity ▪ Maintain significant building heritage values ▪ Create future heritage value	Design professionals, owners, government
Occupants			
Health	Occupants and neighbouring people	Healthy people	Designers, clients, government
Comfort	Occupants	▪ Thermal comfort ▪ Visual comfort ▪ Aural comfort	Designers, clients, government
Economic performance			
Cost effectiveness	Clients, (other) people	▪ Net benefit ▪ Return on investment	Designers, financiers, clients, builders, government
The building			
Longevity	Clients, (other) people	▪ Durability ▪ Adaptability ▪ Serviceability ▪ Maintainability	Designers, clients, governments

The checklist can be applied in the initial stages of a project to decide the actors of the design team and distribute their responsibilities in relation to the issues involved in the project, as well as in relation to the formulation of the objectives in the design brief.

6.3.5 Conclusion

Generally speaking the publications containing methodical process descriptions agree on the importance of inter-disciplinarity and the early integration of building system strategies (e.g. ventilation, heating and cooling) and the importance of the comfort of the user. Rightfully, the approaches do not discuss what type of architectural expression should be the outcome, because the descriptions are focused on letting architects decide that for themselves.

Two of the publications are very comprehensive in their detailed descriptions of the phases of the process and the tasks and issues associated with the different phases, these are authored by the IEA Task 23 team [www.iea-shc.org/task23/ 2003] and Owen Lewis [Owen Lewis 1999]. While the IEA Task 23 publications primarily focus on the integration of engineering related tasks, Owen Lewis [Owen Lewis 1999] take both the perspectives of the engineer and architect into consideration, and both publications were developed by a collaboration of researchers and practitioners.

Two publications were developed for teaching; Knudstrup [Knudstrup 2000, 2004 and 2006] and Williamson, Radford and Bennetts [Williamson, Radford and Bennetts 2003]. Knudstrup primarily focuses on the phase descriptions and the iterations, while Williamson, Radford and Bennetts primarily focus on what sustainability is, the stakeholders and the objectives of these stakeholders.

The following discussion will conclude on the information obtained about the phases, actors and tasks described in the analysed publications, as well as, the approaches to inter-disciplinarity and integration presented in the publications.

Phases

The publications contain four different phase descriptions:

Table 6.31: The different phase descriptions found in the publications containing methodical process descriptions

Publications	*Traditional Design Process, ECBCS IEA Task 23 2001*	*Integrated Design Process, ECBCS IEA Task 23 2001*	*Integrated Design Process (IDP), Knudstrup 2000 and 2004*	*A Green Vitruvius, Owen Lewis 1999*
Phases	Investigation of basics	Basics	Problem / Idea	Inception
			Analysis	Preliminary Studies
	Schematic Design	Pre-design	Sketching	Sketch Studies
	Design Proposal	Concept Development		Pre-project
			Synthesis	
	Preliminary Design	Design Development		Basic Project
	Building Documents	Building documents	Presentation	
	Mass Records and Advertising			Execution of project
	Negotiation Contracting	Negotiation Contracting		Tender Procedure
	Construction Management	Execution and commissioning		Construction Supervision
	Construction Supervision			
	Building Documentation			Acceptance
	Supervision after 1 year of operation	Operation		Defects Period
				Maintenance and Refurbishments

Actors

Based on the study of the methodical process descriptions it is possible to conclude that all the process descriptions relate to multi or inter disciplinarity through the different stakeholders, teachers or practitioners described to be involved in the process, and that they all include the primary actors from the initial stages of the project when the design brief is selected for the project.

There are, however, no reports about hierarchical structures within the design teams except from the distinction between a core design team and changing team specialists in IEA Task 23 [www.iea-shc.org/task23/ 2003].

The Arup interview discussed in chapter 7.4 shows that the design team should preferably have a flat organisational structure. This might explain why none of the publications discuss the issue of hierarchy in relation to the design teams.

Tasks

The methodical process descriptions describe a lot of tasks, some of which are repetitions. A summary of the tasks presented in the methodical process descriptions is available in Enclosure A.

Generally speaking the tasks can be grouped in relation to the following categories:

Table 6.32: Categorisation of tasks found in the process descriptions

Category	*Description*
Project brief	Tasks relating to the formulation of the initial project description and the project vision.
Economy	Tasks relating to the economic frame for the project (e.g. the cost plan) of the project.
Process management	Tasks relating to the management of the process (e.g. meetings, schedule revisions etc.)
Building regulations	Tasks relating to the legislative demands (e.g. for work environment, energy consumptions, fire safety, indoor climate, toxicity of materials etc.)
Site	Tasks relating to the selection of the site and the layout designed for the site and the construction on the site (e.g. wastewater treatment and waste management during the construction phase).
Building	Tasks relating to the building design and the construction of the building
Comfort	Tasks relating to the indoor climate and comfort conditions inside the building
Documentation	Tasks relating to the documentation of the project at different stages in the project.

Of these categories it is especially the project brief, economy, site, building and comfort themes that are interesting to the design of environmentally sustainable buildings.

Inter-disciplinarity and integration

The terms inter-disciplinarity and integration are used as inter-dependent terms in the publications. This is therefore concluded to be a defining character of the process descriptions.

Inter-disciplinarity

Two different kinds of inter-disciplinarity were discussed in the publications; the inter-disciplinary design team and the inter-disciplinary actor.
The inter-disciplinary design team is the most common approach to inter-disciplinarity seen in practices, while the inter-disciplinary actor is more common in the education system. The latter type of inter-disciplinarity has developed through the development of hybrid educations that merge two or more disciplines in the creation of a new type of discipline that should fill a gap experienced in practices.

The issue of the inter-disciplinary design team was discussed in a recent PhD thesis at the Department of Architecture and Design at Aalborg University (Denmark) entitled 'The tectonic practice – in transition from a pre-digital to a digital era' by Schmidt [Schmidt 2007].

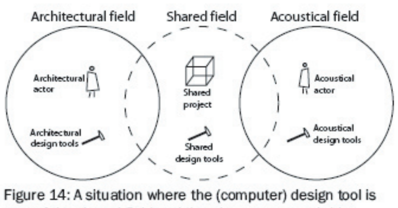


Figure 14: A situation where the (computer) design tool is part of the shared field and thereby serves as a bridge between the two fields.

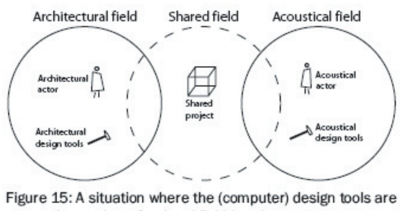


Figure 15: A situation where the (computer) design tools are supporting each professional field but does not serve as a bridge between the two fields.

Illustration 92.1 Different types of design tools in the shared field between the architectural field and the acoustical field [Schmidt 2007:94]

In her thesis Schmidt discusses the formation of design teams as a new and temporary inter-disciplinary field. This has inspired the following illustration of the two kinds of inter-disciplinarity found in this part of the state of the art:

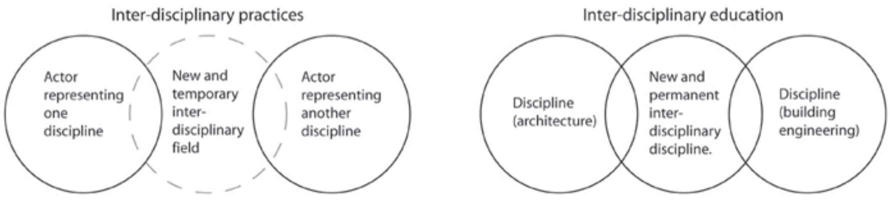


Illustration 93.1: Different approaches to inter-disciplinarity found in the publications containing methodical process descriptions.

The IEA Task 23 [www.iea-shc.org/task23/ 2003] is an example of the inter-disciplinary design team, while Knudstrup [Knudstrup 2001, 2004 and 2006] presents an inter-disciplinary actor working in a design team on an inter-disciplinary project. The inter-disciplinarity is, thus, in this case embedded in one actor, or in a group of actors with similar disciplinary backgrounds.
The difference in ideas of how inter-disciplinarity occurs is therefore significant. The inter-disciplinary actor is, however, intended to take part in inter-disciplinary design teams as a representative of a new discipline or a facilitator of inter-disciplinarity.

Integration
The publications agree on the importance of integration, but what they integrate is quite different in relation to the profession of the authors of the publications, the focus of the publication and the target groups corresponding to these focuses.

In IEA Task 23 [www.iea-shc.org/task23/ 2003] the transitory stage (goal review and decision) in-between the process phases is considered as the key to integration, while the integration in Knudstrup's publications [Knudstrup 2001, 2004 and 2006] occurs via the selection of tasks and issues which are integrated in the decision-making process. Knudstrup furthermore has the review of aims and programme as a task at the end of the analysis phase.

Through application of the IDP it has been my experience, that the review of goals and decisions ensure a high level of quality and a clear argumentation of projects. The review supports the process, but it is not what makes the process integrated. What in my experience enables integration in the IDP is a conscious decision of selecting technical issues of focus early on in the design phase, integration of these issues in the design brief and programme along side the more traditional issues stated in the design brief and programme.
The review is not unimportant, as we shall see in the next chapter, but it has a qualitative function rather than an integrating function.

---

[1] The publication was developed in relation to a course at the University of Adelaide in Australia entitled "Issues in Urban and Landscape sustainability". The book introduces three images in sustainable architecture; Nature, Culture and Technology.
[2] Williamson, Radford and Bennetts 2003 refer to the terms as labels.
[3] Williamson, Radford and Bennetts 2003 refer to the issues as concepts. The word issue is preferred in this case, as the word concept is used for too many different things in both architecture and building engineering. (the definition of the word issue is in this case: 'a point the decision of which determines a matter: *The real issue in the strike was the right to bargain collectively.*' dictionary.reference.com (2006))
[4] The quotation refers to the following note: 'Focault sees such strategies as "systematically different ways of treating objects of discourse … of manipulating concepts (of giving them rules for their use, inserting them into regional coherences, and thus constituting conceptual architectures)' Focault 1972:70'.
[5] The terms were found in publications and online forums.
[6] The description of Fuller's idea of self-sufficient dwellings is based on [Baldwin 1996, and Krausse and Lichtenstein 1999].
[7] Paolo Soleri was educated as an architect from Turin Polytechnic in 1946. After graduation he travelled to the US to work for Frank Lloyd Wright in Arizona. In 1948 he was dismissed and he went back to Italy to work for a few years. In 1951 he returned to the US where he established the Costani Foundation in Paradise Valley in Arizona. [Steele 2005:135]
[8] Claus Bech-Danielsen is a senior researcher at the Danish Building Research Institute.
[9] the title is translated from Danish

[10] James Steele is a Professor of Architecture at the University of Southern California. He specialises in history of architecture and design.
[11] James Wines is a notable American architect who is currently Professor of Architecture at Pennsylvania State University (U.S.). More information about James Wines is available at: www.rps.psu.edu 2007
[12] Brian Edwards is a Professor of Architecture at Edinburgh College of Art in Scotland. More information about Professor Edwards is available at http://www.eca.ac.uk/ecalite/research_staff.cfml?nav2ID=16&nav3ID=100147&resintID=100147 2007
13 Victor Olgyay is currently employed as an Associate Professor of Architecture at the School of Architecture , University of Hawaii at Manoa. More information about the author is available at: http://sundial.arch.hawaii.edu/sundial/vo/vitae98.html 2007
14 Ken Yeang is co owner of the 'TR Hamzah & Yeang Sdn. Bhd' and 'Llewewelyn Davis Yeang' architectural practices. More information about Ken Yeang is available at: http://usa.autodesk.com/adsk/servlet/item?siteID=123112&id=9485529 2007
[15] The categorisation of the dominant concerns was inspired by the three images Nature, Culture and Technology presented by Williamson, Radford and Bennetts [Williamson, Radford and Bennetts 2003: chapter 2] and the categorisation of climatic and cultural differentiation made by [Hagan 2001:chapter 7]. The choice to include climate as an issue was also based on a recognition of the fact that there are large differences between approaches focusing primarily on climate or nature.

7 PROFESSION ANALYSIS

As an engineer specialised in architecture the professional differences between engineers and architects have been a natural fixation of mine. My interest in these differences first occurred during my time as a bachelor and master student at the Department of Architecture and Design at Aalborg University, Denmark. Through the education I was exposed to supervisors and lecturers with a background in either engineering or design (architectural, urban and industrial).
The education at the Department of Architecture and Design builds on problem-based learning and consists of semester projects solved via group work supervised by both engineering and design supervisors. In order to pass the semesters it was necessary to find a way of balancing the requirements set by both professions. In some cases both supervisors were pleased with the projects, while they in other cases disagreed about the projects and it was up to the group to find creative solutions that would satisfy both supervisors.
In relation to this a lot of time was spent contemplating what the reasons for the professional differences were and what kind of methodical approach could help balancing the requirements of the two professions. A suggestion was made for this in the 6th semester study guide authored by associate professor Mary-Ann Knudstrup [Knudstrup 2000, 2004] in the form of the Integrated Design Process (IDP) described in chapter 6.3.2, which suggests that considerations traditionally belonging to engineering disciplines are introduced in the beginning of the process and are integrated throughout the entire process.
The integration of analogue and digital engineering and architectural considerations and tools was however a bit tricky as we had to learn how to do architectural projects and different types of engineering calculations while doing the project. The process applied in these studies were based on the architectural design process in which considerations traditionally relating to building engineering were moved to the sketching phase of the design process from the preliminary design phase, the design development phase, the synthesis phase or the basic project phase depending on which phase description is applied of the design process (Please refer to chapter 6.3.5 for more details). Through this learning by doing process we learned how to deal with differences in terminology and experimentation of the two disciplines, aided by the integrated design process (IDP) formulated by Knudstrup in the study guide [Knudstrup 2000] and a tool developed specifically for the semester.

Through the student projects I found that the architectural supervisors, generally speaking, had an explorative approach to the design process, while the engineering supervisors often focused on determining which solution was the 'optimum' solution from a quantitative perspective. This difference can be quite difficult to deal with when combining the two disciplines from the beginning of a design project, partly because the idea of an 'optimum' solution does not exist in architecture and partly because architectural solutions are evaluated from a qualitative perspective. This means that what is an 'optimum' solution to one person might not be for another unless they both agree on the prioritisation of what is most important and on the architectural vision for the project.
The early integration of the engineering disciplines was also complicated by the fact that the tasks traditionally solved by building engineers in the later stages of the design process require a lot of detailed information about the building design which is not decided in the beginning of a project.

After testing the application of the integrated design process (IDP) [Knudstrup 2000 and 2004] on a number of student design projects I will now turn my attention to existing research about how designers think and professional differences between the engineering and architectural professions, as well as a 'best practice' example of an integrated approach to environmental and sustainable building design applied by one of the leading engineering practices in the UK; Arup Associates, in the hope that this will provide a frame for my own experiences with the integrated design process and a deeper understanding of what the integrated design process requires from the people and the tools involved in the process.

7.1 How designers think

In the book 'How Designers Think – the design process demystified' Professor Bryan Lawson[1] refers to a laboratory study of students, in which two groups of respectively final year students of architecture and postgraduate science students were asked to solve a design-like problem. For the design process each group used a computer which unbeknown to them registered and analysed their problem-solving strategy. [Lawson 2006:41-43]

Lawson reports that 'the two groups showed quite consistent and strikingly different strategies' [Lawson 2006:43] and that the scientist applied an analytical trial and error approach to finding a solution in which they tried out 'a series of designs which used as many different blocks and combinations of blocks as possible as quickly as possible' [Lawson 2006:43] as a way of uncovering the rules for how the blocks could be combined. The students of architecture, on the other hand, would choose the combination of their blocks in relation to their preferred colour scheme starting with their favoured colour combination and when the computer rejected the solution they would choose their second best preference for the colour scheme and so on until they came up with an acceptable solution.
This experiment led Lawson to 'describe the scientists as having a problem-focused strategy and the architects as having a solution-focused strategy'. [Lawson 2006:43]

The issue of whether or not the differences in the strategies were due to educational differences or personal preferences was addressed in a similar study with school pupils at the end of their study immediately before starting university educations and university students at the beginning of the first year of their degree in architecture. This study led Lawson to conclude that 'both these groups were much less good at solving all the problems and neither group showed any consistent common strategy' [Lawson 2006:43] and that 'it is the educational experience of their respective degree courses which makes the science and architecture students think the way they do, rather than some inherent cognitive style' [Lawson 2006:43].

Lawson concluded that the strategies applied by the final year students of architecture and the postgraduate science students are coherent with what is taught to them through their respective educations and the emphasis these education place on the process and method. He also concluded that the first year and final year students of architecture displayed greater spatial abilities and three dimensional skills than the other two groups. [Lawson 2006:44]

Based on this discussion of Lawson's conclusions it is my conclusion that the professional differences between architects and engineers are nested in the differences in the architecture and science educations. This issue of professional differences will be discussed further in the next discussion of the late American philosopher Donald Schön's[2] study of how professionals think in action.

7.2 Professional differences between architecture and engineering design

In the book 'The Reflective Practitioner – how professionals think in action' Donald Schön reports his observational studies of episodes of senior practitioners teaching students how to solve a profession related problem [Schön 1983:viii]. At the centre of his investigation was an interest in how the professions reflect-in-action in problem-solving situations.

Architecture

Schön describes the supervision situation between a studio master named Quist and one of his students Petra in the early stages of her project as a reflective conversation with the design situation in which the supervisor and the student experiment with different ideas for a school building.

Reflection-in-action

Through their discussion the student presents her sketches and her main problem to the supervisor, who in return reflects on the main problem, reframes it and suggests a number of 'local' moves which could solve the reframed problem. The supervisor then continues to do a 'global' evaluation of the consequences of the new moves he has suggested. Via this example Schön identifies the following three levels of evaluation of the moves;

- Desirability of the consequences caused by the moves judged in relation to the normative design domains
- Conformity or violations as a consequence of earlier moves
- Appreciation of new problems or potentials achieved through earlier moves

[Schön 1983:101-102]

The issue of local vs. global moves relate to the scale in which the ideas are developed; when local moves are applied the supervisor and student focus on a specific area of the building or site, whereas the global moves are applied when the consequences of the local moves are evaluated in relation to the rest of the building and in relation to the user's perception of moving through the building, or as Schön explained it; 'the designer must oscillate between the unit and the total' [Schön 1983:102].

This act of moving from local to global can in my opinion be seen as similar to the switch one makes when going back and forth between designing from 'inside - out' and 'outside - in, and 'taking a step back' to get an overview of the consequences of the decisions made in recent iterations.
Schön identifies this move from local (the unit) to global (the total) as a fundamental characteristic of the experienced architect, who 'spins out a web of moves, subjecting each cluster of moves to multiple evaluations drawn from his repertoire of design domains' [Schön 1983:102]. Schön refers to these iterations between the unit and the total as 'Reflection-in-action', which he defines as reflections performed in the middle of an action or in between actions as opposed to reflections on 'Knowing-in-action', which he defines as knowledge gained through retrospective reflection on completed actions (e.g. a completed design project) [Schön 1983:61-62]. The reflection-in-action is caused by the 'back-talk' of the situation, which occurs when the architect moves from the local to the global focus (i.e. from the unit to the total). [Schön 1983:103]

Schön furthermore observes what I think is an interesting trait in the supervisor; that the supervisor in question does not reflect on his reflection-in-action [Schön 1983:104]. This in my opinion corresponds well with some of Schön's other findings in relation to the type of knowledge associated with architectural education; that the knowledge is tacit and normative.

Professional language
Through his studies Schön also discovered a professional language applied by both the supervisor and the student. Here he identifies twelve 'normative design domains' which are implied in their conversation about the project; Program/Use, Siting, Building Elements, Organisation of space, Form, Structure/Technology, Scale, Cost, Building Character, Precedent, Representation and Explanation. These domains are discussed through a 'language of designing' in which drawing and speaking are combined in a language that ascribe different roles to the words, where the words refer to a spatial action and the experience of the spaces created inside and outside the building. Schön reports how students of architecture need to acquire the 'language of design' through their studies and that they must learn how to deal with the multiple reference situations which occur when dealing with the fact that terms (such as stair and gallery) often applied in more than one of the design domains which means that the terms can refer to e.g. both an organisation of the space and to a precedent (i.e. examples in existing architecture). Schön also observes that one can uncover the primary priorities of the design domains at the particular stage in a project by studying which of the design domains are mentioned in the reflective conversation and how often they appear in the conversation [Schön 1983:95-98].

Underlying structure of reflection-in-action
Through a comparison of the architect case and a psychotherapy case Schön finds that both cases display a process where the underlying structure is similar; 'a reflective conversation with a unique and uncertain situation' [Schön 1983:130]. In spite of this approach to projects where every project is treated as unique, both cases frame the unique new project in relation to previous projects which have some degree of similarity to the problem of the new project [Schön 1983:137-141]. Based on this it is my conclusion that the architect and psychotherapist in the specific cases apply knowing-in-action from previous projects or cases when approaching a new and unique project or case.

Other commonalities between the architecture and the psychotherapy case are that in both cases the teacher 'responds by surfacing and criticizing the student's framing of the problem' [Schön 1983:130] and suggesting 'a direction for reshaping the problem' [Schön 1983:131]. The reshaped problem is then subjected to experiments concluding the implications and consequences of the experiments. These implications and consequences lead to new experiments and/or another round of reframing of the project [Schön 1983:131-132].
These iterations of reframing the problem, experimenting and evaluating the experiments continue until the architect is satisfied with the implications and consequences of his moves e.g. when his experiments enable an unexpected benefit or when he feels he has achieved a synthesis of the design criteria he has formulated in his design brief.

Problem setting
Schön also notices a distinguishing feature of the problem setting by both the architect and the psychotherapist; they both try to set a problem they can solve, and when trying to solve the problem they seek to understand and change the situation which in most cases produce both expected and unexpected results [Schön 1983:134].

Based on this it is my conclusion that the architect approaches the problem-setting in an explorative way, while trying to formulate a problem he expects to be able to solve. If he finds that he cannot solve the problem he will reframe the problem until he is able to answer it. There is, thus, an iterative interaction between the problem-setting and the experimentation. [Schön 1983:130-136, 145]

In relation to this issue of exploration Schön distinguishes between three different types of explorative experimentation; 'Exploratory experiment', 'Move-testing experiment' and 'hypothesis testing'. The exploratory experiment is what happens when one has no expectations for the outcome of the experiment. The move-testing experiment is when one intentionally changes something (a move) to se what happens (e.g. the case of the architect supervisor) and the hypothesis-testing experiment is when one wishes to confirm or disconfirm whether or not an intended move results in a predicted outcome. [Schön 1983:145-146].

I find this distinction interesting in relation to the understanding of the professional differences and the application of the criterions of truth discussed in Table 5.2, because I think there is a possible connection between the different types of explorative experimentation and the dominant criterions of truth applied by the architectural and building engineering professions.

Engineering Design
Schön uses the term 'engineering design' for his case study of the engineering profession in relation the development of engineering educations in the U.S.A. after the 2nd world war which ultimately led him to the following suggestion of engineering educations; 'I propose that engineering design is understandable as a reflective conversation with the materials of a situation, a kind of process similar to the ones we have already observed in architecture and psychotherapy. Although is cannot be reduced to an application of general rules or theories, on the model of applied research, some of its main features are constant and amenable to description' [Schön 1983:172].

Schön classifies the engineering design profession as a science-based profession, which he defines as: 'either based directly on science or contain a high component of strictly technological knowledge based on science in the education which they provide.'[Schön 1983:168].

Problem setting
The case study for engineering design is from mechanical engineering in which a group of students were solicited for a project by a gun manufacturer who needed to revise the patina process of their guns. The new patina process had to produce the same patina as the preceding process which was no longer possible. [Schön 1983:173]

Based on this it is my conclusion that the problem setting in the engineering design case was very specific compared to the problem setting in the architecture case where the student pretty much defined the scope of the project herself which in return made it easy for her to reformulate the problem throughout the process.

Problem solving

The problem solving process applied by the students turned out to be a reflective conversation with the materials of the situation, where the conversation went through several stages; diagnosis, experiment, pilot process and production design.

The students based their experiments on theoretical hunches tested through hypothesis-testing experiments, which sometimes led them to unexpected results which caused reflections with respect to the model applied in their experiments and their understanding of the important variables.

During the process the client inquired about the preliminary results of the study which caused an interference with the process, which does not correspond well with the norms of scientific experimentation, in which the experimenter cannot influence the experiment situation. [Schön 1983:173-175, 149-150]

The selection of variables

Schön notices what I think is an interesting comment made by one of the students with respect to how they had initially selected the variables subjected to experimentation; 'one of the students said "Up to this point, we hadn't acted on our idea. When all the variables seem equally important, you do first what's easiest."' [Schön 1983:174]. This is, in my opinion, interesting in relation to the architect case in which the selection of the variables was based on tacit normative design domains implied by both the supervisor and the student, which in the investigated stage of the project related to the use and layout of the building.

Laboratory experiments vs. experiments by practitioners with science-based educations

Schön describes the general differences between experiments performed in a laboratory and experiments performed by a practitioner with a science-based education as; the laboratory experiments strive to follow the scientific norms, which state that the experiments should be performed without the scientist influencing the situation and the experiments should preferably be completed an indefinitely number of times for verification of the confirmation or disconfirmation. In other words the scientist cannot change his hypothesis during the experiment. The practitioner on the other hand, will influence his experiments and hypothesis during the experiment if he finds it necessary, he defines the problem in relation to a problem in relation to a situation he needs to solve and the experiment will continue until the practitioner feels he has found a solution for his problem.

While the scientist will strive for disconfirmation[3], the practitioner will strive for confirmation whilst keeping an open mind to the possibility that the hypothesis will be disconfirmed.

Another difference between the laboratory experiments and experiments by practitioners is the level of control; in laboratory experiments most if not all the variables and influential factors can be controlled, while the level of control is completely different when the experiments are performed by practitioners where a lot of the variables are out of the practitioners control [Schön 1983:149-150]

This is, in my opinion, interesting in relation to the relationship between the science-based education (e.g. engineering design) and educations based on craftsmanship (e.g. architecture) where a wish to live up to the norm of not influencing the experimental process is strong in the science-based educations, while this wish is pretty much non-existent in educations based on craftsmanship, because these educations are focused on the solution to the problem with little interest in the process. This corresponds well with the conclusions made by Lawson in relation to his study of final year students of architecture and postgraduate science students (see description in chapter 7.1).

Engineering design vs. architecture

The engineering design and the architecture cases are both problem-oriented, which means that both cases deal with a practice-related problem which creates similar situations of reflective conversations in both the engineering design case and the architecture case [Schön 1983:172].

A comparison of the two cases presented by Schön for architecture and engineering design leads me to the following conclusions when it comes to the differences between architecture and engineering design:

Differences in approach to problem setting and solving

There are differences in the relationship between the problem and the experimentation in the architectural and engineering cases, where the engineering design experiment strives for solutions that live up to the scientific norms, which means that the problem cannot be revised, and in most cases the problem is defined in relation to a specific outcome (hypothesis-testing experiment), the problem stays the same while the hypothesis changes during the process and the experiments end when the students find a satisfactory solution.

In the architecture experiment the problem is revised throughout the development of a solution; the problem and the solution are interdependent and the problem-formulation is revised during the process as a result of the sketch iterations for a solution and the supervisor and student aim to define a scope of the problem that corresponds with a desirable solution through move-testing experiments. Finding a solution is more important than investigating the problem, and the solution is therefore more important than the problem, which corresponds well with Lawson's findings in his comparison of the problem-solving approach applied by architecture and science students. There is no hypothesis-testing in the architecture case and the different move-testing experiments are similar but they focus on different design domains and different scales.

Differences in control over the selection of parameters

The degree of control over the variables is different in the two cases; both cases have a large degree of control over the variables in the initial stages of the process where the experiments relate to the idea-generation stage. However, the mechanical engineering students apply research-based information about e.g. chemical processes which provide the students with a lot of boundaries. The architecture student works with boundaries set by the site, which to some extend is under her control, and the design domains, which are applied in relation to the student's definition of the problem and her intentions for the building.

The engineering students therefore initially deal with the boundaries set by variables selected in relation to the problem, while most of the variables and the boundaries in the architecture case are set by the student and her supervisor within the flexibility of the normative design domains.

In the later stages of the cases the degree of control changes; the mechanical engineering students build a prototype of a furnace which results in a new hypothesis and experiment. The architecture student never reaches this level of realisation, but I believe that if she were to realise her design she would experience that the closer she comes to a realisation of her project the more difficult it will become to reformulate the problem and apply changes to the design.

Differences in reflection-in-action

Schön reports that the reflection-in-action in engineering design is similar to that found in architecture; 'a reflective conversation with the materials of a situation' and he describes the main features of engineering design as 'constant and amenable to description' [Schön 1083:172]. This was not the case for the architecture example in which the main features were tacit normative design domains [Schön 1983:172, 96], which leads me to conclude that the main difference between the two professions can be found in this interplay between these constant and amenable features on the one hand and the tacit and normative design domains on the other hand. In other words the well-defined and easily described features of engineering design vs. the tacit and value-based features of architecture which are difficult to define.

This leads me to conclude that the differences in the reflective conversation with the situation in the engineering design and architecture cases can be concluded to primarily relate to the approach to problem setting, the type experiments applied for problem solving (hypothesis-testing vs. move-testing), the control over the selection of design parameters and the differences in the main features of architecture and engineering design (tacit and normative features vs. well-defined and amenable).

The traditional design process
When studying the engineer's and the architect's tasks reported by practitioners in relation to the traditional design process in Denmark reported in IEA Task 23 project (depicted in table 6.13) one finds that the architect solves most of the tasks in the early stages of the process while the engineer primarily solves tasks in the last stages of the process.

If this is compared to Schön's case studies of the architecture and engineering professions it is, in my opinion, possible to conclude that these case studies exemplify the fact that it is easy to apply explorative and move-testing experiments in the initial stages of the process where the problem is set because of the degree of control of the selection of the variable design parameters and the possibility of reformulating the problem, while it becomes increasingly difficult to control the selection of the design parameters in the later stages of the project when the problem is fixed, because the problem can no longer be reformulated, which makes the application of explorative and move-testing experiments increasingly difficult in this part of the process.

This leads me to conclude that when applying or creating an inter-disciplinary or multi-disciplinary approach to building design one needs to be aware of the changes this might bring to the type of experimentation (explorative, move-testing and hypothesis-testing) performed by the different team members involved in the project. This will challenge the team members to step out of the norms set by their professional and educational background and require them to explore the different ways of dealing with the relationship between problem and experiment.
Reflection-in-action is in this thesis regarded as a way of achieving a better understanding the decision-making and experimentation process of each member of a multi-disciplinary or inter-disciplinary team, thereby enabling a better understanding of the professional differences of the members of a particular team. An example of a practice which has dealt with multi-disciplinarity in a successful way will be discussed in chapter 7.4.

7.3 Development of the marketplace
The development of the marketplace is interesting in relation to how multi-professional engineering practices have been developed to begin with, as well as in relation to why this type of multi-professional practices is not visible in the Danish marketplace for building design.

In the book 'Architectural Practice – a critical review' Professor Robert Gutman[4] [Gutman 1988] describes the development of architectural practices in the U.S.A. until 1988 when the book was published. In the book Gutman describes how changes in the structure of demand has caused American architects to loose ground to other professions that have entered the domain of coordination of building design and building processes. This experience of invasion of the design domain has caused American architects to seek self preservation through the protection of the architectural title, which means that one has to meet a set of requirements set by the AIA (the American Institute of Architects) to be approved to work as an architect. He also describes how architects have lost ground in the public eye, where they have gone from the ones in control of design projects to in some cases design consultants. [Gutman 1988:61-70]

In his conclusions Gutman identifies 'ten major conditions that for the context for architectural practice, and that have been undergoing significant transformations. They include:
1. the extent of the demand for services
2. the structure of demand
3. the oversupply or potential oversupply of entrants into the profession
4. the new skills required as a consequence of the increased complexity and scale of building types
5. the consolidation and professionalization of the construction industry

6. the greater rationality and sophistication of client organisations
7. the heightened intensity of competition between architects and other professions
8. increased competition within the profession
9. the difficulties of achieving profitability and obtaining sufficient personal income, and
10. greater intervention and involvement on the part of the state and wider public in architectural concerns'

[Gutman 1988:97-111]

Of these issues I think that especially the structure of demands, the new skills required as a consequence of the increased complexity and scale of building types, the greater rationality and sophistication of client organisations and the heightened intensity of competition between architects and other professions that are interesting in relation to the integrated design process. The greater rationality and sophistication of client organisations and the heightened intensity of competition between architects and other professions is in this thesis seen as a response to changes in the structure of demands and the new skills required as a consequence of the increased complexity and scale of building types. The same can in my experience be said for the development of inter-disciplinary and integrated approaches to architectural design and educations dealing with architectural design, which are usually applied in situations when the complexity of the design process exceeds the traditional professional boundaries of architects and engineers.

The fact that architects experience the involvement of other professions in building design and design processes as an intrusion of their professional domain could in my opinion be the explanation of why they Danish architects and engineers are reluctant towards the development of multi-professional practices; they architects want to preserve their professional domain in order to ensure the architectural quality of buildings and the engineers do not want to alienate the architectural profession. This is, in my opinion an issue of trust between the Danish architecture and engineering professions, which the Danish marketplace for building design has tried to overcome through partnering instead of changing the practice structure to a multi-professional structure.

7.4 Integrated building design in practice – interview with two designers with Arup Associates (UK)

The purpose of the interview was to gain an understanding of the methodical approach to integrated and environmental design applied by Arup Associates[5].
The reason for this interest in Arup Associates' approach is that the practice has been involved in a lot of the environmental and sustainable projects reported in publications within the last decade. The practice is, furthermore, interesting in relation to the integrated design process and multi-disciplinary design teams;

> 'Arup associates integrates architecture, structural engineering, environmental engineering, cost consultancy, urban design and product design within one studio.
> Every project expresses the multi-disciplinary philosophy that is at the heart of the practice' [www.arup.com/associates/AA_Intro.html 2007]

The theoretical presumptions behind the interview were that the interviewees are experts in their field and that their answers therefore would be based on years of experiences with the design of environmental, sustainable and integrated design. (Please refer to chapter 5.4 for further details about the methodical approach applied in the interview).

Conclusions of interview

The following description of the multi-disciplinary approach to integrated building design is based on an interview with designers Peter Warburton and Michael Beaven with Arup Associates in London (UK), as well as, files made available by the interviewees after completion of the

interview.
A transcript of the majority of the interview is available in enclosure B and the recorded interview is available in full length on a CD along side the files received from Arup Associates. The interview and some of the files contain confidential information, which means that the files on the CD and the transcript in enclosure B are only available at the discretion of the members of the assessment committee of this PhD thesis.

Multi-disciplinarity
Multi-disciplinarity is embedded in the practice via the structure of the design teams, which both Michael Beaven and Peter Warburton refer to as 'Multi-professional' [Enclosure B: e.g. ll:155 and 561].
The multi-professional design teams consist of architects, structural engineers, service engineers and fire engineers. A project leader is responsible for the client relationship, the design and delivery of the project, as well as, for proposing the composition of a design review panel. The design review panel consists of a multi-professional group of senior people in the practice, which are not a part of the design team. [Enclosure B:ll:305-342, 696-703]

The multi-professional team are seated together in the office where they collaborate from the beginning of the project on the development of a shared vision and a concept for the project, via a process where each team member identifies opportunities for the projects and identifies possible problems in relation to e.g. the site, the user, the environment, the brief and other project related issues identified in the initial stages of the process.
Easy access to the other members of the design team and team meetings enables each team member to present their perspectives on the project and participate in a joint discussion of what the vision and concept for the project should be. [Enclosure B:ll:104-129, 228-232 and 880-924]
Reviews are made with a design review panel at critical points in the process. These points are identified by the team leader in cooperation with the design review panel. Besides the internal members of the design review panel the team leader might also invite the client and other external participants to the review. [ARAS_Getting-It_Right.doc file]

The design review panel was identified by Michael Beaven as an important part of the integrated design process, because the members of the panel share the responsibility for the project with the project leader and provide a fresh and critical set of eyes on the project. The design review panel have the authority to cry foul if they feel the project is getting off track or if they can see that the team work is dysfunctional (e.g. if one member of the team is too dominating) [Enclosure B:ll: 559-607]. The design review panel therefore helps to ensure the quality of the project and that all the members of the multi-professional team agree on the project vision and the concept.

The advantages of the multi-professional approach are many;

- Improved communication across professions as a result of learning each others professional language and concerns. [Enclosure B:ll:134-161]
- Efficiency in the vision and concept development stages, and in the decision-making process due to improved communication which enables easy identification of the main issues of the project. [Enclosure B:ll: 190-273]
- Informal work environment where people can ask 'stupid' questions that they would not normally ask. [Enclosure B:ll: 151-160]
- High quality results achieved via a shared vision for the project, which enables a joint prioritisation across professional disciplines. [Enclosure B:ll: 190-273]
- Dedication to 'make it work' in relation to the shared project vision in spite of professional preferences. [Enclosure B:ll: 652-685]
- The joint concept of a project achieved in the beginning of the process through cooperation of the multi-professional design teams enables a linear process where the phases of the design process follow each other with few or no iterations between the phases. This enables effective use of time. [Enclosure B:ll: 820-852]
- Robust arguments and team unity when facing unexpected or unwanted changes to the project. [Enclosure B:ll: 493-517]

- Talented employees due to close collaboration which quickly exhibits charlatans. [Enclosure B:ll:161-182]
- Shared references to previous projects. [Enclosure B:ll: 241-244]

The only disadvantage identified in the interview was the fact that the multi-professional team in some cases cause conspiracy suspicions with the client, who feels that the design team is too self-contained and therefore will demand that external consultants are brought in, which inhibits the integration process because the quantity surveyor in some cases end up with a supervision or inspection function instead of being an integrated part of the team. This inhibits the fast and easy economic advice and prioritisation during the process when the quantity surveyor is not a part of the integrated team, because he might not share the team's vision for the project and he therefore might not agree with the prioritisation of the important issues in the project. [Enclosure B:ll: 691-728]

Multi-disciplinary vs. multi-professional

There seems to be a clear distinction between multi-disciplinary and multi-professional design teams in the interview, specifically in the part of the interview where Michael Beaven refers to an office review performed by someone from another part of Arup which works in a multi-disciplinary way that is structured in relation to the conventional relationship between the architect and engineer [Enclosure B:ll:238-269]. In the office review Michael Beaven found that an integrated design process was achieved in approximately 20% of the projects of a multi-disciplinary approach while an integrated design process was achieved in approximately 80% of the projects of a multi-professional approach.

This discussion is related to the discussion of multi-, inter- and trans-disciplinarity in chapter 5.2. In relation to this one could argue that the multi-professional approach applied in the design teams at Arup Associates to some extend work in an inter-disciplinary way. This argument is solidified by the description of the application of tools in the design process (e.g. [Enclosure B:ll:860-870, 917-919]), which indicates that the design teams attack the project from various angles through application of methods that traditionally belong to different professions (e.g. physical models, thermal simulations, energy calculations etc.). It also seems that some stages of the process are more inter-disciplinary than others, where the early stages of the design process are the inter-disciplinary and the later stages of the process appear to be more multi-disciplinary [Enclosure B:ll:916-923].

Important phases

Both interviewees agreed that the concept[6] and the detailing phases were the most important phases of the project. The concept stage was identified as the stage where the success of the project is reserved [Enclosure B:ll:545-551] and the detail stage was identified as the stage which ensures successful realisation of the concept [Enclosure B:ll:817-845].

Sustainability

For many years Arup Associates have contributed to the creation of energy-efficient buildings. A fundamental core value embedded in the practice is therefore energy-efficiency as a minimum requirement in all the Arup Associates projects [Enclosure B:ll:312-318, 967-985]. Projects therefore go through a selection process in which projects which do not live up to the ethical standpoint and the fundamental beliefs of the practice (e.g. green-wash projects) are filtered out and turned away by the practice [Enclosure B:ll:967-985].

In 1999 Arup launched the 'Sustainable Project Appraisal Routine' (SPeAR). SPeAR is a design tool for assessment, demonstration and improvement of sustainability in products, project or organisation performance at a point in time. SPeAR is applicable for building design, industrial process, corporate environmental reporting, reporting against industry codes, policy development, development applications, option assessment and monitoring of EMS performance.

The SPeAR diagram is the output of the insertion of input data in a series of spreadsheets, which list all the sustainability indicators used for the appraisal. [AA_SPeAR_poster file]

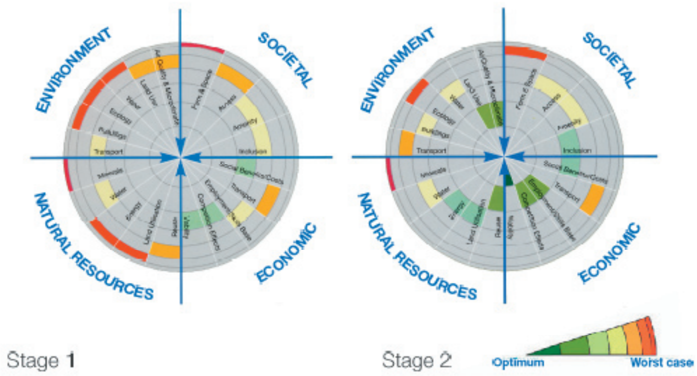


Illustration 105.1:Example of a project subjected to a SPeAR assessment [AA_SPeAR_indicators file]

The indicators are assessed in relation to a colour scale where the green tones are the optimum solution and the red tones are the worst case solutions. The green tones are located near the centre of the circular diagram, while the red tones are located at the outer edge of the circle.
The SPeAR spreadsheets contain a comprehensive collection of sustainability indicators ordered in three layers (referred to here as main indicators, issues and sub-indicators). The main indicators are Environment, Societal, Economic and Natural resources. Five to six issues are defined for each of the four indicators and a series of sub-indicators are defined for each of these issues.
[AA_SPeAR_poster file]

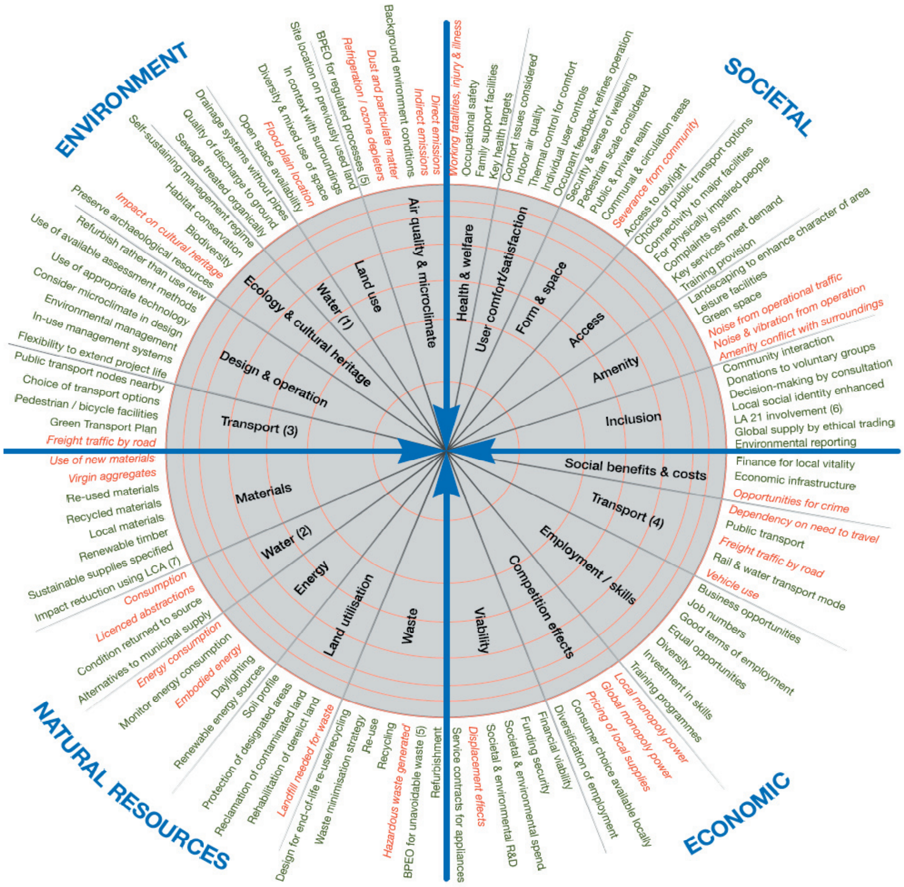


Illustration 105.2: The SPeAR indicators, the green indicators should be increased or improved, while the red indicators should be decreased or discouraged [AA_SPeAR_indicators file]

In the interview Peter Warburton points out that what one, from his point of view, can ‘achieve down the sustainability path is an attitude of mind that drives you in a direction, but you don’t necessarily get all of the way there with all of the projects and all of the clients. You get a bit of the way there with some of the clients and none of the way there with other clients. But you always point in that direction.’ [Enclosure B:ll:444-448].

In order to establish how far down the sustainability path they can get with a client SPeAR is used in the early stages of the design process as a way of describing Arup Associates' approach to sustainability to the client. It is applied in a discussion with the client about the sustainable profile of the project and which indicators to focus on in the project. SPeAR is also used for the education of young people coming into the practice who are asked to perform SPeAR assessments. As indicated in the example in illustration 105.1 SPeAR can also be used to evaluate the progress of the stages of a process. [Enclosure B:II: 995-966]

Another interesting issue raised by Michael Beaven is that, in his experience, the greatest $C0_2$ reduction is achieved in the large urban scale projects where the design of e.g. a master plan an neighbourhood is created[7] [Enclosure B:II:518-547].

Prioritisation

Prioritisation is an issue in all design projects, but prioritisation becomes even more interesting in multi-professional design teams because the multi-professional team has to agree on the prioritisation.

In Arup Associates the prioritisation is facilitated by the multi-professional design teams, which enable a consensus about the priorities through the shared vision for the projects. The prioritisation is based on the brief, the client's expectations, the site and user analyses, and the cost plan for the project supported by conversations with the client about the SPeAR indicators and study trips. Depending on how the team dynamic works the process of prioritisation will run more or less smoothly [Enclosure B:II: 294-299, 559-609].

Type of experimentation

The type of experimentation is interesting to the previous discussion of professional differences (in chapter 7.2) where three types of experiments were discussed by Donald Schön; explorative, move-testing and hypothesis-testing.

The fact that both interviewees stressed the importance of exploring and looking for opportunities in the vision and concept development stages indicates that explorative experiments are carried out at these stages of the process, which differs from Schön's findings in the engineering study but corresponds well with the conclusion that the explorative experiments are suited for the initial stages of design processes.
It is not exactly clear which types of experiments are applied in the later stages of the process, e.g. the detail stage, but it is expected to be either move-testing or hypothesis-testing experiments and the description given by Peter Warburton about how the architect leaves him to get on with it in the detail stage and specification writing [Enclosure B:II:916-923] supports this expectation. It does however seem as if hypothesis-testing is quite rare with Arup Associates when Michael Beaven says that they will not do calculations if they have a good idea of what the answer is going to be [Enclosure B:II:864-869].
In a Danish practice one would, however, have to do hypothesis-testing experiments as part of the final documentation process for legislative approval in order to demonstrate that the project lives up to the Danish Standards and the Danish building codes, which is probably also the case in the UK.

7.5 Conclusions

Professional differences

Bryan Lawson [Lawson 2006:41-44] found that the professional differences between post-graduate science students and final year architectural students were established during their education and that the science students applied a problem-focused strategy for problem-solving, while the architects applied a solution-focused strategy.

The approaches to problem and experimentation

Donald Schön's study of problem-solving situations in an architectural case and a science-based, engineering design case showed that both professions apply reflection-in-action, but that their approaches to the problem and experimentation are different;

Table 7.1: Comparison of the approach to problem and experimentation in the engineering design and architecture case studies by Schön [Schön 1983:76-105, 168-204]

	Engineering design	*Architecture*
Problem	• The problem is constant and the hypothesis changes as a result of experiments. • The solution is dependent on the problem and the hypotheses. • The problem defines the solution • The solution is more important than the problem	• The problem is revised and specified in relation to the results of experiments. • The problem and the solution are interdependent, and the problem does not define what the school building should look like. • The solution is more important than the problem
Experimentation	Hypothesis-testing	Move-testing

These differences can explain why engineers and architects sometimes have difficulties agreeing about how to approach projects. The differences in experimentation are in this thesis ascribed to differences in assignments.

Differences in the criterions of truth

Based on Schön's studies of respectively the architecture and the engineering design cases, it is possible to conclude that the differences in the approaches to problem and experimentation relate to different criterions of truth. The approach taken in the engineering design case would most likely apply the consistency and correspondence criteria of truth while the approach taken in the architecture case would most likely rely on criterions of consensus and coherence, because it is not possible to apply the consistency and correspondence criteria of truth for the type of experiment conduced in the architecture case.

This can obviously cause difficulties of communication during the work process when engineers and architects have to agree on the different decisions involved in the creation of architecture. This might not become a problem if these differences are addressed in the beginning of the project when the inter-disciplinary design team is formed.

Language

In the interview Michael Beaven refers to how the members of the multi-professional design teams work hard at learning each others language [Enclosure B:II:132-160], which corresponds with Schön's identification of a 'language of designing' [Schön 1983:95]. This is a professional difference which should also be considered in relation to the formation of inter-disciplinary design teams.

Integrated design

What makes a design process integrated?

The state of the art chapter displayed two models of inter-disciplinarity found in publications about integrated design, where the inter-disciplinarity is achieved through either inter-disciplinary design teams or inter-disciplinary education.

The interview with two designers with Arup Associates discussed in this chapter supports the idea of integrated design achieved through the utilisation of multi-professional design teams. The model of inter-disciplinarity applied by Arup Associates differs slightly from the two models of inter-disciplinarity found in the chapter 6.3.5;

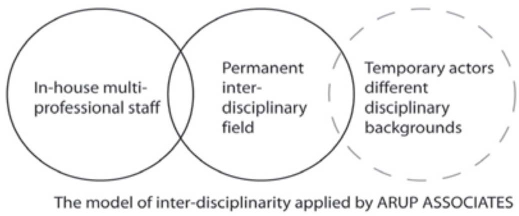


Illustration 107.1: The model of inter-disciplinarity applied by Arup Associates

At Arup Associates the inter-disciplinary field is permanently embedded in the practice and the actors involved in the multi-professional design team are primarily in-house staff.

Temporary actors (e.g. the client and quantity surveyor) are also involved in the design teams. The discussion in the interview of in-house quantity surveyors vs. outside quantity surveyors (Enclosure B:II:696-728) indicates that ideally only the clients and users would be the temporary actors involved in the design team.

Based on the three models of inter-disciplinarity found in Part 1 of this thesis about methodical approaches to sustainable architecture it is my conclusion that integrated design is closely associated to an inter-disciplinary approach to building design and the design process, and that inter-disciplinarity and integrated design is a necessary approach to the creation of environmentally sustainable architecture.

Barriers of development of inter-disciplinary practice and integrated design
Gutman's writings about the architectural practice [Gutman 1988] have led to the realisation that the main barrier to the development of inter-disciplinary of multi-professional practices in Denmark could be explained in perspective of the marketplace development in the U.S.A. in the 1980s, in which architects felt a need to protect their professional domain from intrusion of other professions.
I believe that the situation in Denmark is similar to that described by Gutman, and that this has caused a caution in both architecture and engineering practices in Denmark, where especially the engineering practices are careful not to intrude on the architectural professions domain. This is, in my opinion a shame, because this truly is a barrier to the integrated design process and thus also to the achievement of environmentally sustainable architecture. This barrier will be considered in Part 2 of this thesis which deals with the issue of design strategy development.

Why apply an integrated design process?
As stated in the interview with Peter Warburton and Michael Beaven with Arup Associates there are many benefits to adopting an integrated design process
- Improved communication across professions
- Efficiency
- Informal work environment
- High quality results
- Dedication to 'make it work' in relation to the shared project vision
- Robust arguments and team unity
- Talented employees
- Shared references

What is particularly important in a multi-professional approach to the integrated design?
The notion of integrated design has been adopted on an international level by people who see it as a way of eliminating the professional boundaries which appear in the traditional approach to the design process. There is therefore a great interest in pursuing an integrated approach to design, but most practices who apply integrated design does so within the conventional relationships between the architects and engineers, which means that they end up in the situation similar to the one described by Michael Beaven where it is only possible to achieve integration in a minority of the design projects [Enclosure B: II: 238-265], it is therefore important to break away from the conventional way of approaching the relationship between engineers and architects if one wishes to achieve an integrated design process.

Based on chapter 7.4 it is my conclusion that the issues that are important to address when moving from a traditional design process to an integrated design process are:
- Collaboration in multi-professional design teams where everyone involved in the process have an equal say in the formation of the vision and the concept of the project.
- Create informal environment to enable the removal of language barriers, understanding and appreciation of each team member's abilities.
- Embrace different types of investigation (explorative, move-testing and hypothesis-testing) in relation to the purpose of the investigation and the stages in the design process.
- Hold reviews within the design team and engage a multi-professional design review panel that shares the responsibility of the project, provides critique on the work of the design

team and suggestions for how to proceed. This will also serve as quality and process control of the work delivered by the practice.
- Awareness of the risk of alienating clients who are afraid that the in-house multi-professional design team is too self-contained.

Design strategy development and the formation of shared visions and concepts
The development of design strategies relates to the formation of shared visions and concepts for projects. Design strategies are therefore developed at the concept stage in the beginning of the design process where the project has not found its final form yet. The investigations at this stage of the process will therefore primarily be explorative and move-testing. The tools for support of the development of design strategies therefore need to be explorative rather than determinative. Design strategy development tools should therefore enable exploration of the realm of possibilities, while design support tools should enable move-testing and hypothesis-testing experiments.

ARUP SPeAR
The ARUP SPeAR tool described by the interviewees can be used as both a support tool for design strategy development and an evaluation tool of existing buildings or design projects at different stages in the design process; At the time of the interview ARUP SPeAR was used for engaging the clients in the discussion of which direction to take projects in relation to the sustainability of projects. The 'AA_SPeAR_poster.pdf'[8] file received after the interview indicates that SPeAR is also applied during the design process at different stages in the design process for the evaluation of the sustainability profile of a project.

---

[1] Professor Bryan Lawson is employed by the University of Sheffied (UK), where he is the Dean of the Faculty of Architectural Studies. (for more information please see: http://www.shef.ac.uk/architecture/main/people/p_pag/bl.html 2007.

[2] For more information about Donald Schön please go to http://www.infed.org/thinkers/et-schon.htm 2007

[3] This scientific norm of disconfirmation seems to be based on the theories of Karl Popper, which state that it is easier to falsify a hypothesis than it is to verify, as the verification might just be achieved because one has not found a way of disconfirming the hypothesis and that one therefore cannot ever be sure that the verification is true. [Popper 2002:36]

[4] Robert Gutman is a visiting Professor of Architecture at Princeton University.

[5] Arup Associates is part of the consultancy group of Arup. For more information about the organisation of Arup please refer to http://www.arup.com/aboutus.cfm 2007

[6] The joint concept is developed through participation of all members of the design team in relation to the analysis of the opportunities in the specific project. It is not exactly clear in the interview what the approach to concept development is (whether it is based on analysis only or analysis and sketching), but the fact that all members of the design team are involved in the concept development and the description of the cooperation between the different professions in Enclosure B (e.g. I: 67-78, 208-237) indicates that the approach to the concept development includes both analysis and sketching.

[7] The specific example referred to in the interview was the development of a neighbourhood covering the area of 14 million square feet.

[8] The 'AA_SPeAR_poster.pdf' file is available to the assessment committee on a CD attached to the PhD thesis.

Conclusions PART 1: Methodical approaches

The answers found to the subsidiary questions asked in this part of the thesis were;

Which methodical approaches have been developed for sustainable architecture and what is the difference between these methodical approaches?

There are many different methodical approaches to sustainable architecture (e.g. Self-sufficient, Ecological, Green, Sustainable, Bioclimatic, Environmental, Low energy, and Solar Architecture). What distinguish these approaches from one another are the design strategies they apply for the selection of design principles. The approaches have developed in response to different dominant concerns (Nature, Culture, Climate and Technology). The design strategies applied by the different approaches therefore relate to the dominant concern addressed by the approach. Of these dominant concerns especially the concerns for climate and nature lead to differences in the prioritisation of design principles

Table P1.1: The relationship between the dominant concern for nature and climate, and the primary and secondary design principles applied in design strategies in response to these.

Dominant concern	*Nature*	*Climate*
Main design principles	biodiversity, life cycle profiles and toxicity of materials, reduction of transportation and renewable power sources	reduction of energy loss through the building envelope (insulation, window area to orientation ratio, window to floor area ratio, surface to floor area ratio, zoning, thermal mass, mechanical ventilation) and reduction of electrical energy (utilisation of daylight, natural ventilation and energy efficient appliances)
Secondary design principles	reducing the energy consumption in the building through the building shape	Lifecycle profile and human toxicity of materials, biodiversity and reduction of transportation.

What is the difference between the conventional approach to architectural design and the approaches to the design of sustainable architecture?

The main difference between the conventional approach to architectural design and the approaches to the design of sustainable architecture is the integration of environmental considerations from the beginning of the design process. This usually requires an inter-disciplinary approach to the design process in which an inter-disciplinary design team is formed if the designer does not have an inter-disciplinary education (e.g. a master from the Department of Architecture and Design at Aalborg University (Denmark)).

Is there a difference between how architects and engineers work? And does this influence the development of sustainable architecture and tools for design strategy development?

The main differences between how architects and engineers work are the result of differences in the assignments that the architects and engineers traditionally have to solve. These differences are therefore embedded in the architecture and engineering educations, in the way architects and engineers are taught to approach the problem-setting and problem-solving in projects.

Table 7.1: Comparison of the approach to problem and experimentation in the engineering design and architecture case studies by Schön [Schön 1983:76-105, 168-204]

	Engineering design	*Architecture*
Problem	• The problem is constant and the hypothesis changes as a result of experiments. • The solution is dependent on the problem and the hypotheses. • The problem defines the solution • The solution is more important than the problem	• The problem is revised and specified in relation to the results of experiments. • The problem and the solution are interdependent, and the problem does not define what the school building should look like. • The solution is more important than the problem
Experimentation	Hypothesis-testing	Move-testing

The methodical approaches to sustainable architecture require early integration of environmental design principles, which are traditionally embedded in the engineering profession. This means that engineers now have to be involved from the beginning of the design process, or that the education of architects needs to change.
When an engineer is involved from the beginning of the design process in an inter-disciplinary design team, he or she has to deal with the fact that the traditional problem-solving approaches embedded in his or her education no longer apply, because they were developed for application in the later stages of the design process when the design is close to realisation. The engineer, thus, has to deal with the abstractness of the design development in an explorative or move-testing approach to experimentation, rather than a hypothesis-testing approach to experimentation, which is traditionally applied much later in the design process. This means that there is a need for a development of tools which support this inter-disciplinary integration between the architecture and engineering professions.

Arup Associates is one of the international engineering companies who have worked with a lot of the environmentally sustainable buildings reported in publications. What is significant about their approach to environmentally sustainable building design? And how does this relate to the methodical process descriptions found in publications?

The methodical approach to environmentally sustainable building design applied by Arup Associates relies on an integrated and multi-professional approach to building design. It is my conclusion that the main difference between the Arup Associates' approach to integrated design and the approach presented in e.g. the IEA Task 23 project is that the multi-professional actors primarily are in-house employees, who have worked together a number of times and who have all been educated in Arup Associates' approach to integrated design by senior staff members. This means that the actors of the multi-professional teams in Arup Associates know each others professional language and personal preferences, and that the inter-disciplinary field in the case of Arup Associates is permanently embedded in the practice, while the inter-disciplinary field in most other cases are linked to a specific project, which means that the inter-disciplinary field disappears when the project is completed.

Another significant characteristic of the approach taken by Arup Associates is that the multi-professional design team is linked to a design review panel which provides an outside perspective on the project in order to ensure that the goals for the project are met, that a shared vision for the project is formulated and realised, and that the cooperation within the design team is well functioning.
The IEA Task 23 project and the IDP developed by Knudstrup also point out the importance of review of the goals of the integrated design process, but in these publications the review appears to be performed by the design team working on the project, whereas in the design review panel in the case of Arup Associates is not a part of the design team. The design review panel does, however, still share the responsibility of the project.

The approach taken by Arup Associates builds on years of experiences with integrated design of energy-efficient buildings, which means that integrated design is at the core of the practice. This does, of course, influence the approach taken to the design of environmentally sustainable buildings and the degree to which sustainability is achieved in their projects.
This is not something that can be integrated in Danish practices overnight, but it does indicate that successful integration of environmental considerations in architectural design takes time to master. It also indicates that integration requires a conscious choice of what to integrate and determination to overcome the professional 'barriers' of inter-disciplinary of cooperation, which is also reflected in the publications discussed in chapter 6.3.

The designers from Arup Associates identified the formulation of shared and project specific visions and concepts within the design team as the exercise that reserves the success of the project, and the detail stage as the stage which ensures successful realisation of the concept.

Based on this it is my general conclusion that the key to success in relation to environmentally sustainable architecture is the development of project specific design strategies, which identify the environmental design principles that are to be considered in relation to the architectural design of the building, and a careful detailing of the building in relation to this design strategy. The next part of this thesis will therefore address the issue of design strategy development.

PART 2: Design strategy development

The identification in part 1 of this thesis of design strategies as a core issue of methodical approaches to environmentally sustainable design and the importance of project specific design strategies in relation to the achievement of environmentally sustainable architecture in practice, has led part 2 of this thesis to focus on design strategy development.

This part of the thesis therefore contains a methodical experiment in which a design strategy is developed for an environmentally sustainable residential building in Denmark. Based on this experiment a suggestion is made for the development of a support tool for design strategy development.

The design strategy development experiment is based on a study of 1) design strategies applied in existing environmentally sustainable residential projects and 2) tools available to designers of Danish environmentally sustainable buildings. This study is presented in chapter 8 entitled 'State of the Art 2: Design strategies applied in residential buildings and available tools'.

The design strategy development experiment is presented in chapter 9 entitled 'Design Strategy Development Experiment' in which a sensitivity analysis is applied as the methodical approach to design strategy development. The methodical experiment tests whether sensitivity analyses can be applied as a methodical approach to the development of design strategies in the beginning of design projects when the vision and the concept of the projects are developed. The conclusions of the experiment provide an insight into the strengths and weaknesses of the application of sensitivity analyses for this particular purpose, as well as conclusions about what this methodical approach means to the development of design strategy support tools.

A suggestion for how to develop an existing tool for assessment of energy consumptions in Danish buildings into a support tool for design strategy development is presented in chapter 10 entitled 'Suggestion for Development of Tool'.

The following subsidiary questions are addressed in this part of the thesis:

1. Which design strategies are applied in existing environmentally sustainable residential buildings?
2. Which tools are available for designers of environmentally sustainable buildings?
3. Is it possible to apply sensitivity analysis as a methodical approach to design strategy development? If so, how can it be implemented in a tool?

Questions 1 and 2 are addressed in chapter 8 and question 3 are addressed in chapters 9 and 10.

State of the art 2: Design strategies applied in residential buildings and available tools

Introduction

This chapter entitled ‘State of the Art 2: Design strategies applied in residential buildings and available tools’ contains descriptions of the design strategies applied in five different residential buildings in temperate climates and the tools available to Danish designers of environmentally sustainable buildings.

The purpose of the study of design strategies applied in environmentally sustainable residential buildings has been to study which design principles are applied in these residential building projects. The sources of information used for the study were publications, study trips and web pages.
The studied projects were selected because they allexemplify an integration between the architectural design and the energy requirement of the buildings, because of their location in temperate and European climates, and because of the building type (i.e. residential).

The purpose of the discussion of the available tools has been to make a short presentation of the Danish digital tools (computer programmes) that are available to designers of Danish environmentally sustainable architecture and international tools which can serve as an inspiration for the development of new Danish design support and design strategy support tools.
The international tools included in this chapter are the LT-method and the SPeAR tool developed by Arup Associates which has already been described in chapter 7.4. The sources of information about the international tools are publications ([Bakers and Steemers 2000]) and the interview with two designers from Arup Associates, while the descriptions of the Danish tools are based on programme- and web-based user manuals for these tools and my personal application of the tools.

8.1 Design strategies applied in residential buildings

The design strategies described in the ‘State of the Art 1: Methodical approaches to sustainable architecture’ did not focus on a specific type of building. However, different types of buildings require different design strategies from both an architectural perspective as well as an environmentally sustainable perspective. This is especially the case with residential and non-residential buildings (e.g. office buildings or schools); Residential buildings have low internal heat gains and low ventilation rates due to the large number of square meters per person in the building, while non-residential buildings have high internal heat gains and high ventilation rates due to the small number of square meters per person and a larger number of installations in the building (e.g. computers). Furthermore the users of residential buildings often require higher dimensioning room temperatures than users of non-residential buildings due to differences in clothing and activity levels. The environmental strategies going into residential and non-residential buildings are therefore different in relation to these differences in requirements, where residential buildings in temperate climates usually require a lot of space heating and little or no cooling, and non-residential buildings often requires very little space heating and a lot of cooling.
Architecturally there are also large differences between the scale and programming that goes into the design of residential and non-residential buildings, such as room dimensions, different types of rooms, the time of day when the building is used, the openness of the façade towards the street and the openness between the spaces in the building, differences in materials and ‘iconic’ status, logistic issues relating to the flow of the users in the building etc.

The interview reported in chapter 7 with designers Peter Warburton and Michael Beaven with Arup Associates emphasised how design strategies applied in projects depend on the specific possibilities of the project.
It is therefore interesting to study existing sustainable residential buildings in order to gain an

understanding of the design strategies applied in the projects and, thus, the design parameters selected for these residential buildings and the differences in the application of these design principles. Five sustainable residential buildings were analysed for this purpose:

- BedZED
- Marzahn
- Sustainable Housing Lystrup, Category A
- Eco-house 99 Skejby
- Elephant & Castle

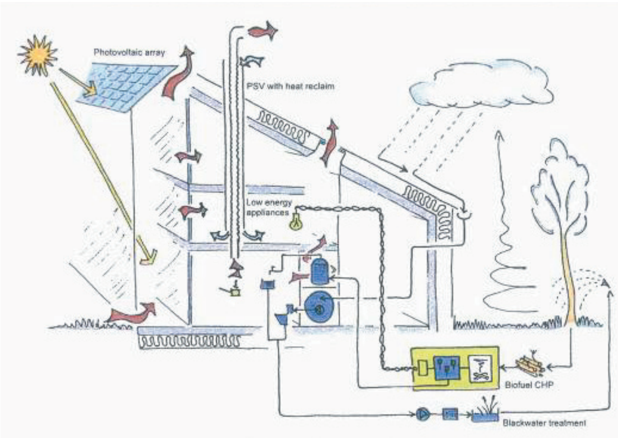
The descriptions of the projects primarily focus on the applied environmental and architectural design strategies. The descriptions are, therefore, not comprehensive studies of the decision-making process or the methodical processes applied.

The conclusions reached through this study with respect to the applied design principles will be used as inspiration for the selection of design principles in chapter 9 in which a design strategy is developed for an environmentally sustainable residential building as a methodical experiment.

8.1.1 Project examples

BedZED

Architect: Bill Dunster Architects
Engineer: Arup Associates
Client: the Peabody Trust and the Bioregional Development Group
User: average or low-income families
Start of operation: June 2001 [5]
Location: Hackbridge, Sutton, U.K.



Illustation 115.1: Diagram with the design principles applied in the BedZED project [Hawkes and Forster 2002]

Illustation 115.2: Picture of the BedZED project [Hawkes and Forster 2002]

This project presents a very comprehensive and urban approach to sustainability, which embodies environmental, social and economic sustainability. The aim of the project was to design an ecological urban development for average and low-income families, which produces as much energy as it consumes [www.peabody.org.uk 2007].

Table 8.1: The environmental and architectural design strategies in the BedZED project [http://Arup.com 2007, Hawkes and Forster 2002, www.peabody.org.uk 2007]

Environmental strategies	*Architectural design strategies*
• Green outdoor spaces for each apartment • Green roofs • Reduction in transportation of materials • Bio fuel • Electric carpool • Green house • Natural ventilation • Photovoltaic cells • Black-water treatment • Low U-values • Rainwater collection • Brown field site • Reduce transportation • Reduce embodied energy • High degree of air tightness in construction • Heat exchange in ventilation system • Visible power meters • Wintergardens	• Mix use • Create a net 'zero fossil energy development' • Address environmental, social and economic needs • Create affordable, attractive and environmentally responsible housing and workspace

Environmental strategies

The building complex is built on a brown field in a London suburban area, which means that the site chosen for the project does not take away from the green surfaces of the area. In spite of this the project has incorporated green roofs in order to reduce the impact on the local nature and create wildlife corridors.

The green roof is, furthermore, integrated in the scheme for the apartment units, which all have exterior garden spaces.

The building complex contains both office and dwelling units where some of the units consist of a combined office and dwelling unit. The offices are primarily used during the day while the dwellings primarily are used outside work hours. The complex also contains a shop which sells the ecological vegetables grown in the onsite greenhouse and a kindergarten. This mix of functions is supposed to reduce the need for transportation. Further means of reducing the environmental impact of transportation were present in the selection of the site, which is within close proximity to the railway with connection to the centre of London.

The heating system is designed with 19^{o}C as a minimum target temperature and the system relies on passive solar heating achieved via winter gardens on the south facades which have a high degree of glazing, internal heat gains from occupants, lighting, cooking, appliances and domestic hot water.

The heating system is designed to maintain a background temperature in the dwellings during longer periods of un-occupancy. This is achieved by using a thermostatically controlled vent from the domestic hot water cylinder cupboard.

Further means of reducing the energy consumption for heating in the building are; low U-values (approx. 0.1 W/m^{2}K for non-transparent and 1.2 W/m^{2}K for transparent building elements), high air-tightness, heat-exchange in the ventilation system, thermal mass, bio-fuelled CHP (combined heat and power) plant on site, Photo voltaic cells integrated in the roof of the winter gardens and visible power meters situated at table height.

The ventilation is based on a natural system with a passive heat- exchange system (wind cowls). The inlets are placed in the low polluting rooms, such as the living and bedrooms, and the extracts are placed in the kitchen, the bathroom. The wind cowls stretch across three floors which enables a chimney effect inside the air duct. The extract air duct is placed inside the inlet air duct which enables heat exchange between the inlet and extract air.
The ventilation is controlled by the users supported by the wind cowls which secure a minimum level of ventilation in the units.

The complex is designed for good daylight levels via orientation of the main window areas. The daylight in the office spaces has been of the highest priority, as these primarily are used during the day. This, and the internal heat gain in the offices, has affected the orientation of the offices in the complex, which means that these have been placed with a north orientation in order to ensure diffuse daylight levels and a minimum degree of solar heat gain.

The complex uses rainwater collection, which is stored in tanks inside the building, thereby also storing low-grade heat for hot water used in the dwellings, black-water treatment on the green areas on the site and low-flush toilets.

[http://Arup.com 2007, Hawkes and Forster 2002, www.peabody.org.uk 2007]

Architectural design strategies
The architectural expression and the terrace-houses seem to be inspired by the architectural expression of traditional British housing and the project has a very comprehensive approach to sustainability, as it considers both urban design and architectural design elements in the solution.
The building design has also been under great influence of the technical solutions and economic considerations e.g. in case of the wind cowls, double high spaces, green terraced roofs, the choice of materials and the orientation of the different units. Especially the wind cowls, choice of materials and the green terraced roofs provide the complex with a unique identity. The identity is very communal and it is based on ecological principles as well as new trends, such as the network community, where people work from their homes. The unique identity is also caused by the urban layout of the project and the variety of the service functions placed on the site.
[Hawkes and Forster 2002]

Performance
Table 8.2: The ecological footprint of the project compared to the footprint of the typical UK lifestyle[www.arup.com 2005]

Lifestyle		*Overall ecological foot print*
Traditional UK lifestyle	Owns car, go on yearly holidays by plane, recycles 11%, eats out of season, eats highly packaged and imported foods	6.19
BedZED conventional lifestyle	Owns car and commutes to work by public transportation, yearly holidays by plane, recycles 60%, moderate meat eater and eats some imported foods	4.36
BedZED ideal lifestyle	Lives and works at BedZED, Recycles office paper, ZED car member (no private car), two yearly holodays by plane, recycles 80% at home, low meat diet with local fresh food	1,90
Global average		2.40

Because the BedZED project is a demonstration project the project has been monitored continuously since the completion, and the first period of monitoring has already shown that compared with current UK benchmarks hot water heating is about 45% less, electricity for lighting, cooking, and all appliances is 55% less and water consumption is about 60% less.' [www.arup.com 2005]

Marzahn low-energy building
Architect: Assmann, Salomon & Scheidt and Partner
Engineer: Arup Associates
Client: WBG Marzahn mbH
User: families
Start of operation: 1997
Location: Marzahn (Berlin), Germany

Illustration 118.1: Pictures of the building from 2005 (Left: south facade. Right: North facade).

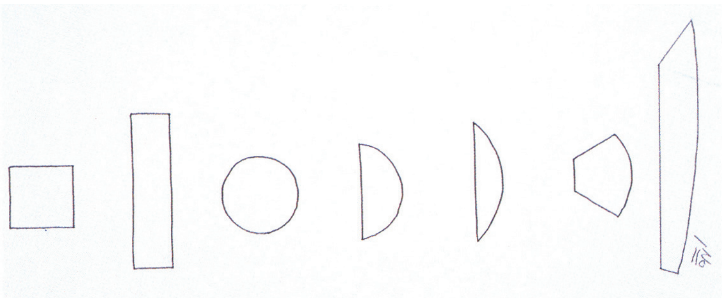


Illustration 118.2: The five different shapes subjected to the energy requirement study in the beginning of the project and the final shape of the building [Hawkes and Forster 2002].

This project is especially interesting from an architectural and process-oriented point of view. Architecturally the project breathes life into a suburban area of Berlin characterized by the cheep and old modernistic concrete residential buildings erected in the DDR after World War II. Inspired by the context, the architects have transformed the modernistic architectural language by applying a process aimed at achieving a low-energy apartment building by focusing on the volume to surface ratio, seasonal ventilation strategies, building orientation, day lighting and other passive techniques.

Table 8.3: The environmental and architectural design strategies in the Marzahn project [www.assmannsalomon.de 2005, www.berliner-impulse.de 2005 and Hawkes and Forster 2002]

Environmental strategies	*Architectural design strategies*
• Volume to surface area ratio • Zoning of functions in accordance with comfort temperatures and daylight requirements • Thermal mass and Night cooling • Seasonal ventilation strategies • Electronic user manual • Passive heat gain from windows • Low U-values • External shade	• Connection between building design and energy consumption for heating; study of different shapes • Spatial flexibility in living rooms • Outdoor spaces for each apartment

Environmental strategies
The volume to surface ratio was determined for five geometrical shapes based on a number of basic assumptions which made the results for the heating demand for the five shapes comparable. The cylinder proved to be the shape with the smallest heating demand (35 kWh/ m^2 per year), the results of this calculation was thus used as the target value for the design of the building shape.

The apartments are divided into thermal zones; the living room and the other primary rooms face south, as these are the rooms which require the highest comfort temperature and the best daylight conditions. The kitchen and the bathroom is placed in the centre of the apartment, while the extra bedroom in the larger apartments is face north, as this room usually requires a lower comfort temperature than the other primary rooms.

Six ventilation strategies were designed for different scenarios; summer day and night, winter, spring/autumn, extreme case (e.g. smoking) and kitchen and bathroom use. The building is naturally ventilated at all times of the year; in the summer night time ventilation remove the excess heat absorbed by the thermal mass in the building materials during the day and during the winter the inlet air is pre-heated by a radiator. During the winter, spring and autumn season the extract happens via the kitchen and bathroom, while the inlet and extract happens through the window during the summer and in extreme cases.
An electronic user manual helps the user ventilate the building in the most energy-efficient way via a weather station on the roof. The user manual ensures that the ventilation system and the heating system are shut down when the windows are open in the apartment and it provides a visible warning to the occupant at times when the windows could provide more effective ventilation than the mechanical fans situated in the kitchen and bedroom. The user manual furthermore provides information about room temperatures, external temperatures, wind speeds and wind directions.

Good daylight levels are established in the living rooms and kitchen, as the building has a narrow plan (7 m) which eases the penetration of direct daylight. Furthermore the internal walls are equipped with internal sliding doors in order to ensure even further penetration of daylight, as this enables the user to open up the rooms facing south, thus making one long room along the southern facade.

The heating system uses hot water supplied, via a heat exchanger, from a local district heating network. The rooms are heated by conventional radiators. The heating system is supplemented with solar heat gain from south facing windows (75% of window area) and internal heat gain and the heating requirement is reduced by the low U-values selected for the building envelope (outer walls 0.25 W/m^2K, roof 0.2 W/m^2K, All floors: 0.3 W/m^2K, windows and doors 1.1 W/ m^2K)

Terraces facing south provide all residents with an outdoor area. These terraces also serve as shading devices for the apartments on the floor below in order to avoid overheating during the summer season.

[www.assmannsalomon.de July 2005, www.berliner-impulse.de July 2005 and Hawkes and Forster 2002]

Architectural design strategies
What makes the project interesting is the way the overall building shape and the energy consumption were interconnected in the design process and the way the architectural disposition of the rooms are based on climatic considerations.

In the beginning of the project the study of the environmental performance of five different shapes was used to identify a target value for the energy consumption for space heating in the building. This led to an architectural design strategy that was very influenced by the connection between the architectural expression and the energy consumption of the building for space

heating:
- A large south facing façade with a high window to wall ratio
- As small a north facing façade as possible with a low window to wall ratio
- The east and the west façade were determined by a systematic experimentation with the lengths in relation to the overall heating demand of the entire building.
- Southern orientation of all apartments.
- Zoning of functions in accordance with comfort temperatures and daylight requirements

The spatial flexibility in living rooms is achieved by separating the south facing rooms with sliding doors. This, furthermore, enables a deeper daylight penetration in the apartment.

The access to outdoor spaces was achieved by integration of balconies on the south façade of the building, which were also designed to provide summer shade.

[Hawkes and Forster 2002]

Performance
Energy consumption:
The target value for the energy consumption of this low-energy building was a 20% reduction in comparison to the 1997 Berlin building codes [Hawkes and Forster 2002]. There is no report on what the actual energy consumption of the building is.

Sustainable Housing Lystrup, category A
Architect: Schmidt, Hammer and Lassen
Engineer: Birch & Krogboe and Arup Associates
Landscape architect: Kristine Jensens tegnestue
Client: Boligforeningen Ringgården (housing association)
User: Average and low-income families
Year of operation: under construction
Location: Lystrup, Denmark

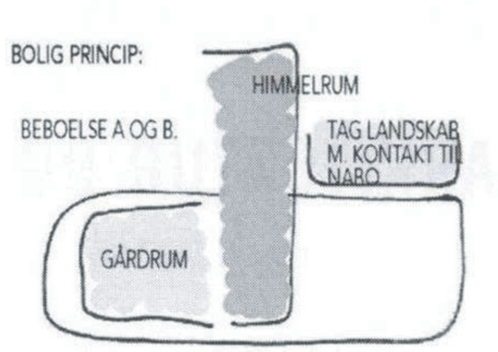


Illustration 120.1: Left: Rendering of the entrance street in the building complex. www.shl.dk 2005 and Right: Principal diagram for the Lystrup project [Arkitekten 28 2003]

In 2003 an international competition for sustainable residential buildings in Lystrup (just outside Aarhus) was arranged by the Ringaarden housing association. Eight international and national architect offices were invited to submit contributions, and the contributors were asked consider three different categories of housing on the selected site:
- Category A: Passive houses with 15kWh/m^2 as a maximum energy requirement for heating
- Category B: Healthy buildings with a good indoor climate and healthy materials (with low air pollution)
- Category C: Senior housing where 50% of the energy consumed in the building is provided by the sun.

Schmidt, Hammer and Lassen won Category A and C and Herzog and Partner won Category B.

The following description will only include the Schmidt, Hammer and Lassen (SHL) contribution to Category A.

Table 8.4: The environmental and architectural design strategies in the Lystrup project [DAL's konkurrence sekretariat 2003, www.shl.dk 2005 and lecture by architect Olav Dahl with Schmidt Hammer and Lassen]

Environmental strategies	*Architectural design strategies*
• Passive solar heating • Sky rooms / light wells • Green houses • Rainwater collection on roof used in common areas on site • Mechanical ventilation with heat recovery • Low U-values for and air tightness of building envelope • Avoid thermal bridges in construction • Compactness (surface to floor area ratio)	• Respectful connection between buildings and landscape, while keeping the buildings and landscape separate from one another. • Touch the earth lightly • Compact buildings with private entrances and gardens/ courtyards • Inspired by Danish courtyard houses from the 1920s and 30s and Mediterranean architecture. • Integrate green houses and fruit garden • Modern and sharp architectural expression • Optimum use of space

Environmental strategies
For the most part the applied environmental strategies correspond with the passive house strategy; passive solar heat gains are achieved by orienting most of the windows towards south, a compact building design which reduces the surface areas of the building envelope, application of mechanical ventilation with heat-recovery, using well-insulated walls, avoiding thermal bridges and ensuring an airtight construction.
A light-well is integrated in the building, which engulfs the staircase inside the building and enables a deep daylight penetration in the building.
Green houses are integrated in the garden space, which enable the inhabitants to grow their own vegetables.

[DAL's konkurrence sekretariat 2003, www.shl.dk 2005 and lecture by architect Olav Dahl with Schmidt Hammer and Lassen]

Architectural design strategies
A Respectful connection between buildings and landscape is achieved through the site layout, the visual connections from the building onto the site and the rooftop gardens in the building. The buildings are laid into the landscape on a grid which enables the wished separation of the buildings and the landscape, and the project touches the earth lightly by being partly built on stilts.

The compact building complex is designed as rows of three storey terraced houses. Each house has a private entrance, courtyard, greenhouse and a rooftop terrace.
Architecturally the buildings are inspired by Danish courtyard houses from the 1920s and 30s by Mogens Lassen and Arne Jacobsen, which is apparent in the courtyard structure, the façade design and the modernistic style of the buildings. The colour of the buildings and the light well towers are inspired by Mediterranean architecture (e.g. in Greece).

Green houses are integrated in the courtyards of each house and are intended for people wishing to grow their own vegetables. A fruit garden is, furthermore integrated in the site plan.

Due to economic constraints and rules for public housing an optimum use of space was prioritised in the project. This influenced the floor plans which have minimum waste of space for walkways, as well as the placement of the ducts for the mechanical ventilation system and the compact aggregate.

[DAL's konkurrence sekretariat 2003, www.shl.dk 2005 and lecture by architect Olav Dahl with Schmidt Hammer and Lassen]

Performance
The project is under construction so there are no measured energy consumptions available. The aim of the project has, however, been to live up to the passive house standard, which dictates a maximum energy requirement for space heating of 15 kWh/m^{2}K and a total use of primary energy of 120 kWh/m^{2}K.

Eco-house 99 Skejby
Architect: Tegnestuen Vandkunsten Aps
Engineer: Domina A/S
Client: Boligforeningen Ringgården (housing association)
Year of operation: 1998
Location: Skejby (Århus N), Denmark


Illustration 122.1: Pictures of the Skejby project [www.vandkunsten.com July 2007, Boligforeningen Ringgården 2004]

This residential project in Skejby was the result of a competition of a national competition entitled Eco-house 99, where Eco stands for both ecology and economy.
The competition was arranged by the Danish ministry of urban development and housing (the current Danish Enterprise and Construction Authority), and two of the submitted projects were realised in Skejby, Ikast and Kolding (Skejby and Ikast originate from the same project). [By og Bolig Ministeriet 2001, Boligforeningen Ringgården 2004]

The overall aim of the Skejby (and Ikast) project was to integrate well-known ecological principles with modern and interesting architecture. [Boligforeningen Ringgården 2004]

Table 8.5: The environmental and architectural design strategies in the Skejby project [Boligforeningen Ringgården 2004]

Environmental strategies	*Architectural design strategies*
• Reduce heating demand • Reduce water consumption • Reduce energy for hot water • Reduce electrical energy consumption for artificial light • Hybrid ventilation • Intelligent building system • Use materials with good life cycle profile • Low maintenance costs • Direct rainwater to percolation basin • Compost of garden waste • Vertical greening • Reduce private transportation	• Create good, beautiful and functional frames for family life • Create connection to existing landscape • Separate living and sleeping functions • Large degree of user control • Enable sense of season • Concentrate installations in ‘chimney’

Environmental strategies
The means of reducing the heating demand were: Low-emission windows (U-value (glass) 0.9 W/m^{2}K), Extra insulation in roof, gables and north façade, Accumulation of passive solar heat in solar space, Heat-recovery and climate control in each apartment and thermal zoning of rooms.

The water consumption is reduced by Low flush cisterns and tabs and visible placement of consumption meters, and channels were integrated in the facades and ground cover as a means of leading rainwater to a percolation basin.

The energy consumption for hot water is reduced by integration of solar panels for hot water and minimising of length of water pipes. There is no air-conditioning in the buildings, as the sunspace is assumed naturally ventilated and shaded during the summer.

The electrical energy is reduced by the introduction of a south oriented solar space, which floods the sunspace, and the rooms adjacent to the sunspace, with daylight.

Materials were selected for their low level of human toxicity, degassing and maintenance, and recycled concrete was chosen for the load-bearing constructions.

A compost area for garden waste was placed centrally on the site and vertical vegetation was integrated on the north façade and gables of the building as a way of creating a 'green' house.

Last but not least the project wished to reduce private transportation, and the housing association, thus, offer half of their vacant apartments to people who live in other regions while commuting to Aarhus for work.

[Boligforeningen Ringgården 2004]

Architectural Design strategies
Post occupancy reviews have revealed a great satisfaction amongst the inhabitants, which is reported as being due to the aesthetic, environmental and social dimensions of the building design.

A connection to the existing landscape was created via the orientation of the windows in the building; large glazing of the sunspace provides a 180 degree view towards the hilly landscape stretching from northwest to east. The sunspace also provides the inhabitants with a sense of season through the visual connection to the landscape and the thermal conditions inside the sunspace.

The sleeping and living functions are separated in the two storey apartments, where the sleeping functions and bathroom facilities are situated on the lower floor and the living functions are situated on the upper floor. This is chosen with respect to the view of the upper floor, as well as due to the fact, that the upper floor is warmer than the lower floor.
Installations from the mechanical ventilation system and the bathroom run in a central 'chimney' in the middle of the apartment. This reduces the length of the pipes and ducts, and it provides a natural partition of the rooms.

A large degree of user control was selected in spite of the large degree of intelligent systems in the apartment, as a way of enabling a sense of control with the user. This also means that the users need to interact with the building systems, e.g. use the shade and open the windows in the sunspace during the summer in order to reduce the cooling load.

[By og Bolig Ministeriet 2001, www.vandkunsten.com July 2007, Boligforeningen Ringgården 2004]

Performance
The primary energy for electricity and heat consumed for building operation is approximately 50% and the $C0_2$-reduction is approximately 14% of that of conventional terraced houses at the time of construction.

The post occupancy review has revealed issues of thermal discomfort in the sunspace at night during cold seasons, due to the fact that residents have to go through the sunspace in order to access the toilet. [By og Bolig Ministeriet 2001]

Elephant & Castle Eco-Towers
Architect: TR Hamzah & Yeang, HTA Architects and Benoy Limited
Project engineer: Battle McCarthy
Client: Southwark Land Regeneration Plc
Year of operation: under construction
Site: Elephant and Castle, South central London, UK

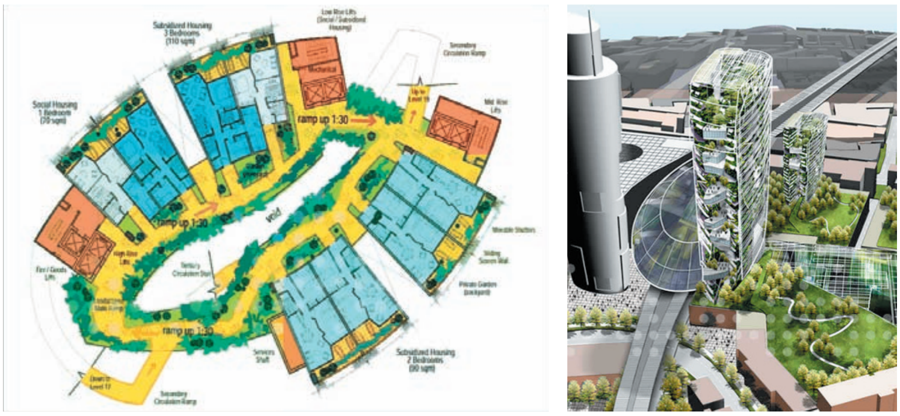


Illustration 124.1: Left: Elephant and Castle floor plan, Right: Rendering of Elephant and castle [www.trhamzahyeang.com]

This project is part of a larger development scheme of the Elephant and Castle area in London. A railway runs through the developed area, and TR Hamzah & Yeang, HTA Architects and Benoy Limited work on the right-hand side of the railway, while Forster and Partners work on the left-hand side.
The project is a recent example of the Yeang skyscraper situated in a temperate climate, and the vertical vegetation in thus project is particularly well integrated in the design where it enables the outdoor spaces of row houses while providing the view and density of a skyscraper.

Table 8.6: The environmental and architectural design strategies in the Skejby project [www.trhamzahyeang.com 2007]

Environmental strategies	*Architectural design strategies*
• Increase biodiversity • Reduce private transportation • Promote passive-mode systems • Maximise solar radiation in the winter months and maximise solar shading in the summer months	• Mix of residents • Provide local retail, leisure and communal activities • Different levels of green spaces (public, semi-private and private) • Provide views of the city

Environmental strategies
The site is what TR Hamzah and Yeang call a ‘zero-culture’ site, which means that there is no original ‘culture’ left on the site. In other words the original ecological systems on the site have been devastated by previous developments on the site.
The aim is, thus, to increase the biodiversity on the site through vertical vegetation in the core atrium of the building, as well as in green areas at each level of the building in connection with the private balconies and the semi-private entrance areas.

A mixed use of the area is expected to enable an increase in the types of users of the area and thus reduce the risk of sleeper cities. This is furthermore expected to ensure the availability of public transportation.
A mix of functions in the eco-tower is also supposed to create a city in the sky, which provides all the basic amenities for the residents and, thus, reduces the need for transportation.

The aim of the project has been to promote passive-mode systems through utilisation of passive solar heat, seasonal shade, evaporation from vegetation and building configuration.

Passive solar heat gains are achieved through an enclosed atrium facing north and south (the north orientation is for visual purposes only), and through the apartment windows orientated towards the east and west. The atrium was designed for direct solar radiation in the winter season while being shaded by upper levels during the summer season.
The apartments are naturally ventilated and the vegetation on the private balconies provides seasonal shade and evaporative cooling during the summer season.

[www.trhamzahyeang.com 2007]

Architectural design strategies
The residents are mixed via the integration of different functions in the skyscraper, such as private accommodation, public housing, communal facilities, hotel etc. This is furthermore underlined in the apartment design, which varies from studio to penthouse apartments.

Local retail, leisure and communal activities are available inside the building, as well as on the other side of the rails in a shopping centre, and the skyscraper is connected to the centre via a bridge leading over the railway.

Different types of green spaces provide an untraditional experience of the skyscraper. Public spaces are available in the form of three public parks in the sky (the sky courts), while semi-private and private green spaces are available at respectively the entrance area for the apartments and the private balconies for each apartment.

Due to its height the skyscraper provides a perfect view of the city north of the site from the apartments facing towards the city of London, as well as, from the communal sky courts in the atrium.

[www.trhamzahyeang.com March 7th 2007]

Performance
The project is under development and there are, therefore, no measured performance evaluation available. There is also no information available about the expected energy consumptions or ecological footprint of the project.

8.1.2 Conclusions

Applied Design principles

The projects apply a wide range of applied design principles.

Table 8.7: The design principles applied in the projects

	BedZED	*Marzahn low-energy building*	*Sustainable housing Lystrup*	*Eco-house Skejby*	*Elephant and castle eco-towers*
Atrium	■			■	■
Shade		■		■	■
Zoning	■	■		■	
Vegetation	■		■	■	■
Mixed Use	■				■
Window type	■	■	■		
Thermal mass	■	■			■
Rainwater collection	■		■	■	
Visible power meters	■			■	
Utilisation of daylight	■	■	■	■	■
Black water treatment	■			■	
Hybrid ventilation	■	■			
Natural ventilation		■			■
Mechanical ventilation			■		
Renewable energy sources	■			■	
Reduce private transportation	■			■	■
Window area to orientation ratio	■	■	■	■	■
Materials; lifecycle assessment	■			■	
Intelligent building automation system		■		■	
Connection with surrounding landscape			■	■	■
Reduce impact on site (ecological footprint)	■		■		■
Insulation and air-tightness of building envelope	■	■	■	■	■
Compact building shape (surface to floor area ratio)		■	■	■	■

Table 8.7 shows that some of the design principles are applied in all the residential projects; Insulation and air-tightness of building envelope, Window area to orientation ratio and Utilisation of daylight.

Other design principles are applied in three or four of the projects; Compact building shape, Vegetation, Atrium, Shade, Window type, Thermal mass, Rainwater collection, Reduce private transportation, Connection with surrounding landscape and Impact on site (ecological footprint).

The rest of the design principles are only applied in two or one of the projects; Visual power meters, Mixed use, Black water treatment, Hybrid ventilation, Natural ventilation, Mechanical ventilation, Renewable energy sources, Materials; lifecycle assessment and Intelligent building automation system.

The relationship between the environmental and architectural design strategies

The projects were selected because of their integration of environmental and architectural design strategies, this means that most of the projects apply an approach in which the environmental and architectural design strategies have developed through a ping-pong process between the environmental strategies and the architectural design strategies, and the projects therefore serve as good examples of an integrated approach to environmentally sustainable design.

Visibility of approach to sustainability

The projects apply the design principles differently in relation to specific scope of the projects. This becomes clear when the projects are placed in relation to the four issues concluded in chapter 6.2.2;

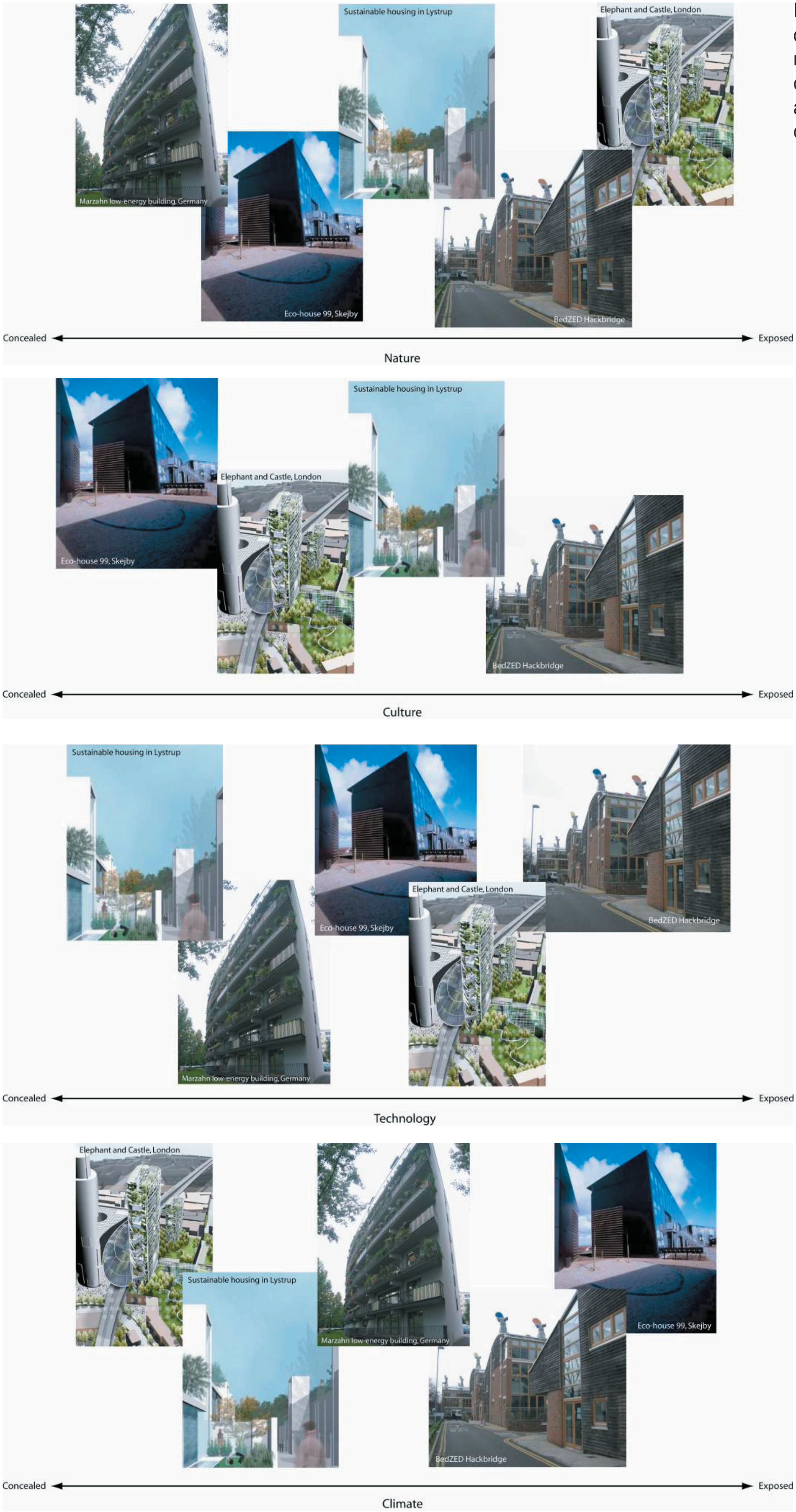


Illustration 127.1: Placement of the analysed projects in relation to respectively the climate, technology, culture and nature categories in chapter 6.2.2

8.2 Available tools

Most of the tools currently[1] available to designers of environmentally sustainable Danish buildings are digital (i.e computer programmes). However, publications containing design principles, guidelines and rules of thumb can also be regarded as analogue tools that enable environmental sustainability. These publications are interesting when acquiring background information about environmental and sustainable design principles applied in specific building types for the development of a design strategy for which of these design principles to include in a specific building project. The computerised digital tools come in handy when one wishes to combine the rules of thumb or the design principles in a new way or simply in a different context than the rules of thumb were developed or the design principles were originally applied. This means that analogue tools are currently applied in the beginning of projects and digital tools so far have been used for evaluation.

Digital tools are usually applied to save time or because it is mandatory (e.g. due to legislative demands). Tools are, however, not always timesaving; in some cases tools are very time consuming to use because they were not originally designed for what they are used for. The following discussion of the digital tools available to designers of environmentally sustainable Danish buildings will demonstrate that there are currently no Danish tools available that were developed to support the design of environmentally sustainable buildings.

Categorisation of tools

As mentioned in the acknowledgements chapter of this thesis this PhD project is part of the ECBCS IEA annex 44 project entitled 'Integrating Environmentally Responsive Elements in Buildings'. During the third expert meeting in Turin (April 2006) the following categorisation of tools was developed as the result of a Subtask B workshop:

Table 8.8: Tool categories developed in Subtask B at the IEA Annex 44 in Turin

Category	*Description*
Design process tool	These are tools which help structure and manage the design process with respect to the phases, tasks and actors.
Design strategy tool	These tools help to structure a for instance the technological design issues or the selected design principles in relation to the formulation of a design strategy.
Design support tool	These are used to get an idea of what design strategies and design principles are the most promising for a given project.
Design evaluation tool	These are tools applied to check the performance of a given design and compare it to a target criteria or another design scheme.
Simulation tool	Simulation tools are used to predict the performance of a specific design solution

Of these categories it is especially the design strategy tools and the design support tools that are of interest in this PhD project, as these are regarded as the most important for the integration of architectural and environmental design strategies in one joint design strategy.

Computer aided tools for environmentally sustainable architecture

In Denmark there are very few tools designed for environmentally sustainable architecture, the development of tools has, however, increased during the last three years. There may, therefore, be tools under development or tools that may have been released recently which are not considered in this state of the art chapter.

Most of the tools discussed here were not designed as tools for enabling environmental sustainability; they were designed as tools for evaluation and simulation of the energy consumption, indoor climate and lifecycle assessment. The Danish tool described in this chapter:

- BEAT 2002
- Be06
- BSim2004
- BuildDesk

There are of course a lot of international computer programmes which could be discussed in this chapter. For demarcation purposes only few of these will be discussed in this chapter:

- LT-method (During my visit to the Martin Centre at the University of Cambridge, UK, I was introduced to an interesting computerised version of the LT-method)
- Arup SPeAR

These tools are included because they serve as examples of tools that can be applied as support tools for design and design strategy development. The LT-method and the Arup SPeAR tools are, thus, included as inspiration for the development of design support tools.

8.2.1 Existing tools

BEAT 2002

The abbreviation BEAT stands for 'Building Environmental Assessment Tool'. The tool was developed by the Danish Building Research Institute, and it is primarily used for life cycle assessment of buildings or building components. The first version of the programme was released in 2000 and the latest version was released in 2002.

The programme contains a large database which enables the application of predefined construction types, as well as user defined construction types.
At the time of release the programme was the only Danish programme, which enabled a comparison between different types of energy sources (incl. renewable energy sources). The energy calculation programmes of today include a few different types of energy sources. These programmes are, however, not as comprehensive with respect to the types of energy sources included in the BEAT database.

The programme consists of three parts;

- A database for energy sources, means of transportation, products, building components and buildings
- A user interface which enables additions, corrections and deletion of data in the database by the user
- A calculation interface which enables calculations of building components and buildings, as well as different kinds of result analyses.

[www.sbi.dk 2007]

The programme enables comparative studies of energy sources, materials and construction types based on databases containing empirically collected information about the life cycle of the materials and the energy sources. The database is, thus, vulnerable to new types of production, new discoveries of material resources, new ways of reusing or demolishing the materials and constructions.

The programme does not enable calculation of the energy requirement of buildings, which means that one needs to calculate the energy consumption of the building in another programme (e.g. Be06) and insert the information in BEAT.

Because of the large database the programme enables very detailed calculations, which can be quite heavy to deal with in the design stages of a building project. A work group consisting of architects and researchers at the Danish Building Research Institute, therefore, developed a publication entitled 'Architecture and environment – form, construction, materials and environmental influence' [Marsh, Lauring and Petersen 2000]. The publication assessed the life cycle of the most commonly used materials and construction types based on:

- The resource consumption in kg/year (reused, renewable or non-renewable resources)
- The energy consumption in MJ/year (Renewable feedstock energy, non-renewable feedstock energy, renewable energy and non-renewable energy)
- The Green house effect in x 100g $C0_2$/year
- Acidification in $gS0_2$/year
- Nitrogen in gN03/year
- Human toxicity in m^3/year
- Removal in kg/year (High degree of reuse, low degree of reuse (combustion) and dangerous waste)

The publication furthermore compared the energy consumption and the green house effect of respectively the materials applied for the construction and the operation of the building

The BEAT programme is designed for evaluation, and it, thus, does not have a design friendly interface, which in this case means an interface which supports easy changes to the shape and design of a building.
The fact that the programme does not have a designer friendly interface does not matter so much in the light of the purpose of the programme, which is to enable comparisons of the material consumption and energy sources of buildings. It would however ease the initial process of inserting the input data if the programme was linked to e.g. the geometry and material selections in BSim models. At the moment this is not possible; in spite of the fact, that the BEAT, Be06 and BSim programmes are all developed by the Danish Building Research Institute their files and calculation cores are currently[2] not compatible with one another.

If BEAT is to be applied as a design support tool the interface should be revised to as a minimum display plans and possibly sections of the building and the programme should enable easy changes to the materials applied in the building. The programme would furthermore need to include a calculation of the energy consumption of the inserted building designs in order to enable true assessments of the environmental performance of buildings.

Be06 [3]

On January 1st 2006 a new set of energy requirements were introduced to the Danish building regulations (for more details please refer to chapter 4.1). Be06 is the official programme developed for evaluation of the energy consumption in buildings as of 2006.
The programme was developed by the Danish Building Research Institute and it is a revision of the previous energy calculation tools Hd95 and Hd98 (BV95 and BV98 in the Danish versions of the programmes). Hd95 and 98 were designed for evaluation of the heating demand of buildings, whereas Be06 also includes the energy requirements for cooling, hot water, electrical appliances and lighting.

The Be06 programme uses mean monthly calculations of the heat balance in the building in accordance with the prEN ISO 13790:2005 [Aggerholm and Grau 2005:22-24]. More detailed information on what the Be06 calculation is based on is available in chapter 9, 10 and 16B.

The mean monthly calculations are not dependent on a specific geometry of a building but on the surface areas and characteristics of the elements of the building envelope (e.g. U-values of the walls, roofs, floors and windows, and the angle, orientation, g-values, area and shade factors (Ff) on windows and doors). The programme is, therefore, easy to apply in the initial stages of the design process for the decision about which design principles are to be included in the project and which target values to aim for.
Because the programme was designed as an evaluation tool it is, however, quite time consuming to apply it for this strategic purpose. This will be discussed in further detail in chapters 9 and 10.
If the Be06 programme is to be applied as a design support tool it needs to adapt an interactive geometry interface that enables fast and easy iterations between the building design and assessment of the energy performance of buildings.

BSim2004

The BSim programme was developed, and is developed continuously by the Danish Building Research Institute. The programme is used for Building Simulation, and previous versions were titled Tsbi.

The programme is applied for thermal building simulations of the indoor climate. The calculations are based on the Danish Reference Year (DRY) and the programme is geometry dependent. The programme is furthermore applicable for multi-zone modelling, and more extensions of the programme are under development, such as models for simulation of heat pumps, ventilation and moist in swimming baths, advanced modelling of solar shading, improvement of models for simulating moist in buildings and moist and heat accumulation in building furniture and equipment, import of CAD files (IFC), integration of BEAT etc. [www.sbi.dk/indeklima/ 2007]

The programme contains databases with wall, floor and rood constructions and the corresponding U-values of these constructions. It is also possible to create new construction types within the database and, thus, update or simply elaborate the database. One can also import a database developed by someone else or applied in another project. The fact that Bsim is applicable in any climatic context, by replacing the DRY file with a similar file for another climatic region, also adds to the flexibility of the programme.

Due to the calculation method this programme provides more detailed results (for e.g. the thermal comfort conditions in buildings at different times of the day and month) than programmes using month mean value calculations, such as Be06 and BuildDesk. However, the BSim programme has, so far, not approved for legislative documentation of the energy requirement of buildings.

The insertion of geometry in the building follows a very rigid procedure, where the building and the rooms inside the building are inserted in a system of coordinates where the dimensions of the building and room are specified. Each surface of a room can be selected in a tree structure in the left-hand side of the interface in relation to selection of the construction of e.g. the walls, floors and roofs.
The geometry has also proven to be sensitive to the degree of complexity in previous versions of the programme; if the building becomes too complex the building becomes leaky in the calculation and the simulation is useless.
Another issue related to the geometry of the BSim programme is, that the rooms must be shaped like a box or a series of boxes. The programme, thus, does not operate with curved shapes and the like.

Besides from the issues of the insertion and model sensitivity of the geometry the programme is very easy to use. These issues do, however, limit the programmes ability of design support, as the insertion of the geometry is quite time consuming and because the geometry is difficult to change without starting over.

If the geometry interface of the Bsim programme was improved or import of 3D files from Architectural Desktop (AutoCad) was enabled the programme might become a lot more attractive to building designers, especially if the programme was also approved for legislative documentation.
The integration of the BEAT programme in BSim is also very interesting, as this might result in one joint programme for environmental assessment of buildings.

BuildDesk 3.2
BuildDesk was developed by the BuildDesk Group – a European collaboration, which was founded in Denmark in 2002 [www.builddesk.de 2007], the group is therefore based in Denmark where it is part of the Rockwool Group. The BuildDesk software has so far been released in Denmark (in 2005), the Netherlands, Germany, UK and Ireland [www.builddesk.com 2007].

The BuildDesk Group is associated with a scientific committee for Energy Design of Buildings. This committee consists of some of the leading experts on Energy Design in Europe;

- Arne Elmroth (Professor (emeritus) at the building physics department at Lund University, Sweden.)
- Harry Niemann (Managing Director of the Dutch Consulting Engineers Company Adviesburo Nieman, Netherlands.)
- Karl Gertis (Professor at the University of Stuttgart, Germany. Former director of the Frauenhofer Institute for Building Physics, Germany.)
- Jean-Christophe Visier, Head of Sustainable development department , Centre Scientifique et Technique du Bâtiment, France.)
- Hermann J. Jahrmann (Managing Director of the software company Ecotech Bauphysik & Energietechnik Software GmbH, Austria.)

- Svend Svendsen (Professor at the Technical University of Denmark, Department for Civil Engineering, Denmark.)

[www.builddesk.com 2007]

The Danish version of the BuildDesk programme uses the same calculation core as the Be06 programme with the same purpose as the Be06 programme; evaluation. And it is possible to import a Be06 file into the BuildDesk programme.
The BuildDesk programme does, however, have an advantage, that the Be06 programme does not; it contains catalogues for boilers, materials, ventilation aggregates etc. This eases the calculation process significantly compared to the Be06 programme, as it enables easy access to information, which would otherwise be difficult to find for non-experts in e.g. HVAC systems.
The BuildDesk programme also contains an interface for the calculation of the U-values of the non-transparent elements in the building envelope, which also makes the programme more appealing than Be06 which refers to the Danish Standard DS418 for manual calculation of U-values of walls, roofs and floors.

The BuildDesk programme provides the same type of results as the Be06 programme. The results are, however, displayed in more detailed graphs and in different contexts than the results of the Be06 programme. This eases the analysis of the results to first time users and newcomers.

Like the Be06 programme, BuildDesk does not have a design friendly interface if it is applied as a design support tool. The BuildDesk programme would therefore need to integrate an interactive geometry interface if it is to be used as a design tool, that enables easy iteration between energy calculation and building design.

LT-method

The LT-method is a product of the Martin Centre at the Department of Architecture at the University of Cambridge. The tool is included in this thesis because of the interface and setup, which can serve as an inspiration for the introduction of improvements of some of the existing Danish tools.

LT stands for Light and Thermal, and the first version of the LT-method was released as a paper version of tables and graphs in the publication ‘Energy and Environment in Architecture – a technical design guide’ by Nick Baker and Koen Steemers [Baker and Steemers 2000]. The purpose of the development of the LT-method was ‘to fill the gap between the prescriptive design guide and the building science text-book’ [Baker and Steemers 2000:vii].
The most recent versions of the LT-method have been in the form of software tools, and further development of the method is under way [www.arct.cam.ac.uk 2007].

The LT-method is an interactive tool based on monthly mean calculations that enables comparative studies of different design solution. It also serves as an interactive design support tool during the design development stages of a project. This programme is, therefore, applicable for design support, design strategy and design evaluation, which makes it unique.

The programme interface provides a nice link between the geometry design and the calculation of energy requirements. It is easy to switch between the design and calculation sheets of the programme, and it is possible to compare different cases (sketches) in the case comparison sheet.
The geometry interface is primarily centred on the floor plan of the building supplied with a section tool. The characteristics of the facades are applied by clicking the façade lines in the plan. The geometry interface is quite simple compared to traditional design support tools like 3D studio max and SketchUp, but it does contain all the elements relevant to environmental design, such as the possibility of adding atriums to the building by defining a space and the type of atrium (based on the location in the building and the ventilation strategy in the atrium), and the geometry is not restricted to straight lines.

The LT-method works within the 'environmental design' approach developed at the Martin Centre (please refer to chapter 6.1.6 for more information). It, thus, operates with zoning of the building into passive and non-passive zones. The passive zones are the zones with sufficient daylight and sufficient natural ventilation, whereas the non-passive zones are zones which need artificial lighting and mechanical ventilation. [Baker and Steemers 2000:96]

Another advantage of the LT-method is that it integrates the evaluation of the daylight conditions and possibilities of natural ventilation with evaluation of the energy requirements of the building, and the results provided by the programme include; the energy required for cooling, lighting and heating of the building, as well as the number of days with overheating temperatures inside the building.

Arup SPeAR

The ARUP SPeAR tool described in chapter 7 has not been tested in this project, so the following description is based on the files received about the tool after the interview and the interviewees' description of the application of the tool.

Based on the description of the tool in the files received from Arup Associates and the description made by the interviewees in chapter 7.4 it is my conclusion that Arup SPeAR is interesting in relation as a support tool for design strategy development and design evaluation.
The reason why it does not appear to be applicable as a design support tool is that the description of the tool indicates that it does not have a geometry interface, which means that it does not support easy changes to the building design within the programme.

The tool is not available to designers of Danish environmentally sustainable buildings unless they cooperate with Arup Associates on the project. The holistic approach to sustainability taken in the selection of indicators for the tool (Illustration 105.2) does, in my opinion, provide a great reminder of all the different indicators that should be integrated in one joint tool for assessment of the sustainability of buildings, as well as, in tools that support design strategy development for environmentally sustainable architecture.

8.2.2 Conclusions

Based on application and literature about these tools it is my conclusion that most of the available tools are applicable for design evaluation, while there are no Danish tools represented in the design support tool category or the design strategy tool category.

Table 8.9: Categorisation of the available tools

Category	Description	Tool
Design process tool	These are tools which help structure and manage the design process with respect to the phases, tasks and actors.	• The IEA Task 23 navigator (described in chapter 6.3.1)
Design strategy tool	These tools help to structure a for instance the technological design issues or the selected design principles in relation to the formulation of a design strategy.	• ARUP SPeAR
Design support tool	These are used to get an idea of what design strategies and design principles are the most promising for a given project.	• LT-method
Design evaluation tool	These are tools applied to check the performance of a given design and compare it to a target criteria or another design scheme.	• BEAT • Be06 • BuildDesk • Bsim • LT-method • Arup SPeAR
Simulation tool	Simulation tools are used to predict the performance of a specific design solution	• BSim • BEAT

Development of Danish design support tools

LT-method

With respect to the development of design support tools a lot can be learned from the LT-method, in fact if the LT-method is updated to the prEN ISO 13790 for Thermal Performance of buildings (which is scheduled for release in 2008) it can be applied in Denmark as the design support tool, because the programme already contains a climatic data set for Denmark. The geometry interface of the LT-method could, however, also be improved to display the sketches in 3D inspired by e.g. the SketchUp programme.

BSim and BEAT

The current developments of the BSim programme will integrate the BEAT programme, which will save time if both programmes were to be applied anyway. This will especially save time if the import of 3D CAD-files is enabled.

The import of CAD-files will, however, not provide an interactive design support tool if the geometry interface of the Bsim programme is not improved. If the geometry interface is not improved one would have to make the changes in a CAD programme and import the file again. The current set up of the programme would then require the user to set up all the systems for the file all over again.

Improvement of the geometry interface as well as the possibility of 3D CAD import and export would, however, enable relatively easy iterations with respect to the building design. A further element inspired by the LT-method could be the comparative interface in which the results of different BSim models can be compared.

BuildDesk and Be06

The BuildDesk and Be06 programmes do not have a geometry interface and it is not needed for the application of the programme. And the programmes would not even be necessary as design support tools if the LT-method is updated to the new prEN ISO 13790 and the geometry interface is improved in the BSim programme to enable import and export of CAD files. If the wish is to develop BuildDesk and Be06 into design support tools an interactive geometry interface is necessary, which enables easy iterations between building design and energy calculation, as well as comparative analysis of design alternatives.

Development of Danish design strategy support tools

There is a need for the development of design strategy tools to enable designers of environmentally sustainable buildings to identify the important design parameters in relation to specific building types or specific projects. Design strategy support tools would not necessarily need an interactive geometry interface because they would be applied early in the design process when the first sketch is made for the architectural design of the building envelope, or maybe even before the first sketch of the building envelope when the first floor plan is made (provided that the designer works from the inside and out).

The calculation parameters in design strategy support tools are a lot more important than a geometry interface, as these should accommodate 'sketchy' and abstract input data e.g. the total window areas of buildings as a percentage of the floor area in the building (window to floor area ratio). A geometry interface would of course appeal to designers of architecture, but the calculation parameters are more important than this, which means that the first priority of developers of such tools should be the selection of these calculation parameters.

Through the development of an experimental design strategy for a Danish environmentally sustainable residential building this PhD project tests a methodical approach for the development of design strategies (i.e. the selection of which design principles to integrate in the building design). This experiment is reported in chapter 9.

---

[1] Spring 2007

[2] This is hopefully about to change as the result of the development of BSim described later in this chapter.

[3] When this PhD project started in 2004 the Be06 programme was not developed yet. The Be06 programme replaced the BV98 programme which until then was used for demonstrating that a building lived up to the energy frame in the Danish building regulations.

9 Design Strategy Development Experiment

Introduction

This chapter contains an experiment in which a sensitivity analysis is applied as a methodical approach to the development of a design strategy for a Danish environmentally sustainable residential building.

The inspiration for the application of sensitivity analysis as a methodical approach to design strategy development was found in the field of building engineering where sensitivity analyses are applied for e.g. single and multi zone modelling of hybrid ventilated buildings [Brohus, Frier and Heiselberg 2002], quantification of uncertainty in thermal building simulation [Brohus, Frier, Heiselberg and Haghighat 2002] and the energy performances of buildings [Lam and Hui 1996].

Design strategy development is in this thesis regarded as the selection of which design principles to apply in the building with respect to the architectural design of the building, the structural design of the building, the design of the indoor climate of the building and the energy performance of the building. Designers of buildings are always faced with a lot of decisions where they have to choose between different design principles, it is therefore important to be able to choose between these. This particular experiment focuses on the interface between the architectural design and the energy performance of the building, which means that issues relating to the structural design and the design of the indoor climate in the building are considered more superficially than the issues relating to the architectural design and the energy performance of the building.

The decision to choose one design principle over another is usually based on the personal preferences of the architect or the design team in relation to the building type and the criteria set by the client. Architects and design teams have developed their preferences though education and practical experiences.

The target group for this PhD project has been architects and engineers with limited or no experience with the design of environmentally sustainable buildings, which means that they have no preferences to base their design strategies for the building design on. In the case of environmentally sustainable buildings even experienced designers cannot base their decisions solely on experiences from previous projects as all projects are unique undertakings [Schön 1983:137-141, Gutman 1988:106 and Enclosure B: II:444-448].

The idea behind the experiment is that *the design strategy development is performed in the beginning of the design process to get a sense of which direction to take the building design by determining which design parameters to focus on in the relationship between the design of the building envelope and the energy performance of the building*. The purpose of the sensitivity analysis was therefore to uncover which design parameters have the greatest influence on the energy consumption in new residential buildings in a Danish context in order to use these actively in the development of a joint design strategy for an environmentally sustainable building. .

The sensitivity analysis is based on a reference building for which a number of selected parameters are varied. The results of the analyses are analysed in relation to the parametric sensitivity to respectively the total energy consumption of the building, and the energy consumption for heating, cooling and hot water. These results provide an indication of which design parameters are respectfully the most sensitive or robust in relation to the energy consumption of the building. The sensitive parameters are the parameters which have the greatest potential to either decrease or increase the energy consumption of the building, whereas the robust parameters are the parameters which can be changed in the project without a great influence to the energy consumption in the building.

The information about the sensitivity and robustness of the design parameters can then be used for the selection of which design parameters to focus on in the design strategy for the building. There are basically two ways to approach the selection of the parameters based on the information provided by the sensitivity analysis; 1) to primarily choose the sensitive parameters

because they can enable a needed or desired reduction in the energy consumption of the building or 2) primarily choose the robust parameters because they are least likely to influence the energy consumption of the building. 2) is only interesting if one has already achieved a low energy consumption in the building and therefore wishes to avoid increasing the energy consumption by applying a sensitive parameter.
The results of the sensitivity analyses are applied in the development of a design strategy for a Danish residential building. The discussion of the input parameters subjected to analysis will try to exemplify how these parameters relate to issues that the design strategy also needs to consider; physical and psychological perception of comfort in a building, functionality, aesthetics and the energy consumption of buildings. The relationship between the developed design strategy and other design principles which go beyond the issue of the energy consumption in a building will be discussed in the conclusion of this chapter.
The conclusions made in the experiment will be the fundament of the development of a design strategy for a new environmentally sustainable residential building in a Danish context. This experiment does not have a specific project to relate to in this exemplification and the design strategy development will therefore have a more discursive character than if it were applied in a real design project.

9.1 Methodology applied in the sensitivity analysis

Sensitivity analyses are basically statistical ways of producing and analysing data, and they are, thus, applied in many different fields. The analyses are usually performed to determine the sensitivity of parameters and/or the importance[1] of parameters (uncertainty analysis) [Hamby 1994].

The sensitivity of parameters is interesting when one needs to choose between a number of parameters, i.e. which parameters to include and which not to include in relation to the decision of which design principles to focus on in the creation of a design strategy for a specific environmentally sustainable building.
The importance of parameters is interesting when one has to prioritise a number of parameters in a decision-making process.

There are many different types of sensitivity analyses [Hamby 1994, Saltelli, Chan and Scott 2004] which according to Hamby 1994 fit into three groups of sensitivity analyses:
1) One at a time (OAT) analyses
2) Analyses that rely on the generation of an input matrix and an associated vector
3) Analyses that require partitioning of a particular input vector based on the resulting output vector

Another distinction in types of analyses is the distinction between local sensitivity analyses and global sensitivity analyses.
The differences between the local and the global sensitivity analyses are:

Local analysis	Global analysis
• One at a time (OAT) • Less complex • Sensitivity ranking is dependent on the reference building • Parameters are assumed independent	• Random sampling • Large degree of complexity • Sensitivity ranking is less dependent on the reference building than in the local analysis, it is however still dependent on the input data in the reference building that is not varied in the global analysis. • Provides information about possible correlations (inter-dependencies) between parameters.

[Hamby 1994]

Based on this it seems, that the global sensitivity analysis is the best and most complete type of analysis, which is correct. It is, however, also very time-consuming and complicated to do, which is why local sensitivity analyses are usually performed before global analyses in order to reduce the number of variable parameters. The risk associated with this reduction of the number of parameters based on the local analysis is that parameters which are seemingly robust (i.e. insensitive) in the local analysis might turn out to be sensitive when multiple variables are changed simultaneously in the global analysis.

The degree of complexity is dependent on the number of variable parameters and the number of steps in the range of the parameters. A study with few variable parameters and few steps in the ranges is less complex and can be investigated via simple analyses e.g. a local analysis combined with a factorial analysis [Box et al 1978].

The analysis applied in this PhD project has been divided into two parts: a local analysis of the OAT variety and a global analysis after the Morris method [Hamby 1994 and Saltelli, Tarantola and Campolongo 2000].
The purpose of the local analysis has been to investigate how a selected group of parameters influence the energy consumption of a residential building, if they are changed one at a time (OAT), whilst the purpose of the global analysis was to identify the robust and sensitive parameters when the parameters are changed simultaneously. A further purpose of the global sensitivity analysis has been to uncover possible inter-correlations between the design parameters.

The process
The process involved in the sensitivity analysis has consisted of nine stages:
1. Choice of reference building
2. Choice of which computer programme to model the reference building in and what to investigate/evaluate
3. Selection of the input parameters
4. Ranges were set up for the input parameters
5. Local sensitivity analysis where the input parameters were changed individually in accordance with the ranges
6. Analysis of the results of the local analysis and a preliminary ranking.
7. Decide the input parameters for the global analysis.
8. Global sensitivity analysis (type 3 in Hamby 1994; an analysis that require partitioning of a particular input vector based on the resulting output vector):
9. Analysis of the results of the global analysis → Design strategy

Theory of science
The sensitivity analysis originally belongs to an empirical-analytical approach to science, in the sense that the sensitivity analysis is based on mathematical models and calculations. The model applied in this particular sensitivity analysis does, however, in spite of this only produce qualitative results, which means that the perspective applied in this PhD thesis is, that the sensitivity analysis can be used to convert otherwise quantitative data to qualitative assumptions about the behaviour of the investigated parameters. These qualitative assumptions can then be applied for the development of design strategies along with other qualitative data.

Documentation
The results of the sensitivity analysis are documented in this thesis. The working documents are available to the PhD assessment committee on a CD in order to enable further insight into the iteration[2] process behind these results.

9.2 Reference building

The reference building in this analysis is a single family home. It is chosen, as single family housing made up approx. 48 % of the newly built residential buildings in Denmark from the year 2000 to 2006.

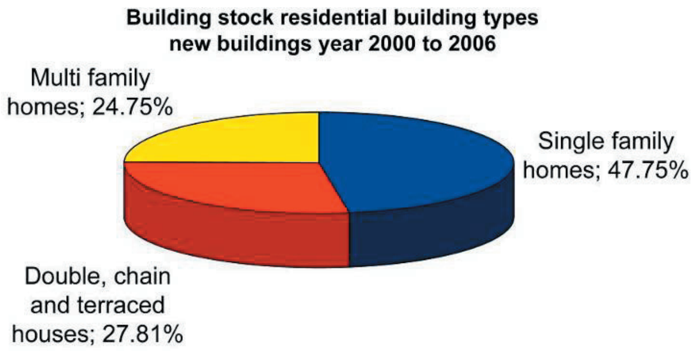


Illustration 138.1: Table generated at www.statistikbanken.dk 2007.

The table shows the percentage distribution of multi family housing, Double, chain and terraced houses and Single family houses built between the years 2000 and 2006. This choice was made in accordance with the focus in the PhD project; new residential buildings (i.e. not retrofit or renovation).

The set-up of the reference building was made in accordance with the legislative demands for residential buildings in Denmark (available at www.ebst.dk) and reasonable comfort requirements, and the reference building has already gone through an 'optimisation' process in order to live up to the energy frame for the building. The energy frame[3] for the building is 86.1 kWh/m^2 year and the total primary energy consumption of the reference building was 85.7 kWh/m^2 year.

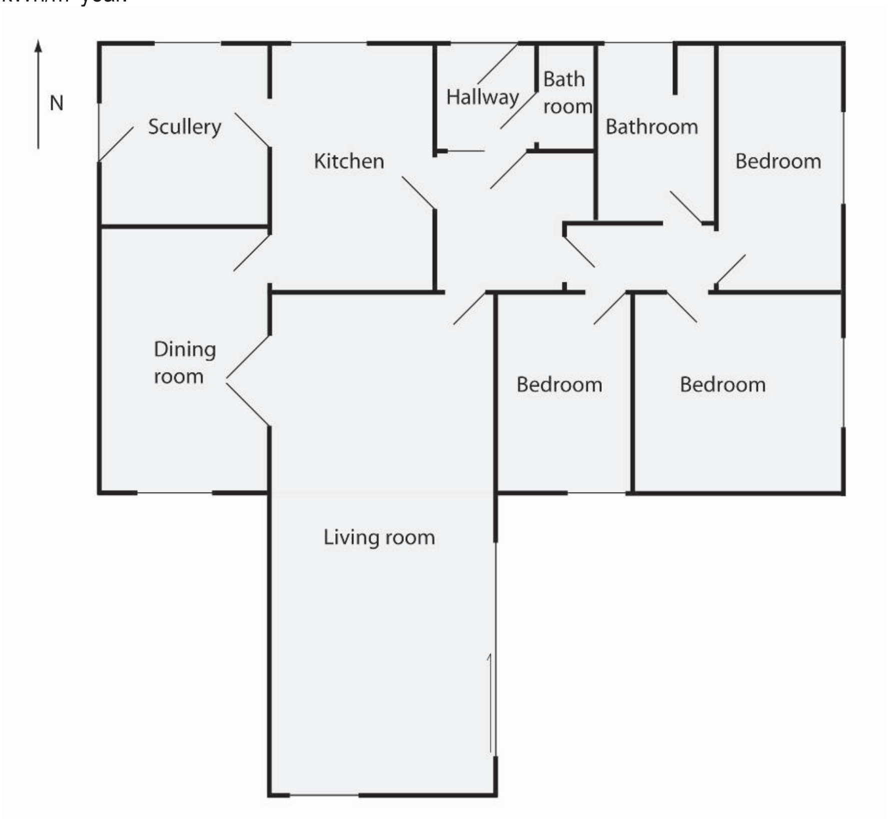


Illustration 138.2: Floor plan for reference building ('Billundhuse Type 147-1' [Andersen M. et. al 1973:204])

Characteristics of reference building:

- Window to floor area ratio: 0.19:1
- Surface to floor area ratio: 3:1
- Floor area to vertical surface area: 1:0.8
- Average façade height: 3.0m
- Average window: 1.22m
- Average door height: 2.1m
- Total window area: 26.5m^2
- Total wall area: 410.6 m^2
- Roof area: 137 m^2
- Area of ground floor:137 m^2
- The percentage window areas facing north/south/east/west (the window area to orientation ratios) are respectively 28.7% / 23.0% / 40.4% / 7.9%
- U-value walls: 0.2 W/m^{2}K, U-value ground floor and roof: 0.15 W/m^{2}K
- Effective U-value[4] window: 0.08 W/m^{2}K in the reference building.
  $U_{eff} = U_w - 2.7gF_f$ for the reference building and for buildings with a similar window area to orientation ratio (28.7%, 23.0% , 48.3% (N,S,E+W)), a shading factor of 1 (~0% shade)
- The building is naturally ventilated[5] with an increased ventilation rate in summer. The ventilation rates live up to the minimum ventilation rates stated in the Danish Building codes ($n = 0.5h^{-1}$).
- The building is exposed to zero shade, in order to simplify the input data for the variable parameters, as the shade changes a lot with different building heights and window dimensions. Furthermore the choice of zero shade was made to simplify the model of the building, to create as clean a canvas as possible for the comparative study of the parametric sensitivity[6].

9.3 Selection of tools

Be06

The reference building is modelled in a deterministic Danish computer programme (Be06). The Be06 programme was designed for demonstrating the legitimacy of Danish building projects with respect to the new energy requirements introduced to the Danish building regulations in April 2006.
In this study the programme is treated as an explorative tool for the development of a design strategy for a residential project.

The Be06 programme applies the stationary equation for the calculation of the heat balance in the building (between heat loss and heat gain), and the programme considers the following contributions to the energy consumption:

- *Heating* (prEN ISO 13790:2005, solar shading, length of heating season, utilisation of part of the heat gain from electrical installations (e.g. Boilers or heat-recovery from mechanical ventilation)
- *Cooling* (prEN ISO 13790:2005, solar shading, cooling from increased ventilation during summer season (during the day or/and night ventilation)
- *Heat loss installations* (prEN 15316 part 2.3 and 3.2, pipes, containers, heat exchanger for district heating, ventilation shafts and aggregate) – distinction between installations placed inside and outside the insulation layer of the building envelope.
- *Boilers* (prEN 15316 method II and part 3.3, efficiency , heat loss to surroundings, control of boiler temperature, production of hot water, electricity for use of fans and automatics) – can be switched off in the summer if the building has other systems to support the production of hot water (e.g. via solar panels) .
- *Heat pumps* (prEN 15316 part 4.2, total efficiency, heat source, flowing media, temperature differences)
- *Solar panels* (prEN 15316 part 4.3, depending on the design of the panels (size, orientation and angle), electricity consumption for pumps and control automatics)
- *Pumps* (Nominal effect, hours of operation and control) – ALL pumps in the heat installation must be included in the calculation)

- *Ventilators* (electricity consumption based on power consumptions and the hours of use) - In VAV installations an average value is used for power consumptions.
- *Refrigerator* (Electricity consumed by refrigerators in accordance with total efficiency, considers help equipment (e.g. pumps, ventilators, electric heating element and automatics).
- *Lighting* (relevant parts of prEN 15193-1)
- *Photo voltaic cells* (prEN 15316 part 4.6)
- *Other electrical consumptions for building operation* (e.g. from automatic components attached to a boiler, from a heat exchanger for district heating, a solar heating system or heatpump)

[Aggerholm and Grau 2005:22-24] (Please refer to chapter 10.1 and Enclosure C for more information about the Be06 programme).

At the time of calculation the Be06 calculation was the only approved programme for validation of the energy requirements of buildings in Denmark. It was therefore the programme designers and engineers had to apply in their projects, which is why the programme was chosen for this study.[7]

SimLab

The SimLab 2.2 programme is used for the statistical analysis performed in the global sensitivity analysis.

> 'Simlab 2.2 is a software designed for Monte Carlo based uncertainty and sensitivity analysis.
> MC-based uncertainty and sensitivity analyses are based on performing multiple model evaluations with probabilistically selected model input, and then using the results of these evaluations to determine 1) the uncertainty in model predictions and 2) the input variables that gave rise to this uncertainty.
> In general, a Monte Carlo analysis involves five steps.
>
> In the first step, a range and distribution are selected for each input variable (input factor). These selections will be used in the next step in the generation of a sample from the input factors. If the analysis is primarily of an exploratory nature, then quite rough distribution assumptions may be adequate.
> In the second step, a sample of points is generated from the distribution of the inputs specified in the first step. The result of this step is a sequence of sample elements.
> In the third step, the model is fed with the sample elements and a set of model outputs is produced. In essence, these model evaluations create a mapping from the space of the inputs to the space of the results. This mapping is the basis for subsequent uncertainty and sensitivity analysis.
> In the fourth step, the results of model evaluations are used as the basis for uncertainty analysis. One way to characterise the uncertainty is with a mean value and a variance. Other model output statistics are provided.
> In the fifth step, the results of model evaluations are used as the basis for sensitivity analysis.
>
> Simlab 2.2 is composed of three modules.
> These modules cover all the steps summarised above.
> 1. The Statistical Pre Processor module executes the first and second steps.
> 2. The Model Execution module accomplishes the third step.
> 3. The Statistical Post Processor module carries out the fourth and fifth steps.'
>
> [User manual SimLab 2.2]

The switch between SimLab and Be06 in the global sensitivity analysis occurs in step three, where the sample created in step two is applied in a series of Be06 calculations. The results of these calculations are inserted in a WordPad document which is inserted in the SimLab programme (Step four). (Please refer to chapter 10.1 for more information about the SimLab programme).

9.4 Local Sensitivity Analysis

As mentioned in chapter 9.1, the purpose of the local analysis has been to investigate how a selected group of parameters influence the energy consumption of a residential building, if they are changed one at a time (OAT).

The local sensitivity analysis is used to screen the sensitivity of the parameters and determine their statistical behaviour. The local sensitivity analysis will, thus, result in information about the distribution functions and an initial ranking of the parameters. This information is needed for the set-up of the global sensitivity analysis performed later on in the process.

9.4.1 Methodology

The local sensitivity analysis is performed as an OAT (one at a time) analysis, in which a number of selected input parameters are changed one at a time within a specified range.
The analysis is based on a reference building modelled in the Danish computer programme Be06, which at the time of application was the only approved programme for the demonstration of the estimated energy consumption of buildings.

The results of the OAT analysis are then analysed with respect to the deviation from the index values calculated for the reference building for the total energy consumption of the building, and the energy consumption for heating and removing overheating. These deviations a studied in relation to what the results say about the sensitivity of each parameter.

9.4.2 Input parameters and ranges

Selection of the input parameters

A lot of effort has been put into the selection of the appropriate input parameters and the range of each parameter, as this is crucial when the results of the analysis need to be applied in the development of a design strategy. The selection of the input parameters is therefore based on:

- The design principles found in the state of the art study of design strategies applied in residential buildings (chapter 8.1)
- The design principles applied by design strategies found in the state of the art study of terminology (chapter 6.1),
- The calculation parameters applied by the tool selected for this analysis.

A study of the design strategies described in publications reveals that the primary issues of environmentally sustainable architecture are Energy, Materials, Preservation of nature and biodiversity, Comfort and Use.
The primary issues investigated in this experiment are the energy consumption and use of buildings in relation to the architectural design process. Comfort is considered implicitly in the analysis in relation to the use of buildings, while preservation of nature and biodiversity relates to the specific site and the selection of this site. Finally materials are considered in the discussion of the input parameters (e.g. in relation to thermal mass and insulation of the non-transparent parts of the building envelope), but they are not included directly in the analysis, because the programme used for the analysis does not enable analysis of the environmental performance of materials.

Energy consumption
A study of the calculation in the Be06 programme revealed that the energy calculation focuses on the following issues relating to the design of residential buildings:

Heat loss and cooling	*Heat gains*	*Other issues relating to energy use*	*Comfort*
• Heat transmission through building envelope • Heat loss and cooling (summer season) via ventilation	• Internal heat gains from people and installations • Passive heat gain from solar radiation	• Hot water consumption • Thermal mass of building (relates to the calculation of variations in the indoor temperature)	• Dimensioning room temperatures winter and summer

[DS 418, Valbjørn et al 2000:141, 143 and prEN ISO 13790 (2005):14-18]

Based on this it is my conclusion that the calculation of the energy consumption in the Be06 programme relates to the architectural design of buildings when it comes to the design of the building envelope, the characteristics of the ventilation in the building, the thermal mass of the building materials inside the building and the user of the building (temperature preferences, internal heat gain from people and installations and hot water consumption).

A mind map was made for the issues relating to the design of the building envelope and the ventilation and use of the building. The mind map was based on a study of the elements used in building envelopes, e.g.:

Illustration 142.1
A: Apartment building in Lisbon at the Expo site

B: 'Tietgenkollgiet' (student housing) by Lundgaard & Tranberg Arkitekterfirma A/S in Copenhagen

C: 'Eichgut Winterthur' (apartment building) by Baumschlager and Eberle in St. Gallen Switzerland

D: 'Fred and Ginger' by Frank O'Gehry (office building) in Prague

E: Apartment building in Prague

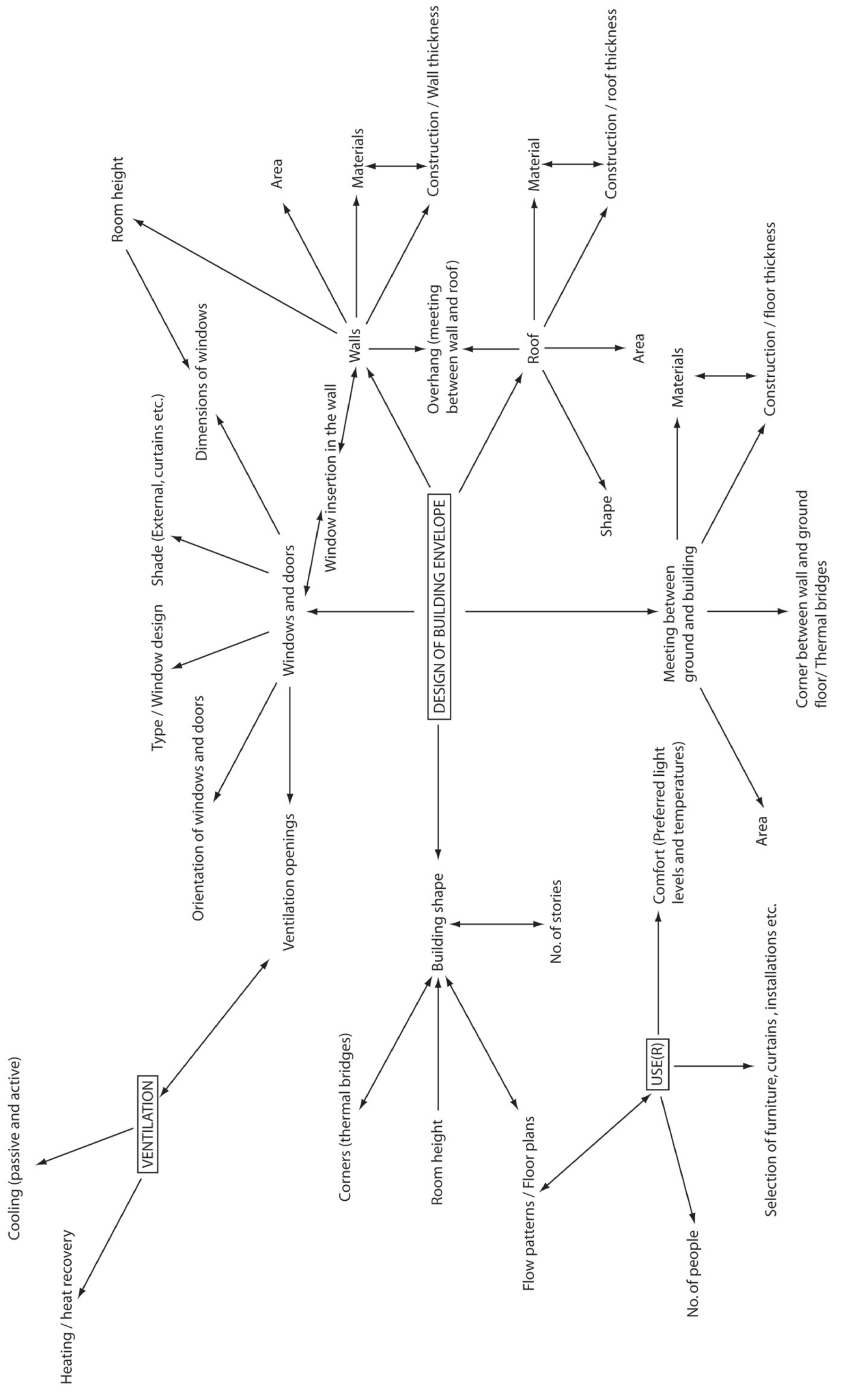


Illustration 143.1: The illustration shows a mind map which was made for the issues relating to the design of the building envelope and the ventilation and use of the building in residential buildings.

Based on the mind map the following input parameters were selected for the sensitivity analysis[8]:

Design of building envelope

Building shape

The surface area of the building has an impact on the architectural expression, as it is a direct result of the shape of the building. There is a big difference in the architectural expression and the surface area of e.g. a compact minimalistic building and a fragmented deconstructivistic building.

The building shape also depends on the building type; whether it is e.g. a residential, office, institution or culture building.

Examples of the relation between the architectural expression of buildings and the compactness of two buildings with the same function (Museum):

Illustration 144.1:
Left: 'Guggenheim Bilbao' by Frank O' Gehry in Bilbao (Spain) [Thomas Mayer and DAC exhibition about digital project]

Right: 'Kunsthaus Bregenz' by Peter Zumthor in Bregenz (Austria) [http://de.wikipedia.org/wiki/Bild:Kunsthaus_Bregenz.jpg]

The surface area is interesting in relation to the environmental profile of the building due to the heat transmitted through the building envelope. This heat transmittance depends on the surface area of the building envelope, the U-values of the building elements and the difference between the indoor and outdoor temperatures. When designing energy-efficient buildings it is, thus, interesting to consider minimising the surface area of the building envelope in relation to the floor area.

An issue relating to the surface area of each story in the building is the height of the rooms inside the building. Aside from the surface area the room height also influences the spatiality of the rooms inside the building as well as the ventilation rates needed in the rooms. Different room heights can be desired in relation to the other dimensions of the room (width and depth); the room height has a large impact on the perception of a space; tall rooms can make narrow and tight spaces seem more narrow or tight, while low rooms can make a wide space seem wider or squeezed. Double high rooms are very popular in residential buildings in Denmark in living and kitchen spaces.

Illustration 144.2:
Left: Glass shutter house Tokyo by Shugeru Ban. [Jojidio 2001 p.95]

Middle: Rendering of residential buildings Øster Hurup (Denmark) by Arkitema. [www.byggeri.dk 2007] http://www.byggeri.dk/maned/07-06/billeder.asp

Right: Fjordstokkene i Holbæk af SHL. Arkitektur DK december 2004 p.609

The fact that the room height increases the surface area and principally also the minimum air change rates[9] in the building causes a wish to decrease the room heights in buildings, while the wish for spaciousness usually causes a wish to increase the room heights in buildings. It is therefore interesting to determine how influential this parameter is in a specific project.

The analysis will primarily focus on the heat transmittance through the façade (except for the average room height which focuses on both the surface area of the façade and the basic ventilation rate in the building) and the calculation parameters will be:

- Average room height; 2.5 to 4.5 m
- Surface area façade; different shapes (circle, square, half circle, rectangles with different

width to depth ratios (1:2, 1:3, 1:4, 1:5 and 1:6)
- Number of storeys; 1 to 253[10]

Shade
Shade can be regarded as both positive and negative in relation to the environmental performance of the building, and the user's perception of architectural quality and comfort in the building.[11]
Sometimes it is desirable to have shade if one has a problem with overheating inside the building (e.g. in the case of high internal loads), and/or if the functions or people inside the building need protection from glare (e.g. in buildings with a high usage of computer screens or in museums, where the exhibited art needs protection from direct sunlight.). In other cases shade may be undesirable, for instance in buildings, where the internal loads are low, and where people wish to have as much sunlight and solar radiation as possible inside the building. The user's desire for sunlight is also influenced by geographical and cultural differences.

Shade influences the choices made with respect to the architectural expression of the building in relation to the context, the site and the building itself:

Context related shade can either provide the needed protection from the solar radiation or block out the needed solar radiation. In most cases too much context related shade is undesirable because it also blocks out daylight. There are different kinds of context related shade; permanent and seasonal. Neighbouring buildings or topographic conditions provide permanent shade onto the site. The size of this shade varies in relation to the altitude and azimuth angle of the sun and the urban density of the area.
Vegetation can provide seasonal shade if the particular vegetation defoliates in accordance with seasonal changes in the weather. Usually one cannot change the context related shades, as it extends the purchased site.

Examples of three different urban scales:

Illustration 145.1:
Left: High urban density. Office skyscrapers in the Shinjuku area in Tokyo (2005).
MIddle: Average urban density. Old and narrow street in Lisbon (2007) situated on a slope. Tiles are used on the façade to reflect the sunlight into the narrow street.
Right: Low urban density. Residential passive house project in Lystrup, Denmark by Schmidt, Hammer and Lassen [www.shl.dk 2007] The project is situated on a large field in a rural area next to the Aarhus suburb Lystrup.

Site related shade pretty much consists of the same elements as the context related shade. However, one usually has the power to make minor or major changes to the shading elements. One could change the vegetation by cutting it, move it elsewhere on the site, remove it completely, or replace it with a different type of vegetation. Sometimes it is also possible to make minor topographical changes on the site and remove unwanted buildings on the site, whilst considering the impact of this on the neighbouring sites.

Building related shade is the type of shade one has the most ability to avoid or enable. It is also the type of shade that is the most interactive in relation to the building design. The rules of thumb are; the functions/spaces inside the building should be placed in relation to whether or not shade is desirable and the building volumes should ideally be placed so they cast shadows where shade is desirable and so they do not cast shadows where shade is undesirable. If shade is desired in the building in spite of orienting the functions towards shaded areas it is necessary to integrate actual shading devices or indirect light in the architectural expression of the building or reduce the window area towards the particular directions.

Examples of building related shade:

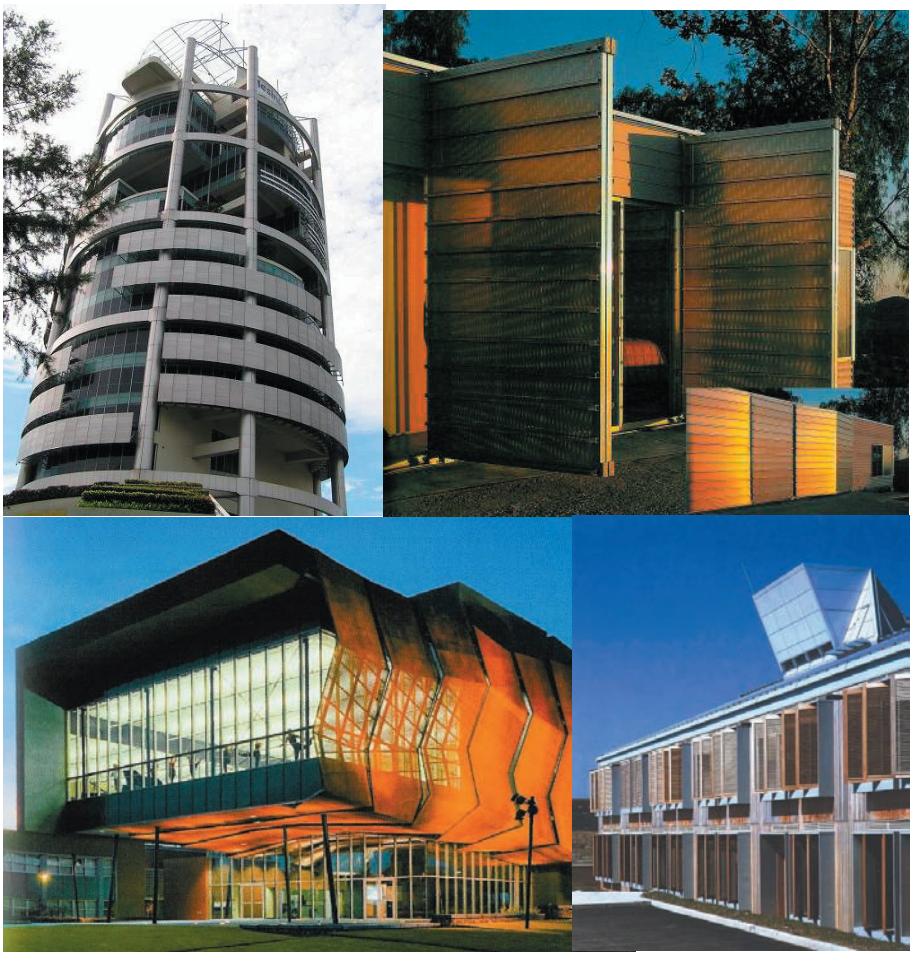


Illustration 146.1:
Left: Menara Mesiniaga, Selangor (Malaysia) [Jane Christoffersen]

Right: Valley Center House, California, Daly Genik. [Jojidio 1999 p.161]

Left: Stevie Eller Dance Theater Tucson, Arizona by Gould Evans. [Jojidio 2001 p.287]

Right: Arup Campus in Solihul (UK) by Arup Associates, [Hawkes and Forster 2002]

The 'shade' design parameters are interdependent with the window type, size when it comes to the energy performance of the building, and these are usually applied in the same iterations in the design process.

The input parameters applied in this investigation of the environmental impact of shade will be:

- placement of window in the depth of the façade (0 to 500 mm)
- size of overhang (0 to 3000 mm)
- shade from surroundings (0 to 90°)
- External shade in front of windows (all directions, north, south, east and west) (0 to 100% shade)

Window type
The window type clearly has an impact on the architectural expression of the building envelope, through the dimensions of the window and the materials, the colour of the type of glass and coating and the window casing and moulding used for the selected window.

Examples of two different window types from www.velfac.dk;

Illustration 147.1
Left: Building with a window similar to the ones used in Denmark the early 1900s and until the age of modernism.

Right: Building with a modern window

Except from the visual impact on the facades of the building, the colour and moulding of the selected window influences the spatial perception of the room and the perceived light conditions in the room in relation to differences in the daylight quality in the room due to the light transmittance through the window, the colours of the glass and shadows cast by the window case and the moulding used in the particular window type.

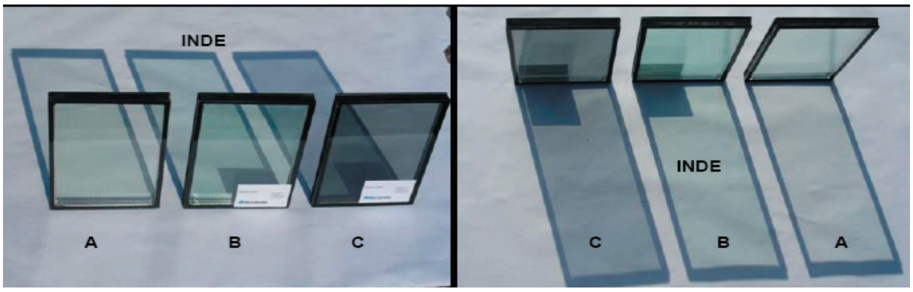
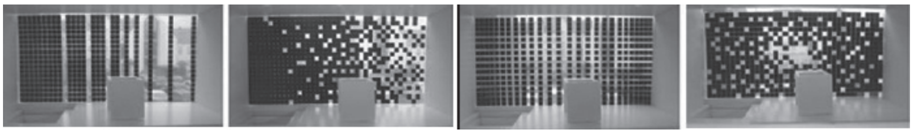


Illustration 147.2: Experiment conduced with three different types of Velfac windows by Associate Professor Ellen K. Hansen at the Department of Architectural Design at the Aarhus School of Architecture.

A) Energy glass with filter, VELFAC CLEAR ENERGY 4-16-4 argon, Ug-value: 1.1 W/m^{2}K, LT-value: 0.81, g-value:0.64 and Rw = 32 dB
B) Sunglass with filter VELFAC SUN 1, 6-14-4 argon, Ug-value: 1.1 W/m^{2}K, LT-value: 0.67, g-value: 0.37 and Rw = 35 dB
C) Sunglass with coloured glass VELFAC SUN 4 and 5, 6-14-4 argon, Ug-value: 1.2 W/m^{2}K, LT-value: 0.39, g-value: 0.35 and Rw = 35 dB

The shadows are cast towards the side that would be the inside of the house. [Ellen K. Hansen 2007]



Illus 147.3: Example from a workshop on the 2nd year at Aarhus School of Architecture about integration of photo voltaics in window glass. The workshop is held annually by Associate Professor Ellen K. Hansen at the Department of Architectural Design at the Aarhus School of Architecture. [Ellen K. Hansen 2007]

When it comes to the energy performance of the building the window type influences both the heat loss and the passive solar heat gains through the building envelope.

The selected input parameter is:

- Different types of VELFAC windows with no visual coating

Window area, angle and orientation

The window area, angle and orientation influence the architectural expression of the building envelope and the interior of the building. The window area, angle and orientation has a major influence on how the composition of the building is perceived (light or heavy), as well as, how the spaces inside the building are perceived (dark or bright). The window area, angle and orientation parameters are known to have an impact on the environmental performance of the building and the comfort conditions inside the building, through passive solar heat gains.

Examples of how the window areas, angles and orientations influence the architectural expression of buildings:

Illustration 148.1
Left: : 'Palais de beaux arts' (museum) extension in Lille (France) by Ibos and Vitart

Roight:: 'Lois and Richard Rosenthal Center for Contemporary Art' by Zara Hadid in Cincinnati, Ohio (USA) [Jojido 2004:300]

Left: 'Paper house' in Japan by Shiguru Ban, [Jodidio 1999:82]

Depending on the function of the building, one needs to consider how to gain or avoid the passive heat gain and, thus, also whether or not the building should be subjected to shade. Solar radiation enters the building through transparent building elements in the building envelope. The amount of solar radiation differs in relation to the altitude and azimuth angle of the sun, as well as in relation to the characteristics of the glazing utilised in the window.
The area, angle, type and orientation of this transparent building element, thus, influence the amount of solar radiation entering the building.

The focus of the analysis will be the impact on the energy consumption of the building and the input parameters will be:

- Different window to floor area ratios (0 to 100%)
- Different window area to orientation ratios
- Rotation of the building 0° to 360°
- Window angle (0° to 90°, 0 = horizontal, 90 = vertical)

Insulation of the non-transparent parts of the building envelope
The insulation of the building envelope is interesting in relation to the thermal heat transmittance through the building envelope. The heat transmittance is calculated by multiplying the building elements with the transmittance value of the element (the U-value) and the difference between the indoor and out door temperature [DS418:12-16].

The insulation of the building envelope is interesting from an architectural point of view in relation to the wall, roof and floor thickness of the building envelope, which depends on the insulative characteristics of the materials used for the construction of the building envelope, e.g. wood, brick, concrete, mineral wool, paper wool etc. This means that the wall thickness will depend on the materials used for the construction of the wall, roof and floor of the building, and thus the materials used for the architectural expression of the building and the structural stability of the building.

The material which has the greatest impact on the U-value in Denmark is what is commonly referred to as the insulation of the building; e.g. mineral wool, paper wool, hemp or flax, which means that the thickness of this layer will be approximately the same regardless of the other materials used for the construction of the building envelope. This means that one can achieve different wall thickness for walls with the same U-value through utilisation of e.g. wood, brick or concrete constructions.

Illustration 149.1:
Left: House France Herzog and Demeuron. [Jojidio 2000:247]

Right: Pærehaven af Juul og Frost. [Arkitektur DK 2004:616]

Bottom: Housing blocks on the Java peninsula in Amsterdam's east harbour 1995 Sjoerd Soeters. [Arkitektur DK 2004 p.575]

Visually the thickness of the building envelope effects how the window hole is perceived, the thicker the wall the deeper the holes, which means that the thickness of the wall will influence how dominating the window and door holes will appear in the building (the deeper the hole the more dominating). This can be a desired or undesired effect from an architectural point of view.
This architectural effect of the thickness should also be considered in relation to the placement of the windows in the depth of the façade (shade input parameter), as both of these parameters can be regarded as inter-dependent with the architectural expression of the building.

The input parameters are in this case:
- U-value walls; 0.05 to 0.4 W/m^{2}K
- U-value ground floor; 0.05 to 0.4 W/m^{2}K
- U-value roof; 0.05 to 0.4 W/m^{2}K

Thermal mass
Thermal mass is interesting as a design parameter in relation to the environmental performance of a building, due to the fact that thermal mass helps stabilising the indoor temperature by absorbing some of the excess heat entering the building during the day and releasing it during the night.

From an environmental perspective thermal mass is interesting in relation to both the cooling and heating loads of the building, especially if the loads differ significantly over a 24 hour period.

Thermal mass relates to the material choices for the building and thus the architectural expression of the building, as the thermal mass relates to the density of the building materials inside the building. These materials need to be exposed to the room air, which means that this parameter is difficult to change after the final sketches for the project have been completed, because changing this would change the architectural material selection for the interior of the building, and the relationship between the inside and outside expression of the building if this is considered in the design of the building.

Illustration 150.1:
Left: Deloitte headquarters in Copenhagen by 3XNielsen A/S [http://www.byggeri.dk/maned/05-12/billeder.asp]
Right: Berman House Australia by Harry Siedler [Jojidio 2000:445]

Besides aesthetic consideration the materials selected for the interior of a building have both functional and acoustic implications that also need consideration, such as whether the materials that provide the desired level of thermal mass are suited for the intended use of the building in relation to e.g. the reverberation time in the room and the maintenance needed to clean and preserve the materials.
In relation to residential buildings a high thermal mass (160 Wh/km^2) can be difficult to achieve because people in Denmark tend to prefer hardwood floors in their homes over concrete or tile floors, and a low thermal mass (40 Wh/km^2) can be difficult to achieve because people tend to prefer brick walls over wood walls inside their homes.

The focus of the analysis is the impact of thermal mass on the energy consumption of the building and the input parameter is:

- Heat capacity of the building materials; 40 to 160 Wh/K m^2

Ventilation
It is interesting to compare natural and mechanical ventilation in relation to the environmental profile of a building. The architectural consequences of natural and mechanical ventilation are rarely considered in the beginning of the design process, as it is most often regarded as possible to solve the ventilation later on in the process. One could, however, argue that the integration of the ventilation system is a lot easier and the system is a lot more effective, when it is considered from the beginning of a project.

Some design strategies found in the state of the art prefer natural over mechanical ventilation and vice versa (e.g. in 'The selective environment – An approach to environmentally responsive architecture' [Hawkes, McDonald and Steemers 2002] vs. the passive house standard [www.passiv.de]). It is interesting to compare the performance differences of the two types of ventilation. On the one hand one has the price and the electricity consumption of the aggregate and the heat-recovery from the mechanical system, on the other hand one has the heat loss for the natural ventilation when the outside air is colder than the inside air.

The architectural implications of the ventilation strategy are in the case of natural ventilation the need for ventilation openings placed in different directions and at different heights (depending on the internal loads, room volume, effective opening areas) and requirements for maximum room depths in relation to the room height.

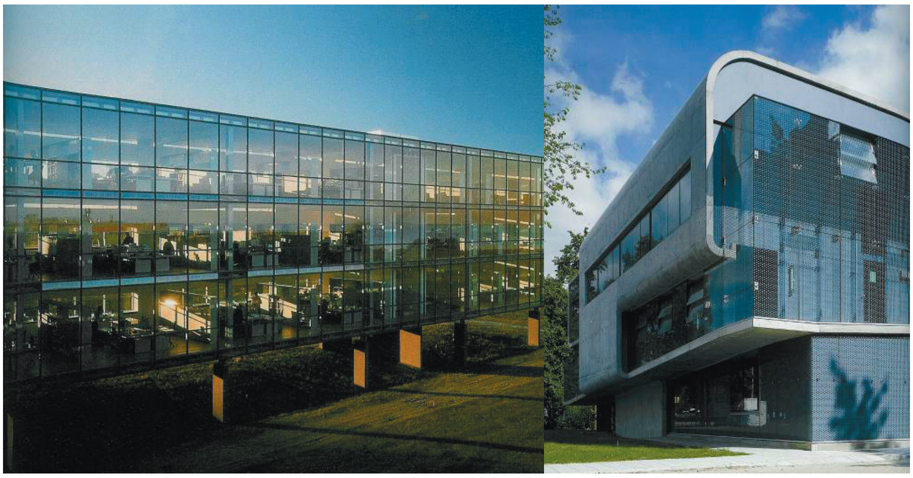


Illustration 151.1:
Left: B&O hovedkvarter, KHRAS arkitekter. [Jojidio 1999: 315]
Right: Neutron Magnetic Resonance Facilities Utrecht, UN studio. [Jojidio 2000:500]

From an environmental performance point of view the following input parameters are of interest:

- Heat-recovery; 0 to 95% (mechanical all year, and mechanical in winter and natural in summer)
- Comfort criteria for ventilation rates; 0.23 l/s m^2 to 0.56 l/s m^2.
- Ventilation rates winter; 0.35 to 0.63 l/s m^2.
- Ventilation rates summer; 0.42 to 2.14 l/s m^2.

The study is, thus, not directly concerned with whether or not the building is ventilated via a natural or mechanical system. The input parameters do, however, in most cases determine a specific type of ventilation, either through the introduction or a mechanical system via the calculation, or by being related to the reference building, which is naturally ventilated.

Use of the building
The use of the building is not directly related to the building design. It is, however, still included in this study as post-occupancy reviews of passive and low-energy houses have revealed large discrepancies between the calculated energy consumptions and the measured energy consumptions of a building [www.passiv.de/07_eng/news/CEPHEUS_final_long.pdf 2007]. The use of the building is one of the parameters suspected to be the cause of this (another is inconsistency between the drawings and the actual construction of the building).

The Be06 calculation considers the following parameters in the estimation of the energy consumption of the building, which are therefore considered in this analysis:

- Internal heat gain people; 0.66 to 2.63 w/m^2
- Internal heat gain appliances; 210 to 840 w/m^2
- Comfort temperature of user; 18 to 26°C
- Hot water consumption; 109 to 438 l/year m^2

The internal heat gain from people relates to the number of people in the building and their activity levels (e.g. standing sitting, running).
The internal heat gain from appliances relates to the installations in the house and the appliances introduced in the building (e.g. dishwasher, lamps, TVs, stereos, computers etc).
The comfort temperature depends on the activity levels[13] of the users and the clothes they are wearing. The comfort temperature of the users will also be lower if the users a wearing a lot of clothes whereas it will be higher if they are wearing very little clothes.

The hot water consumption relates to how many litres of hot water the users utilise during the year divided by the m^2 of the house.

The use of the building therefore depends on the building type; the consumption of water, electricity and heat is different in e.g. residential buildings, office buildings and sports arenas due to differences in installations, hours of use and internal heat gains in these buildings. So are the activities and clothing of the users, and thus their comfort temperature.

The use of the building is something one can influence through the building design, but it is not something one can ensure because the use of the building is heavily influenced by the lifestyle of the particular user. Building should therefore consider how to make the consumption visible to the user of the building, and how to ease energy and water savings in the building e.g. by using low-flush toilets, mixer taps, enabling the user to turn of all his electrical devices that are on standby by the flick of one switch etc.

If the parameters turn out to be sensitive, designers should make it a point to make sure the design criteria in the design brief corresponds with the expected use of the building and not some standardised value.

9.4.1 Results local analysis

As mentioned in the description of the methodology the results of the local sensitivity analysis will be dependent on the reference building, which means that the results are relative to the input data of the case, and that the results of this analysis cannot be used to conclude a general behaviour of the parameters.
The results do instead give an indication of whether or not the parameters are sensitive to changes in relation to cases similar to the reference building, and they indicate whether or not a parameter can be changed in the reference building in order to reduce the energy consumption.
Furthermore, the results indicate the sensitivity and robustness of a parameter in this type of building, when it is the only parameter subjected to variation.

The Be06 programme calculates monthly mean values of the heat balance in the building. Besides providing the total energy consumption, the energy required for space heating, the energy needed for heating hot water and the energy needed for removal of overheating.
The programme also reports electrical energy consumptions (e.g. for fan power, artificial lighting etc.) and the energy required for the removal of excess heat (overheating).

The results of the local sensitivity analysis are studied for their deviation from the energy consumption of the reference building with respect to the energy required for space heating, hot water and removing overheating. This division of the energy consumption is made in order to account for whether or not a parameter influences the space heating, the removal of overheating and/or the how water production. This enables qualitative conclusions about when and for which purpose one should change the parameter when designing a residential building. These deviations are reported as deviation percentages[14]. The negative values for deviation percentages (marked with a green colour) show the reduction potential in relation to the reference building, whilst the positive values for the deviation percentages (marked with a red colour) show where there are risks of increasing the energy consumption in relation to the reference building. The blue coloured columns mark the values of the reference building.

Because the deviation percentages are dependent of the reference building the value of the deviation percentage is highly relative to the energy consumption in the reference building and to the range of the specific parameter. This means that in the deviation percentages must be multiplied with the energy requirement of the reference building in order to get the reduction potential or the increase risk in kWh/m^2 pr year. In some cases the deviation percentage of the energy for removing overheating seems much larger than the deviation of the energy for space heating. The resulting reduction or increase in the energy consumption for removing overheating is, however, in most cases quite small because the energy consumption for removing overheating is small in the reference building. 10% deviation in the energy for removing overheating is an increase or decrease of 0.52 kWh/m^2 year, while a 10% deviation in the energy for space heating is an increase or decrease of 6.7 kWh/m^2 year.

The energy required for removal of overheating is indirectly related to the energy required for space heating (as the results will show). Overheating occurs when the internal heat gain and the passive solar heat gain exceeds the energy required for space heating and/or when the outside temperatures are higher than the required indoor temperatures.

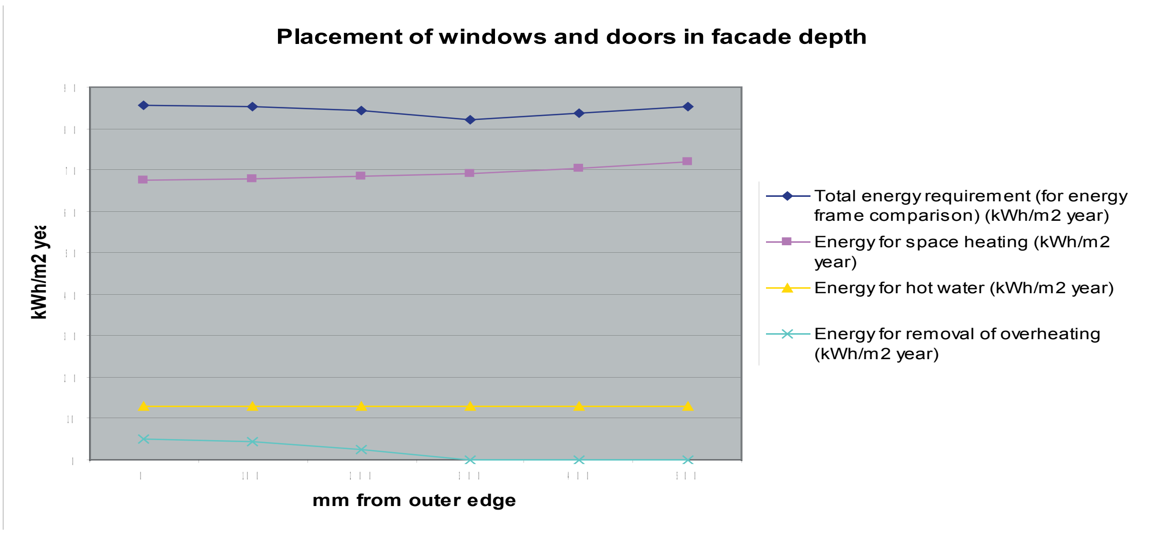
This is a seasonal problem in temperate climates like the Danish, and the overheating in residential buildings are usually solved by increasing the ventilation rates in the building temporarily or by shading transparent building elements facing southern, eastern or western directions.
Problems with overheating are not great in Danish residential buildings due to the low internal heat gains and the seasonal changes in the Danish climate. If a residential building in Denmark suffers from problems with overheating it is usually due to large passive solar heat gains. The situation would be different if the purpose of the experiment was to develop a design strategy for an office or a school building, which have high internal heat gains.
Overheating during the summer season is becoming an issue in residential buildings due to better air-tightness of the constructions, better insulation of the building envelope, heat-recovery in the ventilation system and increased summer temperatures (global warming). This is assumed to be one of the reasons for the recent introduction of the calculation of energy required for removing excess heat was introduced in the energy calculations in 2006.

Shade[15]

Placement of window and doors (depth of façade)

Table 9.2: Results for changes in the Placement of window and doors (depth of façade) input parameter

Range (mm)	*0*	*100*	*200*	*300*	*400*	*500*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**85.7**	**85.20**	**84.20**	**82.20**	**83.60**	**85.20**
Energy for space heating (kWh/m2 year)	**67.4**	**67.7**	**68.5**	**69.1**	**70.5**	**72**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.2**	**4.4**	**2.6**	**0**	**0**	**0**
Percentage deviation from reference building, total energy consumption	0.00	-0.58	-1.75	-4.08	-2.45	-0.58
Percentage deviation from reference building Space heating	0.00	0.45	1.63	2.52	4.60	6.82
Percentage deviation from reference building overheating	0.00	-15.38	-50.00	-100.00	-100.00	-100.00



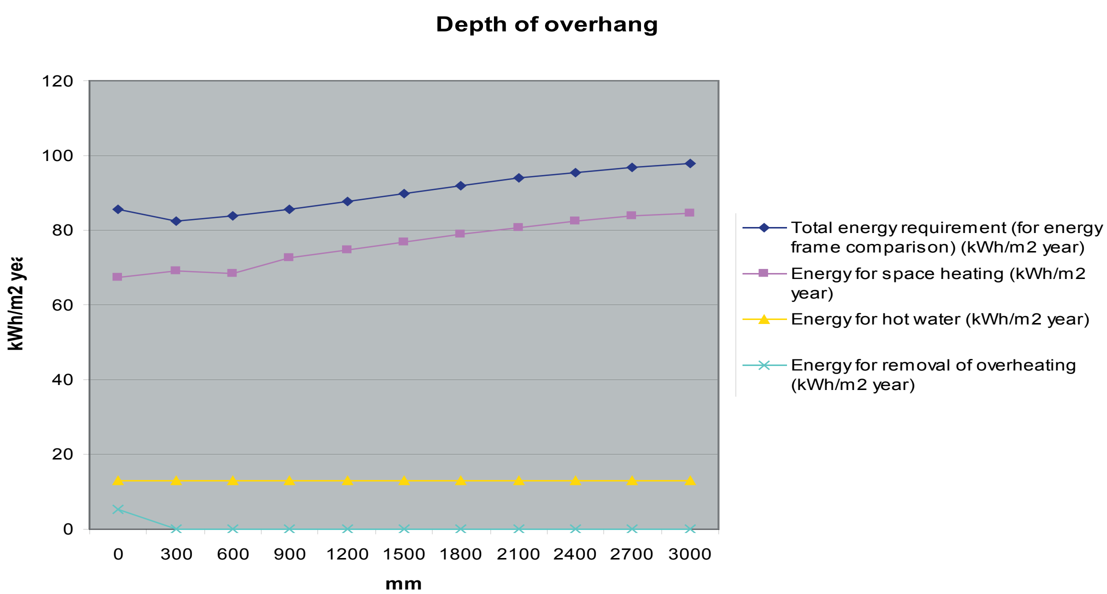
The total energy consumption and the energy required for the removal of overheating is reduced, while the energy required for space heating is increased by increasing the distance to the outer edge of the façades. The deviation caused my increasing the distance is small (approx. 4%).

The reduction potential peaks at 300mm depth for the total energy consumption (approx. 4% reduction).
The energy required for space heating is increased (by up to approx. 7%), whilst the energy required for overheating is reduced (by up to 100%).

Depth of overhang

Table 9.3: Results for changes in the Depth of overhang input parameter

mm	*0*	*300*	*600*	*900*	*1200*	*1500*	*1800*	*2100*	*2400*	*2700*	*3000*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**85.7**	**82.30**	**83.7**	**85.60**	**87.80**	**89.9**	**92.00**	**93.9**	**95.5**	**96.8**	**97.8**
Energy for space heating (kWh/m2 year)	**67.4**	**69.1**	**68.5**	**72.5**	**74.7**	**76.8**	**78.9**	**80.8**	**82.3**	**83.7**	**84.7**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Percentage deviation from reference building	0.00	-3.97	-2.33	-0.12	2.45	4.90	7.35	9.57	11.44	12.95	14.12
Percentage deviation from reference building Space heating	0.00	2.52	1.63	7.57	10.83	13.95	17.06	19.88	22.11	24.18	25.67
Percentage deviation from reference building overheating	0.00	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100

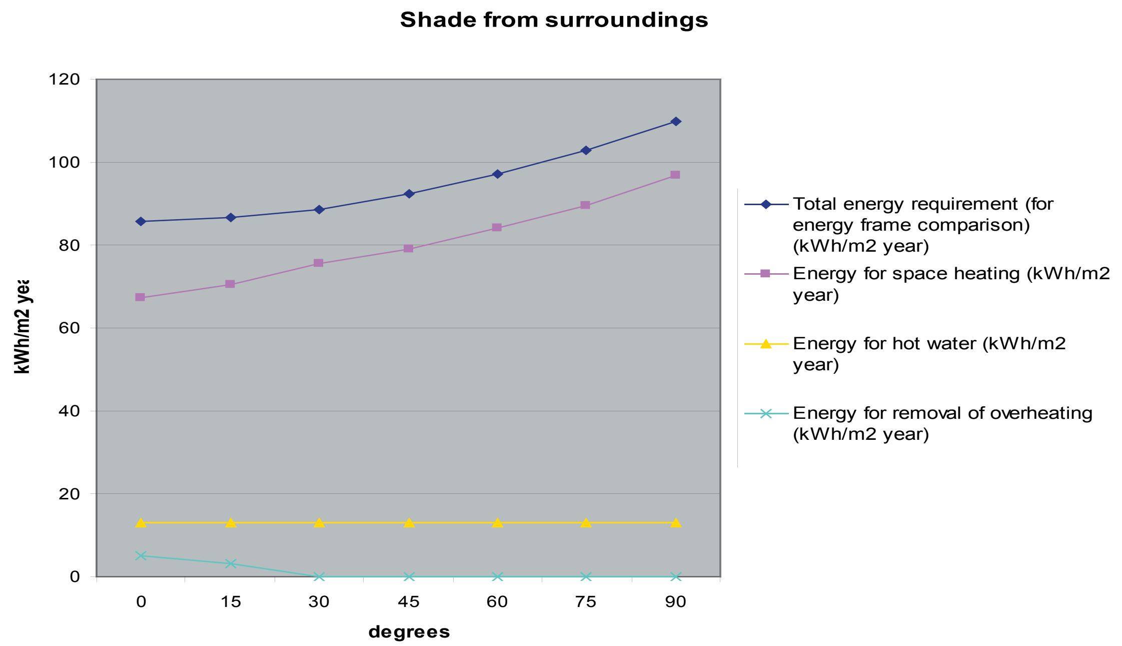


Changes in the depth of the overhang has caused reductions in the energy requirement for removing overheating, while causing an increase in the energy required for space heating. For a depth between 0 and 900mm this causes a reduction in the total energy consumption. For depths larger than 900mm there is an increase in the total energy consumption, which is estimated to be due to the fact that the energy requirement for overheating is completely removed at 900mm, while the increase in the energy requirement for space heating keeps increasing with an increase in the depth of the overhang.
The deviation from the reference building is significant (approx. 18%), the reduction potential of the reference building is, however, quite small (approx. 4%) and the reduction is achieved by elimination of the energy requirement for the removal of overheating.

Shade from surroundings

Table 9.4: Results for changes in the Shade from surroundings input parameter

degrees	*0*	*15*	*30*	*45*	*60*	*75*	*90*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**85.7**	**86.7**	**88.5**	**92.3**	**97.2**	**102.7**	**109.9**
Energy for space heating (kWh/m2 year)	**67.4**	**70.5**	**75.4**	**79.2**	**84.1**	**89.5**	**96.8**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.2**	**3.1**	**0**	**0**	**0**	**0**	**0**
Percentage deviation from reference building	0.00	1.17	3.27	7.70	13.42	19.84	28.24
Percentage deviation from reference building Space heating	0.00	4.60	11.87	17.51	24.78	32.79	43.62
Percentage deviation from reference building overheating	0.00	-40.38	-100.00	-100.00	-100.00	-100.00	-100.00



The more shade from the surroundings the larger the increase in the energy required for heating, while the energy required for the removal of overheating is reduced. The reduction in the energy needed for removing overheating s, however, greatly outweighed by the increase in the energy required for space heating.

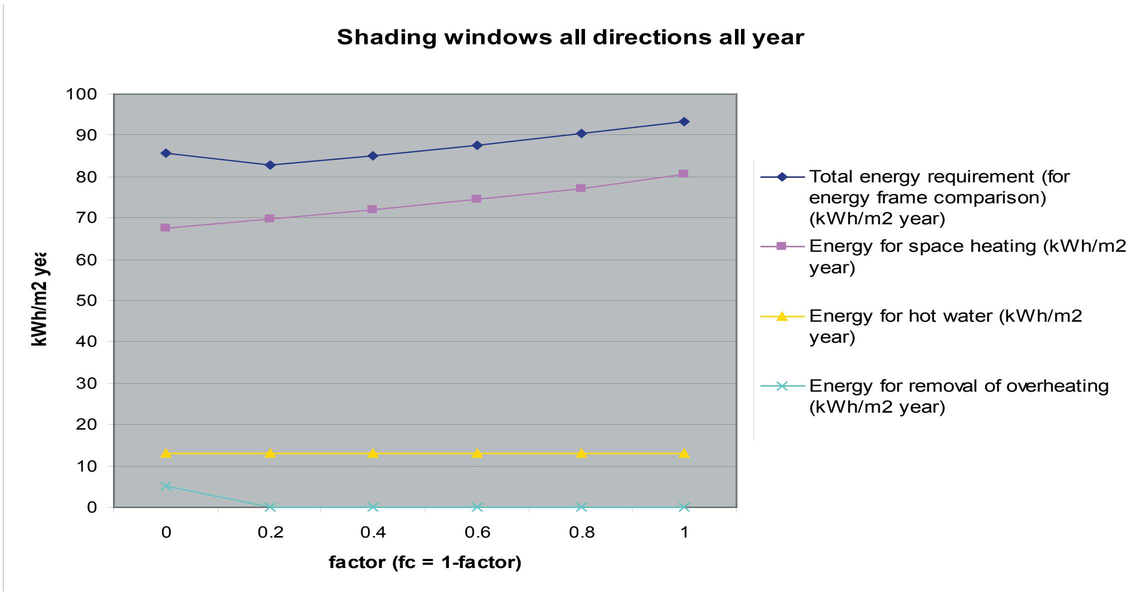
This parameter cannot be changed much through the building design, unless one is designing the urban development plan for the entire area and, thus, building volumes shading each other.

The results found here are, however, important to keep in mind during the site selection phase of the process, as the site one chooses has a great influence on the total energy consumption in the building by approx. 28%, there is, however, no reduction potential for the reference building found in the local analysis.

Shading device in front of windows all directions (all year)

Table 9.5: Results for changes in the Shading device in front of windows all directions (all year) input parameter

faktor (fc = 1-factor)	*0*	*0.2*	*0.4*	*0.6*	*0.8*	*1*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**85.7**	**82.7**	**85**	**87.5**	**90.4**	**93.4**
Energy for space heating (kWh/m2 year)	**67.4**	**69.6**	**71.9**	**74.4**	**77.2**	**80.5**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.2**	**0**	**0**	**0**	**0**	**0**
Percentage deviation from reference building	0.00	-3.50	-0.82	2.10	5.48	8.98
Percentage deviation from reference building Space heating	0.00	3.26	6.68	10.39	14.54	19.44
Percentage deviation from reference building overheating	0.00	-100.00	-100.00	-100.00	-100.00	-100.00

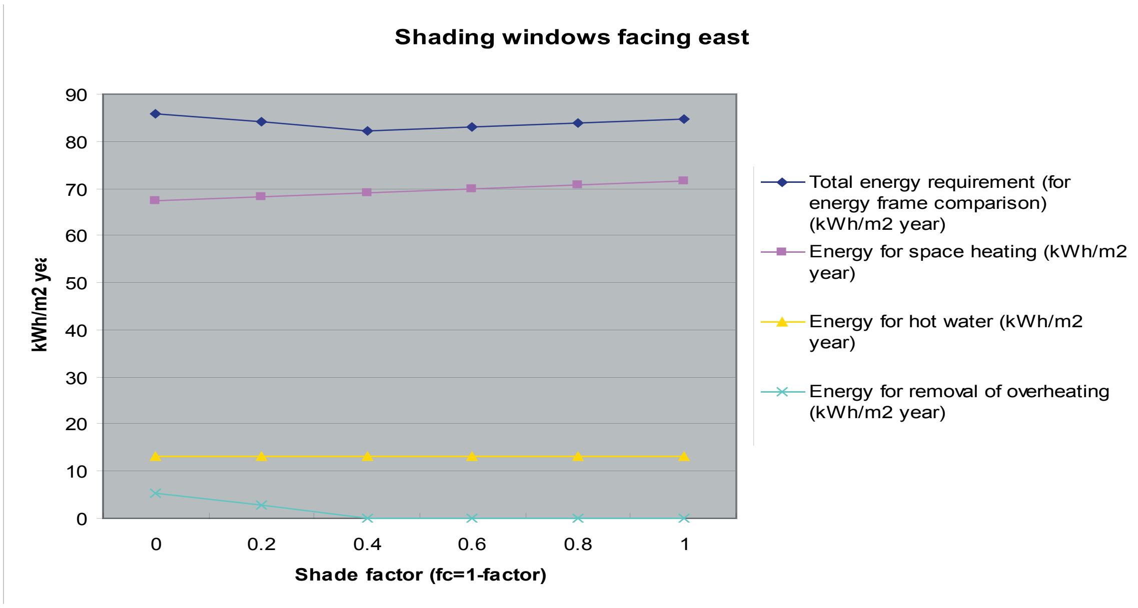


The introduction of an external shading element causes an increase in the energy required for space heating and a reduction in the energy required for the removal of overheating.
A shading factor of 1 (corresponding with 100% shade) is, however, not a very realistic scenario in residential buildings, as the window practically becomes non-transparent.

The deviation percentage is approximately 12.5%, the reduction potential in relation to the reference building is, however, quite small (approx. 3.5%) and the reduction is achieved by elimination of the energy requirement for the removal of overheating.

Shading device in front of windows east (all year)
Table 9.6: Results for changes in the Shading device in front of windows east (all year) input parameter

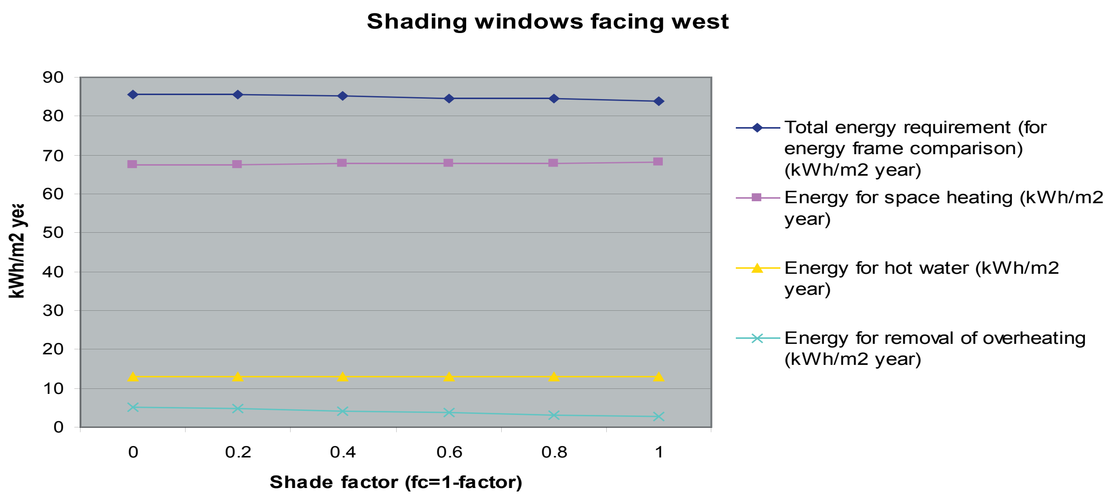
faktor (fc = 1-factor)	*0*	*0.2*	*0.4*	*0.6*	*0.8*	*1*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**85.7**	**84**	**82.1**	**82.9**	**83.8**	**84.7**
Energy for space heating (kWh/m2 year)	**67.4**	**68.2**	**69**	**69.8**	**70.6**	**71.5**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.2**	**2.7**	**0**	**0**	**0**	**0**
Percentage deviation from reference building	0.00	-1.98	-4.20	-3.27	-2.22	-1.17
Percentage deviation from reference building Space heating	0.00	1.19	2.37	3.56	4.75	6.08
Percentage deviation from reference building overheating	0.00	-48.08	-100.00	-100.00	-100.00	-100.00



Shading in front of the windows on the east facade causes a reduction in the total energy consumption and the energy required for removing overheating, while the energy required for space heating is increased.
The deviations caused by the shade are small (approx. 4%), this would probably be larger if the window area was larger. The reduction is achieved by elimination of the energy requirement for the removal of overheating.

Shading device in front of windows west (all year)
Table 9.7: Results for changes in the Shading device in front of windows west (all year) input parameter

faktor (fc = 1-factor)	*0*	*0.2*	*0.4*	*0.6*	*0.8*	*1*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**85.7**	**85.4**	**85.1**	**84.7**	**84.4**	**84**
Energy for space heating (kWh/m2 year)	**67.4**	**67.6**	**67.7**	**67.9**	**68**	**68.2**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.2**	**4.7**	**4.2**	**3.7**	**3.2**	**2.7**
Percentage deviation from reference building	0.00	-0.35	-0.70	-1.17	-1.52	-1.98
Percentage deviation from reference building Space heating	0.00	0.30	0.45	0.74	0.89	1.19
Percentage deviation from reference building overheating	0.00	-9.62	-19.23	-28.85	-38.46	-48.08



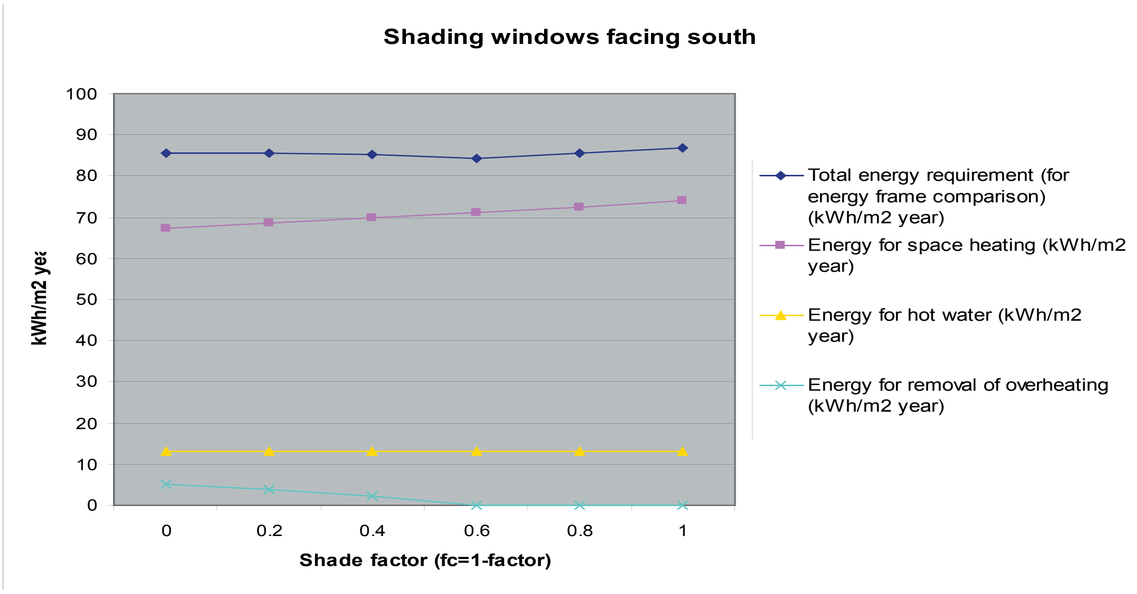
Shading in front of the windows on the west facade causes a reduction in the total energy consumption and the energy required for removing overheating, while the energy required for space heating is increased.
The deviations caused by the shade are small (approx. 2%), this would probably be larger if the

window area was larger. The reduction is achieved by elimination of the energy requirement for the removal of overheating.

Shading device in front of windows south (all year)

Table 9.8: Results for changes in the Shading device in front of windows south (all year) input parameter

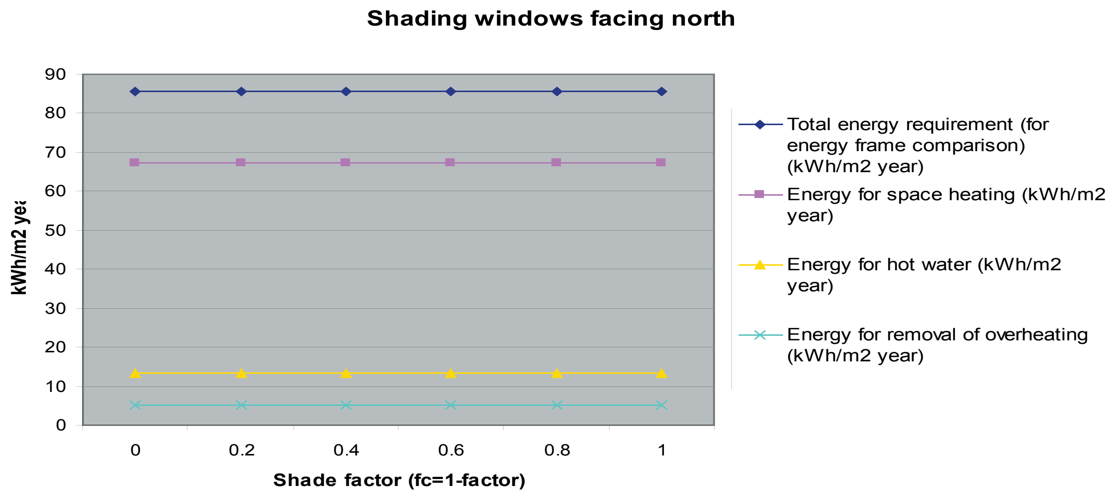
faktor (fc = 1-factor)	*0*	*0.2*	*0.4*	*0.6*	*0.8*	*1*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**85.7**	**85.5**	**85.4**	**84.3**	**85.6**	**87**
Energy for space heating (kWh/m2 year)	**67.4**	**68.7**	**69.9**	**71.2**	**72.5**	**73.9**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.2**	**3.7**	**2.3**	**0**	**0**	**0**
Percentage deviation from reference building	0.00	-0.23	-0.35	-1.63	-0.12	1.52
Percentage deviation from reference building Space heating	0.00	1.93	3.71	5.64	7.57	9.64
Percentage deviation from reference building overheating	0.00	-28.85	-55.77	-100.00	-100.00	-100.00



Shading in front of the windows on the west facade causes a reduction in the total energy consumption for shading factors 0.2 to 0.8, and the energy required for removing overheating is reduced in all cases, while the energy required for space heating is increased.
The deviations caused by the shade are small (approx. 3%), this would probably be larger if the window area was larger. The reduction is achieved by elimination of the energy requirement for the removal of overheating.

Shading device in front of windows north (all year)
Table 9.9: Results for changes in the Shading device in front of windows north (all year) input parameter

faktor (fc = 1-factor)	*0*	*0.2*	*0.4*	*0.6*	*0.8*	*1*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**85.7**	**85.7**	**85.7**	**85.7**	**85.7**	**85.6**
Energy for space heating (kWh/m2 year)	**67.4**	**67.4**	**67.4**	**67.4**	**67.4**	**67.4**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.2**	**5.2**	**5.1**	**5.1**	**5.1**	**5.1**
Percentage deviation from reference building	0.00	0.00	0.00	0.00	0.00	-0.12
Percentage deviation from reference building Space heating	0.00	0.00	0.00	0.00	0.00	0.00
Percentage deviation from reference building overheating	0.00	0.00	-1.92	-1.92	-1.92	-1.92



The effect of shading the windows facing north is practically non-existent. This makes sense when seen in a Danish context where there is no solar radiation on the north façade.

Window type

Different types of window frames are studied in relation to the U-values of the windows with different types of glazing, and thus different g-values and LT-values. The U-value for the entire window can be calculated as:

$$U = \frac{A_g U_g + l_g \psi_g + A_p U_p + A_f U_f + l_k \psi_k}{A_g + A_p + A_f}$$

Where:
A_g is the glass area in m^2.
l_g is the circumpherence of the glass area in m.
A_p is the area of the panelling in m^2.
A_f is the area of the window frame in m^2.
L_k is the length of the linear thermal bridges in m.
U_g is the transmission coefficient at the centre of the glass area in W/m^2K.
ψ_g is the thermal bridge for the moulding between the outer and inner layer of glass W/mK.
U_p is the transmission coefficient for the panelling in W/m^2K.
U_f is the transmission coefficient for the frame in W/m^2K.
Ψ_k is the thermal bridge for other parts of the cinstruction in W/mK.
[DS418 2002:30]

The values applied in this study were found on the webpage of a Danish window supplier (VELFAC) via a web-based tool on the company's webpage (http://193.163.166.189/step1.aspx August 2007).

The VELFAC 200 K22 window type

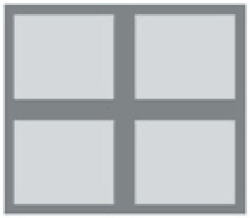
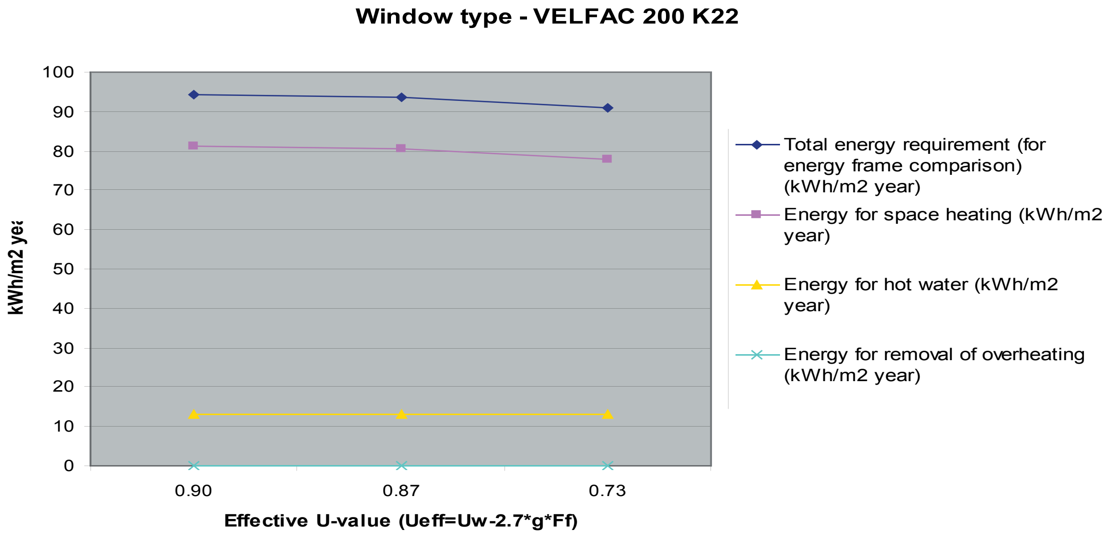


Table 9.10: Results for changes in the Window type (VELFAC 200 K22) input parameter

	VELFAC 200 (K22), U_g =	*VELFAC 200 (K22), U_g =*	*VELFAC 200 (K22), U_g =*
Effective U-value; Ueff = Uw - 2.2 * g-value * Ff (ref: www.ebst.dk/intro-skemaer/0/94/0 and DTU (ISSN: 1396-4046)	0.90	0.87	0.73
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**94.2**	**93.6**	**90.9**
Energy for space heating (kWh/m2 year)	**81.1**	**80.4**	**77.7**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**0**	**0**	**0**
Percentage deviation from reference building	9.92	9.22	6.07
Percentage deviation from reference building Space heating	20.33	19.29	15.28
Percentage deviation from reference building overheating	-100.00	-100.00	-100.00

The increase in the effective U-value causes an increase in the total energy consumption and the energy required for space heating, while the problem with overheating is eliminated.
The deviation from the reference building caused by applying this particular window type (with different glazing) is approximately a 6 to 10% increase of the total energy consumption of the reference building. There is, thus, no reduction potential by the application of this window type.



The VELFAC 200 K12 window type

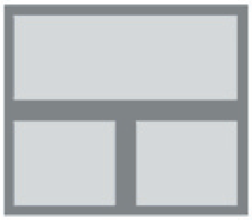
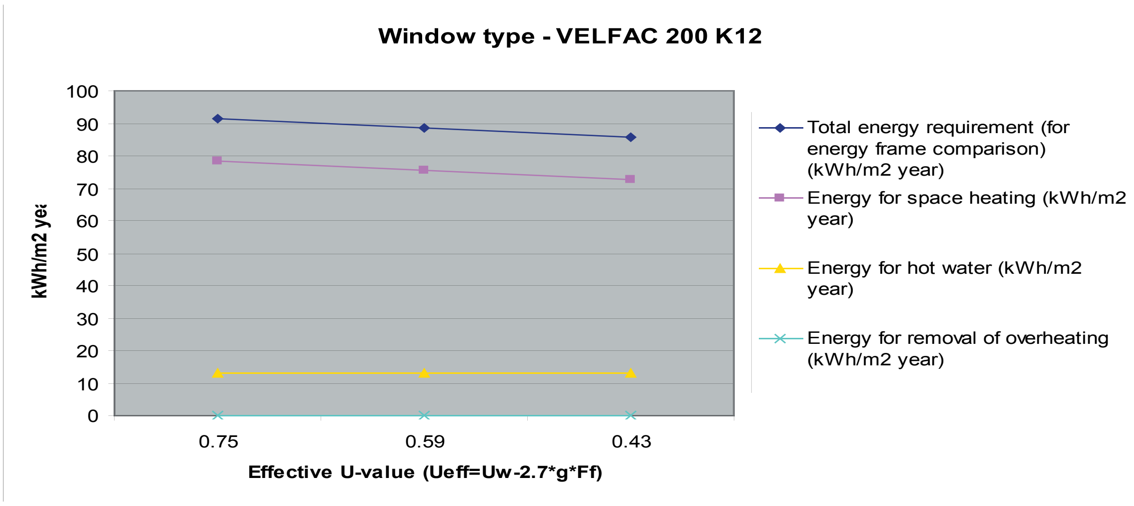


Table 9.11: Results for changes in the Window type (VELFAC 200 K12) input parameter

	VELFAC 200 (K12), U_g =	*VELFAC 200 (K12) , U_g =*	*VELFAC 200 (K12) , U_g =*
Effective U-value; Ueff = Uw - 2.7 * g-value * Ff (ref: www.ebst.dk/intro-skemaer/0/94/0 and DTU (ISSN: 1396-4046)	0.75	0.59	0.43
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**91.3**	**88.5**	**85.7**
Energy for space heating (kWh/m2 year)	**78.2**	**75.4**	**72.5**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**0**	**0**	**0**
Percentage deviation from reference building	6.53	3.27	0.00
Percentage deviation from reference building Space heating	16.02	11.87	7.57
Percentage deviation from reference building overheating	-100.00	-100.00	-100.00



The increase in the effective U-value causes an increase in the total energy consumption (except in the last case which has the same total energy consumption as the reference building) and the energy required for space heating, while the problem with overheating is eliminated. The deviation from the reference building caused by applying this particular window type (with different glazing) is approximately a 0 to 6.5% increase of the total energy consumption of the reference building. There is, thus, no reduction potential by the application of this window type. It is, however, possible to maintain the same total energy consumption as the reference building by choosing the window with the lowest effective U-value.

The VELFAC 200 K5 window type

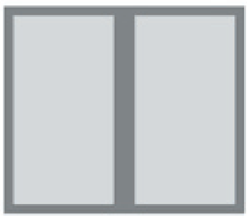
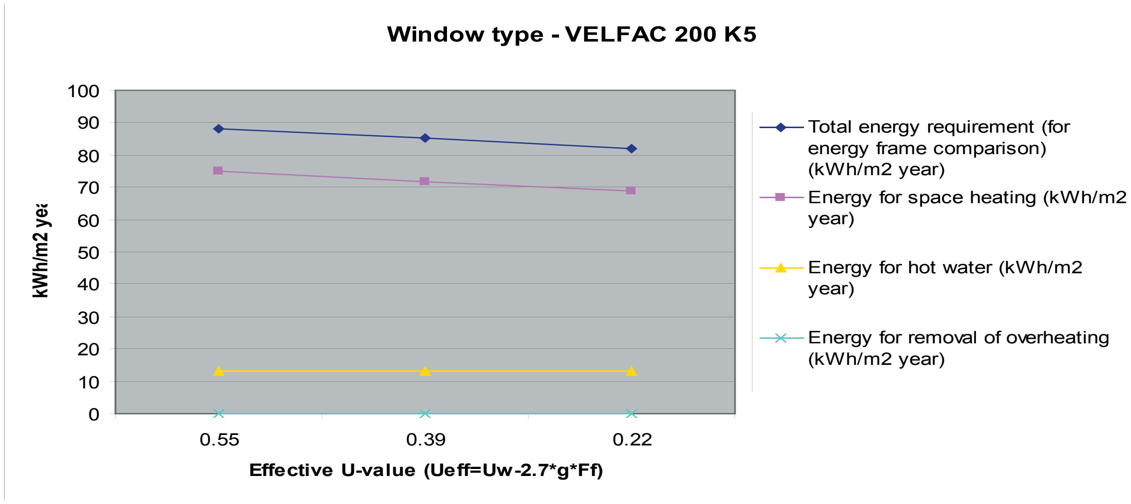


Table 9.12: Results for changes in the Window type (VELFAC 200 K5) input parameter

	VELFAC 200 (K5) , U_g =	*VELFAC 200 (K5) , U_g =*	*VELFAC 200 (K5), U_g =*
Effective U-value; Ueff = Uw - 2.2 * g-value * Ff (ref: www.ebst.dk/intro-skemaer/0/94/0 and DTU (ISSN: 1396-4046)	0.55	0.39	0.27
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**88**	**85.1**	**82.1**
Energy for space heating (kWh/m2 year)	**74.9**	**71.9**	**69**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**0**	**0**	**0**
Percentage deviation from reference building	2.68	-0.70	-4.20
Percentage deviation from reference building Space heating	11.13	6.68	2.37
Percentage deviation from reference building overheating	-100.00	-100.00	-100.00

The increase in the effective U-value causes an increase in the energy required for space

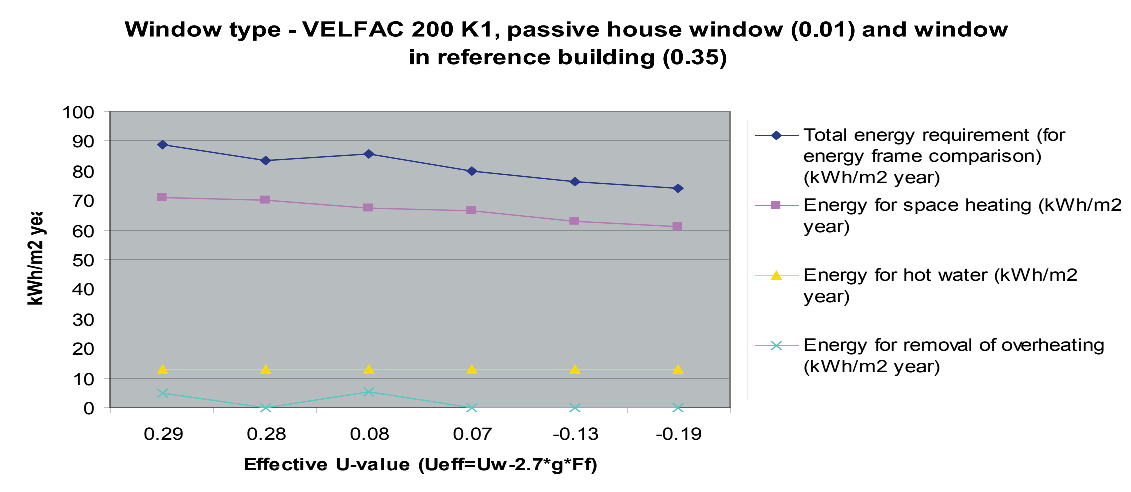


heating, while the problem with overheating is eliminated. The total energy consumption is larger than that of the reference building in the case with an effective U-value of 0.76, and smaller than that of the reference building in the other two cases.
The deviation from the reference building caused by applying this particular window type (with different glazing) is approximately 7%, and there is a reduction potential of up to approx. 4%.

The VELFAC 200 K1 window type

Table 9.13: Results for changes in the Window type (VELFAC 200 K1) input parameter

	VELFAC 200 (K1), U_g =	*VELFAC 200 (K1), U_g =*	*reference building, U_g =*	*VELFAC 200 (K1), U_g =*	*VELFAC 200 (K1), U_g =*	*Passiv haus window, U_g =*
Effective U-value; Ueff = Uw - 2.2 * g-value * Ff (ref: www.ebst.dk/intro-skemaer/0/94/0 and DTU (ISSN: 1396-4046)	0.29	0.28	0.08	0.07	-0.13	-0.19
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**88.8**	**83.4**	**85.7**	**79.7**	**76.2**	**74.1**
Energy for space heating (kWh/m2 year)	**71**	**70.3**	**67.4**	**66.6**	**63.1**	**61**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**4.7**	**0**	**5.2**	**0**	**0**	**0**
Percentage deviation from reference building	3.62	-2.68	0.00	-7.00	-11.09	-13.54
Percentage deviation from reference building Space heating	5.34	4.30	0.00	-1.19	-6.38	-9.50
Percentage deviation from reference building overheating	-9.62	-100.00	0.00	-100.00	-100.00	-100.00



There is a decrease in the total energy consumption in all cases but one (U_{eff} = 0.29). The energy required for space heating is increased in for (U_{eff} = 0.29 and 0.28), and reduced in the rest of the cases. The energy required for removing overheating is reduced in all cases. The two cases for which there is an energy requirement for removing overheating the problem is suspected to be caused by the g-values, which are 0.63 (VELFAC 200 K1, U_{eff} = 0.29) and 0.7 (the reference building, U_{eff} = 0.08). A low effective U-value does, thus, not alone ensure low energy consumption.

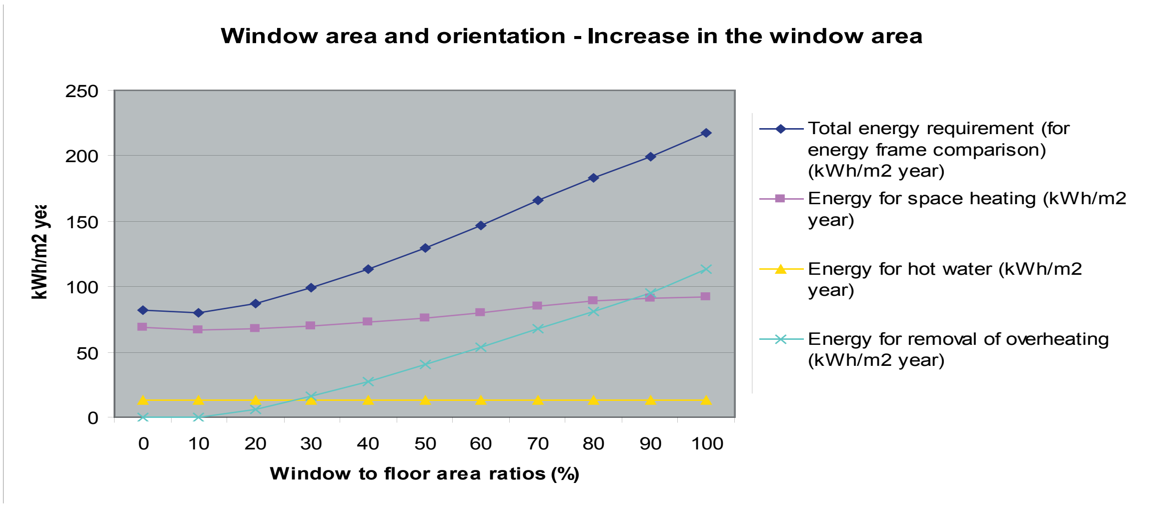
The deviation for the total energy consumption is approx. 23.5%, and the reduction potential is approx. 13.5%.
The calculation shows the effect of applying the same window with different combinations of frame types and glazing. For instance if one wishes to apply a window with the K22 frame, one needs to achieve reductions in the energy requirement for space heating else where e.g. via heat recovery in the ventilation strategy.

Window area and orientation
For these calculations an approximation of the thermal bridges at the joints between the wall and the windows and doors was made. This approximation was based on a study of the length thermal bridges for different sizes of windows (See details in the local sensitivity analysis excel-file on the CD).

Increase in window to floor area ratio
The window to floor area ratio is approx. 19% in the reference building, and the window area to orientation of the reference building is: 28.7%North / 23% South / 40.4% East / 7.9% West. The calculation sticks to this window area to orientation of the reference building for as long as possible, after that the negative areas for east are transferred to the western façade (for ratios of 50% and larger), and after that the negative values are transferred evenly to the north and south facing facades (for 70% and larger).

Table 9.14: Results for changes in the Window to floor area ratio input parameter

Window area to floor area ratio (%)	*0*	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*	*100*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**81.8**	**80.1**	**87.1**	**99.5**	**113.3**	**129.3**	**147**	**165.7**	**182.9**	**199.3**	**217.9**
Energy for space heating (kWh/m2 year)	**68.7**	**67**	**68.2**	**70.3**	**73.1**	**76**	**80.2**	**84.7**	**89.3**	**91.3**	**91.6**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**0**	**0**	**5.8**	**16.1**	**27**	**40.1**	**53.6**	**67.9**	**80.5**	**94.9**	**113.1**
Percentage deviation from reference building	-4.55	-6.53	1.63	16.10	32.21	50.88	71.53	93.35	113.42	132.56	154.26
Percentage deviation from reference building Space heating	1.93	-0.59	1.19	4.30	8.46	12.76	18.99	25.67	32.49	35.46	35.91
Percentage deviation from reference building overheating	-100	-100	11.5	209.6	419.2	671.2	930.8	1205.8	1448.1	1725	2075



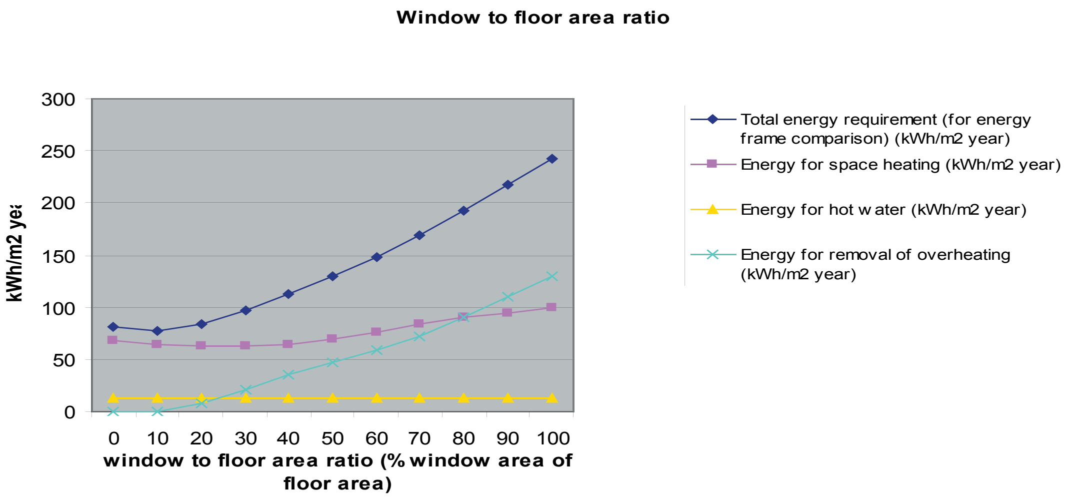
This result shows that a reduction in the window to floor area ratio to approx. 10% will cause a small reduction in the total energy consumption of the reference building, as well as in both the energy required for space heating and removing overheating. This is a bit surprising, and it is expected to be caused by the window area to orientation of the building, which is investigated in the following experiment where the reference building is rotated 90 degrees and subjected to the same study.

Increase in window to floor area ratio, reference building rotated 90°

The reference building is rotated 90° resulting in a total energy consumption of 83.0kWh/m^{2}K. The energy required for space heating is 62.3kWh/m^{2}K and the energy required for removing overheating is 7.5kWh/m^{2}K.

Table 9.15: Results for changes in the Window to floor area ratio input parameter when the building is rotated 90°

Window area to floor area ratio (%)	*0*	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*	*100*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**81.1**	**77.7**	**84.3**	**96.7**	**112.2**	**129.7**	**148.6**	**168.5**	**193.2**	**217.4**	**242.3**
Energy for space heating (kWh/m2 year)	**68.7**	**64**	**62.9**	**62.9**	**64**	**69.5**	**76.4**	**83.3**	**90**	**94.2**	**99.9**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**0**	**0**	**8.3**	**20.7**	**35.1**	**47.1**	**59.1**	**72.1**	**90**	**110**	**129.3**
Percentage deviation from reference building	-2.3	-6.4	1.6	16.5	35.2	56.3	79.0	103.0	132.8	161.9	191.9
Percentage deviation from reference building Space heating	10.3	2.7	1.0	1.0	2.7	11.6	22.6	33.7	44.5	51.2	60.4
Percentage deviation from reference building overheating	-100.0	-100.0	10.7	176.0	368.0	528.0	688.0	861.3	1100.0	1366.7	1624.0

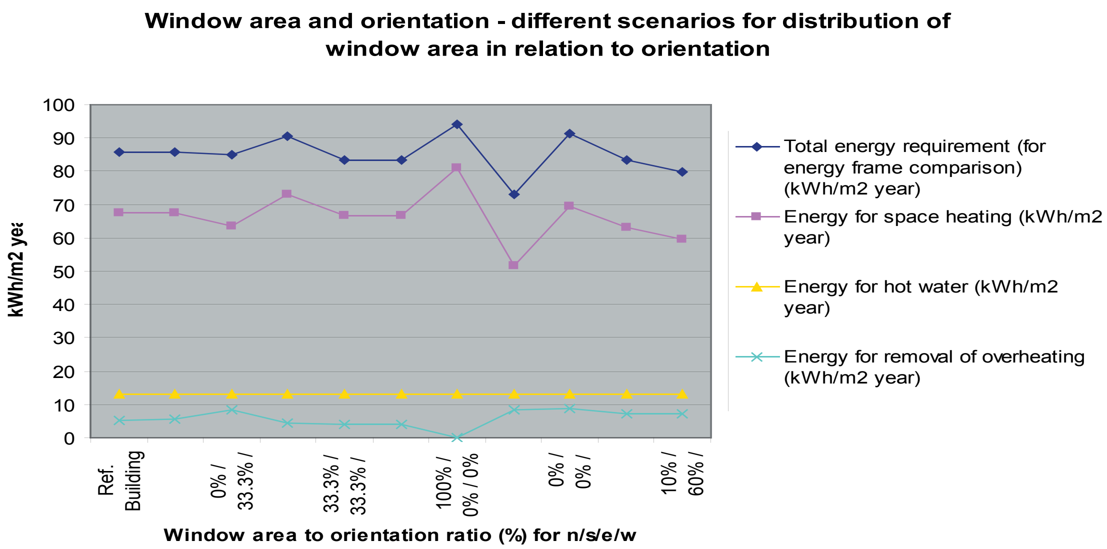


These results are for the situation where the reference building is rotated 90 degrees, which means that the window area to orientation ratio is changed to 7.9%North, 40.4% South, 28.7% East and 23% West.
The results do not differ greatly from the previous case, and the tendency is the same; the reduction in the total energy consumption is largest in the case where the window area in the building is 10% of the floor area.
The only difference from the previous case is that there is an increase in the energy required for space heating in all cases, the increase is, however, pretty low for the interval where the window area is approx. 10 - 40% of the floor area. The increase in the total energy consumption is in these cases caused by increases in the energy required for removing overheating.
In general the increase in energy for removing overheating is larger in the latter case due to the new window area to orientation ratio.

Same window area to floor area ratio as in reference building different window area to orientation ratios

Table 9.16: Results for changes in the Window area to orientation ratio input parameter

Window area to orientation ratio (N / S / E / W)	*Ref. Building aprox: 29% / 23% / 40% / 8%*	*25% / 25% / 25% / 25%*	*0% / 33.3% / 33.3% / 33.3%*	*33.3% / 0% / 33.3% / 33.3%*	*33.3% / 33.3% / 0% / 33.3%*	*33.3% / 33.3% / 33.3% / 0%*	*100% / 0% / 0% / 0%*	*0% / 100% / 0% / 0%*	*0% / 0% / 100% (towards east or/ and west)*	*10% / 40% / 25% / 25%*	*10% / 60% / 15% / 15%*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**85.7**	**85.9**	**85**	**90.3**	**83.4**	**83.4**	**94.1**	**73.2**	**91.4**	**83.5**	**79.9**
Energy for space heating (kWh/m2 year)	**67.4**	**67.3**	**63.4**	**72.9**	**66.5**	**66.5**	**81**	**51.6**	**69.6**	**63.1**	**59.6**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.2**	**5.5**	**8.4**	**4.3**	**3.8**	**3.8**	**0**	**8.5**	**8.7**	**7.2**	**7.2**
Percentage deviation from reference building	0.00	0.23	-0.82	5.37	-2.68	-2.68	9.80	-14.59	6.65	-2.57	-6.77
Percentage deviation from reference building Space heating	0.00	-0.15	-5.93	8.16	-1.34	-1.34	20.18	-23.44	3.26	-6.38	-11.57
Percentage deviation from reference building overheating	0.00	5.8	61.5	-17.3	-26.9	-26.9	-100	63.5	67.3	38.5	38.5



Changing the window area to orientation ratio has proved to cause a deviation of up to approx. 21% from the total energy consumption for the selected ranges. Of these 21% there is a chance of reducing the total energy consumption up to approx. 14.5%.

The results show very different cases of either increasing or reducing the energy requirements for space heating and removing overheating:

- The case with the largest reduction potential is when all the windows face south, which is not a very realistic scenario, which is why the calculation for a 10/60/15/15 distribution was made (causing an approx. reduction of 7%).
- The largest risk of increasing the energy consumption is when all the windows face north.
- The case when the window area is distributed evenly causes a small increase in the total energy consumption.
- There is also an increase in the total energy consumption (caused by increases in the energy consumption for both space heating and removing overheating) if all the windows face either east or west.

The results correspond well with the corrective solar heat gains from north, south east/west in Denmark which are:

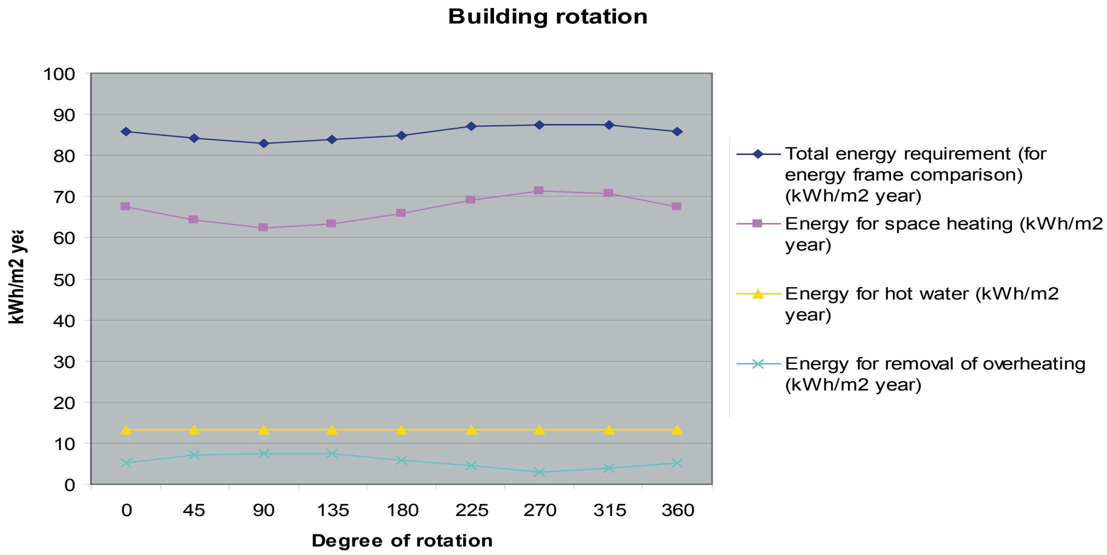
- The corrective solar heat gain from 1 m^2 window facing north ~ 104.5 kWh/m^2 in Denmark
- The corrective solar heat gain from 1 m^2 window facing south ~ 431.4 kWh/m^2 in Denmark
- The corrective solar heat gain from 1 m^2 window facing east and west ~ 232.1 kWh/m^2 in Denmark [BYG.DTU 2003:30]

From this one can conclude, that the corrective solar heat gain from $1m^2$ window with a southern orientation would be approx. 4.1 times that of $1m^2$ with a northern orientation, and approx. 1.9 times that of a $1m^2$ window with an eastern or western orientation, presuming that the windows have the same conditions of exposure to the sun.
It, thus, makes sense to decrease the window area facing north and increase the window area facing south in buildings with low internal heat gains, while it makes sense to increase the window area facing north and decrease the window area facing south in buildings with high internal heat gains.

Rotation of the building

Table 9.17: Results for changes in the Rotation of the building input parameter

o / degrees	*0*	*45*	*90*	*135*	*180*	*225*	*270*	*315*	*360*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**85.7**	**84.4**	**83**	**83.8**	**84.8**	**87.2**	**87.6**	**87.6**	**85.7**
Energy for space heating (kWh/m2 year)	**67.4**	**64.2**	**62.3**	**63.2**	**65.8**	**69.2**	**71.5**	**70.7**	**67.4**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.2**	**7**	**7.5**	**7.5**	**5.8**	**4.5**	**3**	**3.7**	**5.2**
Percentage deviation from reference building	0.00	-1.52	-3.15	-2.22	-1.05	1.75	2.22	2.22	0.00
Percentage deviation from reference building Space heating	0.00	-4.75	-7.57	-6.23	-2.37	2.67	6.08	4.90	0.00
Percentage deviation from reference building overheating	0.00	34.62	44.23	44.23	11.54	-13.46	-42.31	-28.85	0.00



The results show what happens if the building is rotated 360° (0° = 360°).

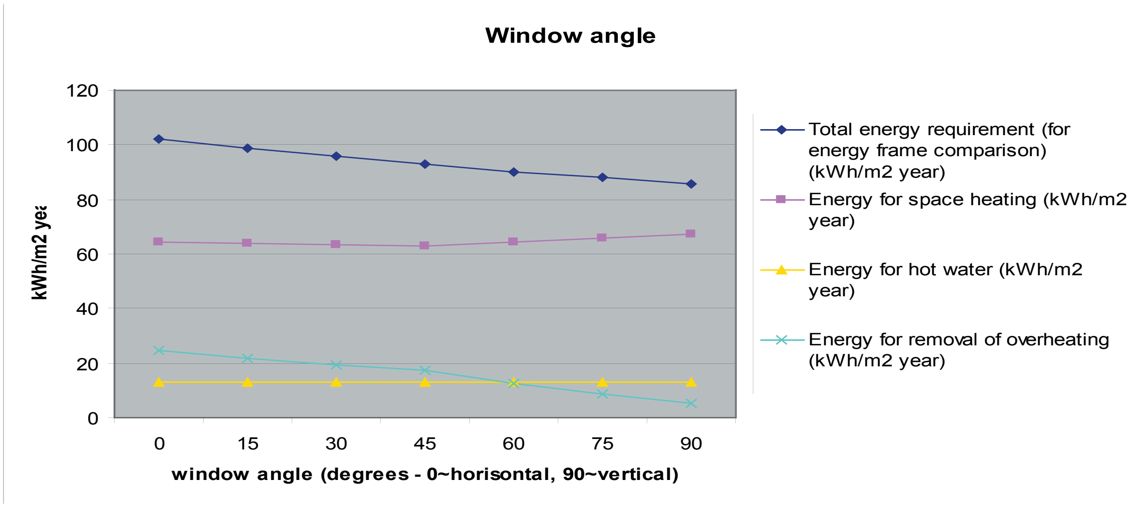
For angles between 0° and 180° there is an increase in the energy required for removing overheating and a decrease in the energy required for space heating and the total energy consumption. This reduction peaks around 90°.
For angles between 180° and 360° there is an increase in the total energy consumption and the energy required for space heating, while there is a decrease in the energy consumption for removing overheating.

The deviation from the result of the reference building that this rotation causes is small (approx. 5.5% for the total energy consumption), and the reduction potential is approx. 3% of the total energy consumption achieved by reducing the energy required for space heating.

Window angle
This calculation does not consider the changes in the shadows from the overhang and the window holes in the façade.

Table 9.18: Results for changes in the Window angle input parameter

o / degrees	*0*	*15*	*30*	*45*	*60*	*75*	*90*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**102.1**	**98.8**	**95.9**	**93.1**	**90.1**	**87.9**	**85.7**
Energy for space heating (kWh/m2 year)	**64.3**	**63.8**	**63.3**	**62.7**	**64.2**	**65.9**	**67.4**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**24.6**	**21.9**	**19.5**	**17.2**	**12.8**	**8.9**	**5.2**
Percentage deviation from reference building	19.14	15.29	11.90	8.63	5.13	2.57	0.00
Percentage deviation from reference building Space heating	-4.60	-5.34	-6.08	-6.97	-4.75	-2.23	0.00
Percentage deviation from reference building overheating	373.08	321.15	275.00	230.77	146.15	71.15	0.00



The results show what happens when the windows are tilted from their vertical position to a horizontal.

The changes to the window angle cause an increase in the total energy consumption of up to approx. 19%. This increase in energy consumption is due to increases in the energy required for the removal of overheating. There is a small reduction in the energy required for space heating, which peaks around a 45° angle. This reduction is, however, not enough to gain a reduction in the total energy consumption at any time.

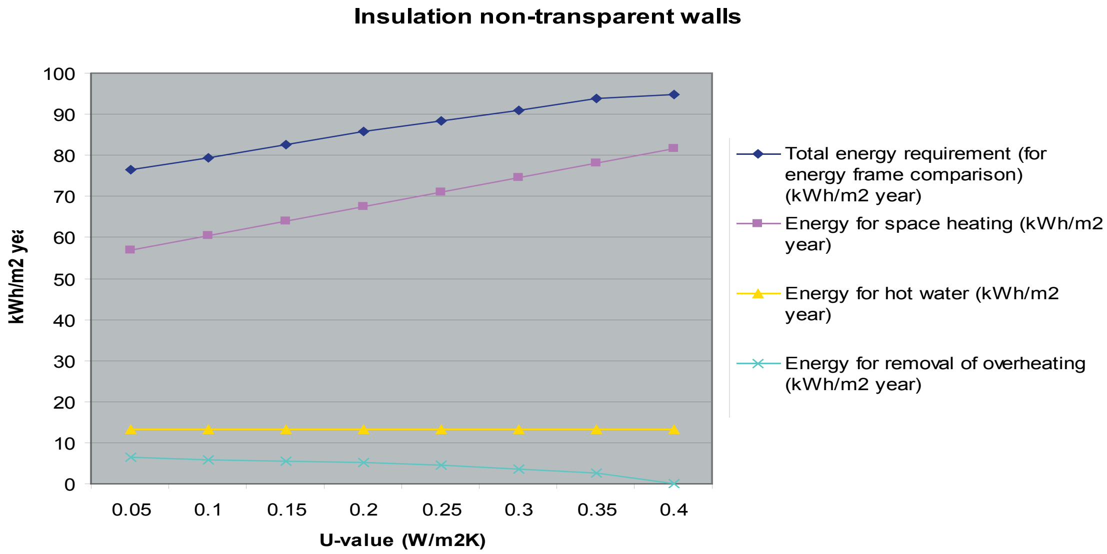
If the angle of a window is changed the interval of 45° to 90° is preferred, and not all the windows should have this angle. If the angle is larger than 90° the window would partly shade itself, which could eliminate the need for shading the window, this is, however, not possible to test in the Be06 programme in its current version.

Insulation of the building envelope

U-value of non-transparent walls

Table 9.19: Results for changes in the U-value of non-transparent walls input parameter

U-value (W/(m2K))	*0.05*	*0.1*	*0.15*	*0.2*	*0.25*	*0.3*	*0.35*	*0.4*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**76.4**	**79.5**	**82.6**	**85.7**	**88.5**	**91.1**	**93.9**	**94.9**
Energy for space heating (kWh/m2 year)	**57**	**60.4**	**63.9**	**67.4**	**71**	**74.5**	**78.1**	**81.8**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**6.3**	**5.9**	**5.6**	**5.2**	**4.4**	**3.5**	**2.7**	**0**
Percentage deviation from reference building	-10.85	-7.23	-3.62	0.00	3.27	6.30	9.57	10.74
Percentage deviation from reference building Space heating	-15.43	-10.39	-5.19	0.00	5.34	10.53	15.88	21.36
Percentage deviation from reference building overheating	21.15	13.46	7.69	0.00	-15.38	-32.69	-48.08	-100.00



These results show how changes in the U-value (heat transmittance value) of the outer walls of the building.

For values lower than 0.2 W/m²K there is a decrease in the total energy consumption and the energy required for space heating and an increase in the energy required for removing overheating.
For values larger than 0.2 W/m²K there is an increase in the total energy consumption and the energy required for space heating and an decrease in the energy required for removing overheating.

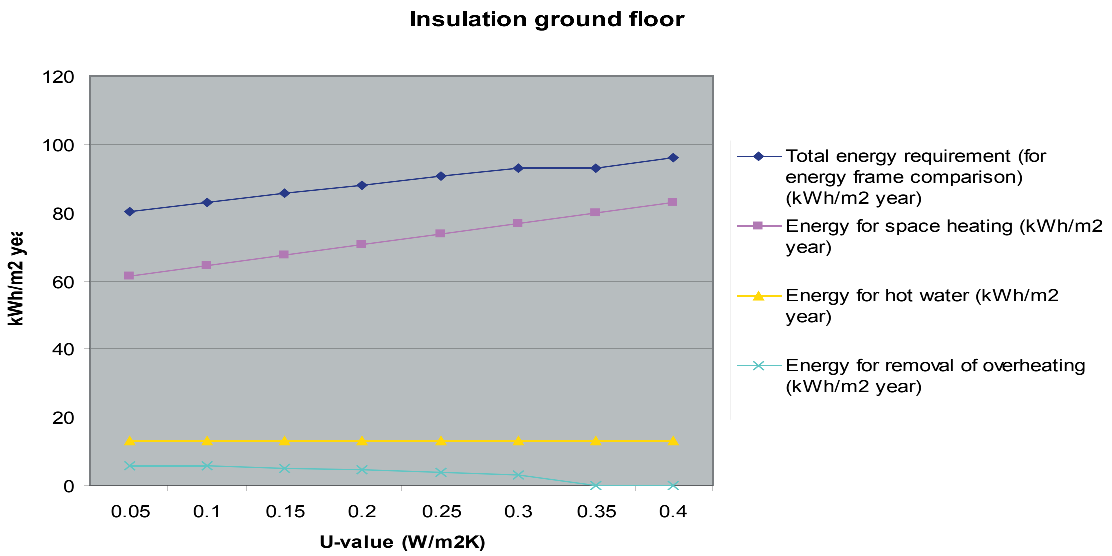
The results show a deviation from the total energy consumption of up to approx. 21.5%, half of which is reduction potential.

The U-value for the walls in the reference building was 0.2 W/m²K, had this value been 0.4 W/m²K the reduction potential would have been 21.5%.

U-values lower than 0.9 W/m²K are not very realistic.

U-value of non-transparent ground floor
Table 9.20: Results for changes in the U-value of non-transparent ground floor input parameter

U-value (W/(m2K))	*0.05*	*0.1*	*0.15*	*0.2*	*0.25*	*0.3*	*0.35*	*0.4*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**80.3**	**83**	**85.7**	**88.1**	**90.5**	**92.8**	**93**	**96.2**
Energy for space heating (kWh/m2 year)	**61.4**	**64.4**	**67.4**	**70.5**	**73.6**	**76.7**	**79.9**	**83.1**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.8**	**5.6**	**5.2**	**4.5**	**3.7**	**3**	**0**	**0**
Percentage deviation from reference building	-6.30	-3.15	0.00	2.80	5.60	8.28	8.52	12.25
Percentage deviation from reference building Space heating	-8.90	-4.45	0.00	4.60	9.20	13.80	18.55	23.29
Percentage deviation from reference building overheating	11.54	7.69	0.00	-13.46	-28.85	-42.31	-100.00	-100.00



These results show how changes in the U-value (heat transmittance value) of the ground floor of the building. The U-value for the ground floor in the reference building was 0.15 W/m^{2}K.

For values lower than 0.15 W/m^{2}K there is a decrease in the total energy consumption and the energy required for space heating and an increase in the energy required for removing overheating.
For values larger than 0.15 W/m^{2}K there is an increase in the total energy consumption and the energy required for space heating and an decrease in the energy required for removing overheating.

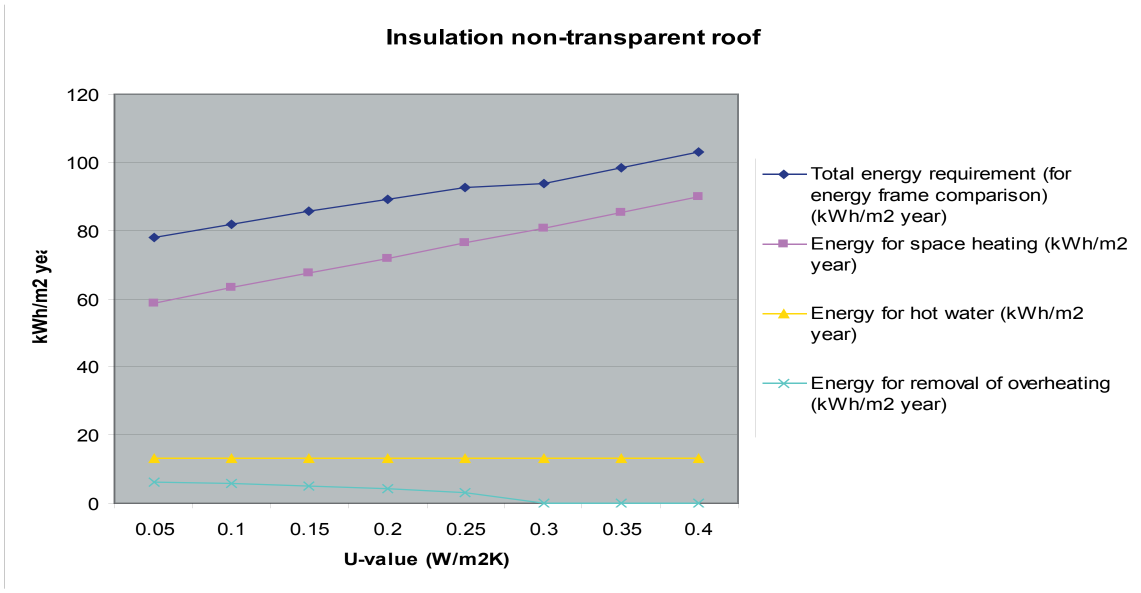
The results show a deviation from the total energy consumption of up to approx. 18.5%, of which the reduction potential is approx. 6.5%. This relatively low reduction potential compared to the calculations for the insulation of the walls is due to the fact that the U-value for the roof (and ground floor) has already been reduced in order to keep the calculated energy consumption lower than the energy frame for the building. Differences in the surface areas of the walls, roof and ground floor cannot be the reason for this, as the ratio between the surface areas are almost the same (the difference is approximately 0.1%).

U-values lower than 0.9 W/m^{2}K are not very realistic.

U-value of non-transparent roof

Table 9.21: Results for changes in the U-value of non-transparent roof input parameter

U-value (W/(m2K))	*0.05*	*0.1*	*0.15*	*0.2*	*0.25*	*0.3*	*0.35*	*0.4*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**78**	**81.9**	**85.7**	**89.1**	**92.5**	**93.9**	**98.5**	**103**
Energy for space heating (kWh/m2 year)	**58.7**	**63.1**	**67.4**	**71.9**	**76.3**	**80.8**	**85.3**	**89.9**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**6.1**	**5.7**	**5.2**	**4.1**	**3.1**	**0**	**0**	**0**
Percentage deviation from reference building	-8.98	-4.43	0.00	3.97	7.93	9.57	14.94	20.19
Percentage deviation from reference building Space heating	-12.91	-6.38	0.00	6.68	13.20	19.88	26.56	33.38
Percentage deviation from reference building overheating	17.31	9.62	0.00	-21.15	-40.38	-100.00	-100.00	-100.00



These results show how changes in the U-value (heat transmittance value) of the roof of the building. The U-value for the roof in the reference building was 0.15 W/m^{2}K.

For values lower than 0.15 W/m^{2}K there is a decrease in the total energy consumption and the energy required for space heating and an increase in the energy required for removing overheating.
For values larger than 0.15 W/m^{2}K there is an increase in the total energy consumption and the energy required for space heating and an decrease in the energy required for removing overheating.

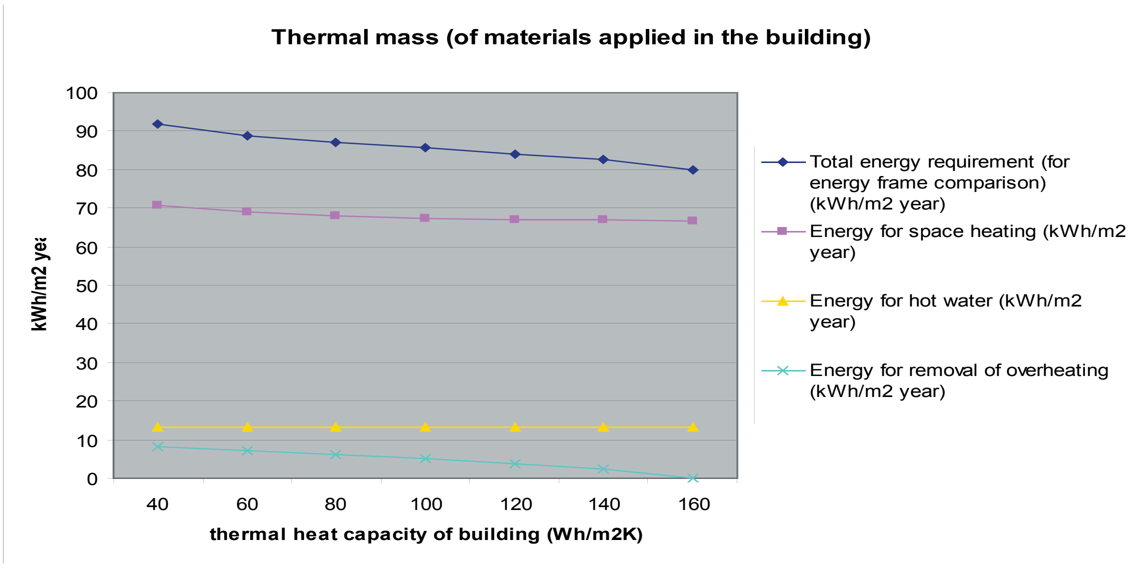
The results show a deviation from the total energy consumption of up to approx. 29%, of which the reduction potential is approx. 9%. This relatively low reduction potential compared to the calculations for the insulation of the walls is due to the fact that the U-value for the ground floor (and the roof) has already been reduced in order to keep the calculated energy consumption lower than the energy frame for the building. Differences in the surface areas of the walls, roof and ground floor cannot be the reason for this, as the ratio between the surface areas are almost the same (the difference is approximately 0.1%).
The difference between the deviation caused by changing the insulation of the ground floor and the roof is due to the fact that the transmission loss towards the ground is smaller than towards the air, due to a smaller temperature difference between the dimensioning indoor and outdoor temperatures.

U-values lower than 0.9 W/m^{2}K are not very realistic.

Thermal mass

Table 9.22: Results for changes in the thermal mass input parameter

Wh/(m2K)	*40*	*60*	*80*	*100*	*120*	*140*	*160*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**91.8**	**88.9**	**87.1**	**85.7**	**83.9**	**82.5**	**79.9**
Energy for space heating (kWh/m2 year)	**70.7**	**68.9**	**67.9**	**67.4**	**67.1**	**66.9**	**66.8**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**8**	**7**	**6.1**	**5.2**	**3.7**	**2.4**	**0**
Percentage deviation from reference building	7.12	3.73	1.63	0.00	-2.10	-3.73	-6.77
Percentage deviation from reference building Space heating	4.90	2.23	0.74	0.00	-0.45	-0.74	-0.89
Percentage deviation from reference building overheating	53.85	34.62	17.31	0.00	-28.85	-53.85	-100.00



This calculation shows how differences in the thermal mass (heat capacity of the materials in the building). The thermal mass of the reference building was set to 100 Wh/m^{2}K.

The changes only cause small deviations from the energy consumption of the reference building of approx. 14%, half of which is reduction potential.

An increase in the thermal mass (>100 Wh/m^{2}K) causes a decrease in the total energy consumption, the energy required for space heating and the energy required for removing overheating, whilst a decrease in the thermal mass (< 100 Wh/m^{2}K) causes an increase in the total energy consumption, the energy required for space heating and the energy required for removing overheating

Ventilation

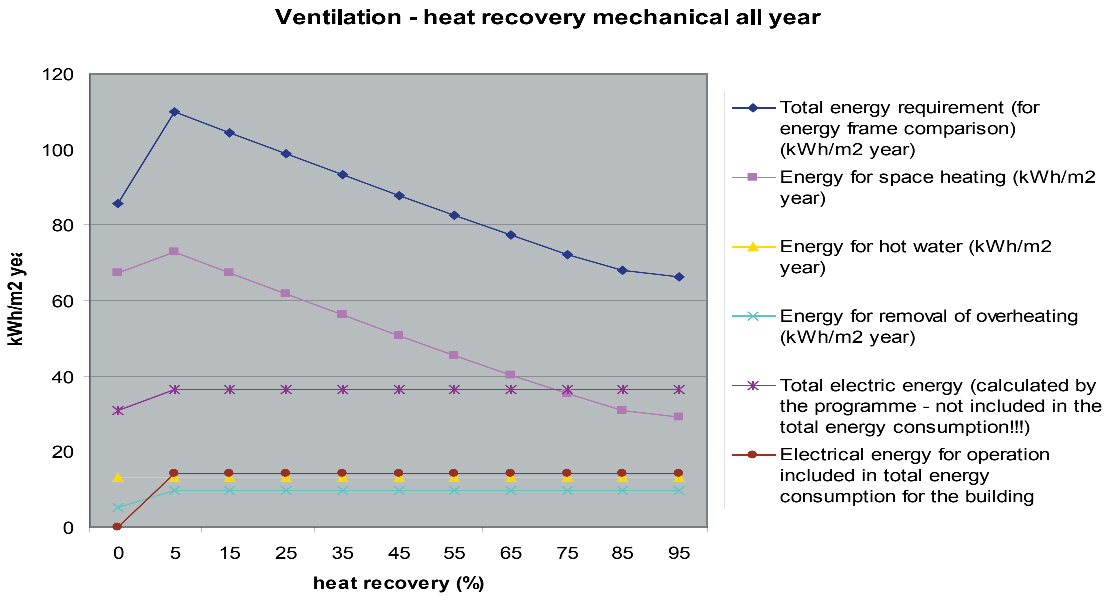
Heat-recovery, mechanical all year

Table 9.23: Results for changes in the Heat-recovery, mechanical all year input parameter

Heat recovery (%)	*0*	*5*	*15*	*25*	*35*	*45*	*55*	*65*	*75*	*85*	*95*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**85.7**	**109.9**	**104.4**	**98.8**	**93.3**	**87.8**	**82.5**	**77.3**	**72.3**	**67.9**	**66.3**
Energy for space heating (kWh/m2 year)	**67.4**	**72.9**	**67.4**	**61.9**	**56.3**	**50.8**	**45.5**	**40.3**	**35.3**	**30.9**	**29.3**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.2**	**9.7**	**9.7**	**9.7**	**9.7**	**9.7**	**9.7**	**9.7**	**9.7**	**9.7**	**9.7**
Total electric energy (calculated by the programme - not included in the total energy consumption)	**30.7**	**36.3**	**36.3**	**36.3**	**36.3**	**36.3**	**36.3**	**36.3**	**36.3**	**36.3**	**36.3**
Electrical energy for operation included in total energy consumption for the building	**0**	**14.25**	**14.25**	**14.25**	**14.25**	**14.25**	**14.25**	**14.25**	**14.25**	**14.25**	**14.25**
Percentage deviation from reference building	0.00	28.24	21.82	15.29	8.87	2.45	-3.73	-9.80	-15.64	-20.77	-22.64
Percentage deviation from reference building Space heating	0.00	8.16	0.00	-8.16	-16.47	-24.63	-32.49	-40.21	-47.63	-54.15	-56.53
Percentage deviation from reference building overheating	0.00	86.54	86.54	86.54	86.54	86.54	86.54	86.54	86.54	86.54	86.54
Percentage deviation from reference building total electrical energy consumption	0.00	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24

If the heat recovery is achieved via mechanical ventilation the heat recovery percentage must be over 65% according to the Danish building codes (BR95).

The calculation does not consider the increased pressure loss in the mechanical system.



This calculation shows the effect of introducing heat recovery in the reference building. The reference building was naturally ventilated with no heat recovery.

The results show a great potential for reducing the energy required for space heating (by up to approx. 22.5% of the total energy consumption).

The introduction of heat recovery causes an increase in the energy required for the removal of overheating. This increase seems a bit strange, as it does not change at all for the different values of heat recovery (5 to 95%).

Values > 15% cause a decrease in the energy required for space heating and values > approx. 45% cause a decrease in the total energy consumption.

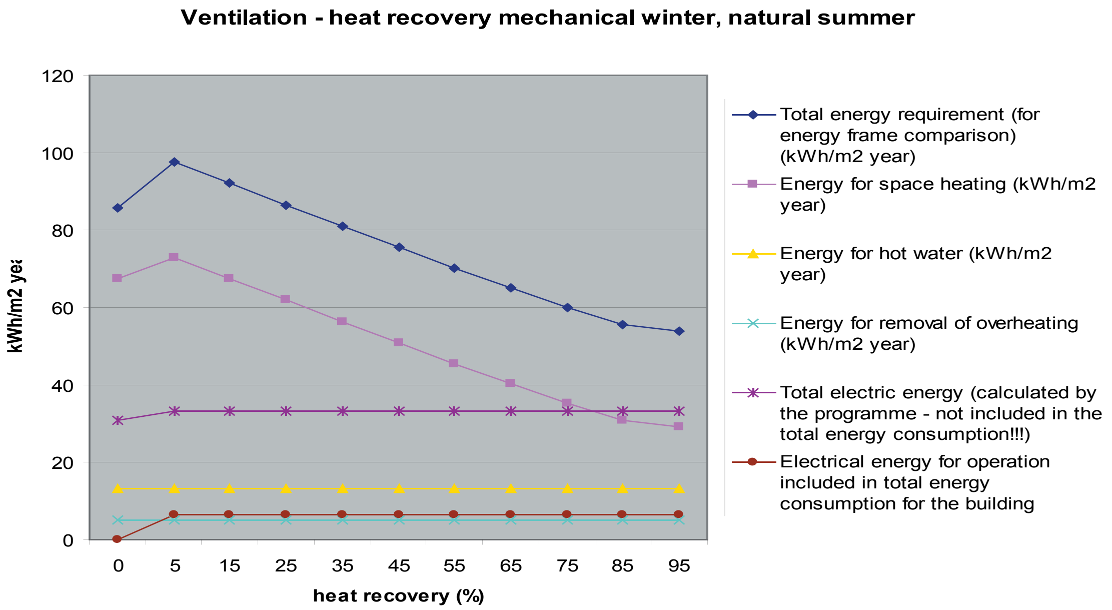
Heat recovery, mechanical ventilation winter, natural ventilation summer

Table 9.24: Results for changes in the Heat-recovery, mechanical ventilation winter and natural summer ventilation input parameter

Heat recovery (%)	*0*	*5*	*15*	*25*	*35*	*45*	*55*	*65*	*75*	*85*	*95*
Total energy requirement (for energy frame comparison) (kWh/ m2 year)	**85.7**	**97.6**	**92.1**	**86.6**	**81**	**75.5**	**70.2**	**65.1**	**60**	**55.6**	**54**
Energy for space heating (kWh/m2 year)	**67.4**	**72.9**	**67.4**	**61.9**	**56.3**	**50.8**	**45.5**	**40.3**	**35.3**	**30.9**	**29.3**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/ m2 year)	**5.2**	**5.1**	**5.1**	**5.1**	**5.1**	**5.1**	**5.1**	**5.1**	**5.1**	**5.1**	**5.1**
Total electric energy (calculated by the programme - not included in the total energy consumption)	**30.7**	**33.3**	**33.3**	**33.3**	**33.3**	**33.3**	**33.3**	**33.3**	**33.3**	**33.3**	**33.3**
Electrical energy for operation included in total energy consumption for the building	**0**	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**
Percentage deviation from reference building	0.00	13.89	7.47	1.05	-5.48	-11.90	-18.09	-24.04	-29.99	-35.12	-37
Percentage deviation from reference building Space heating	0.00	8.16	0.00	-8.16	-16.47	-24.63	-32.49	-40.21	-47.63	-54.15	
Percentage deviation from reference building overheating	0.00	-1.92	-1.92	-1.92	-1.92	-1.92	-1.92	-1.92	-1.92	-1.92	-1.9
Percentage deviation from reference building total electrical energy consumption	0.00	8.47	8.47	8.47	8.47	8.47	8.47	8.47	8.47	8.47	8.5

If the heat recovery is achieved via mechanical ventilation the heat recovery percentage must be over 65% according to the Danish building codes (BR95)

The calculation does not consider the increased pressure loss in the mechanical system.



This calculation shows the effect of introducing heat recovery in the reference building. The reference building was naturally ventilated with no heat recovery.

The results show a great potential for reducing the total energy consumption (by up to approx. 37% of the total energy consumption), especially with respect to the energy required for space heating. There is a small increase in the energy required for space heating; this is concluded to be due to the introduction of the mechanical ventilation for the heat recovery for which the inlet air is preheated to 18°C.

The introduction of heat recovery causes a very small reduction in the energy required for the removal of overheating.

Values > approx. 25% cause a decrease in the total energy consumption and in the energy required for space heating.

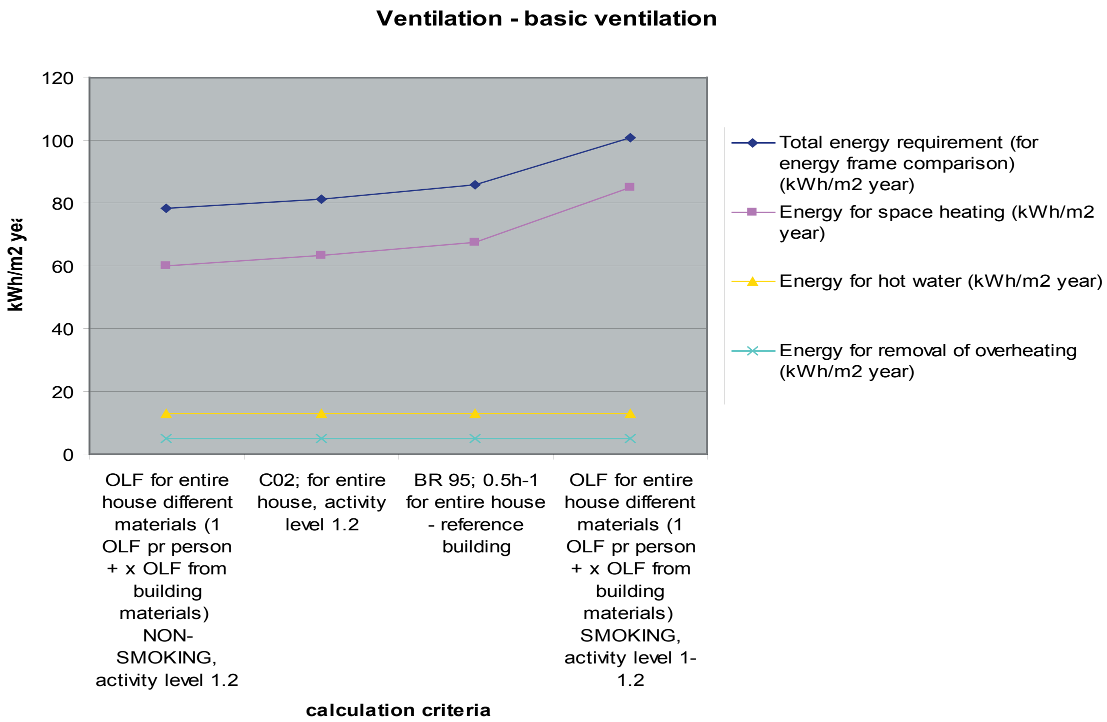
The Danish building codes require a heat recovery of 65% in mechanical ventilation systems. The results presented here show that even a smaller percentage of heat recovery matters if this is achieved via mechanical ventilation is does, however, make sense to have as large an heat recovery as possible, as the increase in the construction costs would be relatively small. Is the heat recovery achieved through a naturally ventilated system (e.g. with wind cowls) one should weigh the reductions in the construction costs against the reduction in running costs compared to a mechanical system with a larger heat recovery percentage.

Basic ventilation rates (based on different criteria)

Table 9.25: Results for changes in the Basic ventilation input parameter

Criteria	*OLF for entire house different materials (1 OLF pr person + x OLF from building materials) NON-SMOKING, activity level 1.2*	*C02; for entire house, activity level 1.2*	*BR 95; 0.5h-1 for entire house - reference building*	*OLF for entire house different materials (1 OLF pr person + x OLF from building materials) SMOKING, activity level 1-1.2*
Ventilation rate (h-1)	0.27	0.3	0.5	0.67
Ventilation rate (l/s m2)	0.23	0.25	0.42	0.56
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**78.2**	**81.4**	**85.7**	**100.8**
Energy for space heating (kWh/m2 year)	**60.1**	**63.2**	**67.4**	**85.2**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5**	**5.1**	**5.2**	**5.2**
Percentage deviation from reference building	-8.75	-5.02	0.00	17.62
Percentage deviation from reference building Space heating	-10.83	-6.23	0.00	26.41
Percentage deviation from reference building overheating	-3.85	-1.92	0.00	0.00

According to the Danish building codes the basic ventilation of any residential building must be at least 0.5 h^{-1}, which in this case corresponds with 0.42l/s m^2.



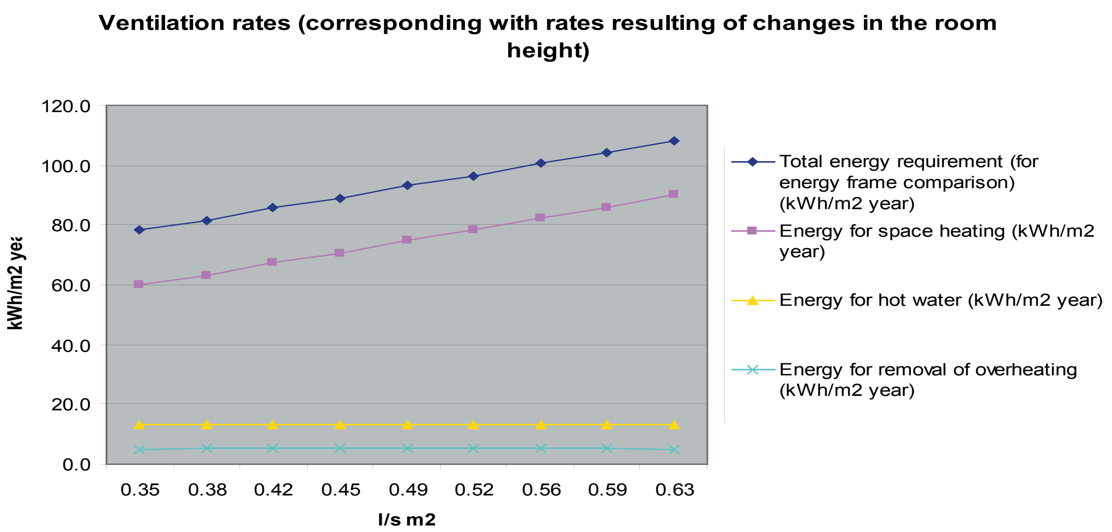
This calculation investigates the impact of different ways of determining the basic ventilation. Only the results for 0.42 and 0.56 l/s m^2 are legal in Denmark.

A decrease in the ventilation rates shows a potential for reducing the total energy consumption via a decrease in the energy required for space heating, whilst an increase in the ventilation rates results in an increase in the total energy consumption and the energy required for space heating.
The reason why the energy required for the removal of overheating is not reduced is that the summer ventilation rates in the reference building is 1.2l/s m^2, which means that the ventilation rate during the cooling season exceeds the basic ventilation in the building for all the cases investigated in this particular study.

In naturally ventilated residential buildings it is not possible to control if the ventilation is larger or smaller than 0.5 h^{-1}. It is, thus, interesting to see how the use of a building can influence the energy consumption. It is also interesting seen in the light of the fact that the ventilation rate in some passive houses is as low as 0.2h^{-1}.[16]

Ventilation rate, winter (natural ventilation)
Table 9.26: Results for changes in the Ventilation rate, winter (natural ventilaiton) input parameter

Ventilation rate (l/s m2)	*0.35*	*0.38*	*0.42*	*0.45*	*0.49*	*0.52*	*0.56*	*0.59*	*0.63*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**78.2**	**81.4**	**85.7**	**89.0**	**93.3**	**96.5**	**100.8**	**104.1**	**108.3**
Energy for space heating (kWh/m2 year)	**60.1**	**63.2**	**67.4**	**70.6**	**74.9**	**78.2**	**82.5**	**85.9**	**90.3**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.0**	**5.1**	**5.2**	**5.2**	**5.2**	**5.2**	**5.2**	**5.1**	**4.9**
Percentage deviation from reference building	-8.75	-5.02	0.00	3.85	8.87	12.60	17.62	21.47	26.37
Percentage deviation from reference building Space heating	-10.83	-6.23	0.00	4.75	11.13	16.02	22.40	27.45	33.98
Percentage deviation from reference building overheating	-3.85	-1.92	0.00	0.00	0.00	0.00	0.00	-1.92	-5.77



As an extension to the later study of the effect of changing the room height, this study of different winter ventilation rates was performed. The study is linked to the study of the effect of the room height (under building shape) in which both the ventilation rate and the surface area of the building is changed in relation to different average room heights.

The results show how the energy consumption corresponding with different ventilation rates. The results are similar to the results from the study of the basic ventilation; decreases in the ventilation rates show a potential for reducing the energy required for the total energy consumption, the energy required for space heating and small reductions in the energy required for removing overheating. An increases in the ventilation rates show a risk of increasing the total energy consumption, the energy required for space heating and small reductions in the energy required for removing overheating.

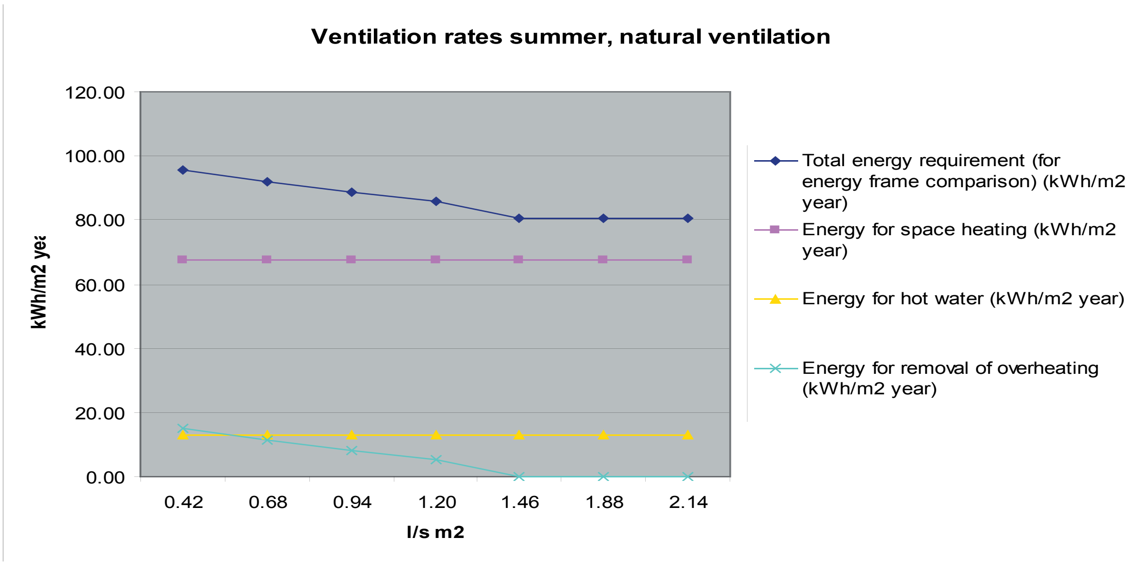
Reducing the average room height is one way of reducing the ventilation rate whilst living up to the requirement of $0.5h^{-1}$ in the Danish building codes. This would, however, have a large impact on the spatial experience of the building and the penetration of daylight, which should also be considered.

The deviation from the total energy consumption of the reference building is approx. 35%, of which the reduction potential is approx. 9%. This reduction should, however, be achieved whilst living up to the Danish energy requirements, which can only be achieved by reducing the average room height.

Ventilation rate summer (natural ventilation)

Table 9.27: Results for changes in the Ventilation rate summer (natural ventilation) input parameter

Ventilation rate (l/s m2)	*0.42*	*0.68*	*0.94*	*1.20*	*1.46*	*1.88*	*2.14*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**95.60**	**92.10**	**88.80**	**85.70**	**80.60**	**80.60**	**80.60**
Energy for space heating (kWh/m2 year)	**67.40**	**67.40**	**67.40**	**67.40**	**67.40**	**67.40**	**67.40**
Energy for hot water (kWh/m2 year)	**13.10**	**13.10**	**13.10**	**13.10**	**13.10**	**13.10**	**13.10**
Energy for removal of overheating (kWh/m2 year)	**15.00**	**11.50**	**8.20**	**5.20**	**0.00**	**0.00**	**0.00**
Percentage deviation from reference building	11.55	7.47	3.62	0.00	-5.95	-5.95	-5.95
Percentage deviation from reference building Space heating	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Percentage deviation from reference building overheating	188.46	121.15	57.69	0.00	-100.00	-100.00	-100.00



This calculation shows the effect of changing the summer ventilation rate in the naturally ventilated reference building. The ventilation rate in the reference building has been increased from the basic ventilation rate (0.42l/s m^2) to 1.2 l/s m^2 in order to reduce the overheating problems in the building and live up to the energy frame.

The results show that the change only effects the total energy consumption and the energy consumption for removing overheating, which makes sense, as the changes only effects the summer situation for the building. The results also show that the change only causes an effect until the overheating is eliminated.

The deviation from the total energy consumption of the reference building is 17.5%, of which the reduction potential is approx. 6%, which can happen, if the ventilation rate is increased to a value between 1.2 and 1.462 l/s m^2.

Building shape

The calculations for the building shape have a special reference building in which the eight edges of the reference building are included with thermal bridges at the joints. These joints were accidentally left out in the initial reference building applied for the rest of the studies presented in the local sensitivity analysis.

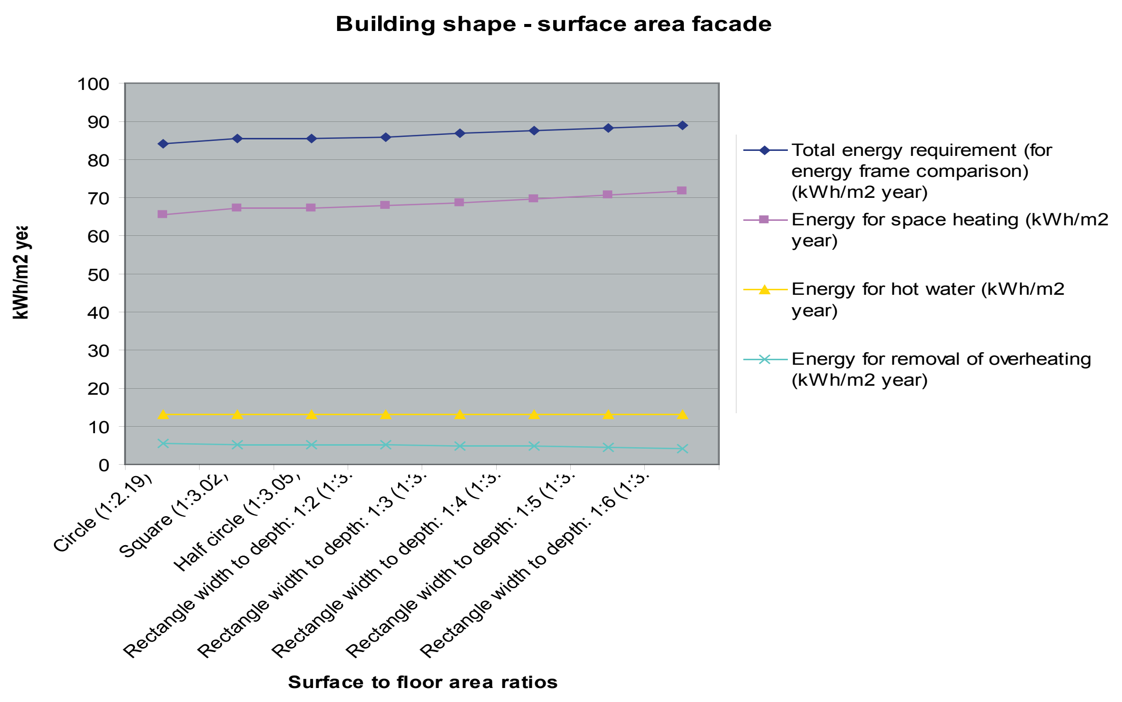
The annual energy consumption of the 'special' reference building applied in this study is 86.8 kWh/m^2 for the total energy consumption, 73.8 kWh/m^2 for space heating, 13.1 kWh/m^2 for hot water and 0 kWh/m^2 for removing overheating.

The surface to floor area ratio of the reference building is 1:3, and the window to floor area ratio is kept constant.

Surface area façade (for a one storey building)

Table 9.28: Results for changes in the Surface area façade (for a one storey building) input parameter

Shape and surface to floor area ratio	*Circle (1:2.19)*	*Square (1:3.02)*	*Half circle (1:3.05)*	*Rectangle width to depth: 1:2 (1:3.09)*	*Rectangle width to depth: 1:3 (1:3.18)*	*Rectangle width to depth: 1:4 (1:3.28)*	*Rectangle width to depth: 1:5 (1:3.38)*	*Rectangle width to depth: 1:6 (1:3.46)*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**84.1**	**85.5**	**85.5**	**86**	**86.8**	**87.5**	**88.3**	**88.9**
Energy for space heating (kWh/m2 year)	**65.5**	**67.1**	**67.2**	**67.8**	**68.7**	**69.7**	**70.7**	**71.6**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.4**	**5.3**	**5.2**	**5.1**	**4.9**	**4.7**	**4.4**	**4.2**
Percentage deviation from reference building	-2.66	-1.04	-1.04	-0.46	0.46	1.27	2.20	2.89
Percentage deviation from reference building Space heating	-3.96	-1.61	-1.47	-0.59	0.73	2.20	3.67	4.99
Percentage deviation from reference building overheating	5.88	3.92	1.96	0.00	-3.92	-7.84	-13.73	-17.65



These results show the impact of changes in the surface to floor area ratios of a one storey building with 137m^2 heated floor area (like the reference building). The range is determined in relation to different basic shapes (circle, half-circle, square and rectangles of different depth to width ratios (1:2, 1:3, 1:4, 1:5 and 1:6)).

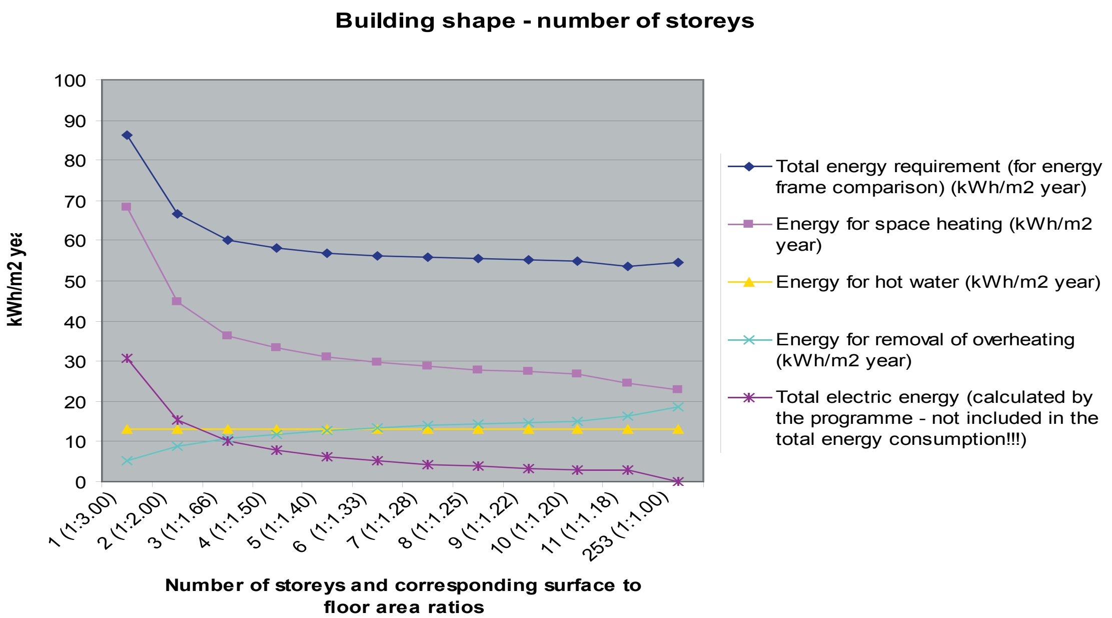
The results show a small deviation form the energy consumption of the reference building (up to approx. 5.5%), half of which is the approx. reduction potential.
The size of the deviation is expected to be different if the u-values of the walls were increased in the reference building. If the U-value for the walls was decreased the deviation percentages for space heating would be even smaller, whilst an increase in the U-values for the walls would cause an increase in the deviation percentages for space heating.
The changes in the surface area of the walls in the building is, however, also very small, which might also account for the small deviations, especially seen in the light of the later study of the impact of the number of storeys in the building.

For surface to floor area ratios between 1:2.19 and 1:3.09 there is a small decrease in the total energy consumption and the energy required for space heating and a small increase in the energy requirement for removing overheating. While surface to floor area ratios between 1:3.18 and 1:3.46 there is a small increase in the total energy consumption and the energy required for space heating and a small reduction in the energy requirement for removing overheating.

Number of storeys

Table 9.29: Results for changes in the Number of stories input parameter

No. of stories in the building	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*253*
Total energy requirement (for energy frame comparison) (kWh/ m2 year)	**86.4**	**66.7**	**60.1**	**58.2**	**57**	**56.2**	**55.8**	**55.4**	**55.2**	**55**	**53.6**	**54.7**
Energy for space heating (kWh/m2 year)	**68.2**	**44.7**	**36.3**	**33.4**	**31.2**	**29.7**	**28.7**	**27.9**	**27.3**	**26.8**	**24.4**	**22.8**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.1**	**8.9**	**10.7**	**11.7**	**12.7**	**13.4**	**13.9**	**14.4**	**14.7**	**15.1**	**16.2**	**18.7**
Total electric energy (calculated by the programme - not included in the total energy consumption)	**30.7**	**15.3**	**10.2**	**7.7**	**6.1**	**5.1**	**4.4**	**3.8**	**3.4**	**3.1**	**2.8**	**0.1**
Percentage deviation from reference building	0.00	-22.8	-30.4	-32.6	-34.0	-35.0	-35.4	-35.9	-36.1	-36.3	-38.0	-36.7
Percentage deviation from reference building Space heating	0.00	-34.5	-46.8	-51.0	-54.3	-56.5	-57.9	-59.1	-60.0	-60.7	-64.2	-66.6
Percentage deviation from reference building overheating	0.00	74.5	109.8	129.4	149.0	162.8	172.6	182.4	188.2	196.1	217.7	266.7



This calculation shows the impact of multiple storeys and the study relates to the changes in the surface to floor area ratios. The calculation is made by keeping the ground floor and roof area constant and increasing the heated floor area, and window and wall areas corresponding with the number of storeys.

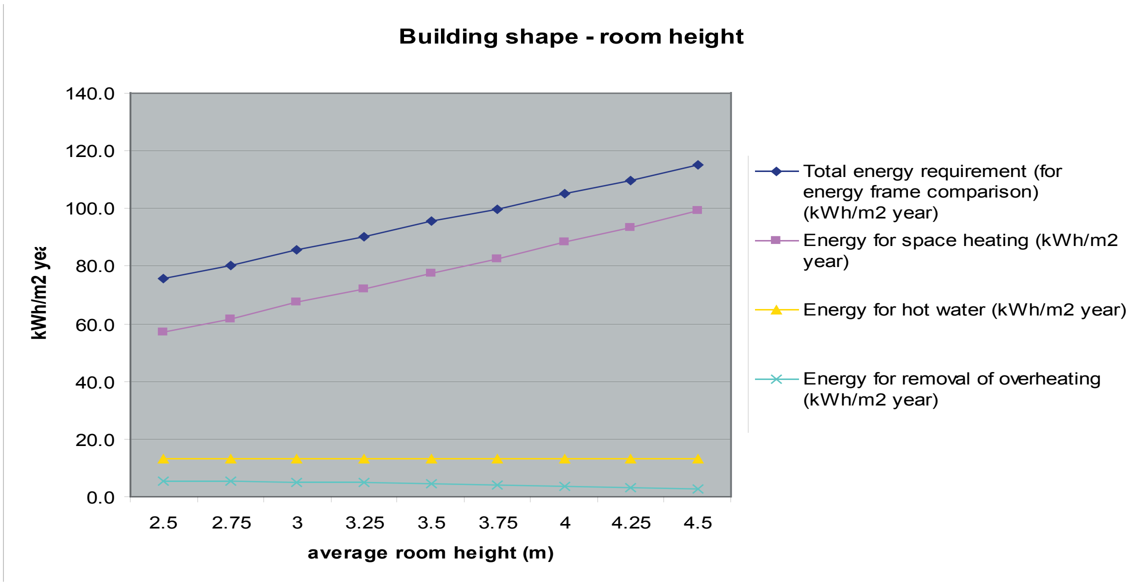
The results show is a great reduction in the total energy consumption of the building and the energy required for space heating, as well as an increase in the energy required for removing overheating.
The reduction potential of the total energy consumption is approx. 38% for a building with a surface to floor area ratio of 1:1.18.
If one wishes to reduce the surface to floor area ratio even further a solution is to increase the number of floors, this is, however, quite ineffective.

It is interesting to note how large an impact the first three storeys have on the surface to floor area ratio. This means that by adding a few extra storeys to the reference building one can reduce the energy consumption in the building significantly.
The problems with overheating could be solved or at least reduced with e.g. an increase in the ventilation rates in summer (and perhaps also winter) or the introduction of shading devices.

Average room height
An increase in the average room height causes increases the ventilation rate (for basis ventilation 0.5h^{-1}) and increases in the surface area of the facades.

Table 9.30: Results for changes in the Average room height input parameter

Average room height (m)	*2.5*	*2.75*	*3*	*3.25*	*3.5*	*3.75*	*4*	*4.25*	*4.5*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**75.7**	**80.1**	**85.7**	**90.1**	**95.5**	**99.8**	**105.2**	**109.6**	**115.1**
Energy for space heating (kWh/m2 year)	**57.1**	**61.6**	**67.4**	**72.0**	**77.7**	**82.5**	**88.4**	**93.3**	**99.3**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.4**	**5.4**	**5.2**	**5.0**	**4.6**	**4.2**	**3.7**	**3.2**	**2.7**
Percentage deviation from reference building	-11.67	-6.53	0.00	5.13	11.44	16.45	22.75	27.89	34.31
Percentage deviation from reference building Space heating	-15.28	-8.61	0.00	6.82	15.28	22.40	31.16	38.43	47.33
Percentage deviation from reference building overheating	3.85	3.85	0.00	-3.85	-11.54	-19.23	-28.85	-38.46	-48.08



This study relates to the dimensions of the building and the composition of the building in relation to the average room heights. Average room heights are interesting in relation the spatial perception of the building, the strategies for natural ventilation of a space[17] and the penetration of daylight into a building.

The results show that a decrease in the room height causes a reduction in the total energy consumption and the energy required for space heating, and that an increase in the room height causes an increase in the energy required for removing overheating. While an increase in the average room height has the opposite effect.

The deviation from the total energy consumption of the reference building is quite significant (approx. 46%), of which the reduction potential is approx. 11.5%.

Another issue which needs consideration when deciding the average room height relates to the perception of draught from cold surfaces. This is especially important for building elements with high U-values (e.g. windows). The perception of draught is dependent on the height of the surface, the U-value of the building element, and the temperature difference between the interior and exterior space [Heiselberg 1994].

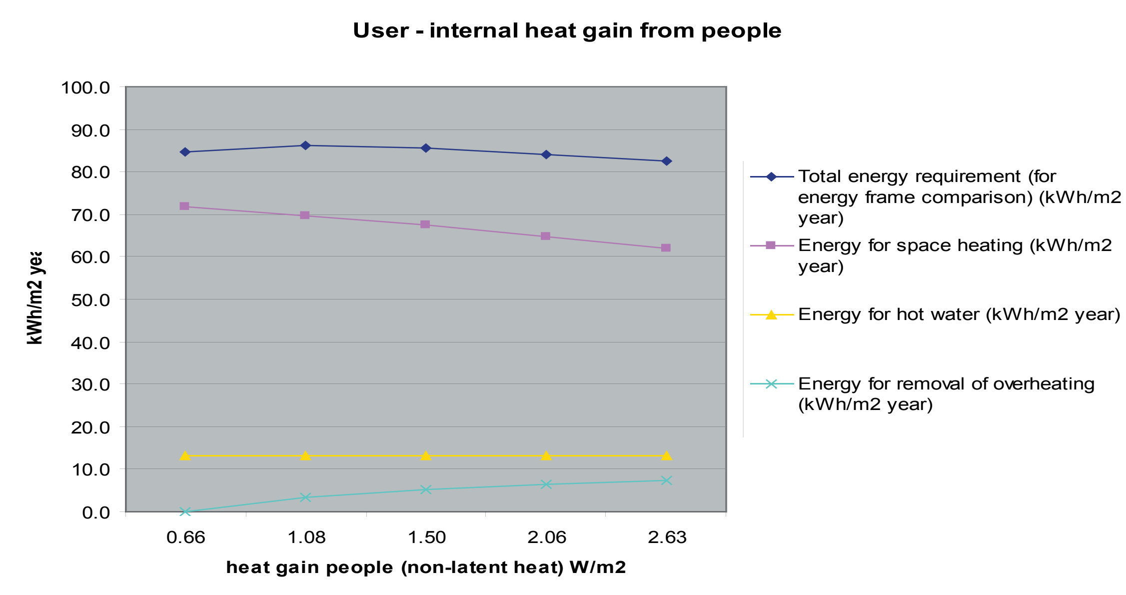
Use of building

Internal load from people

Table 9.31: Results for changes in the Internal loads from people input parameter

Internal heat gain people (W/m2)	*0.66*	*1.08*	*1.50*	*2.06*	*2.63*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**84.8**	**86.1**	**85.7**	**84.1**	**82.5**
Energy for space heating (kWh/m2 year)	**71.7**	**69.6**	**67.4**	**64.7**	**61.9**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**0.0**	**3.4**	**5.2**	**6.3**	**7.5**
Percentage deviation from reference building	-1.05	0.47	0.00	-1.87	-3.73
Percentage deviation from reference building Space heating	6.38	3.26	0.00	-4.01	-8.16
Percentage deviation from reference building overheating	-100.00	-34.62	0.00	21.15	44.23

This calculation studies the impact of the internal heat gain from people in the building. The internal heat gain can be increased by increasing the number of people in the building or the activity level of the people in the building (e.g. people sitting, standing, running, exercising).



The larger the level of activity or the number of people the larger the internal heat gain from people is.

The results show that:

- An increase in the internal heat gain from people (W/m^2) causes a reduction in the total energy consumption and the energy required for space heating, and an increase in the energy required for the removal of overheating.
- A decrease in the heat gain from people causes an increase in the energy required for space heating and a reduction in the energy required for removing overheating. The total energy consumption is reduced for the lowest internal heat gain from people (due to the elimination of overheating), while there is a small increase in the total energy consumption for the situation where the internal heat gain is 1.08W/m^2.

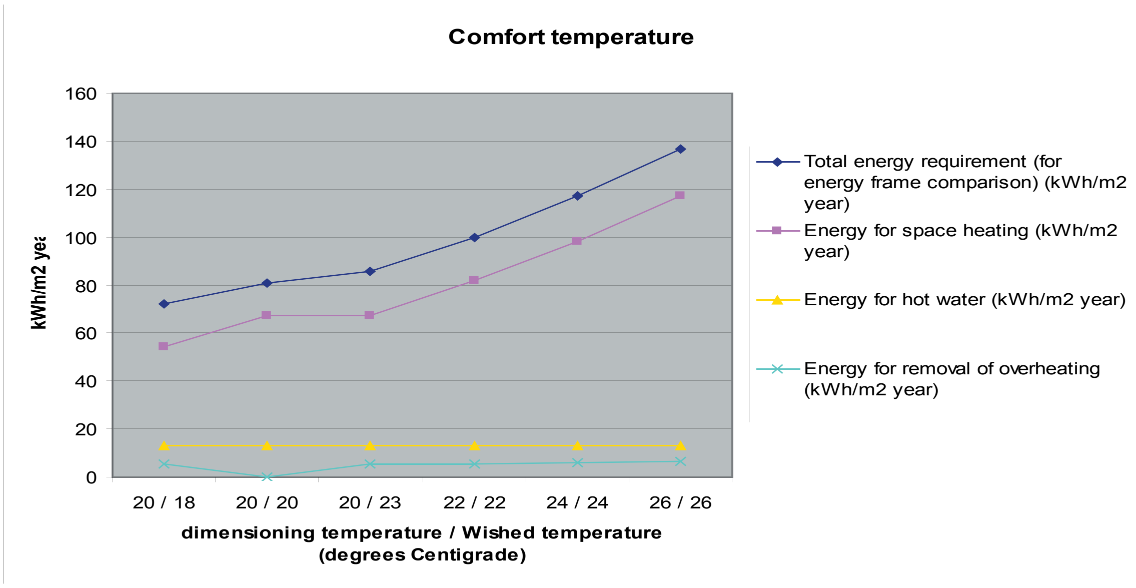
The deviation from the total energy consumption in the reference building is approx. 5%, which is quite low.

The building design does not influence the activity level or the number of users in the building. However, these need to be established in the initial stages of the design process, so the appropriate building design is made in relation to the use of the building, as the use of the building influences both the energy required for space heating and removing overheating in the building.

Comfort temperature

Table 9.32: Results for changes in the Comfort temperature input parameter

Dimensioning temperature / Wished temperature	*20 / 18*	*20 / 20*	*20 / 23*	*22 / 22*	*24 / 24*	*26 / 26*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**72.3**	**80.6**	**85.7**	**100**	**117**	**136.6**
Energy for space heating (kWh/m2 year)	**54**	**67.4**	**67.4**	**81.7**	**98.1**	**116.9**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**5.2**	**0**	**5.2**	**5.2**	**5.8**	**6.5**
Percentage deviation from reference building	-15.64	-5.95	0.00	16.69	36.52	59.39
Percentage deviation from reference building Space heating	-19.88	0.00	0.00	21.22	45.55	73.44
Percentage deviation from reference building overheating	0.00	-100.00	0.00	0.00	11.54	25.00



This calculation studies how the variation of the comfort temperature influences the energy consumption in the building. The dimensioning temperature in the reference building is 20°C and the wished temperature is 23°C. The results in the reference building are the same as the 20/20 case.
The programme operates with special comfort temperatures in summer. These were only changed for the cases in which the comfort temperatures for the rest of the year exceeded the summer comfort temperature.
The 20/18 situation is only included for experimental reasons, as the temperatures must be at least 20/20 in the calculation of the energy consumptions in order to live up to the Danish building codes.

The results show that an increase in the comfort temperature causes an increase in the total energy consumption and an increase in the energy required for space heating and removing overheating, and that a decrease in the comfort temperature causes a decrease causes a reduction in the total energy consumption and a reduction or no change in the energy required for space heating and removing overheating.

The deviation from the total energy consumption of the reference building is approx. 75%, which is a very large deviation.

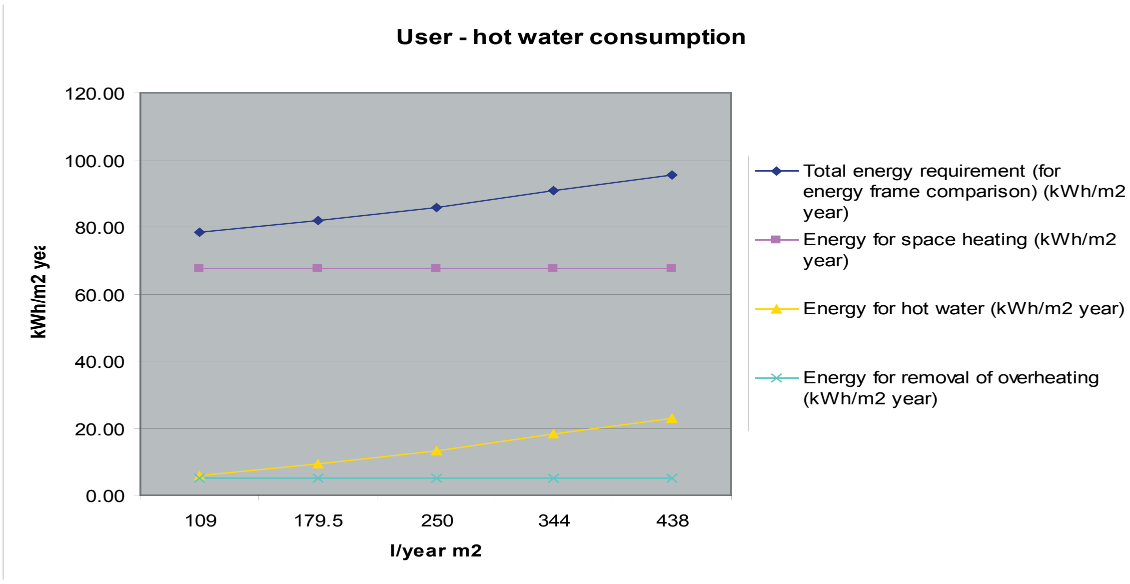
The results from the Be06 programme show that there is a problem with overheating in the 26/26 case. This does not make sense. If there was a problem with overheating this problem should also occur in the rest of the cases where the comfort temperatures are lower.

The comfort temperature is not directly related to the building design, it does, however, relate to the use of the building and the comfort requirements the user sets up for the building. This is a tricky parameter to deal with as different people have different comfort temperatures; some people prefer a low room temperature while others prefer a high room temperature.
The study shows that there a significant deviation in relation to the energy consumption of the reference building, which is why it is important to consider what the average comfort temperature of the inhabitants will be, and what set up appropriate design criteria in accordance with this.

Consumption of hot water

Table 9.33: Results for changes in the Consumption of hot water input parameter

Hot water consumption (l/year m2)	*109*	*179.5*	*250*	*344*	*438*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**78.30**	**82.00**	**85.70**	**90.70**	**95.60**
Energy for space heating (kWh/m2 year)	**67.4**	**67.4**	**67.4**	**67.4**	**67.4**
Energy for hot water (kWh/m2 year)	**5.7**	**9.4**	**13.1**	**18.1**	**23**
Energy for removal of overheating (kWh/m2 year)	**5.20**	**5.20**	**5.20**	**5.20**	**5.20**
Percentage deviation from reference building	-8.63	-4.32	0.00	5.83	11.55



This calculation studies how the consumption of hot water influences the energy consumption in the building. The hot water consumption in the reference building was set to 250l/year m^2.

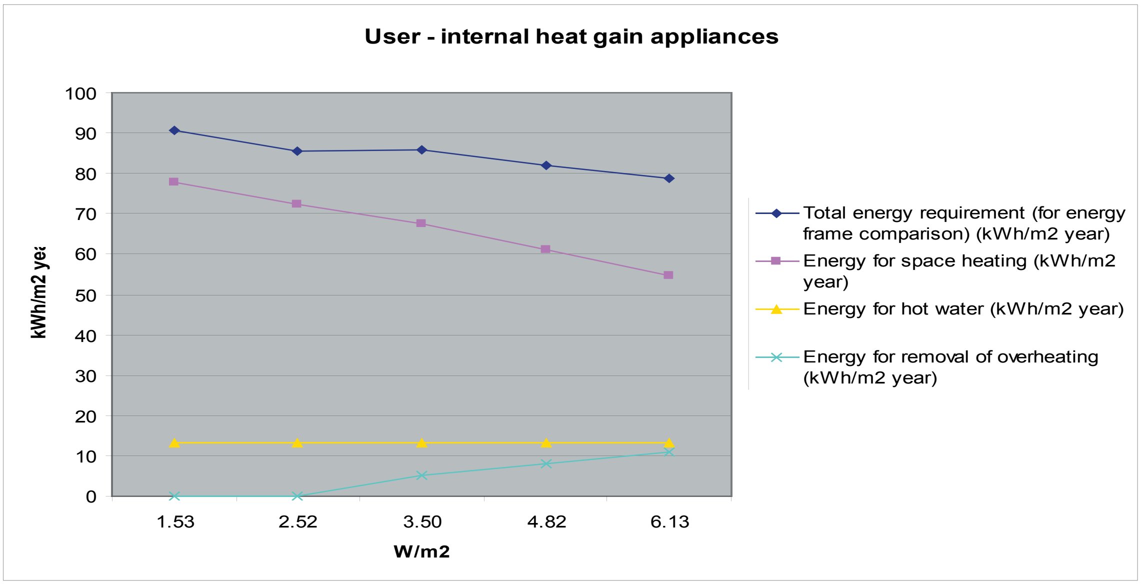
A reduction in the hot water consumption causes a reduction in the energy required for the production of the hot water, while an increase in the hot water consumption has the opposite effect.

The deviation from the total energy consumption is approx. 20%, of which the reduction potential is approx. 8.5%.
This is not really a parameter one can do a whole lot to change, except from the obvious; low-flush toilets and water saving shower heads and appliances. If the building is designed for a family or a person who uses a lot of hot water one should consider reducing the energy required for space heating, and maybe even introduce solar panels in the design of the building in order to use renewable energy sources for the production of this hot water.

Heat gain from electrical appliances

Table 9.34: Results for changes in the Heat gain from electrical appliances input parameter

Internal heat gain appliances (W/m2)	*1.53*	*2.52*	*3.50*	*4.82*	*6.13*
Total energy requirement (for energy frame comparison) (kWh/m2 year)	**90.8**	**85.5**	**85.7**	**82.1**	**78.8**
Energy for space heating (kWh/m2 year)	**77.7**	**72.4**	**67.4**	**61**	**54.7**
Energy for hot water (kWh/m2 year)	**13.1**	**13.1**	**13.1**	**13.1**	**13.1**
Energy for removal of overheating (kWh/m2 year)	**0**	**0**	**5.2**	**7.9**	**10.9**
Percentage deviation from reference building total energy consumption	5.95	-0.23	0.00	-4.20	-8.05
Percentage deviation from reference building Space heating	15.28	7.42	0.00	-9.50	-18.84
Percentage deviation from reference building overheating	-100.00	-100.00	0.00	51.92	109.62



This calculation studies the impact of different levels of heat gain from electrical appliances in the building.
The calculation does not consider the electricity consumed by the appliances in order to release these levels of heat gain (W/m^2). The heat gain from appliances was set to 3.50 W/m^2 in the reference building.

The results show that an increase in the heat gain from appliances causes an increase in the energy required for the removal of overheating and a reduction in the energy required for space heating, as well as in the total energy consumption.
A decrease in the heat gain from appliances causes an increase in the energy required for space heating and a reduction in the energy required for removing overheating. The total energy consumption is reduced for the situation with an internal heat gain of 2.52W/m^2, while it is increased for the situation with an internal heat gain of 1.53 W/m^2.

The reduction in the total energy consumption would be different if the energy consumption of the electrical appliances contributing to this heat gain were considered. The electrical energy consumption for the appliances should be multiplied with a factor of 2.5 and added to the total energy consumption, which would reduce the incentive to use the heat gain from appliances as a heat source in buildings;

Table 9.35: The resulting electrical consumption of electrical energy to achieve the different levels of heat gain from electrical appliances

Internal heat gain	*1.53*	*2.52*	*3.50*	*4.82*	*6.13*
Resulting electricity consumption[18] (kWh/m^2)	13.4	22.1	30.7	42.2	53.7
Resulting electricity consumption x 2.5 (kWh/m^2)	33.5	55.2	76.7	105.3	134.2

These values should be added to the total energy consumption of the building;
Table 9.36: Results for changes in the Heat gain from electrical appliances input parameter when the energy consumption of the electrical appliances is added to the results from Be06

Internal heat gain	*1.53*	*2.52*	*3.50*	*4.82*	*6.13*
Total energy consumption of the building (kWh/m^2)	124.3	140.7	162.4	187.4	213
Percentage deviation	-23.5	-13.4	0.0	25.0	31.2

This shows why one should not be tempted to increase the internal heat gains from appliances in order to reduce the energy required for space heating; the reduction in the total energy consumption does not even come close to outweigh the primary energy consumed by the appliances.

9.4.2 Conclusions local analysis

Based on the preceding presentation of the results of the OAT analysis, the following conclusions were made:

The local analysis has provided a screening of the input parameters and their ranges, and the following was concluded with respect to the input parameters ability to reduce the energy required for space heating and removing overheating in the reference building when the input parameters are changed one at time.

Included in this conclusion are also suggestions for reducing the energy consumption for hot water and electrical appliances, even though these suggestions cannot be directly concluded from the study. The suggestions are, thus, not ranked in relation to their sensitivity, and they are based on existing projects or existing solutions used in other types of buildings (such as sport facilities and shopping malls).

Means of reducing the energy required for space heating

The following input parameters have shown potential of reducing the energy requirement for space heating in the reference building.

Table 37: Ranking of the input parameters with the largest deviation from the energy consumption for space heating in the reference building

Input parameter (ranked)	*Deviation, space heating*	*Deviation, total*
Reduce the surface to floor area ratio (from 1:3.0 to 1:1.2	Up to 64% reduction	Up to 38% reduction
Use mechanical ventilation with heat-recovery in winter and natural ventilation in summer	Up to 56.5% reduction	Up to 37% reduction
Change window type to window	Up to 10% reduction	Up to 13.5% reduction
Reduce room height	Up to 15.5% reduction	Up to 11.5% reduction
Reduce the U-values of walls, roof or ground floor	Up to 11.5% reduction	Up to 11% reduction
Change window area to orientation ratio (e.g. 0/33/33/33, 10/60/15/15 or 10/40/25/25) or rotate the building (90°)	Up to 11.5% reduction	Up to 7% reduction
Increase thermal mass	Up to 1% reduction	Up to 15.28% reduction
Change the window angle of windows)	Up to 7% reduction	Up to 8.5% **INCREACE**

This means that changing the window angle is not really an attractive possibility, as this increases the total energy consumption of the reference building, due to an increase in the energy required for removing overheating.

Means of reducing the energy required for removing overheating

The following input parameters have shown potential of reducing the energy requirement for removing overheating in the reference building

Table 38: Ranking of the input parameters with the largest deviation from the energy consumption for removing overheating in the reference building

Input parameter (ranked)[19]	*Deviation, space heating*	*Deviation, total*
Change the window type for a window with a lower g-value	100% reduction	Up to 13.5% reduction
Increase summer ventilation (natural ventilation)	100% reduction	Up to 6% reduction
Apply shading (devices, overhangs, plant vegetation providing seasonal shade or place the windows deep in the façade)	100% reduction	Up to 4% reduction
Increase thermal mass	100% reduction	Up to 7% reduction
Increase U-value of walls, roof or ground floor	100% reduction	Up to 8,5/9.5/11% **INCREASE**
Increase ventilation rate (only in naturally ventilated situations) for winter if there is overheating during the winter months.	Approx. 6% reduction	Up to 26.5% **INCREASE**

Increasing the U-values for the walls, ground floor and roof does not seem to be a good way of achieving the reduction in the energy for removing overheating, as this increases the total energy consumption significantly due to an increase in the energy required for space heating. The same happens if the winter ventilation rate is increased. It only reduces the energy required for overheating by approx. 6% (~0.3 kWh/m^{2}K) and it increases the total energy consumption by approx. 26.5% (~22.7 kWh/m^{2}K).

Means of 'reducing' the energy required for hot water
Some of the following means of reducing the water consumption are already a natural part of new buildings, while others are not implemented yet and may not ever be implemented. Some of the means save both hot and cold water, while others help heat the cold tap water in a more environmentally friendly way.

- Install water-saving shower heads and mixers
- Install timers in the shower and photocells at the taps
- Install visible water meters
- Install solar panels

Means of 'reducing' the electrical energy consumed by appliances
Some of the following means of reducing the energy required for electrical appliances are already a natural part of new buildings, while others are not implemented yet and may not ever be implemented.

- Install visible power meters
- Install energy efficient appliances
- Create cold spaces for food storage
- Create spaces for drying clothes in the winter and transitional seasons
- Install 'intelligent switches' or enable easy turn off of standby appliances
- Ensure good daylight conditions in your building (reduce artificial heating).

The weakness of the local sensitivity analysis is that it does not account for what happens when these parameters are changed simultaneously. Maybe changing two parameters instead of just one can cause larger increases or reductions in the energy consumption, or maybe they cancel each others effect out?
This is why the global sensitivity analysis is necessary.

9.5 Global Sensitivity Analysis

The purpose of the global analysis was to identify the sensitive and robust input parameters when groups of the parameters were changed simultaneously. A further purpose of the global sensitivity analysis was to uncover any inter-correlations between the design parameters.

9.5.1 Methodology

The Morris Method is applied for the global sensitivity analysis, as it enables parameter sensitivity analysis through a random sampling method. The Morris Method is a methodical approach to reducing the number of simulations whilst achieving credible results; if one was to do all the possible combinations of the investigated parameters one would have to do $parameters^{steps}_{in\ range}$ simulations (in this case this would be at least $7^3=343$ calculations assuming that each parameter is investigated for its mean, maximum and minimum value). This would not be a big problem, if one only had a few parameters with small ranges or a small number of steps in the selected range.
A further advantage of the Morris Method is its ability to analyse the interdependency (inter correlation) between parameters. In the field of building physics are a large number of parameters are interdependent and it is therefore relevant to apply statistical models for reducing the number of simulations without reducing the credibility of the results significantly.

The Morris method was selected because it has already been used in a number of sensitivity analyses in the field of building physics with a successful outcome. It is therefore the preferred method for global sensitivity analyses in the field due to the fact that the results achieved through application of the Morris method are very close to the exact results achieved if all the calculations were performed (e.g. Breesch and Janssens identification of the most influential parameters on thermal comfort [Breesch and Janssens 2004]).

The Morris Method enables qualitative determination of which parameters can be considered 'to have effects, which are negligible, linear and additive, or non-linear or involved in interactions with other parameters' [SimLab User manual: Chapter 1.1.2]. The results of the global analysis are displayed in a coordinate system displaying the mean values (μ) of the outputs[20] for each of the input parameters on the x-axis and the deviation (σ) outputs for each of the parameters on the y-axis (these are also referred to as the elementary effects) [SimLab User manual: Chapter 1.1.2 and Heiselberg et al 2007].
The negligible parameters are identified as the parameters which have both low μ and σ values, the linear and additive effects are identified as the parameters which have high μ and low σ values and the non-linear and inter-correlation effects are identified as the parameters which have low μ and high σ values.
[Saltelli, Tarantola, Campolongo and Ratto 2004:103]

In the Morris Method the number of input parameters (k) defines the dimension of the analysed input vector, which defines the space of possible value combinations. The space is divided into steps defined by the number of levels in the analysis (r), and the size of the steps are determined by the programme based on the no. of levels selected for the simulation and the distribution functions assigned to the input parameters. The parameters are changed one at a time in the defined space, where each simulation execution takes a randomly selected route through the space, and the number of model executions can be determined by: $r \cdot (k+1)$.[21]
[SimLab User manual: Chapter 1.1.2 and Saltelli, Tarantola, Campolongo and Ratto 2004].

Steps

The global analysis went through the following steps:

1. Decide the input parameters for the global analysis.
2. Global sensitivity analysis (type 3 in Hamby 1994; an analysis that require partitioning of a particular input vector based on the resulting output vector):
    a. Insertion of input parameters and their distribution functions in SimLab programme
    b. SimLab is asked to generate the 'input' vector with a setup for calculations to be performed in the Be06 programme.
    c. Be06 calculations are made and the results are reported in an input vector for SimLab.
    d. Simlab calculates the sensitivity and ranking of the input parameters
3. Analysis of the results of the global analysis → Development of design strategy

9.5.1 Input parameters, ranges and their distribution

The input parameters for the global analysis are selected in accordance with the most sensitive parameters found in the local analysis with respect to both the energy required for space heating and the energy required for the removal of overheating.

In a real life design project one would select the input parameters, their range and distribution functions by attuning the findings in the local analysis with the design brief of the project, the findings in a site analysis or in an initial design concept for the building. This part of the process is, thus, very selective and the ranges and distribution functions for the input parameters would be selected by the design team in correspondence with the probability of them selecting a specific range for the respective input parameters, unlike measured parameters (e.g. weather data for solar radiation, wind speeds and directions).

This means that one can go about the selection of ranges and distribution functions in two ways;

1) Choose narrow range and uniform distribution functions for all or the majority of the parameters
2) Choose large range and assign non-uniform distribution functions (e.g. normal, binominal, weibull etc.) to all or the majority of the parameters

A uniform distribution function is selected when the probability of selecting all the values in the range is equal, while a non-uniform distribution function is selected when the probability of selecting a specific part of a range is higher than for the rest of the range.

1) is easy to apply without statistical education and when one deals with small ranges of the investigated parameters, while 2) requires knowledge of statistics but enables examination of a wider range for the parameters while still enabling concentration on a specific part of the investigated range. By including a wider range or a uniform distribution one might get unexpected results which can influence the qualitative ranking of the parameters.
The selection of either 1) or 2) therefore depends on the setup of the project, and the creative freedom and priorities in the design team. In this global sensitivity analysis all the input parameters are chosen to be uniform and the ranges are narrowed based on the results of the local sensitivity analysis.

This analysis applies 1), which means that all the input parameters were assigned uniform distribution functions and the ranges for each parameter were narrowed in relation to the findings in the local sensitivity analysis.
The input parameters and their distribution functions were inserted into the SimLab programme. The programme was then asked to generate a sample matrix through application of the Morris method. The generated sample matrix was then applied in an external Be06 model where a series of calculations were made that correspond with the values for the input parameters generated in the sample matrix. The calculation results were reported in an output matrix. The output matrix was inserted in the SimLab programme for analysis of the sensitivity and interdependency of the sampled parameters.

Use

The parameters relating to the use of the building are not included in the global analysis, as these relate more to the design criteria formulated in the brief. They were included in the local analysis to determine the importance of the parameters and get an idea of how sensitive the definition of the design criteria is to the actual use of the building. It is, thus, not a parameter that is considered to be changeable during the design process.

Building shape

The following parameters from the study of the impact of the building shape are included in the global sensitivity analysis:

Number of stories (1 to 6)

The number of stories is selected, as an input parameter for the global sensitivity analysis because it is the input parameter for which the reduction potential in the surface to floor area ratio is largest. The surface to floor area ratio is interesting in relation to the compactness of the building which is best achieved via an increase in the number of stories in the building[22]. The number of stories in the building were selected as a parameter instead of 'surface to floor area ratio', as this can seem a bit abstract when one has to apply it in relation to architectural design.

Room height (2.5 to 3.0m).
The room height is included in the study, as it has an impact on both the surface area of the building and the basic ventilation rate inside the building. It is, thus, not directly related to the study of the surface to floor area ratio, and can therefore not be included in the no. of stories parameter.

Insulation of the building envelope
Effective U-value of the non-transparent parts of the building envelope ($U_{eff,\ BE}$)(0.09 to 0.2)
The three U-values for the walls, ground floor and roof are combined in the global sensitivity analysis in an effective U-value for the building envelope ($U_{eff,\ BE}$). $U_{eff,BE}$ is calculated as:

$$U_{eff,BE} = \frac{A_{wall} \cdot U_{wall} + A_{roof} \cdot U_{roof} + A_{groundfloor} \cdot U_{groundfloor} \cdot (1-b)}{A_{wall} + A_{roof} + A_{groundfloor}}$$

Where:
A_{wall}, A_{roof} and $A_{groundfloor}$ are the respective areas of the walls, roof and ground floor [m^2]
U_{wall}, U_{roof} and $U_{groundfloor}$ are the respective U-values of the walls, roof and ground floor [W/m^2K]
b is the temperature factor, which for building elements without floor heating facing the ground is 0.3.
The effective U-value of the building envelope is 0.15W/m^{2}K in the reference building.

The relationship between the U-values of the non-transparent elements of the building envelope and the architectural expression primarily relates to the material selection for the walls, roof and ground floor and the construction of the building envelope, and the resulting wall thickness. The architectural composition of the façade is not directly influenced by the U-value as this relates to the area of the non-transparent building elements. The areas are included in the U_{effBE}-value calculation, but only because the U-values of the walls, roof and ground floor are different, and because of the temperature factor b.

Window type, areas and orientations
Window to floor area ratio (20 to 40%)
The range for the window to floor area ratio is narrowed in the global sensitivity analysis to 20% to 40%. The ratio has a impact on both the heating and cooling load in the building and is therefore an interesting parameter to explore in a global sensitivity analysis.
The window to floor area of the building refers to the relationship between the floor area of the building and the window area of the building, which for 20% means that the window area is 20% of the floor area.

Window area to orientation ratio, window type ~Effective U-value windows (0.5 to -0.5)
The window area to orientation ratio is combined with the study of the effect of the window type via the calculation of the effective U-value for the windows in the building. The $U_{eff,win}$ can be regarded as a combination of a number of the input parameters applied in the reference building (please refer to note 4 for more information about the calculation of $U_{eff,win}$) and the means of achieving the $U_{eff,win}$ values in Be06 will happen in a prioritised order; first the window type will be changed in accordance with the interval of 0.5 to -0.5 W/m^{2}K, then the window area to orientation ratio will be changed while keeping the window to floor area ratio constant in order to achieve $U_{eff,win}$ values of -0.5 to 0.5 W/m^{2}K. This means that the total window area in the building stays the same and only the orientation of the window (the window area to orientation ratio[23]), the window type (in relation to the U-value of the entire window and the corresponding g-value) and possibly the shade factor[24] is changed.
This simplification of the parameters is made to minimise the number of variables in the global

analysis. This would not be necessary if the sensitivity analysis happened within the calculation programme, as one would not have to do the calculations by hand. It can however enable a degree of freedom in the early stages of the design process if $U_{eff,win}$ is used in the calculation programme as well, because the value can be achieved by varying the window type, the window area to orientation ratio and the shade factor. This means that if the $U_{eff,win}$-value is used in the calculation programme it can provide a target value which can be achieved through a series of variations of the window type, the window area to orientation ratio and the shade. This target value will enable design strategy development without necessarily requiring a fixed façade design.

Shade

Depth of window (0 to 500 mm)

The shade parameter selected for the study is the depth of window (i.e. the distance between the outer edge of the façade and the window glass). This parameter is preferred over the depth of the overhang as the shade parameter, because the shade caused by an overhang is sensitive to the distance between the middle of the window (on the vertical axis) and the overhang. This distance witll change from storey to storey in a building with more than one storey and the depth of overhang parameter is therefore sensitive to number of stores in the building, whereas the depth of window is not. The study performed in the local sensitivity analysis showed that the effect of the depth of the window and the depth of the overhang in a one storey building were approximately the same, which is why this calculation applies the depth of the window as the shade parameter.

Ventilation

Ventilation rate summer (0.42h^{-1} to 2.18 h^{-1})

The ventilation rate during the summer season is included in this study in relation to the cooling load in the building. In this study the summer ventilation is naturally driven, which means that this parameter corresponds to increasing the ventilation rate inside the building by opening the windows and doors. How much the window needs to be opened depends on the particular wind speeds and directions on the particular day. The Be06 calculation does not consider how the ventilation rates are achieved and if they are indeed achieved in the building design, it assumes only considers the air change rate in relation to the mean monthly outdoor temperature in the DRY (Danish Reference Year) data. It is therefore up to the designer of the building to ensure that the ventilation system can provide the ventilation rates inserted in the programme.

Heat-recovery winter (35 to 95%)

Heat-recovery during the winter season is investigated for heat recovery percentages of 35 to 95%. The Danish building codes require a heat recovery percentage of minimum 65% in mechanical ventilation systems, which means that heat recovery values of less than 65% should be integrated in passive systems (e.g. wind cowls). This study does, however, disregard this in the calculation which means that the study applies mechanical ventilation for all the heat recovery percentages. This means that the results for heat recovery percentages lower than 65% seem worse with respect to the electrical energy consumption for the fan than they actually would be if the heat recovery percentage is achieved through a passive system e.g. via wind cowls or natural ventilation that passes through thermal storage wall before entering the room.

The passive systems influence the architectural expression of the building via the integration of the wind cowls in the architectural expression or the integration of the sunspace needed for the thermal storage wall (e.g. a large glass area in close proximity to a concrete wall).

Ventilation rate winter

The ventilation rate for the winter season relates to the building heat loss via ventilation during the winter season. This is especially interesting for naturally ventilated buildings, whereas it is less interesting in relation to buildings that apply mechanically ventilated buildings with heat recovery because the heal loss will be larger in naturally ventilated buildings than it will in mechanically ventilated buildings. The energy consumption of the mechanically ventilated buildings will, however, be increased in relation to increases in the ventilation rates because

the ventilation system needs to move more air through the system, which causes an increase in the fan power.
In the global sensitivity analysis the ventilation rate during the winter season is changed with the changes made to the average room height parameter. 'Ventilation rate winter' is therefore not treated as an independent parameter in the global sensitivity analysis.

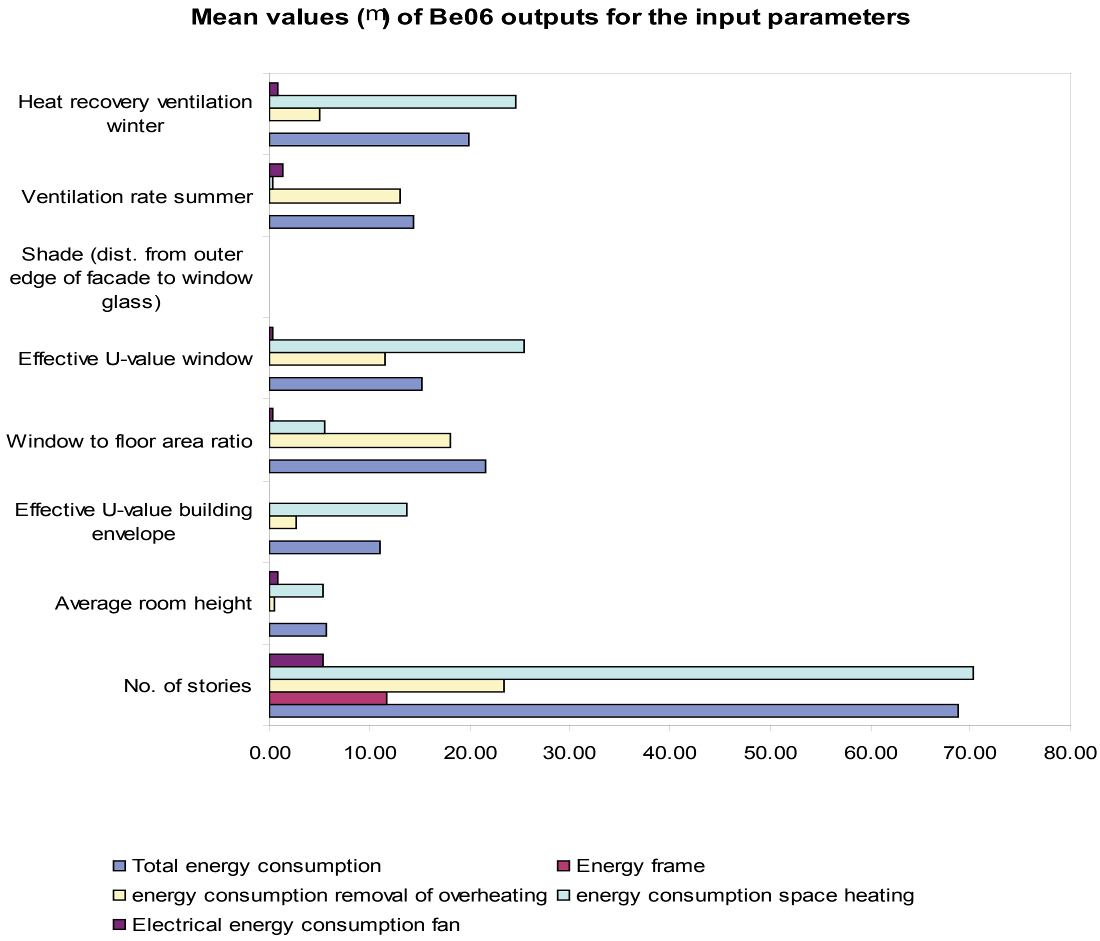
Thermal mass
The significance of thermal mass does not appear to be great in the local analysis, and increasing the thermal mass is a win/win situation from an energy point of view the parameter is, thus, not included in the global sensitivity analysis.
The thermal mass parameter relates to the density of the materials inside the building that are exposed to the air. A thermal mass of 120Wh/Km^2 or more requires a concrete or brick construction where the majority of the construction is exposed to the air, and a thermal mass of e.g. 140Wh/Km^2 or more requires a concrete construction where all the construction elements are exposed to the air. An increase in the thermal mass therefore might not be a win/win situation in relation to the architectural expression or the construction of the building, e.g. if the architectural vision of the building was a wooden construction or hardwood floors.

9.5.2 Conclusions global analysis

Sensitivity[25]
Table 39: Tabulated values from sensitivity analysis containing the mean values (μ) and the deviation (σ) of the outputs of the respective input parameters in relation to the results from the Be06 programme (the Total energy consumption of buildings, Energy frame, Energy consumption for removal of overheating, Energy consumption for space heating and the Electrical energy consumption of the ventilation fan). The values marked with a bold font in the table are the parameters which are sensitive in relation to the respective outputs of the Be06 programme.

	Total energy consumption of the building		Energy frame		Energy consumption for removal of overheating		Energy consumption for space heating		Electrical energy consumption of the ventilation fan	
Morris Index	Mean value (μ)	Deviation (σ)	Mean value (μ)	Deviation (σ)	Mean value (μ)	Deviation (σ)	Mean value (μ)	Deviation (σ)	Mean value (μ)	Deviation (σ)
No. of stories	**68.76**	32.25	**11.68**	4.60	**23.36**	27.56	**70.36**	36.11	**5.40**	1.64
Average room height	**5.72**	2.49	0.00	0.00	0.44	0.38	**5.36**	2.16	**0.90**	0.22
Effective U-value building envelope	**11.08**	6.89	0.00	0.00	**2.76**	2.26	**13.76**	5.09	0.00	0.00
Window to floor area ratio	**21.56**	2.41	0.00	0.00	**18.00**	3.37	**5.60**	3.80	0.30	0.27
Effective U-value window	**15.24**	7.75	0.00	0.00	**11.60**	19.32	**25.36**	10.48	0.30	0.27
Shade (dist. from outer edge of facade to window glass)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ventilation rate summer	**14.32**	6.48	0.00	0.00	**13.08**	5.58	0.32	0.72	**1.30**	1.30
Heat recovery ventilation winter	**19.92**	15.22	0.00	0.00	**5.08**	3.23	**24.60**	14.21	**0.90**	1.08

Based on the values in Table 39 the following graph can be made for the results of the global sensitivity analysis:



Total energy consumption
The following parameters are sensitive in relation to the total annual energy consumption of the residential building (listed by degree of sensitivity starting with the most sensitive):

1. No. of stories
2. Window to floor area ratio
3. Heat recovery ventilation
4. Effective U-value window
5. Ventilation rate summer
6. Effective U-value building envelope
7. Average room height

whereas the Shade parameter is robust in this particular case.

Energy frame
The only parameter that is sensitive in relation to the energy frame of the residential building is:

1. No. of stories (due to the changes in the surface to floor area ratio)

Energy consumption for space heating
The following parameters are sensitive in relation to the energy consumption for space heating in the residential building (listed by degree of sensitivity starting with the most sensitive):

1. No. of stories
2. Effective U-value window
3. Heat recovery ventilation winter
4. Effective U-value building envelope
5. Window to floor area ratio
6. Average room height

Whereas the Shade and Ventilation rate summer parameters can be identified as robust in this particular case.

Energy consumption for removal of overheating
The following parameters are sensitive in relation to the energy consumption for removal of overheating in the residential building (listed by degree of sensitivity starting with the most sensitive):

1. No. of stories
2. Window to floor area ratio
3. Ventilation rate summer
4. Effective U-value window
5. Heat recovery ventilation winter
6. Effective U-value building envelope

Whereas the Shade and Average room height parameters are robust.

Electrical energy consumption
The following parameters are sensitive in relation to the electrical energy consumption of the ventilation fan in the residential building (listed by degree of sensitivity starting with the most sensitive):

- No. of stories
- Ventilation rate summer
- Heat recovery winter
- Average room height

Whereas the Shade, Effective U-value window and Effective U-value building envelope parameters are robust.
It seems a bit strange that increases in the summer ventilation rate influences the energy consumption of the ventilation fan, as the mechanical ventilation system is only used during the winter season, while the building is naturally ventilated during the summer.

General conclusions
Shade is generally robust in this global analysis, which could be due to the fact that the selected window type for all the Effective U-value for the windows has removed the overheating problem in the building, and the low internal heat gains in the building.

The fact that the number of stories in the building is sensitive for all types of results calculated in the Be06 programme shows underlines the interdependence between energy consumption and the surface to floor area ratio. The local sensitivity analysis showed that an increase in the number of stories led to a decrease in the energy consumption for space heating and an increase in the energy required for the removal of overheating. The decrease in the energy consumption for space heating is, however, greater than the energy consumption for removing overheating.

Inter-correlation
The inter-correlation between the investigated input parameters is studied by placing the mean values (μ) and the standard deviation (σ) of the elementary effects (i.e. the results from Be06)) for the respective parameters in a coordinate system and inserting a line in the coordinate system, which usually follows the following relation:

$$\sigma = \frac{\mu \cdot \sqrt{r}}{2}$$

Where

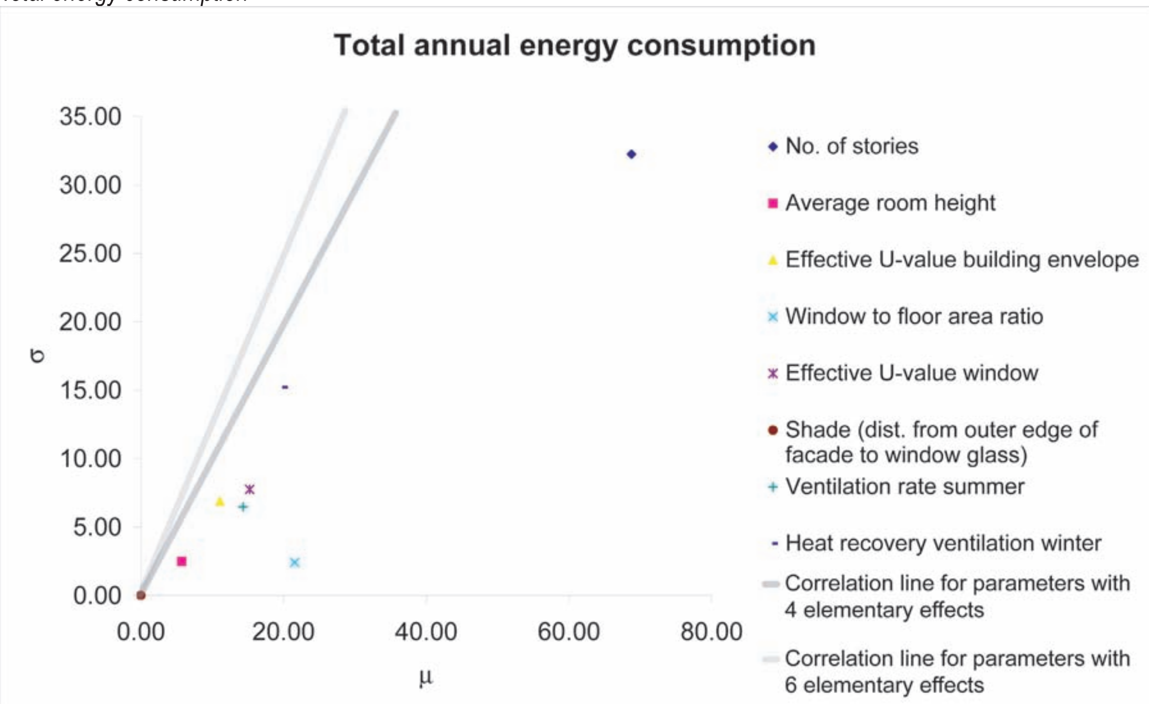
σ is the standard deviation of the elementary effects of the input parameter
μ is the mean value of the elementary effects of the input parameter
r is the number of elementary effects per input parameter
[Heiselberg et al 2005:4-6]

In this case the parameters have respectively 4 and 6 elementary effects per input parameter, which means that the study of the inter-correlation requires the insertion of two lines; $\sigma = \mu$ for input parameters with four elementary effects and $\sigma = 1.2\ \mu$ for input parameters with 6 elementary effects.

Table 40: The number of elementary effects for each parameter

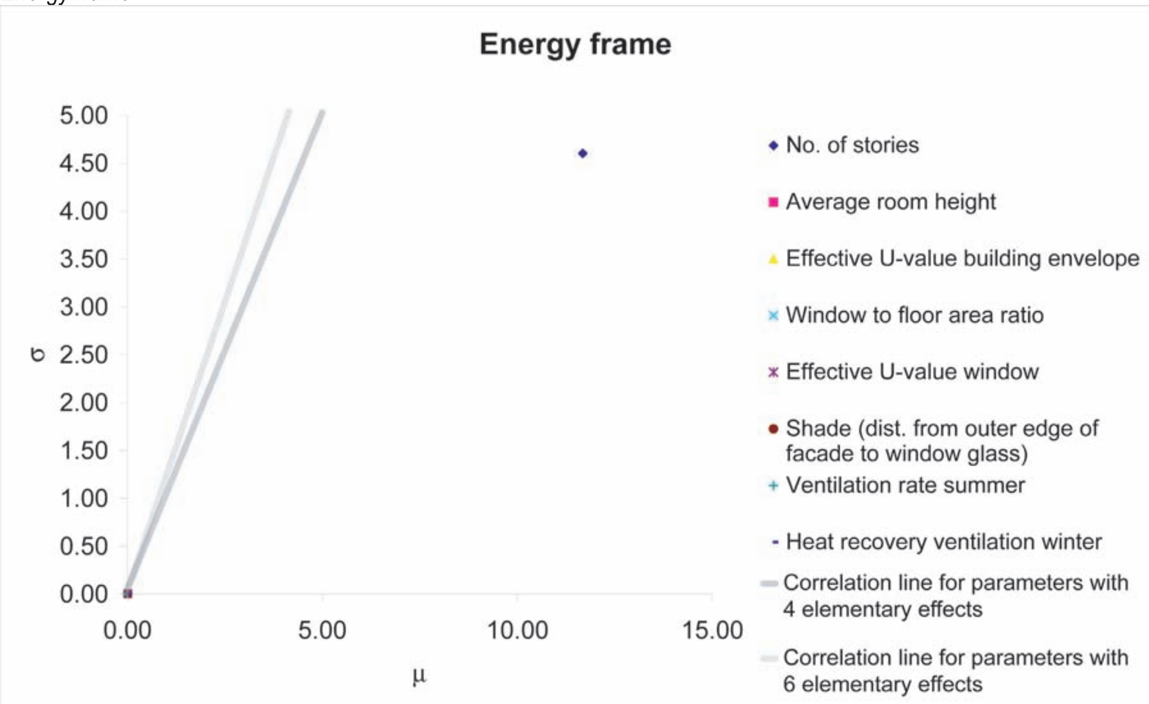
Input parameter	*Number of elementary effects*	*Correlation line*
No. of stories	4	$\sigma = \mu$
Average room height	6	$\sigma = 1.2\ \mu$
Effective U-value building envelope	4	$\sigma = \mu$
Window to floor area ratio	4	$\sigma = \mu$
Effective U-value window	6	$\sigma = 1.2\ \mu$
Shade (dist. From outer edge of façade to window glas)	4	$\sigma = \mu$
Ventilation rate summer	6	$\sigma = 1.2\ \mu$
Heat-recovery ventilation winter	4	$\sigma = \mu$

Total energy consumption



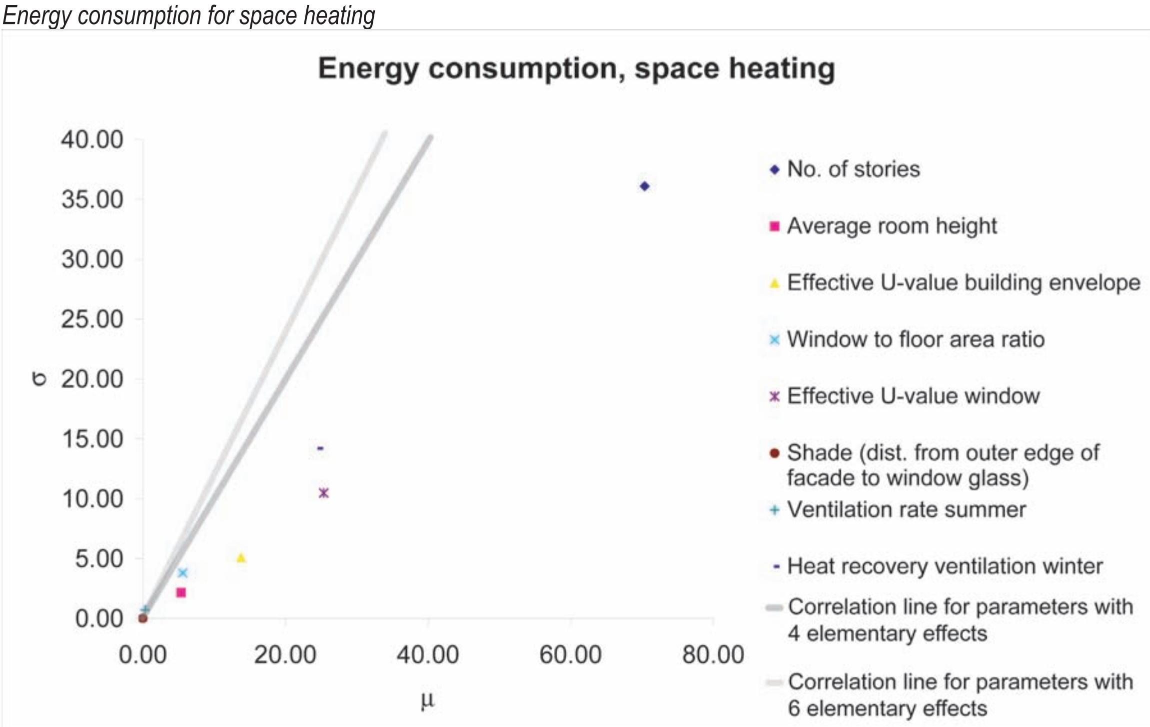
All the input parameters are situated under their correlation line, which means that there is no inter-correlation between the parameters.

Energy frame



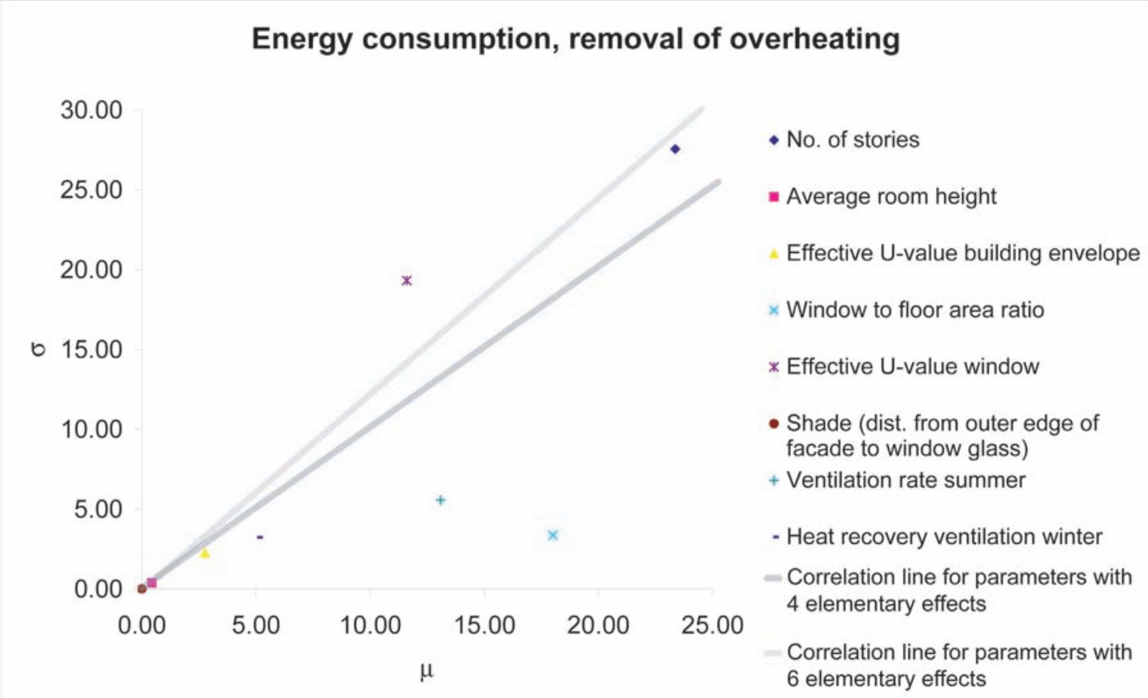
All the input parameters are situated under their correlation line, which means that there is no inter-correlation between the parameters.

Energy consumption for space heating



All the input parameters are situated on or under their correlation line, which means that there is no inter-correlation between the parameters.

Energy consumption for removal of overheating

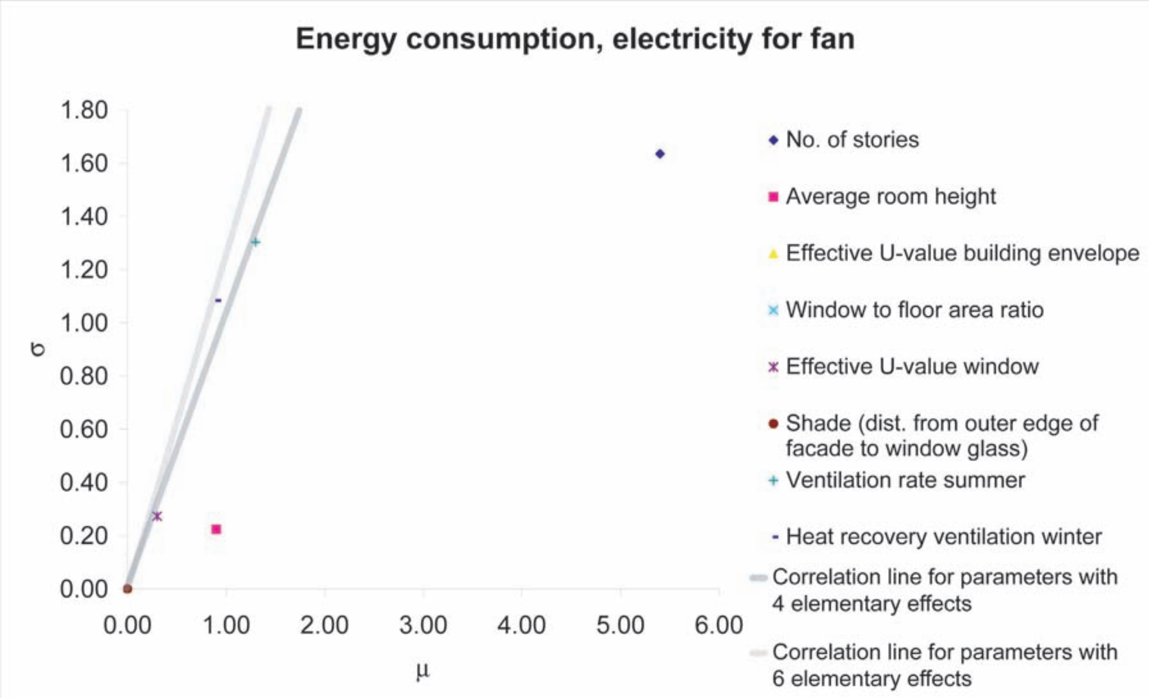


All the input parameters except the effective U-value window parameter and the no. of stories parameter are situated under their correlation line, which means that these particular parameters could be non-linear. The parameters are both close to their correlation line (the effective U-value window parameter has 6 elementary effects and the No. of stories in the building parameter has 4 elementary effects), so they could turn out to be linear.

The effective U-value window parameter is however a composition of many variables in the calculation (U-value and g-value of the window, and window area to orientation ratio in the building), which might cause the effects of the parameter to be non-linear.

The No. of stories parameter is, as described in Enclosure C, inter-dependent with three other parameters in the calculation; the Average room height parameter, the Window to floor area ratio parameter and the Window area to orientation ratio. This does, however, not change the sensitivity of the parameter, as the Morris Method applied for the analysis is not dependent on assumptions regarding inter-correlation [Heiselberg et al 2007:3]

Electrical energy consumption for ventilation fan



All the parameters are situated under or on their correlation lines, except for the Heat recovery winter parameter, which is situated slightly above its correlation parameter (4 elementary effects). The Heat recovery ventilation winter parameter could therefore have non-linear and interactive effects; the parameter is situated close to its correlation line, which means that it might have linear effects.

9.6 Development of design strategy

The sensitivity and robustness of the parameters do not display whether the parameter has a positive or negative effect on the energy consumption of the building. It merely displays which parameters are sensitive and the results therefore need to be regarded in relation to either a local sensitivity analysis of each of the parameters or in relation to the many existing publications available on the topic of energy consumption in buildings (e.g. based on rules of thumb presented by these publications).
In this investigation a local analysis was performed which provides an understanding of whether or not changes made for a parameter will have a positive or negative effect on the overall energy consumption.

The results of the global sensitivity analysis can be applied in a development of a design strategy. This would, however, require more information about the specific project e.g. in relation to the context of the site and the topography of the site, the orientation of the rooms, preferences with respect to daylight etc. It is the general assumption in this project that a large window to floor area ratio (e.g. 30-40%) is desirable in relation to the architectural experience of the building (e.g. the connection between inside and outside, perception of colour and shape) and the daylight levels inside the building. This is therefore not something that can be compromised in the design strategy development.

The approach taken in the development of the design strategy is a 'passive' approach in which the energy consumption in the building is reduced through a reduction in energy consumption in the building through passive solar heat gains, insulation of the non-transparent elements of the building envelope and effective U-values for the windows lower than 0, as well as reductions in the electrical energy consumption through availability of daylight and increased air change rates of the natural ventilation in the summer period and seasonal shade if necessary. Active measures can then be added if necessary e.g. a mechanical ventilation system for the winter and transitional seasons with heat recovery, availability of daylight.

The design strategy development deals with three different scenarios:

1. A residential building in an open area with no contextual shade where the city development plans dictate a maximum building height of one storey
2. A residential building in an open area with none or little contextual shade where the city development plans do not dictate a maximum building height
3. A residential building in an inner city area with contextual shade where the city development plans do not dictate a maximum building height

Scenario 1

Because one can only build a one storey building the building needs to be very compact in order to achieve the lowest possible surface to floor area ratio. A further restraint with respect to the design strategy development is the window to floor area ratio of approx. 30 to 40% which is desired for the architectural experience of the building and the daylight levels inside the building.

The building should therefore consider the following design principles in order to reduce the energy consumption in the residential building (the iterations are listed in a preferential order determined by their sensitivity):

1. Mechanical ventilation system with heat recovery during the winter and transitional seasons
2. An effective U-value for the non-transparent elements of the building envelope of 0.09 W/m^2K
3. Increased ventilation rates during the summer season
4. An effective U-value for the transparent elements of the building envelope of -0.5 or lower if possible. (e.g. by adjusting the window area to orientation ratios in the building or improving the window type)
5. Addition of seasonal shade if necessary (e.g. via overhang, vegetation or distance from outer edge of the façade and the window glass)

Scenario 2

Because it is possible to increase the number of stories it might not be necessary to introduce a mechanical ventilation system with heat recovery in the building design to reduce the energy consumption in the building. Heat recovery is therefore prioritised differently in the preferential order of the design principles which should be considered:

1. Design the building to be two to three stories depending on e.g. the total area of the residential unit, the logistics inside the building and the transitional area to room area ratios.
2. Average or low effective U-value for the non-transparent elements of the building envelope (e.g. 0.15 – 0.09)
3. Low effective U-value for the transparent elements of the building envelope of e.g. -0.25 (the effective U-value for the windows need not be as low as for the one storey building because of the increase in the number of stories).
4. Introduce mechanical ventilation system with heat recovery during the winter and transitional seasons
5. Increase summer ventilation for removal of overheating
6. Increase winter ventilation in south and west facing rooms if there are problems with overheating during the winter or transitional seasons (which would also improve the air quality inside the building)
7. Introduce seasonal shade for removal of overheating

Scenario 3

In an urban area some degree of contextual shade from other buildings will be an issue. In this case it is therefore necessary consider the impacts of the contextual shade on the effective U-value of the transparent building elements and increase the number of stories in the building in order to reduce the energy consumption for space heating. This would normally cause an increase in the energy requirement for removal of overheating, this might, however, not become an issue if the building is shaded by the surroundings.

The building should therefore consider the following design principles in order to reduce the energy consumption:

1. Design the building to be four to ten stories in order to reduce the surface to floor area ratio.
2. Low effective U-value for the transparent elements of the building envelope (e.g. -0.25 or lower depending on the shade, the window area to orientation ratios and the window type)
3. Increase the ventilation rate of the natural ventilation during the summer season
4. Average or low effective U-value for the non-transparent elements of the building envelope (e.g. 0.15 – 0.09)
5. Increase winter ventilation in south and west facing rooms if there are problems with overheating during the winter or transitional seasons (which would also improve the air quality inside the building)
6. Introduce mechanical ventilation system with heat recovery during the winter and transitional seasons
7. Introduce seasonal shade for removal of overheating

9.7 Conclusions sensitivity analysis

Design strategy residential building

Based on the global sensitivity analysis three different design strategies were developed for a residential building with a floor area to vertical façade area ratio of 1:0.80**.** The design strategies correspond to three different scenarios of possible building heights and contextual shade conditions.

The results of both the local and global sensitivity analyses were applied for the design strategy development, through which an understanding of the behaviour of each parameter was achieved and a qualitative ranking of the investigated parameters.

The design strategy is dependant on the design of the reference building, the setup of the input parameters and their ranges and distributions. A criterion which underlines the applicability of sensitivity analyses for the development of project specific design strategies.

Other issues of environmental sustainability

The experimental design strategies developed in this chapter only relates to the energy consumption of buildings in relation to the design of the building envelope and three scenarios for the urban context of the project. Other issues relating to environmental sustainability can, however, easily be integrated in the design strategy:

- Materials; the design strategy does not require the application of specific materials in the construction of the building or inside the building. It only states which effective U-value the non-transparent parts of the building envelope should aim for.
- Landscape, Flora and fauna; these issues are site specific and design parameters relating to this can therefore easily be integrated in the design strategy developed in this chapter. The only consideration one needs to make in relation to this is whether the vegetation on the site cast undesired shade onto the building or if it can be integrated in the building concept as seasonal shade. The only design principle relating to landscape which is a bit tricky to apply in the design strategy developed here is the 'footprint' of the building on the site (i.e. there the building touches the ground). This footprint is of course improved when the number of stories in the building is increased. The building can, however, not be situated on stilts without influencing the design strategy developed here, as this would cause the reference building used in the analysis to change in a way, which is not accounted for in the experiment.

Architectural implications of design strategies

The architectural implications of the design strategies primarily relate to the compactness of the building (e.g. the number of stories in the building), wall thicknesses in relation to the effective U-values for the non-transparent parts of the building envelope (e.g. the walls, roof and ground floor) in relation to the materials selected for the building, consideration of how to integrated heat-recovery in the ventilation system for the building (whether it be in a natural or mechanical ventilation system). Lastly the targets for the effective U-values for the transparent parts of the building envelope relate to the window type, the orientation of the windows in the building and the shade of these windows; the design strategy does not require that a specific window type, shade or window area to orientation ratio for the building. It merely defines a target, which can be reached in a number of ways (e.g. by using a passive house window and/or primarily orienting the windows towards a southern direction depending on the target set for the project).

Methodology

The local sensitivity analysis is interesting for screening purposes when one has to do the simulations in an external model. The analysis is however extremely sensitive to the setup of the reference building because it only considers changes in one parameter at a time.

The global sensitivity analysis enables analysis of the sensitivity of the calculation parameters when the parameters are changed simultaneously. This reduces the dependency on the reference building, without ever enabling complete independency of the reference building, which is why the analysis must be applied every time one does a new project. If one instead chooses to develop stationary design strategies based on global sensitivity analyses these would suffer from the dependence on the reference building, which is why it is the conclusion of this design development experiment, that the approach should be integrated in a design development tool, which enables project specific global sensitivity analyses in the early stages of the design process through identification of the most influential parameters in a given situation determined by the ranges and distribution functions of the parameters.

In its current form the global sensitivity analysis is very time consuming, because one has to go through the process of:

1) Determining the calculation parameters, their ranges and distribution functions.
2) Inserting these into a statistical simulation programme (e.g. SimLab) which develops a matrix for different variations of the calculation parameters.
3) Inserting the different variations in an external model (e.g. an energy performance calculation programme) and develop a matrix for insertion in the simulation programme
4) Import the matrix with the results of the external model into the simulation programme and start the simulation

This PhD thesis therefore suggests that the sensitivity analysis should be integrated in a design strategy development version of e.g. the Be06 programme.

The strength of having an external programme like SimLab performing the Monte Carlo Simulation is that one can combine different results from different programmes like energy calculation (Be06) and daylight levels (DialEurope) in the same analysis. It is, however, very time consuming to do this, so it would be better to integrate the consideration of daylight levels and the resulting energy consumption for artificial lighting in the energy calculation programme, which is already done in the Be06 programme for non-residential buildings. This does, however, not solve the problem of determining the relationship between the daylight levels and the window size, shade and room dimensions, which needs to be determined by applying explorative analogue calculations or through investigation in a global sensitivity analysis integrated in e.g. the DialEurope tool.

---

[1] It is interesting to note, that important parameters identified in uncertainty analyses are always sensitive, as the sensitivity of a parameter will cause it to be important [Hamby 1994]

[2] The iterations performed in the sensitivity analysis are described in Enclosure C

[3] The energy frame of a building is determined in accordance with the Danish Building Codes of 1995. The energy frame states a target value for the maximum permitted energy consumption of the building. The energy frame is calculated by the equation: (70+2200/A) kWh/m^2 pr. year, where A is the heated floor area [BRS 98:paragraph 5.2.6].

[4] The effective U-value is calculated by:

$$U_{eff} = U_{win} - \frac{f_s(\%A_{north} \cdot I_{corr,north} + \%A_{south} \cdot I_{corr,south} + \%A_{east+west} \cdot I_{corr,east+west})}{G} \cdot g \cdot F_f$$

where:

U_{win} is the U-value of the window (=1.5 in the reference building)
g is the g-value (heat transmittance) through the glass (=0.7 in the reference building)
F_f is the frame to glass area ratio of the window(=0.75 in the reference building)
G is the Degree hours ~ 90.36 for Denmark [kKh]
f_s is the shading factor(1 - %shade/100% = 1in the reference building)
$\%A_{north}$, $\%A_{south}$ and $\%A_{east+west}$ are the percentage distribution of the window area facing the different directions (correspondent to the window area to orientation ratio: 28.7%, 23.0%, 40.4% + 7.9% in thereference building)
$I_{corr, north}$ is the corrective solar heat gain from 1 m^2 window facing north ~ 104.5 in Denmark [kWh/m^2]
$I_{corr, south}$ is the corrective solar heat gain from 1 m^2 window facing south ~ 431.4 in Denmark [kWh/m^2]
$I_{corr, east+west}$ is the corrective solar heat gain from 1 m^2 window facing east and west ~ 232.1 in Denmark [kWh/m^2]
[BYG.DTU 2003:30-31]
$U_{eff} = U_w - 2.7gF_f$ for the reference building and for buildings with a similar window area to orientation ratio (28.7%, 23.0% , 48.3% (N,S/E/W)) a shading factor of 1 (~0 shade).
The factor of 2.7 would be different for different window area to orientation ratios and different shading factors. A different shading factor would reduce the value and thus increase the effective U-value, while the resulting $U_{eff, win}$ caused by changes in the window area to orientation are more difficult to predict.
[5] Natural ventilation has been the most common ventilation strategy in Danish homes until recently where mechanical ventilation has been introduced as a means of reducing the heating requirements in order to enable standard houses designed before the new energy regulations (2006). The reference building is chosen to be naturally ventilated and it is investigated what the introduction of heat-recovery means for the energy consumption in the building, because of considerations about the psychological comfort of the inhabitants in the building. The windows in mechanical ventilated buildings are usually kept shut in order to avoid short circuiting the system, or the mechanical system is turned of when the windows are opened. The ability to open the windows and control one's own environment has proven to have a large impact on the perception of comfort of the users [Steemers and Steane 2004].
[6] (The results of the variations are dependant on the design of the reference building, which means that a complex model creates a complex situation of result analysis , which clutters the effects of the different parametric variations)
[7] There are other computer programmes available for dynamic simulation of the thermal performance of buildings, e.g. BSim2004 (formerly known as tsbi). BSim does, however, require a specific and somewhat detailed geometry which practically disqualifies it for the early sketches of design projects.
[8] The descriptions of the calculation parameters are based on the fundamental teachings at the Department of Architecture and Design (on both the bachelor and master part of the education), as well as on courses followed at the Department of architecture at University of Cambridge.
[9] The minimum air change rates in buildings relate to a minimum ventilation rate of $0.5h^{-1}$ for residential buildings the Danish building regulations, which means that when the volume of a space is increased so is the minimum air change rate in the building.
[10] The resulting surface to floor area ratios of the range in the number of stories is 3:1 for the 1 storey building and 1:1 for the 253 storey building.
[11] The architectural perception is often associated with the daylight and artificial light in the building, due to the fact that the quantity and the quality (colour and distribution) of the light influences how shapes and, thus, spaces are perceived, dark spaces are for instance often perceived to be heavy while bright spaces are perceived as light – the darker the space the harder it is to actually perceive the shape of the space.
The daylight conditions in a building also influences the users concentration and it can influence their mood (this is especially apparent in areas with dark winters – like Denmark – where some people have what is known as seasonal affective disorder (SAD)).
[12] This issue of iterations between the size of the pipes is an issue of space (and in some cases aesthetics) vs. economy, effectiveness of the ventilation system and the legislative demands in the Danish building codes.
[13] If the users a very active their comfort temperature will be lower than if they are sitting still because they will produce a lot of heat by moving around.
[14] Calculated as: (energy consumption for the situation with a changed parameter – energy consumption of the reference building)/energy consumption of the reference building x 100%
[15] The results of the investigation of the effects of external shade in front of the windows must be seen in relation to the window area to orientation ratios of the reference building.
[16] This is the experience from a passive house study trip to Switzerland and Austria in 2005.
[17] (the rules of thumb for the depth of the rooms in relation to the room height for different types of natural ventilation (one-sided, cross, displacement ventilation) are described in Anv. 202 from the Danish Building Research Institute)
[18] The resulting electricity consumption (kWh/m^2) is calculated as; Internal heat gain appliances (W/m^2)

x 8760h / 1000

[19] The ranking of the input parameters is sensitive to the range of the parameters, which means that the ranking will change if the ranges of the parameters are changed.

[20] The outputs referred to here are the results of the calculations performed in the Be06 programme which are imported in the SimLab programme for the sensitivity analysis.

[21] SimLab goes about this in the reversed order; the user specifies the number of runs and the number of levels and the programme assigns the number of steps to each parameter in relation to this.

[22] The study of building shape in the local analysis revealed that it is easy to increase the compactness of the building through increasing the number of stories in the building, while it was difficult to increase the compactness of the building if the building shape was changed for a one storey building (please refer to the 'Local sensitivity analysis.xls' file on the CD for more information).

[23] The window area to orientation ratio is the percentile distribution of the total window area in relation to the orientation of the facades in the building. This means that if a building has a total window area of 50m^2 and a window area to orientation ratio of N/S/E+W of 10/50/40 the window area facing north would be 5m^2, the window area facing south would be 25m^2 and the window area facing east and west would be 20m^2.

[24] The shade factor is determined in the programme in relation to shade situated directly in front of the window (e.g. shade from overhangs, window holes, external louvers etc.)

[25] The Morris Method only enables sensitivity analysis, which means that one has to apply another method if the purpose of the Monte Carlo Simulation is to uncover the uncertainty of the parameters.

10 Suggestion for development of tool

Introduction

The conclusion of the design strategy development experiment in the previous chapter was that the global sensitivity analysis can enable the identification of the most influential parameters in a project specific situation in the beginning of the design process. This corresponds with the conclusions in Part 1 of this thesis, in which the development of project specific design strategies and concepts are identified as the defining character of integrated design processes applied by actors with inter-disciplinary educations and inter-disciplinary design teams.

A success criterion for the application of sensitivity analysis as a methodical approach to project specific design strategy development is how the input parameters are selected;

1) that the selection of the variable input parameters focuses on the inter-disciplinary interface between the calculation parameters used in the external model (in this case the Be06 programme), the architectural design of buildings and the design principles applied existing in environmentally sustainable buildings and the design strategies described in publications, and
2) that selected external model selected for the analysis enables an explorative and qualitative evaluation of the input parameter's sensitivity that relates to the architectural decisions faced in the beginning of a design project.

In its current form the method behind the sensitivity analysis experiment is very time consuming because of the switch between the Be06 programme and the SimLab programme, and the fact that every 'simulation' in the external model is changed by the analyst. This led me to conclude that a design strategy development tool should be developed for early implementation in the design process where the most influential input parameters can be identified in a project specific situation.

The reason why the sensitivity analysis needs to be project specific is 1) sensitivity analyses are dependent on the insertion of a reference building which the results of the analysis are sensitive to and 2) because most if not all architectural design projects are unique undertakings. This exemplifies why sensitivity analysis is a perfect match for project specific design strategy development, and why it was considered in this PhD project as a methodical approach to design strategy development to begin with.

The purpose of the sensitivity analysis interface

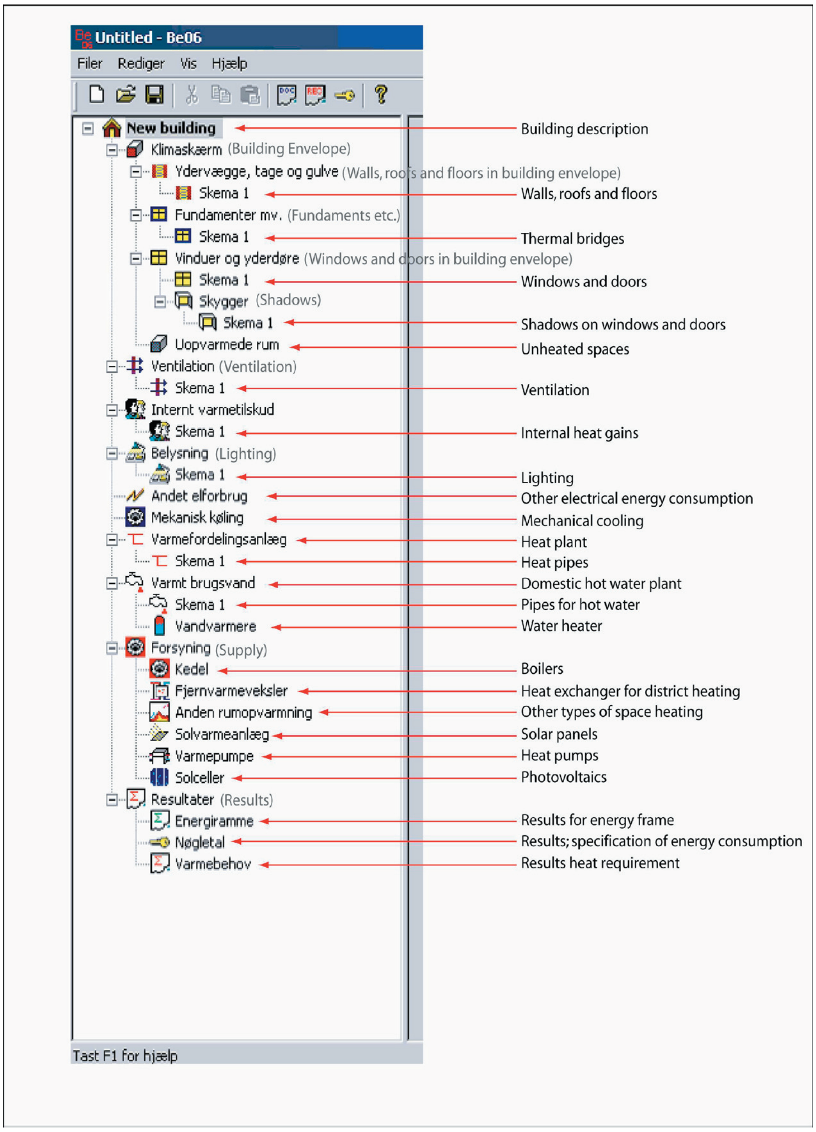
The early identification of the most influential input parameters in a project specific situation is interesting, because it provides the designer with an understanding of the sensitivity of the creative space of the project he is working on. The creative space is (or should be) determined through dialogue with the client and the other participants of the design team about the use of the building, the architectural expression of the building, the environmentally sustainable profile of the building and the results of e.g. the site and user analyses. Through this dialogue the design team identifies and priorities the issues they want to focus on in the project, and a first sketch is made (e.g. inspired by an existing building) which is inserted in the design strategy development programme e.g. in the Be06 programme.

This chapter contains a sketch for how sensitivity analysis can be added to the interface of Be06. The sketch suggests how the interfaces of Be06 and SimLab can meet each other in a way that enables easy application to users with little or no experience with statistical analysis.

10.1 The current interfaces of Be06 and SimLab

Be06

Chapter 9.1 describes how the Be06 programme considers *Heating*, *Cooling, Heat loss from installations, Boilers, Heat pumps*, *Solar panels, Pumps* , *Ventilators, Refrigerators* , *Lighting, Photo voltaic cells* and *Other electrical consumptions for building operation (*[Aggerholm and Grau 2005:22-24]). This chapter describes how this is presented in the Be06 programme interface and the calculation parameters that are available in the 'sub-interfaces' of this menu (Screen shots of the 'sub' interfaces are available (in Danish) in Enclosure D).



Ilustration 211.1: Translation of the current menu in the Be06 programme, which is currently only available in Danish.

Table 10.1: The calculation parameters available in the different 'sub-interfaces' of the Be06 programme

Menu	*Programme variables (i.e. calculation parameters and inserted information)*
Building description	Name of building, Type of building (single family house, row-house, flats or other (non-residential), Number of units, Heated floor area, Rotation of building, Heat capacity of building, Average hours of use pr week and time of day, Heat supply, Other energy contributions (Electrical radiators, Wood burning stove and gas burners, Solar panels, Heat pumps and Photovoltaics), Mechanical cooling, Energy mark category.
Walls, roofs and floors in building envelope	Areas and U-values of walls, roofs and floors in the building envelope, Temperature factor (e.g. if one or more walls, roofs or floors in the building faces an under-heated space or the ground), dimensioning indoor and outdoor temperatures.
Thermal bridges	U-values, Temperature factors and Length of thermal bridges at fundaments and around openings, and Dimensioning indoor and outdoor temperatures
Windows and doors	Number, Orientation, Angles, Areas, U-values, Temperature factors, Area factors (Ff), g-value (heat transmittance), Shade and Solar shade factor of windows and doors, and Dimensioning indoor and out door temperatures
Shadows on windows and doors	Horizontal shade from context, Overhang, Window hole % and shadows on the windows and doors from left and right.
Unheated space	Name and Area of unheated space, Ventilation rate of space, Area and U-values of surfaces between the heated and unheated space and of surfaces in the building envelope the unheated space.

Table 10.1: The calculation parameters available in the different 'sub-interfaces' of the Be06 programme (Continued)

Menu	*Programme variables (i.e. calculation parameters and inserted information)*
Ventilation	Zones, area, Air change rates natural and mechanical ventilation summer and winter during hours of use and outside hours of use, Heat-recovery percentage, Temperature of inlet air, 1 or 0 Electrical heating surface, Specific electrical energy consumption for air movement, Infiltration.
Internal heat gains	Zones, Area of zones, Heat gains from people, Heat gain from appliances/installations and Heat gain from appliances/installations outside hours of use.
Lighting	Zones, Area of zone, Minimum and installed electrical effect of general lighting (e.g. roof lighting), Light levels (Lux), Daylight factor, Control of lighting, Utilisation factor (hours of use of lighting vs. hours of use in the building), Electrical effect of individual lighting, Electrical effect of other lighting (e.g. spots), Standby effect of lighting, Electrical effect of lighting outside hours of use.
Other electrical energy consumption	Other electrical energy consumption that is not included in the energy frame or the heat balance in the building. Electrical effect of outdoor lighting and special appliances/installations e.g. servers, cooling of server rooms etc.) during hours of use/always in use.
Mechanical cooling	Cooling efficiency (incl. all pumps, ventilators and automatics), Extra energy consumption as a result of water fluctuations.
Heat plant	Dimensioning supply-pipe and return-pipe temperatures, Plant type, Nominal effect and Reduction factor of pumps that are used all year, during the entire heating season, during parts of the heating season, combi-pumps
Heat pipes	Lengths of supply- and return-pipes, temperature factor, Compensation for outdoor temperatures, Seasonal (turned of during summer season).
Domestic hot water	Average annual use pr area, Temperature of domestic hot water, Addition of individual electrical or gas heaters, Volume, supply-temperature, electrical heating, solar heating and heat loss of Hot-water tank and temperature factor for the room the tank is placed in.
Pipes for hot water	Length and Temperature factor of supply- and return-pipes.
Water heater	Type of water and/or gas heater, number and placement of water heaters, gas and water heater's share of the total hot water consumption and Temperature factor for room with gas or water heaters. Efficiency and heat consumption of pilot flame of gas heater
Boilers	Type of boiler (oil, gas or bio fuel), heating capacity, Nominal effect and share of total hot water production, Nominal efficiencies (loads, efficiency, boiler temperature, temperature correction), losses when idle, Running conditions and electrical consumption of ventilator and automatics.
Heat exchanger for district heating	Nominal effect and heat loss from heat exchanger, minimum heat exchange temperature, Temperature factor of room, Standby effect.
Other types of space heating	Electrical heater's share of total floor area, Woodburning stove's and gas heater's share of total floor area, efficiency and needed air change rates.
Solar panels	Type (domestic hot water, space heating or combination), Area, Orientation, Angle, horizontal shade, vertical shade (left and right), U-value (heat transmittance coefficient) of solar panels. Length of pipes and Heat loss of pipes for solar panels. Start efficiency and circulation efficiency of solar panels. Electrical energy consumption of circulation pump and standby of automatics.
Heat pumps	Type of heat pump (domestic hot water, space heating, combination or duo), Share of total floor area, Space heating (nominal effect, nominal efficiency, relative efficiency at 50% load), Test temperatures (cold and warm sides), Medium on cold and warm sides (cold; earth tube, outlet or outside air. Warm: room air, inlet or heating plant). Electrical energy consumption of ancillary equipment that is not included in the nominal efficiency and standby automatics. Heat pumps coupled with ventilation: Temperature efficiency of heat-recovery of ventilation in front of heat pump, Dimensioning temperature of inlet air and Needed ventilation rate.
Photovoltaics	Area of Photovoltaic (PV) panel, Orientation (north, north-east, east etc.), Angle (between horizontal plane and PV panel), Horizontal shade, Vertical shade (left and right), Peak poser, System efficiency.

Table 10.1: The calculation parameters available in the different ‘sub-interfaces’ of the Be06 programme (Continued)

Menu	*Programme variables (i.e. calculation parameters and inserted information)*
Energy frame	Total energy requirement of building, Calculated energy frames (low-energy class 1 and 2, and overall energy frame), Supplements to energy frame (no supplements, supplement for mechanical outlet without heat recovery, supplement for special conditions
Specification of energy consumption	Total energy requirement, Total electrical energy consumption, Contributions to energy requirement (heat, electricity for building operation and overheating of space), Net requirements (Space heating, domestic hot water, cooling), Selected electricity requirements (lighting, electrical heating, ventilators, pumps, cooling), Supply from special energy/heat sources (solar panels, heat pumps, photovoltaics).
Heat requirement	Monthly heating requirement for Heat loss for transmission and ventilation, Ventilation heating surfaces, Reduction in heat-recovery to meet desired temperature of inlet air, Resulting heat loss incl. regulated contribution from ventilation, Passive solar heat gains, Internal heat gains, Heat gains from pipes and hot-water tank, Total heat gains, Relative heat gains (total heat gains divided by the resulting heat loss), Percentile of month when heat is required, Variable heat gains (e.g. from pipes), Total heat gains incl. variable heat gains, Relative total heat gains (total heat gains incl. variable heat gains divided by resulting heat loss), Utilisation factor for heat gains, Heat requirements of rooms when the total heat gains are utilised, Heat from ventilation heating surfaces, Total net heat requirement.

The Be06 programme does not have a geometry based interface, which means that the only way the building shape and the calculation is related is in the surface areas and characteristics of the different components of the building envelope (e.g. ground floor, roof, exterior walls, windows and doors).

SimLab

The SimLab interface consist of three parts;

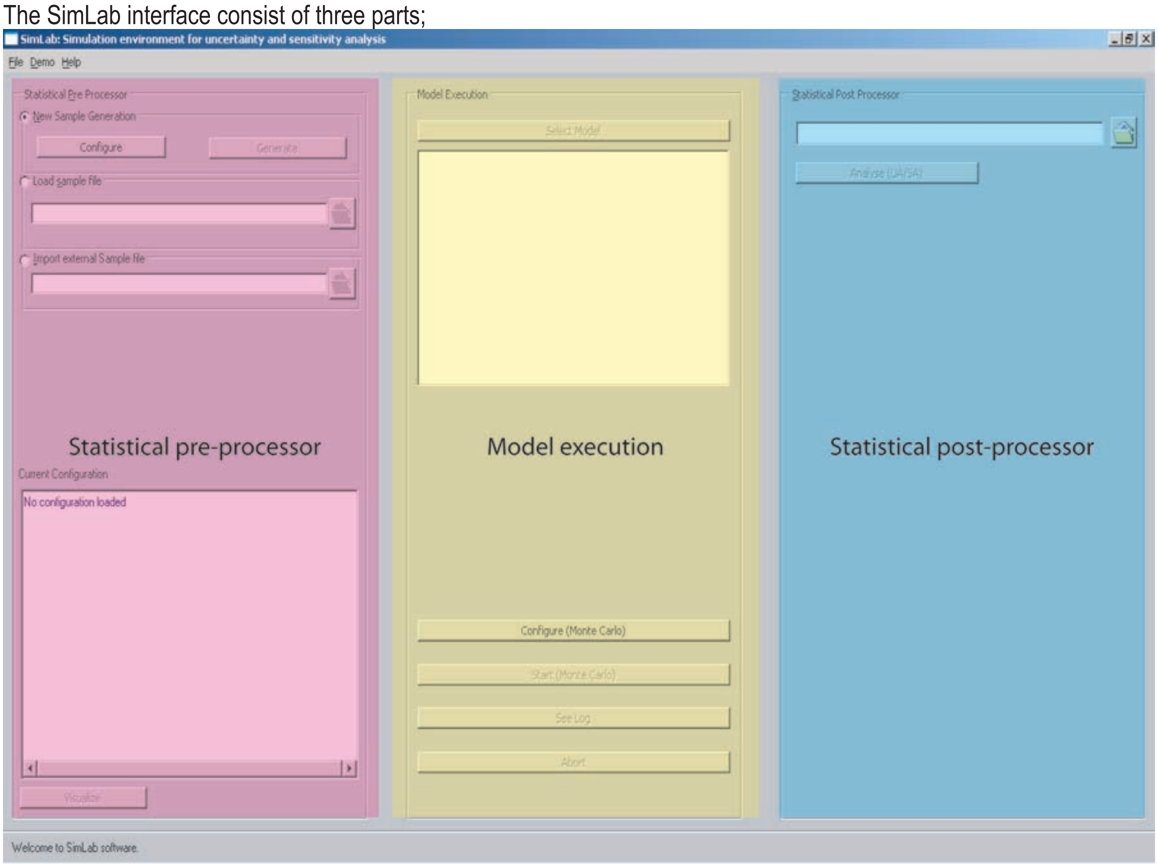


Illustration 213.1: The division of the main interface in the SimLab programme

Statistical pre-processor

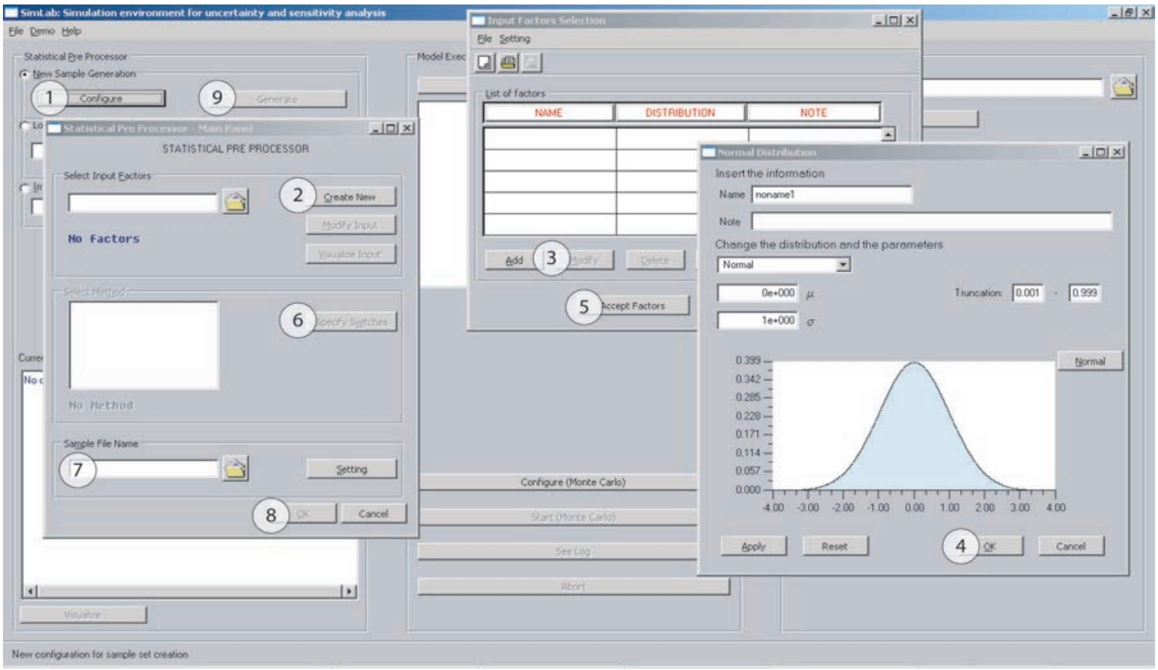
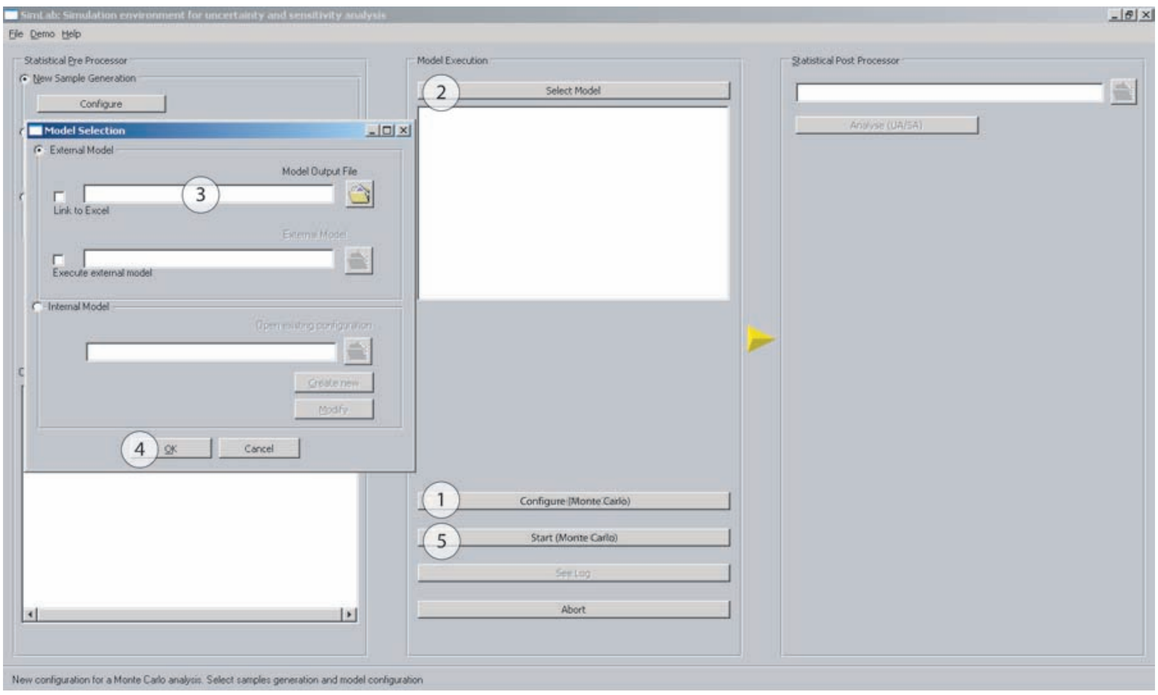


Illustration 214.1: The 'sub-interfaces' of the statistical pre-processor in the SimLab programme

The distribution functions and names for each of the input parameters are inserted in the pre-processor (1 to 5). After the insertion of this information the switches of the Morris Method are selected (number of runs and how to order the runs (by parameter or by run)) (6). A name is inserted for the sample file (7). After this the 'Generate' button is clicked (9) and the programme generates an 'input' matrix which is used in an external model (in this case the reference building inserted in the Be06 programme). The 'input' matrix contains information about the number of calculations performed in the external model with different combinations of the input parameters. When all the calculations are performed in the external model an 'output' matrix is created in a WordPad and the 'Model execution' interface is used.

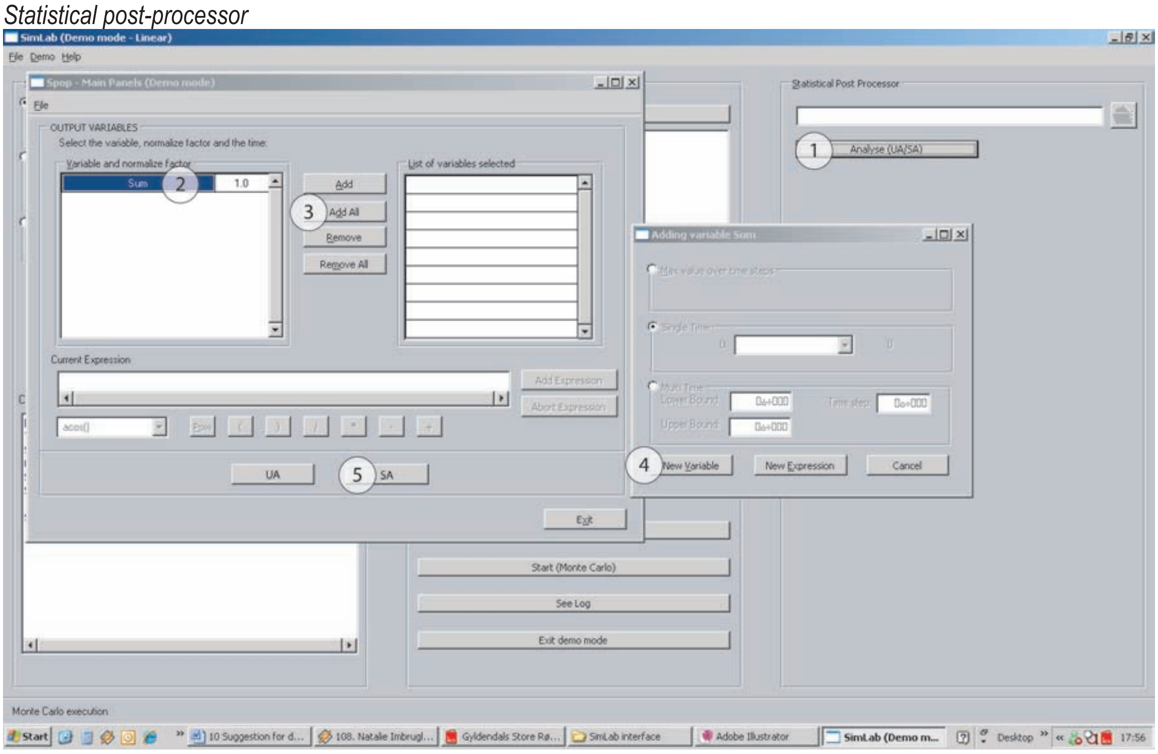
Model execution



IIllustration 214.2: The 'sub-interface' of the Model execution in the SimLab programme

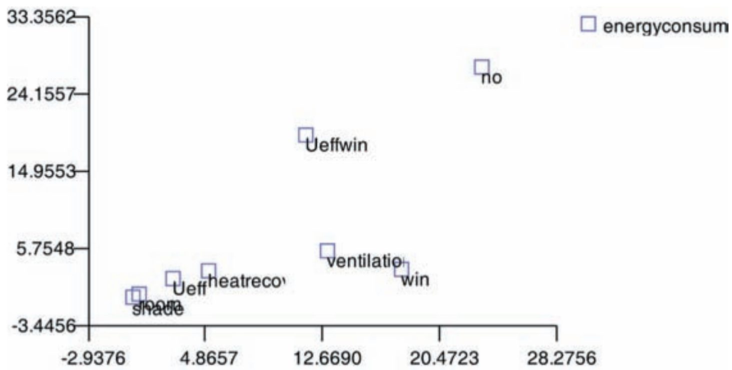
The simulation is configured (1) by selecting a model (2). If an external model is used the WordPad file with the 'output' matrix is loaded (3-4). After selecting the model the simulation is started by pressing the 'Start (Monte Carlo)' button (5).

Statistical post-processor



Illlustration 215.1: The 'sub-interface' of the statistical post-processor of the SimLab programme

After the Monte Carlo simulation is completed the post-processor is used to analyse the results (1). The parameters of interest are selected as new variables (2-4), a sensitivity analysis is selected (5) and the results of the analysis are displayed in graphs and tables with the mean values (μ) and standard deviations (σ) of the outputs of the external model for each of the input parameters:



Energy consumption for overheating		
Morris Index	μ	σ
no	23.36	27.5588
room	0.44	0.3847
Ueff	2.76	2.2601
win	18	3.3675
Ueffwin	11.6	19.3241
shade	0	0
ventilation	13.08	5.576
heatrecovwin	5.08	3.2268

Illustration 215.1: Example of results from the sensitivity analysis in SimLab.

10.2 Addition of sensitivity analysis to the Be06 interface

This PhD thesis suggests that sensitivity analysis is added to the Be06 interface:

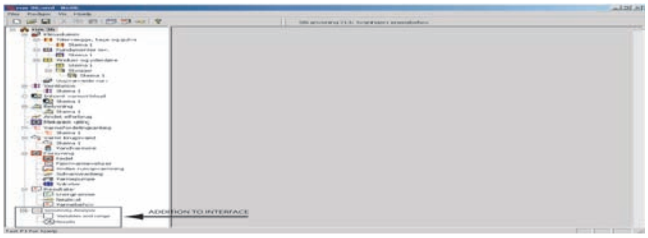


Illustration 216.1: The suggested addition to the menu of the Be06 programme.

It is of utmost importance that the interface of a design strategy support tool appeals to designers if they are to be applied in the early stages of the design process. It is the opinion of this PhD that this can be achieved by selecting input parameters for the interface of the sensitivity analysis that relate to architectural considerations for e.g. the building envelope design and by changing the input parameters of e.g. the existing Be06 programme slightly towards a more 'abstract' type of calculation parameters that correspond better with the detail level of the architectural design in the beginning of the design process (e.g. by applying changes like the ones suggested in chapter 10.3).

The interface suggested in this chapter is a sketch for how the input parameters applied in the design strategy development experiment in the previous chapter, and a other input parameters which have not been tested in the experiment, can be integrated in the existing Be06 programme interface.

10.2.1 Application

The application of the sensitivity analysis interface suggested in this chapter is envisioned to go through the following stages:

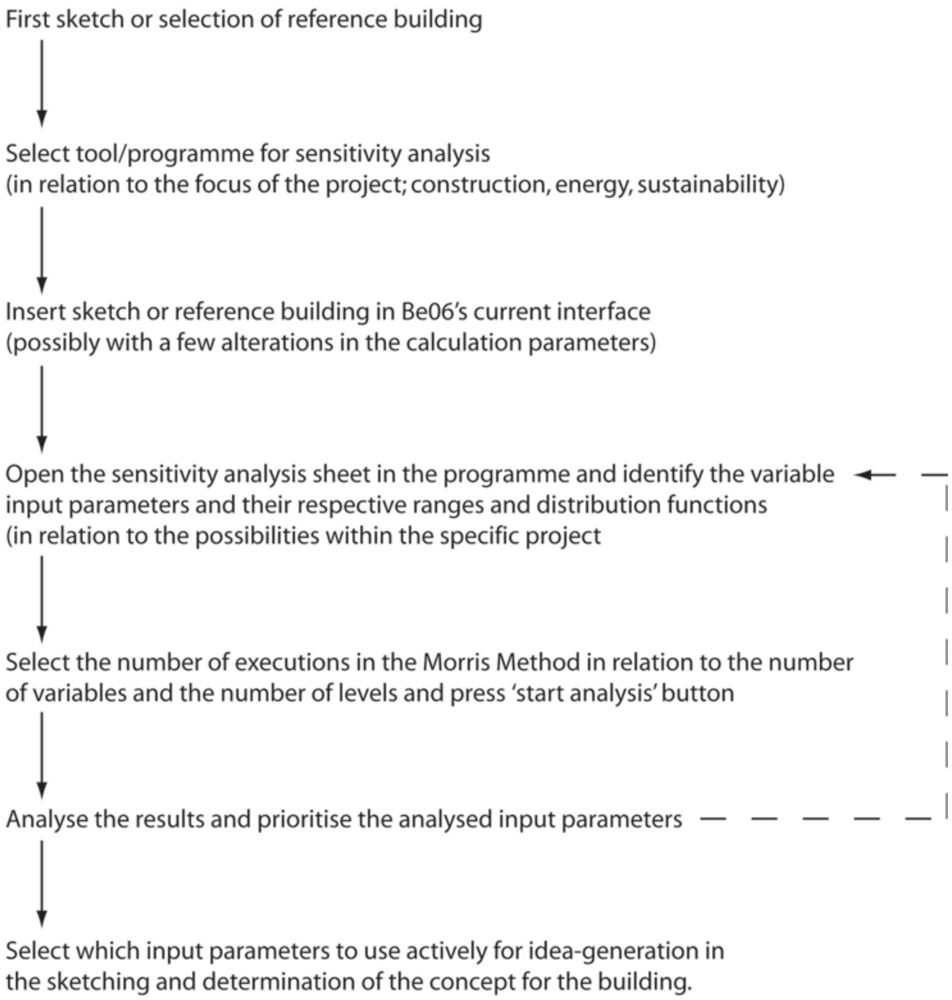


Illustration 217.1: Process map for the application of the design strategy development support tool

After insertion of the data for the reference building in the current interface of the Be06 programme the sensitivity analysis extension of the programme is opened, which consists of two 'sub-interfaces'; Variables and range, and Results.

Insertion of sketches in the existing interface of the Be06 programme

The information inserted in the current version of the Be06 programme information:

- The surface areas of the different elements of the building envelope and their respective U-values (and g-values, glass to frame ratio factor (Ff), shade factors (Fs) and orientations of windows)
- The heated floor area
- shades from surroundings, overhangs and windows
- The lengths and U-values of thermal bridges
- Characteristics of ventilation (heat recovery, temperatures of inlet air, air tightness of the building (infiltration), the specific electrical energy consumption for air transport, ventilation rates summer and winter, day and night)
- Internal heat gains people and appliances
- Lighting – not required in residential buildings
- Mechanical cooling if applied in the building
- Lengths and thermal insulation of water pipes outside the insulation in the building envelope.
- Estimated annual use of hot water, and
- Energy sources for supply

The 'Variables and ranges' interface

The variable input parameters available in the programme should be based on research of existing design principles applied in e.g. residential, office and institutional environmentally sustainable buildings in specific climatic contexts.

The following sketches for the 'Variables and range' interface are, therefore, based on the experiment in chapter 9 of the development of a design strategy for a residential building. This means that the suggested input parameters are subject to change for other types of buildings if a decision is made to move forward with the development of a design strategy development tool.

As mentioned earlier in this chapter it is important that the pre-defined input parameters enable creative freedom with respect to e.g. the window area to orientation ratio, the window size or shading elements in the building, because it is too early in the process to freeze these parameters. If the pre-defined input parameters made available in the programme are too rigid the programme will not be applicable in the early stages of design processes.

The range and distribution functions of the pre-defined[1] input parameters are specified in relation to the initial discussions about the e.g. visual and functional issues of concern. The set up of the Morris Method (no. of executions and no. of levels) is decided and a global sensitivity analysis is conducted.

The input parameters can be frozen at the value of the reference building if some of the input parameters are not permitted to change, e.g. if the design team wants a specific type of ventilation, a specific comfort temperature or a specific window area to orientation ratio in relation to the site.

As a default in the programme the distribution functions are set to be uniform, which the user can change by clicking 'change distribution function'. If possible it would be interesting to enable changes the mean value of a specified non-uniform distribution function by moving the faders to where the analyst wants the new mean value to be.

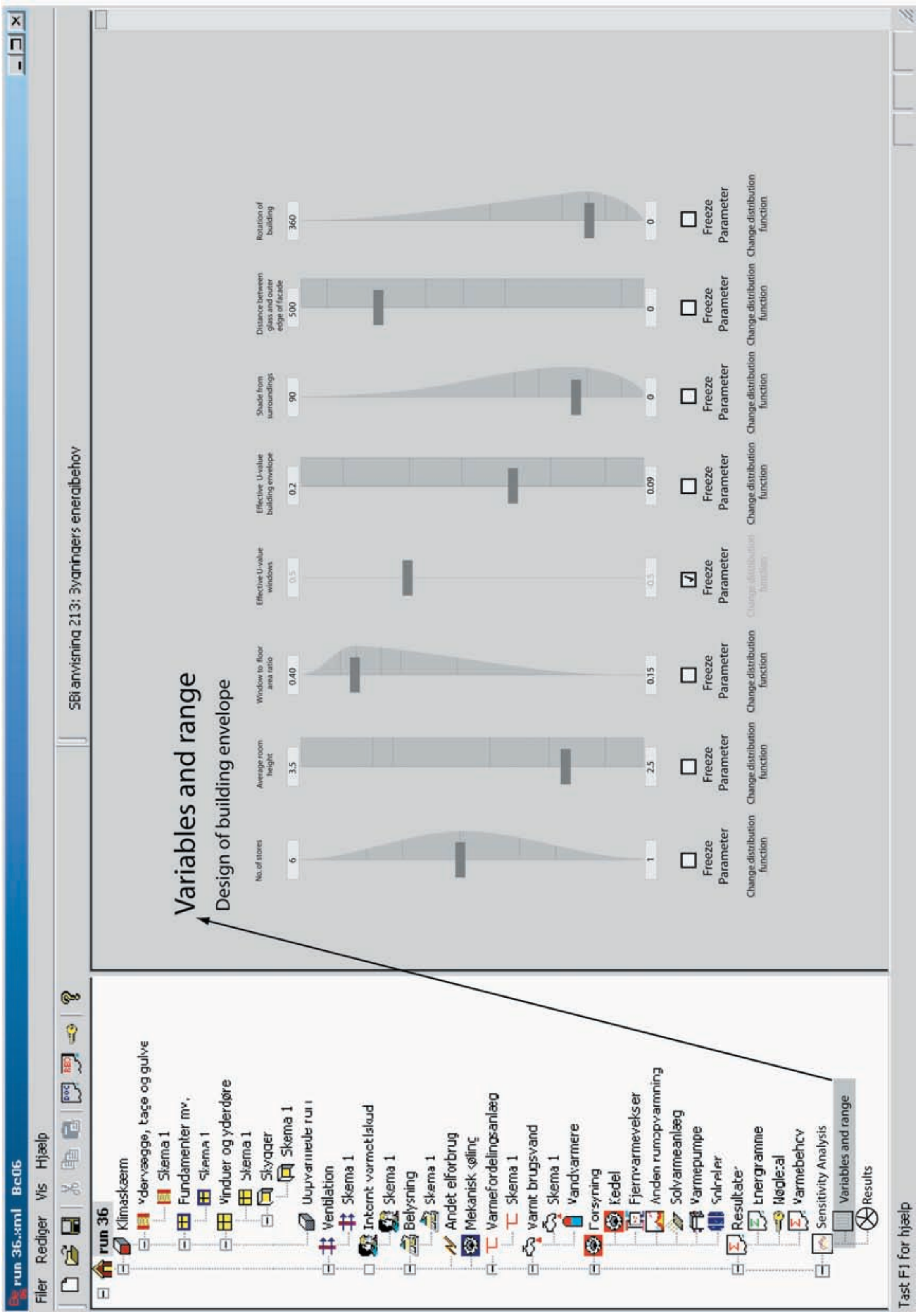


Illustration 219.1: The illustration displays a sketch for the interface of the sensitivity analysis added to the Be06 programme. The sketch contains a suggestion for which input parameters to include in the analysis in relation to the design of the building envelope.

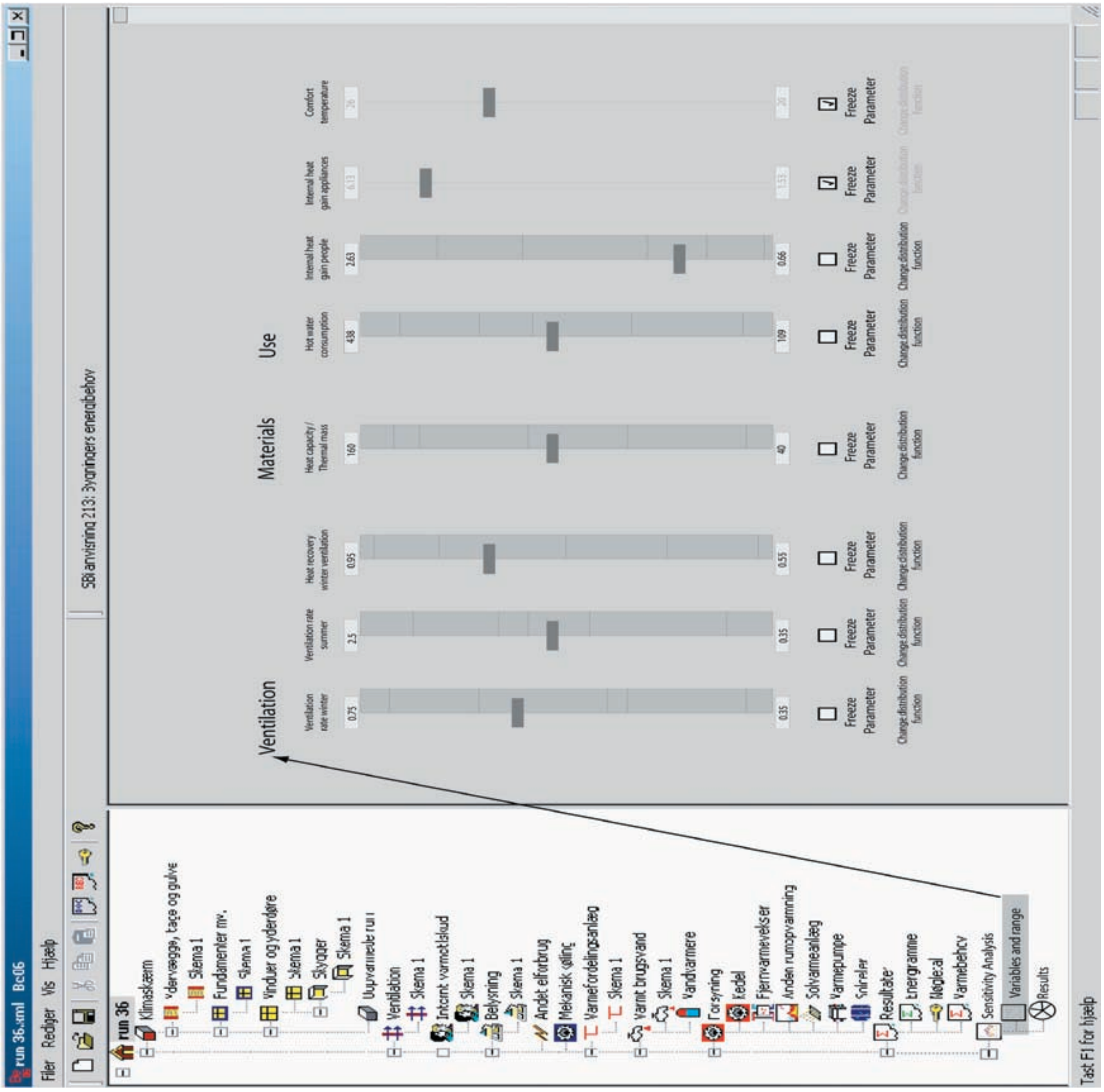


Illustration 220.1: The illustration displays a sketch for the interface of the sensitivity analysis added to the Be06 programme. The sketch contains a suggestion for which input parameters to include in the analysis in relation to the ventilation and use of the building as well as the materials used for the interior of the building.

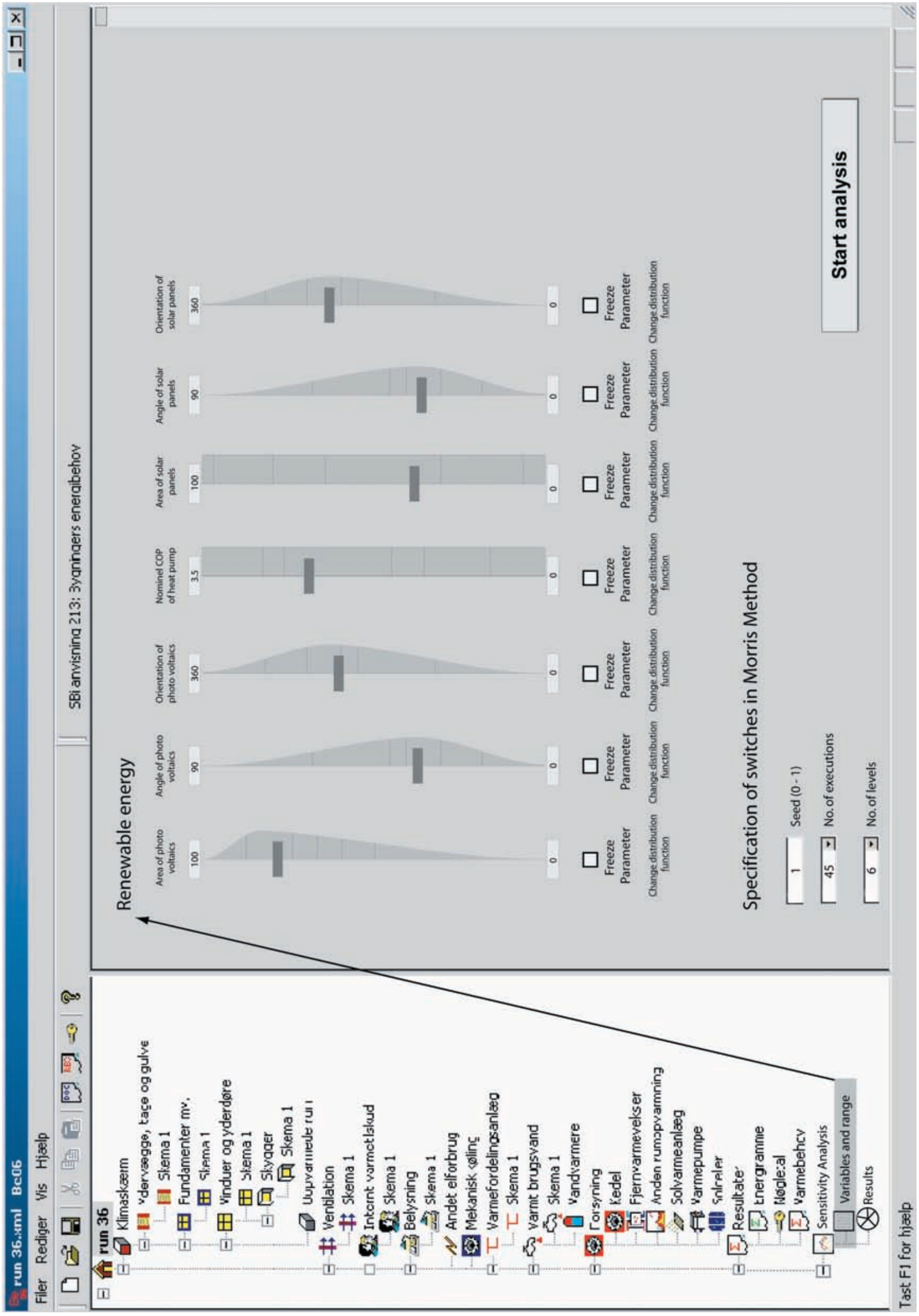


Illustration 221.1: The illustration displays a sketch for the interface of the sensitivity analysis added to the Be06 programme. The sketch contains a suggestion for which input parameters to include in the analysis in relation to renewable energy sources available in the current version of the programme as well as the 'start analysis button after all the input parameters in the programme have been reviewed and changed in accordance with the specific project.

The 'Results' interface

The result of the analysis would be a qualitative evaluation of the negligible, linear & additive and non-linear & inter-correlated parameters similar to the ones presented in chapter 9.6.

The results of the analysis do not identify which combination of the parameters enable the 'optimum' solution, it merely identifies the parameters which should be applied cautiously because their value has a great impact on, in this case, the energy consumption in the building.

The Morris Method furthermore identifies the input parameters that are inter-dependent (inter-correlated) (please refer to chapter 9.6 for exemplification of this).

The fact that an optimum solution is not identified is in this PhD project regarded to be a good thing, as it preserves the creative freedom of the design team while identifying the sensitive calculation parameters.

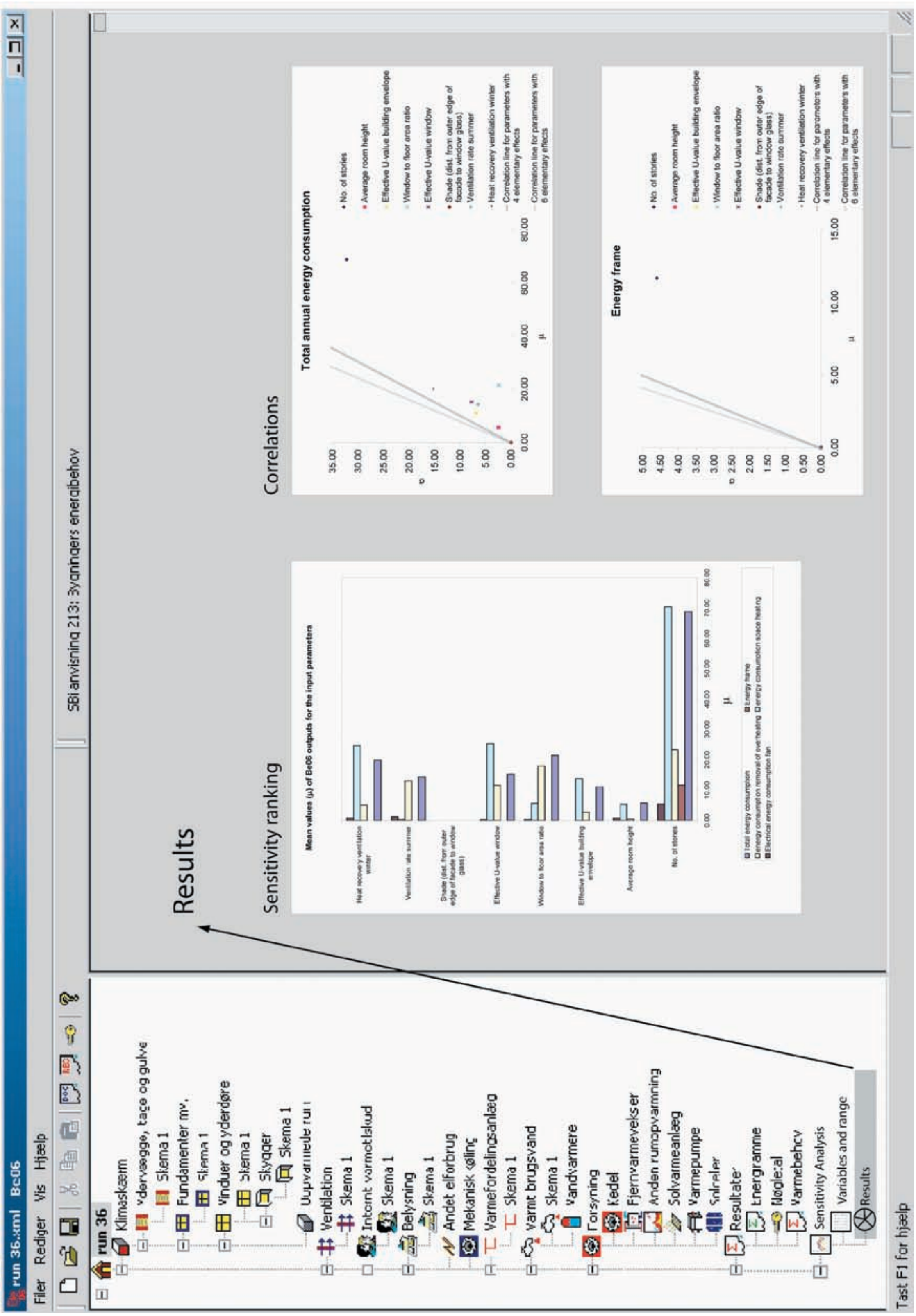


Illustration 223.1: The illustration displays a sketch for the interface of the sensitivity analysis added to the Be06 programme. The sketch shows the results of the global analysis.

Analysis of results

After completion of the sensitivity analysis the findings are evaluated in relation to the initial identification and prioritisation of e.g. visual and functional issues, as well as similar sensitivity analyses in other programmes.

The prioritisation of e.g. the visual and functional issues is revised in relation to the sensitivity of the input parameters concluded in the analysis and a design strategy for the project is developed that defines which design principles to apply actively in the design process as idea-generating elements in the sketching process for the development of a concept for the project.

The project then moves into the concept development phase of the design project, but before this happens revisions in e.g. the visual and functional issues may lead to another round of global sensitivity analysis (indicated by the dashed line in the process map).

In the concept development phase design support tools are applied which enable iterations between building design and energy calculation (e.g. the LT-method or a revised version of the Bsim programme where the geometry interface has been improved for easy evaluation of the changes achieved in the programme).

10.3 Development perspectives

The interface

The sensitivity analysis interface suggested in this chapter is a first sketch of how sensitivity analysis could be integrated in the interface of the Be06 programme, and how the variability, range and distribution functions of the input parameters can be visualised.

A basic assumption behind the sketches for the sensitivity analysis interface presented in this chapter is that the statistical calculation model for the Morris Method in SimLab can be transferred to the Be06 programme. This does however not instruct the programme on how to perform the actual iterations suggested by the statistical calculation model from SimLab, which means that software development of this is necessary. This software development can to some extend be based on the iterations performed in the design strategy development experiment in the previous chapter of this thesis, which are presented in Enclosure C.

Assuming that it is possible to merge the software of the Be06 and SimLab programmes and develop the iteration software, the ad-on to the Be06 programme suggested here can enable sensitivity analysis for people who are familiar with the Be06 programme.

The target group of this PhD has been engineers and architects who have little or no experience with environmentally sustainable design of buildings, which means that the target group might not be able to apply the Be06 programme.

In this light it would be interesting to consider how the interface of the Be06 programme can be adapted to ease the application of the programme for this particular target group and whether a new tool should be developed that focuses a lot more on the generation of design in the early stages of the design process, e.g. by merging the 'design strategy tool' suggested here with a 'design support tool' (please refer to table 8.9 for clarification of the difference between the two). This could possibly be considered in the current development of the BSim programme (described in chapter 8.2), in which the BEAT programme and the import of CAD files are integrated. The BSim programme development has the potential to enable one joint programme for design and evaluation of environmentally sustainable buildings if the geometry interface of the programme is improved to enable quick iterations between the design of the building and the simulation, and sensitivity analysis is added to the programme.

The Be06 programme

The Be06 programme was developed for deterministic studies of whether or not a building design lives up to the legislative demands stated in the Danish building codes. It therefore requires input data which is not easily determined in the early phases of the design process when the design strategy is developed.

The fact that the Be06 programme was developed for deterministic investigation does result in complications when the programme is applied in the early stages of a design project. In this PhD project this was solved by treating each calculation as a new version of the building, thus calculating e.g. the shade for the window holes etc. for each situation based on average window dimensions of the reference building.
A few examples of where the level of detail was experienced to be too high in the sensitivity analysis presented in chapter 9 are: the U-value for the windows and doors, the window and door shade parameters, and the length of the thermal bridges surrounding the window and doors.

Thermal bridges, U-values of windows and Shade in relation to the dimensions of windows
The calculation of the U-value of the windows and doors (U_{win}) was discussed in connection with the presentation of the results of the local analysis of the window type (page 160-161). In relation to this it is apparent that the U-values of windows depend not just on the type of frame and moulding, but also on the dimensions of the window and glass area.
The dimensions of windows is also an issue when having to calculate the shade from the window hole in the Be06 programme, because it presumes that the window size has been determined already. This is a problem that needs to be dealt with if one wishes to develop a design strategy development tool (e.g. by changing the shade input parameters in the Be06 programme from the window hole % and the calculated angles in the existing version of the programme to an insertion of the average window dimensions and door dimensions).
The calculation of thermal bridges around the windows and doors needs some built-in flexibility in relation to an explorative study of the sensitivity of parameters (e.g. in connection with the window to floor area ratio calculation). In the analysis presented in the previous chapter a study was performed of the length of the thermal bridges for different window areas and dimensions (1:1, 1:2, 1:3 etc.). A similar study can be performed for the design strategy development programme, or maybe the length of the thermal bridges for windows and doors can be linked to the window to floor area ratio or the average window and door dimensions suggested for the shade calculation parameters.

Introduction of window to floor area ratios and effective U-values for windows
Another area where the Be06 programme could be improved in order to enable early design strategy development is in relation to the window area. In the current version of the programme one has to insert the window areas in the respective directions. This could however be changed in a revised version of the programme, to be inserted as a percentile of the floor area in the building (i.e. a window to floor area ratio).
Usually the approximate floor area of a project is determined quite early in the project (e.g. in the first meeting with the client or in the design brief). It would therefore be quite easy to insert the total window area in the building in relation to the floor area and then insert the percentile distribution of the total window area on the respective facades. This would correspond well with the calculation of the U_{effwin}-value of the reference building and it possibly simplify the software programming for the design strategy development support tool.

Issues like these need to be addressed in the software development of e.g. a sensitivity analysis ad-on to the Be06 programme or in the development of a new programme. It is a balance act of designing the software in a way that enables abstract studies of the sensitivity of parameters while producing realistic results.
The fact that I was able to perform the analysis reported in this thesis testifies that it should be possible to develop software, which enables this type of calculation. This PhD thesis will not go into further detail about this software development, as this should be developed by specialists. The iterations performed in the analysis are described in Enclosure C.

[1] The input parameters should be determined by the developers of the programme to ease the application of the programme of people who have limited or no experience with this type of calculation.

Conclusion PART 2: Design strategy development

The answers found to the subsidiary questions asked in this part of the thesis were;

Which design strategies are applied in existing environmentally sustainable residential buildings?
The design strategies applied in the five environmentally sustainable residential buildings studied in chapter 8.1 in this project considered the design principles displayed in Table 8.7.

Table 8.7: The design principles applied in the projects

	BedZED	*Marzahn low-energy building*	*Sustainable housing Lystrup*	*Eco-house Skejby*	*Elephant and castle eco-towers*
Atrium	X			X	X
Shade		X		X	X
Zoning	X	X		X	
Vegetation	X		X	X	X
Mixed Use	X				X
Window type	X	X	X		
Thermal mass	X	X			X
Rainwater collection	X		X	X	
Visible power meters	X			X	
Utilisation of daylight	X	X	X	X	X
Black water treatment	X			X	
Hybrid ventilation	X	X			
Natural ventilation		X			X
Mechanical ventilation			X		
Renewable energy sources	X			X	
Reduce private transportation	X			X	X
Window area to orientation ratio	X	X	X	X	X
Materials; lifecycle assessment	X			X	
Intelligent building automation system		X		X	
Connection with surrounding landscape			X	X	X
Reduce impact on site (ecological footprint)	X		X		X
Insulation and air-tightness of building envelope	X	X	X	X	X
Compact building shape (surface to floor area ratio)		X	X	X	X

The analysis of these projects demonstrated how different design principles are integrated differently in the architectural expression of the building in relation to the dominant concerns (for nature, culture, climate and technology) addressed in the projects and the visibility (i.e. the exposure vs. concealment) of these concerns. (Please refer to chapter 8.1.2 for further details).

The study of the applied design strategies underlines the importance of enabling project specific design strategy development, and the importance of thinking about the design strategies described in publications as guidelines that describe examples of design principles and issues which need consideration, rather than strategies that can be reproduced in other projects.

Which tools are available for designers of environmentally sustainable buildings?
The tools available to designers of Danish environmentally sustainable buildings primarily enable assessment and evaluation of the performance of buildings in relation to the energy consumption, thermal comfort and lifecycle of buildings. None of the tools were developed as 'design support

tools' or 'design strategy tools' and application of the tools for design strategy development and move-test experiments in relation to the building design is therefore quite time consuming. Two tools developed in the UK were therefore included in the study of available tools as examples of respectively a 'design strategy tool' and a 'design support tool'.

Table 8.9: Categorisation of the available tools

Category	**Description**	**Tool**
Design process tool	These are tools which help structure and manage the design process with respect to the phases, tasks and actors.	• The IEA Task 23 navigator (described in chapter 6.3.1)
Design strategy tool	These tools help to structure a for instance the technological design issues or the selected design principles in relation to the formulation of a design strategy.	• ARUP SPeAR
Design support tool	These are used to get an idea of what design strategies and design principles are the most promising for a given project.	• LT-method
Design evaluation tool	These are tools applied to check the performance of a given design and compare it to a target criteria or another design scheme.	• BEAT • Be06 • BuildDesk • Bsim • LT-method • Arup SPeAR
Simulation tool	Simulation tools are used to predict the performance of a specific design solution	• BSim • BEAT

Based on the application of the majority of the tools and the literature about the tools it is my conclusion that several of the Danish tools can be developed into 'design support tools', but that this requires introduction or improvements of geometry interfaces in the programmes. The Danish tools can also be developed to support design strategy development, this does, however, require that the tools adapt a methodical approach to the evaluation of the elementary effects of design parameters (e.g. through the integration of sensitivity analysis) that enables the designer to demark the creative space of this project in relation to e.g. the energy consumption and use of the building. The design evaluation tools and simulation tools are interesting in relation to the development of 'design support tools' if they already have geometry interface, while the tools without geometry interfaces are applicable for the development of 'design strategy tools'.

Is it possible to apply sensitivity analysis as a methodical approach to design strategy development? If so, how can it be implemented in a tool?

Global sensitivity analyses are applied to identify sensitive and robust input parameters when these parameters are changed in a reference model of e.g. a building. This means that sensitivity analyses are sensitive to the calculation parameters that are not varied in the of the reference building.

It is therefore my conclusion that global sensitivity analyses can support the development of project specific design strategies, and sensitivity analysis is an interesting methodical approach to the development of design strategies for environmentally sustainable architecture, because this type of architecture requires consideration of many different types of design principles relating to the architectural design of the building, the climatic comfort conditions inside and outside the building, the expected use of the building, the energy consumption of the building, the impact on the surrounding landscape, availability of materials and the lifecycle of the building.

Global sensitivity analysis can be applied for identification of which of the design principles relating to these issues are most sensitive in relation to the site, climatic context, building type, user of the building etc. in the specific project.

Based on the application of sensitivity analysis as a methodical approach to design strategy development in chapter 9 it is my conclusion that it is the calculation parameters in the existing tools, and the relationship between these parameters and the design of buildings that set the boundaries of the application of sensitivity analyses as a methodical approach to design strategy development.

Chapter 10 in this thesis presents a suggestion for how sensitivity analysis can be integrated in an ad-on to the Be06 programme.

11 Conclusion

This PhD project contributes to the field of methodical approaches to environmentally sustainable architecture by suggesting that sensitivity analysis is applied as a methodical approach to the development of design strategies for which design principles to apply in a specific project.
This suggestion is based on the study of existing methodical approaches to sustainable architecture, as well as, an interview with two designers from Arup Associates (UK), in which design strategy development, integration and inter-disciplinarity were identified as the core issues of methodical approaches to sustainable architecture.

This PhD thesis concludes that existing approaches to sustainable architecture, presented by publications about these approaches, are distinguishable by which design principles are emphasised in the publications, and thus the design strategy developed for these approaches to sustainable architecture (please refer to chapter 6.1).
A study of the existing environmentally sustainable buildings and the approach applied by Arup Associates for the creation of sustainable architecture also reveals, that the selection of design principles, and thus the development of design strategies, is at the core of successful achievement of environmentally sustainable design in practice and the ‘visual translation’ (i.e. the integration in the architectural expression) of these design strategies in the specific projects.

A study of the process descriptions for methodical approaches to sustainable architecture reveals that the design process involved in the creation of sustainable architecture requires integration and inter-disciplinarity of either the designer (via education) or of a multi-professional a design team.

11.1 Methodical approaches to sustainable architecture

Different approaches to sustainability

This PhD project concludes that differences in the approaches to sustainable architecture are manifested in differences in the way the different approaches respond to some or all of the dominant concerns identified in chapter 6.1 (Nature, Culture, Climate and Technology). Based on the study of definitions and design strategies suggested by different publications containing guidelines and descriptions of design principles and issues relating to the respective approaches to sustainable architecture, it is my conclusion that the way the respective approaches respond to the dominant concerns is reflected in the design principles they apply, and thus in the design strategies, applied by the different approaches to sustainable architecture.

The study of the approaches to sustainable architecture does not provide consensus about what sustainable architecture is, it does, however, provide a mapping of the design principles and dominant concerns found in descriptions of the different approaches to sustainable architecture. This mapping contributes to the field of methodical approaches to sustainable architecture by providing a way of navigating and comparing these different approaches in relation to which dominant concerns they address, which design principles they apply when addressing these issues and to the differences in the scale of focus (Urban development, Site selection, Building design, Manufacture of building materials). This mapping is applicable in the beginning of design projects when the approach to sustainability has to be determined for the specific project

Based on the study of the application of design strategies in environmentally sustainable residential buildings it is my conclusion that it is in the interface between the environmental and architectural strategies and the formation of one joint design strategy for the projects that the approach to environmental, and social, sustainability is determined for the specific project. This provides a frame for the application of the methodical approach to design strategy development and the development of tools suggested in this thesis, as it underlines how important it is to be able to estimate the sensitivity of parameters in relation to a given project, and thus the importance of digital and interactive tools that supports this estimation.

Inter-disciplinarity and integration

The main conclusions of the study of existing process descriptions and the interview with Arup Associates are that inter-disciplinarity of multi-professional design teams is a defining characteristic of an integrated design approach to environmentally sustainable architecture, and that it is a shared vision and concept for a project and proper detailing that ensures the integration and the type of sustainability achieved in the project.

Three approaches to inter-disciplinarity were identified through a study of the process descriptions in existing publications and the interview about the approach applied by Arup Associates.

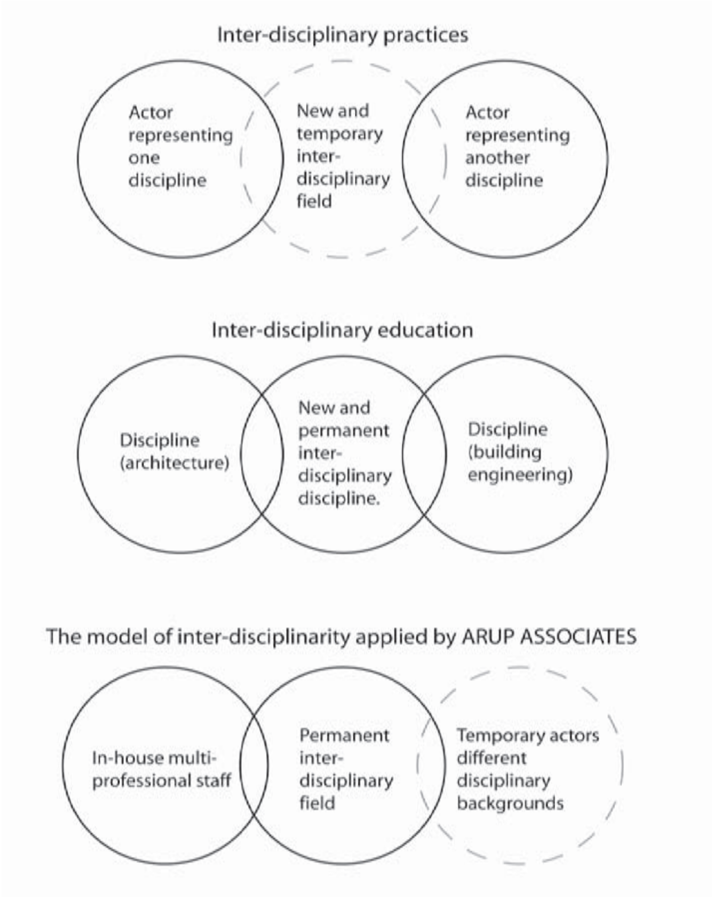


Illustration 229.1: The three models of inter-disciplinarity concluded in this thesis

The three models of inter-disciplinarity all involve actors with different professional backgrounds, but these actors are involved in different ways and with different purpose; In the first model of inter-disciplinarity the inter-disciplinary field created between the actors is temporary because the actors represent different companies and the actors are brought together by the project. The inter-disciplinary field in the second model (for education) is permanent and it relates to the creation of a new type of discipline and a new type of actor. The actors in model two are also permanent for the most part. The inter-disciplinary field in the third model (for Arup Associates) is also permanent and most of the actors are in-house staff with different educational backgrounds.

The experiences with the application of the Integrated Design Process (IDP) developed by Knudstrup [Knudstrup 2001 and 2004] for teaching has been that the integration of architecture and engineering courses is most successful if the actors involved in the inter-disciplinary field (in the second model) are permanent (i.e. consistent from semester to semester). This experience is similar to the experiences reported in the interview with two designers with Arup Associates, where the interviewees mention how new staff in the practice often takes one to two years before they fully understand the common frame of the multi-professional design teams (Enclosure B II: 151-160 and 410-415).

Based on this it is my conclusion that integration is best achieved through the creation of permanent fields of inter-disciplinarity e.g. in education, practice or via partnering agreements.

The application of sensitivity analysis by inter-disciplinary design teams or actors

The methodical approach suggested here will be applied by different actors in the different models of inter-disciplinarity; In model one it will most likely be applied by the energy engineer or another engineer in the design team, because this is the model of inter-disciplinarity that resembles the traditional design process the most, and thus the roles and tasks of the different actors in the design team.

In model two is applied by the inter-disciplinary actor, and in model three it is likely to be applied by the architect, possibly, in cooperation with other actors involved in the design team.

The application of the tool developed here therefore depends on the model of inter-disciplinarity; whether the field of inter-disciplinarity is embedded in the project, the actor or the practice.

This might change if the tool suggested here is developed further into a design support tool that also supports design strategy development, and thus does not require the insertion of a reference building in Be06 (because the design made in the geometry interface provides the reference building), as this would make it easier for the designer to apply the interactions without knowledge of how the current version of the Be06 programme works.

Conditions for success of inter-disciplinarity

The study of process descriptions and the interview with Arup Associates has facilitated the identification of a number of conditions which were concluded to be important in relation to success of an integrated design process;

- Collaboration in multi-professional design teams where everyone involved in the process have an equal say in the formation of the vision and the concept of the project.
- Create informal environment to enable the removal of language barriers, understanding and appreciation of each team member's abilities.
- Embrace different types of investigation (explorative, move-testing and hypothesis-testing) in relation to the purpose of the investigation and the stages in the design process.
- Hold reviews within the design team and engage a multi-professional design review panel that shares the responsibility of the project, provides critique on the work of the design team and suggestions for how to proceed. This will also serve as quality and process control of the work delivered by the practice.
- Awareness of the risk of alienating clients who are afraid that the in-house multi-professional design team is too self-contained.

The large emphasis on design strategies and concepts in relation to methodical approaches to sustainable architecture led to the conclusion that design strategy development is at the centre of both the success of integrated design and the achievement of sustainability.

11.2 Design strategy development

The study of exiting methodical approaches revealed that the current descriptions of methodical approaches are based on process descriptions and descriptions of which design principles and issues to consider when creating environmentally sustainable architecture.

The process descriptions all stress the need for an integrated approach to the design process, a fact which was also stressed in the interview with two designers from Arup Associates, where the early formulation of a shared vision and a joint concept of multi-professional design teams were identified as the main criteria for success. This fact, and the recognition that the different approaches to sustainable architecture apply many of the same, or similar, design principles depending on the overall focus of the approach (e.g. ecological, green, environmental, solar, low-energy etc.) led to the conclusion that it does not make sense to create yet another design strategy for an environmentally sustainable residential. Instead a new type of tool, which supports project-specific design strategy development across professional disciplines, is needed in order to enable a link between the design principles available in existing design strategies and the scope of a specific project[1].

The methodical approach suggested for design strategy development in this PhD thesis addresses the issue of how to select between the different approaches to sustainable architecture in relation to a given project.
Design projects address different dominant concerns, building types, clients, climates, sites, urban scales etc. which influence which design principles can considered a project. Based on the study of existing methodical approaches reported in publications it is my conclusion, that the project specific design principles should be identified in the beginning of the project.
The methodical approach to design strategy development and the suggestion for development of a design strategy support tools in this PhD thesis are a response to this. It therefore suggests a way of identifying the sensitivity of the design principles that are considered in relation to a specific project.

Achieving architecture
The methodical approach and tool development suggested in this thesis does not ensure that architectural is achieved in the buildingdesign, it merely enables the designer to get an overview of the sensitivity and possible inter-correlations of the design principles considered in a specific project. The further development of the suggested tool might enable the designer to test his or her different architectural ideas, presuming that the development integrates a geometric interface (thereby turning the tool into both a design strategy tool and a design support tool), but even this does not ensure architectural quality in the building, because the ability to achieve this is embedded in the designer (via his or her education, and whether he or she has developed or is born with an understanding for architectural proportions, an ability to get in the mind of the user etc.).

Existing tools
A study of the existing tools for energy performance, thermal comfort and lifecycle assessment in Denmark has revealed that none of the existing tools were developed as explorative design support tools; in fact all the Danish tools seem to be developed for deterministic studies with evaluation or simulation purposes.
Two international tools were included in the study. These tools are applied as design support tools and design strategy tools, and the tools therefore serve as examples this type of tools.

It was the conclusion of the study of existing tools that the Danish evaluation and simulation tools need to be developed to support explorative design strategy development and sketching in the beginning of the project where the user and site analyses are carried out and the first sketches are made for the project.

Sensitivity analysis as a methodical approach to design strategy development
It is the conclusion of this PhD project that sensitivity analysis is a very relevant as a methodical approach to the development of project specific design strategies, because it provides qualitative information about the sensitivity and robustness of selected input parameters in a project specific situation.
The sensitivity analysis does not result in an ‘optimum’ solution for changes to the reference building, which means that it does not restrict the creative freedom of how the designer achieves the values applied in the analysis. It is the conclusion of this PhD project that the selection of the variable input parameters needs careful consideration, and that these should be determined through a study of the design principles suggested in design strategies for e.g. office buildings or institutions described in methodical approaches for this type of building as well as a study of the applied design principles in these buildings.
The input parameters suggested in this project are based on a study of design principles for residential buildings, as well as the possible parameters made available in the Be06 programme. There is therefore a need for further research in relation to which input parameters should be made available for e.g. office buildings and other types of non-residential buildings. In the Be06 programme this could for instance include the level of artificial lighting and daylight, as well as differences in day and night time cooling as variable input parameters for non-residential buildings.

It is the conclusion of this PhD project that the methodical approach of sensitivity analysis is too time consuming in its current form and it, therefore, needs to be integrated in a dynamic design strategy support tool. This integration can either happen via the development of one of the existing tools or a new tool which enables investigation of more than just the predicted energy consumption in buildings, e.g. inspired by the Arup SPeAR tool.
This PhD thesis therefore contains a suggestion for how sensitivity analysis can be integrated in the existing Be06 programme. This suggestion should be regarded as an early sketch for the sensitivity analysis interface the Be06 programme for which input parameters could be interesting to vary. The suggestion does not discuss the details of the software development, which needs to be designed in cooperation with a software developer.

The interface sketch is based on the assumption that the mathematical models applied for the Morris Method in SimLab can be transferred to the Be06 software in combination with a 'simulation model' which need to be developed. The 'simulation model' should contain the information about how the changes in the parameters correspond to changes in the input data in the Be06 reference building during the simulation.
This was solved in this project for some of the suggested input parameters via manual changes in an excel spreadsheet and insertion of the corresponding changes in a new calculation in the Be06 programme (please refer to Enclosure C for a short description of these iterations). The experiment conducted in this thesis can therefore serve as inspiration for the software development needed for the Be06 programme.

11.3 Research question

The research question presented in the introduction chapter of this PhD thesis was: 'How can existing design evaluation tools be adapted to support the development of design strategies for environmentally sustainable buildings?'

This PhD attempts to answer this question based on a study of the methodical approaches to environmentally sustainable buildings (process descriptions and design strategies), a study of the professional differences and a best practice example of a multi-professional practice (Arup Associates), and an experimental sensitivity analysis applied for design strategy development. The conclusions of these studies were that the development of a design strategy in the early stages of the design process is important. This led to an experimental sensitivity analysis, which tested whether sensitivity analyses can be applied as a methodical approach to early design strategy development.

It is the overall conclusion of this PhD project that sensitivity analysis can be used to identify the sensitive parameters in the early stages of the design process, but that sensitivity analysis in its current form is too time consuming because one has to switch back and forth between the sensitivity analysis programme (e.g. SimLab) and the energy calculation programme (Be06).
It is the conclusion of this PhD thesis that existing design evaluation tools can be adapted to support the development of project specific design strategies for environmentally sustainable buildings through the integration of e.g. the Morris Method for sensitivity analysis. This PhD project therefore suggests that the sensitivity analysis should be integrated in a tool either via an extension to the existing programmes (e.g. the Be06 programme) or the development of a new environmental performance programme that supports project specific design strategy development for environmentally sustainable buildings.

[1] The scope of the project will dictate the parameters selected as variable and permanent and the ranges and distribution functions of the variable parameters, which are defined by the design team in relation to the specific project.

12 Perspectives

This chapter contains a discussion of the perspectives of the project in relation to the design strategy development experiment in chapter 9, the implications that the findings have on the design process and the development of new tools, as well as perspectives for future research.

12.1 Sensitivity analysis as a methodical approach to design strategy development

If integrated in a tool that supports design strategy development, sensitivity analysis can enable the architect to reclaim some of his or her former power in relation to the interaction with engineers. Today some architects feel forced to accept changes made by engineers in the detailing stage of design processes because they have no way of engaging in a dialogue with the engineers. The methodical approach to design strategy development suggested in this thesis addresses this issue by engaging in the inter-disciplinary interface between the architectural and building engineering professions and suggesting that sensitivity analyses, which are usually applied by engineers in relation to optimisation, are used as the facilitator of this inter-disciplinary interface, by enabling a discussion between the architect and engineer about which input parameters should be variable in relation to a specific project.
The inter-disciplinary interface enabled by the sensitivity analysis is defined by the selection of input parameters in relation to the way calculations are performed by the programme (the Be06 programme in this project) and an identification of the architectural issues relating to the calculation parameters that the programme applies for the calculation (e.g. the surface areas of the respective elements of the building envelope and the U-values of these elements etc.). This means that the selection of the pre-defined input-parameters in this specific type of tool needs careful consideration , and that the programme selected for the external model in the sensitivity analysis (in its current form) or for integration of a sensitivity analysis interface (as suggested in this thesis) will have a great influence on the design of the inter-disciplinary interface and how well this enables an integrated design process.

If integrated in a simple design strategy development support tool the sensitivity has the potential to enable easy application of environmentally sustainable considerations in Danish building design by people who have limited or no experience with the design of environmentally sustainable buildings. It is the idea, that the designer inserts his reference building in e.g. the Be06 programme, specifies which of the pre-defined variable he wants to vary in his analysis along with the ranges and distribution functions of each of these variable parameters and asks the programme to perform a sensitivity analysis.

In order to achieve environmentally sustainable buildings that consider more than just the energy performance of buildings, a new tool would need to be developed that considers a more holistic range of sustainability indicators than just the energy consumption of buildings, such as ecology and cultural heritage, materials, land use, transportation, economic viability, waste etc (illustration 105.2).

12.2 Implications on design

The development of a design strategy development support tool based on sensitivity analysis requires that the designer embraces the inter-disciplinarity of environmentally sustainable design. This will require a change in the mindset of Danish mainstream architects and engineers and changes in the organisational structure of practices and the recruitment of a multi-professional staff. These changes do not come easy as they tap into the survival instincts of the architectural profession and their concern for the preservation of architectural quality in building design.
Maybe the future will see a merge of architectural and engineering practices, or maybe the architectural profession will try to regain its former status as the leader of project teams by branching out and hiring engineers to supplement their current staff (e.g. staff with hybrid and inter-disciplinary educations like the one developed at the Department of Architecture and Design at Aalborg University (Denmark)). The is, however, somewhat unlikely seen in the light of the development in other countries (e.g. the UK) where it has been the engineering practices

(a.g. Arup Associates) that have branched out and hired their own in-house architects.
With this PhD thesis I would like to encourage Danish architectural practices to embrace the multi-professional development caused by increases in the complexity of especially environmentally sustainable building design and engage actively in setting the agenda for how architects and engineers should cooperate in the current and future marketplace.

Design strategy development support tools, like the one suggested in this thesis, could facilitate an inter-disciplinary approach which does not require a lot of changes in the current organisational structure of Danish architectural and engineering practices if architects and engineers can agree on which tools to apply, which input parameters to vary and what the ranges and distribution functions of the parameters should be.
Design strategy development support tools can, however, also easily be used by inter-disciplinary and multi-professional design teams. The main difference between the traditional team structure and an inter-disciplinary and multi-professional team would probably be in the selection of the tools, input parameters, and the ranges and distribution functions, where the inter-disciplinary and multi-professional design team would come to an agreement a lot faster than a design team following the traditional team structure.

The approach taken in the sensitivity analysis approach to design strategy development requires a parametric approach to the design process in which input parameters relating to both the architectural design and the engineering design of buildings are regarded as variables one can change within a spectrum defined by the scope of the project. This approach might not appeal to all types of architects, because it requires a lot of reflection-in-action as well as a large degree of process awareness, which may not come natural to some architects educated in the existing architectural education system.
In relation to this it is important to acknowledge that a parametric approach to the design process does not necessarily limit the creative freedom of the architect. In fact it might even increase this creative freedom because it enables a 'tug of war' between the architects and the building engineer in which the boundaries of the project are debatable, instead of the current situation where a lot of architects experience a sense of impotence when it comes to discussing design changes with the engineer because of communication boundaries on both sides of the table.

12.3 Research perspectives

The research presented in this PhD thesis only touches the surface of the development of a design strategy development tool. There is therefore a need for further research in relation to which calculation parameters to apply for non-residential buildings and in relation to the development of existing deterministic programmes into explorative programmes or the development of a new type of programme for design strategy development for environmentally sustainable buildings which takes a more holistic approach to sustainability e.g. inspired by the indicators of the Sustainable Project Appraisal Routine (SPeAR) depicted in illustration 105.2.
The development of the programme software needs to take place in a multi-professional environment to ensure the quality of the interface and calculations.

The project has furthermore increased the interest in doing participatory observation of integrated design projects aiming at environmentally sustainable architecture, in order to study firsthand what the success-criteria are for the application of integrated design processes and the achievement of environmentally sustainable architecture. It would also be interesting to participate in the development of tools that integrate sensitivity analysis as a methodical approach to design strategy development, and do a case study of how it is applied in practice.

13 BIBLIOGRAPHY

This chapter contains an overview of the references applied in this PhD project with respect to publications, web pages and study trips.

Publications are usually regarded as the most valid sources of information because they have gone through an editing process and because they are often written by researchers, while web pages are usually regarded as the least valid sources of information because they are not subjected to editing and can be posted by both laymen and professionals. Web pages do, on the other hand, have the advantage of easy and quite revision, which means that it is possible to find information on web pages which might not be published for a couple of years, and in some cases it is possible to find information which will not be published at all because it is only of interest to a small group of people.

The approach taken in this PhD project to the sources of information has been as follows; publications were preferred over web pages for definitions and information about methodical approaches and built examples. In some cases the web pages of architects and engineers were preferred over publications with respect to getting the architect's and engineer's idea about a project in his or her own words.
Web pages have also been used for supplementing information about building projects that were already published or for information about unpublished building projects. When web pages were used as the primary source of information an attempt was made to find a supplementing source of information that could verify the information of the primary source. Web pages were also used for verification of information acquired on study trips.

Publications

ADA 1997: "Associerede Danske Arkitekter nr. 9 – oktober 97", Denmark 1997

Andersen M. et. Al 1973: "Byg 73 - aalborghallen 14.-23. september Bygge og Boligudstilling", printed in Denmark.

Aggerholm and Grau 2005: 'SBi anvisning 213 Bygningers energibehov – PC program og beregningsvejledning' by S. Aggerholm and K. Grau, Danish Building Research Institute, Hørsholm, Denmark

Andersen et. al 2002: 'INTRODUKTION Videnskabsteori og Metodelære' ('INTRODUCTION Theory of Science and Methodology') by Heine Andersen m.fl., Samfundslitteratur, Frederiksberg, Denmark

Andresen 2000. "A Multi.Criteria Decision-Making Method for Solar Building Design", PhD Thesis, (Trondheim University), Norway

Andrews R. 2003: 'Research Questions' by Richard Andrews, Continuum, London & New York.

Baker N. and Steemers K. 2000, Energy and Environment in Architecture – A technical design guide, E&FB Spon, London, U.K.

Baldwin 1996: "Bucky Works – Buckminster Fullers Ideas for Today" by J. Baldwin, USA 1996

Ballantyne 2001: 'What Is Architecture?' by Andrew Ballantyne, Routledge.

Baynes, Bohman and McCarthy 1987: 'After Philosophy – end or transformation' edited by K. Baynes, J. Bohman and T. McCarthy, MIT Press, USA. Page: 325-338 (Gadamer: Hermeneutics as Practical Philosophy)

Behling 2000: 'Solar Power – the evolution of sustainable architecture' by Sophia and Stefan Behling, Prestel Verlag, London

Bech-Danielsen 2005: ‘Ecological Reflections in Architecture’ by Claus Bech-Danielsen, The Danish Architectural Press, Copenhagen, Denmark

Boligforeningen Ringgården 2004: Material received from the housing association in 2004 about the Eco-house 99 Skejby.

Box et al 1978: ‘Statistics for Experimenters - An Introduction to Design, Data Analysis, and Model Building’ by Box, G.E.P., Hunter, W.G., Hunter, J.S, John Wiley & Sons, 1978.

Breesch and Janssens 2004: ‘Uncertainty and Sensitivity Analysis of the Performances of Natural Night Ventilation’ by H.Breesch and A. Janssens. Published in the conference proceedings of Roomvent 2004, 9th International Conference on Air Distribution in Rooms, Coimbra, Portugal, 5 – 8 September, 2004.

Brohus, Frier and Heiselberg 2002: ‘Stocastic Single and Multizone Models of a Hybrid Ventilated Building – A Monte Carlo Simulation Approach’ by H. Brohus, C. Frier and P. Heiselberg, IEA Annex 35 – Technical Report (TR19)

Brohus, Frier, Heiselberg and Haghighat 2002: ‘Quantification of Uncertainty in Thermal Building Simulation by means of Stochastic Differential Equations’ by H. Brohus, C. Frier, P. Heiselberg and F. Haghighat, IEA Annex 35 – Technical Report (TR18)

By og Bolig Ministeriet 2001: ‘Bæredygtigt byggeri betaler sig – evaluering af ØKOHUS 99’ by By og Bolig Ministeriet, 2005 (Available at http://www.social.dk/media/SM/Bolig/Baeredygtighed_og_oekologi/Baeredygtigt_byggeri_betaler_sig.ht August 2007)

BYG.DTU 2003: ‘Ruder og vinduers energimæssige egenskaber – compendium 1: Grundlæggende energimæssige egenskaber’ by BYG.DTU, Technical University of Denmark, Kgs. Lyngby, Denmark

Cox and Fischer Boel 2002: ‘EUROPA-PARLAMENTETS OG RÅDETS DIREKTIV 2002/91/EF
af 16. december 2002 om bygningers energimæssige ydeevne’ by P. Cox and M. Fischer Boel. Published in ‘De Europæiske fællesskabers tidende’, 2002, Denmark. The internet link is from November 11th 2004. (Available at http://europa.eu.int/eur-lex/pri/da/oj/dat/2003/l_001/l_00120030104da00650071.pdf)

Dahl 2006: lecture by architect Olav Dahl (recorded file available on project CD)

DAL 2003: ‘Arkitektur og bæredygtighed i dansk boligbyggeri – dommerkomiteens betænkning’ by DAL’s competition secretariat. Published by Boligforeningen Ringgården, Denmark

Daniels 1997: ‘The technology of ecological building – basic principles and measures, examples and ideas’ by Klaus Daniels, Birchhäuser Verlag 1997

Daniels 1998: ‘Low-tech light-tech high-tech: building in the information age’ by Klaus Daniels, translated by Elizabeth Schwaiger, Birkhäuser, Basel, Switzerland

DS418 2002: ‘Calculation of heat loss from buildings’, Danish Standard Association, Charlottenlund, Denmark

Edwards 2003: Green Buildings Pay, by Brian Edwards, Spon Press, New York (isbn: 0-415-26271-2)

Eiler-Rasmussen 1989: ‘Om at opleve arkitektur’ by S. Eiler-Rasmussen, Fonden til udgivelse af arkitekturværker, Aarhus School of Architecture, Denmark

Ellen K. Hansen 2007: http://www.lysnet.com/download/Vinduet_som_lyskilde_EKH_09-07.pdf September 2007

Foucault 1972: The archaeology of knowledge, London:Travistock

Foucault 1980: 'Power/ Knowledge: Selected Interviews and Other Writings, 1972-77' by M. Foucault, edited by Colin Gordon. Harvester Wheatsheaf. Chapter 6.

Fromonot 2003: "Glenn Murcutt buildings + projects 1962-2003" by Francoise Fromonot, UK 2003

Gibbons 2001: 'Re-thinking Science – knowledge and the public in an age of uncertainty' by Gibbons, Nowotny and Scott, polity press and Blackwell publishers Ltd, Cambridge and Oxford 2001.

Gauzin-Müller D. 2002, Sustainable Architecture and Urbanism – concepts, technologies, examples, birkhäuser, Basel, Switzerland.

Gore 2006: 'An Innocent Truth - The planetary emergency of global warming and what we can do about it' by Al Gore, Bloomsbury Publishing PLC

Gram-Hansen and Petersen 2005: 'Husholdningers energi og vandforbrug – afhængighed af socio-økonomiske baggrundsvariable' SBi, 2005:9, Hørsholm, Denmark.

Gutman 1988: 'Architectural Practice – a critical review' by Robert Gutman, Princeton Architectural Press, New York, U.S.A.

Hagan 2001: 'Taking Shape – A new contact between architecture and nature' by Susannah Hagan, Architectural Press, Great Britain.

Hamby: 1994: 'A review of techniques for parameter sensitivity analysis of environmental models' by D. M. Hamby in Environmental Monitoring and Assessment, Vol. 32 pp. 135-154

Hansen, Kjerulf-Jensen and Stampe 1997: 'Varme og klimateknik, Grundbog' by H.E. Hansen, P. Kjerulf-Jensen and Ole B. Stampe. Published by Danvak Aps, Denmark

Hansen and Knudstrup 2005: 'The Integrated Design Process (IDP) – a more holistic approach to sustainable architecture' by H. T. R. Hansen and M. Knudstrup, Dept. of Architecture and Design, Aalborg University (Denmark) for The 2005 World Sustainable Building Conference, Tokyo, 27-29 September 2005 (SB05Tokyo)

Hansen 2006: 'Synthesis through trans-disciplinarity' by H. T. R. Hansen, Dept. of Architecture and Design, Aalborg University (Denmark) for Scroope 18, Department of Architecture at the University of Cambridge, UK, May 2006, ISSN: 0966-102, page: 36-43

Hansen, Knudstrup and Heiselberg 2007: 'A parametric design strategy aiming at environmentally sustainable residential buildings' by H. T. R. Hansen and M. Knudstrup, Dept. of Architecture and Design, and P. Heiselberg Dept. of Civil engineering, Aalborg University (Denmark) for the Central Europe towards Sustainable Building 2007 (CESB07) conference, Prague, Czech Republic, September 2007

Hansen, Madsen and Madsen 2003: Den integrerede design process fokuseret på bæredygtighed og methode' ('The Integrated Design Process Focused on Sustainability and Method') by H. T. R. Hansen, K. M. H. Madsen and B. J. Madsen, 9th semester project, Dept. of Architecture and Design, Aalborg University (Denmark).

Hascher, Jeska and Klauck 2002: 'Office Buildings – a design manual' by Rainer Hascher, Simone Jeska and Birgit Klauck, Brikhaüser, Basel

Hawkes 1995: The environmental tradition studies in the architecture of the environment, by Dean Hawkes, Taylor and Francis, UK

Hawkes, McDonald and Steemers 2002: 'The Selective Environment – An approach to environmentally responsive architecture' by Hawkes D., McDonald J. and Steemers K. 2002, Spon press, London, U.K.

Hawkes and Forster 2002: 'Architecture, Engineering and Environment' by Dean Hawkes and Wayne Forster, 2002, Laurence King Publishing, London

Heidegger 1977: 'The Question Concerning Technology and other essays' by M. Heidegger, translated with an introduction by William Lovitt, Page: 3-35. Harper & Row,

Heiselberg 1994: 'Draught Risk From Cold Vertical Surfaces' by P. Heiselberg. Published in Building and Environment Vol. 29, No. 3, pp. 297-301

Heiselberg et al 2007: 'Application of Sensitivity Analysis in Design of Sustainable Buildings' by P. Heiselberg, H. Brohus, A. Hesselholt, H. Rasmussen, E. Seinre and S. Thomas, Department of Civil Engineering, Aalborg University (Denmark) for The International Conference on Sustainable & Development in Building and Environment Chongqing, China September 2007

HVAC 2004: Hjortekær lavenergihus – 25 år 'and still going strong', by J. M. Schultz, P. Riis and L. L. Overgaard, HVAC 8 2004, Denmark

IEA ANNEX 44 2004: 'Meeting Minutes, IEA ANNEX 44 2nd Preparation workshop Trondheim (Norway)' by P. Heiselberg.

Jansen and Johnsen 2000: 'Sundhedsfremme i teori og praksis. En lære-, debat- og brugsbog på grundlag af teori og praksisbeskrivelser' by T. K. Jansen and T. J. Johnsen. Philosiphia, Århus, Denmark, Appendix 1.

Jensen 2002: 'Livsstil, boform og ressourceforbrug' by J. O. Jensen, PhD thesis from the Danish Building Research Institute, BookPartner, Nørhaven Digital A/S, Denmark, chapters 5 and 6 (available at http://www.sbi.dk/miljo-og-energi/livsstil-og-adferd/livsstil-boform-og-ressourceforbrug/livsstil-boform-og-ressourceforbrug August 2007)

Jodidio 2001: 'Architecture Now!' by Philip Jodidio, Taschen, Cologne, Germany.

Jodidio 2002: 'Architecture Now!2' by Philip Jodidio, Taschen, Cologne, Germany.

Jodidio 2004: 'Architecture Now!3' by Philip Jodidio, Taschen, Cologne, Germany.

Jodidio 2006:'Architecture Now!4' by Philip Jodidio, Taschen, Cologne, Germany.

Knudstrup and Marling 1998: 'Bymiljøvurdering af danske boligbebyggelser', Department of Planning and Development, Aalborg University (Denmark), Handelstrykkeriet, Aalborg.

Knudstrup 2000: 'Study guide for 6th semester, Architecture. Architecture and Ecology – Energy and environment in Architecture' by M. Knudstrup, Department of Architecture & Design, Aalborg University (Denmark)

Knudstrup 2004: 'INTEGRATED DESIGN PROCESS IN PROBLEM-BASED LEARNING -Integrated Design Process in PBL, The Aalborg PBL model – Progress, Diversity and Challenges' by M. Knudstrup, editors: Kolmoes A., Fink K. F, Krogh L., Aalborg University Press, Aalborg University, Denmark. (Draft available at http://www.aod.aau.dk/institut/ansatte/Dokumenter/artikel.%20PBL.Engelsk.%20MAK.25%20juni.2.pdf)

Knudstrup 2006: 'Barriers and Challenges in the Integrated Design Process Approach' by M. Knudstrup, Dept. of Architecture and Design, Aalborg University (Denmark) for The International Conference on Asia – European Sustainable Urban Development, Chongqing, China April 4-6 2006

Knudstrup, Hansen and Brunsgaard 2007: 'Approaches to Sustainable housing in Denmark and the international inspiration' by M. Knudstrup, H. T. R. Hansen and C. Brunsgaard, Dept. of Architecture and Design, Aalborg University (Denmark) for The International Conference on Sustainable & Development in Building and Environment Chongqing, China September 2007

Kommunefunktionærernes Boligforening 1980 'En bolig på Østerbro ved Kildeværldsparken – afdeling 3, Copenhagen 1980

Krausse and Lichtenstein 1999: "Your Private Sky - R. Buckminster Fuller" written by R. Buckminster Fuller, edited by J. Krausse and C. Lichtenstein, USA

Kuben Boligbyg a/s 1992: '30 andelsboliger Stolpedalsparken Hasseris', case no. 5961.

Kuhn 1996: 'The Structure of Scientific Revolutions' by T. S. Kuhn (2nd edition), postscript 1969. University of Chicago Press, USA

Kvale 1997: 'Interview – En introduktion til det kvalitative forskningsinterview' by S. Kvale, Hans Reitzels Forlag, Denmark

Lam and Hui 1996: 'Sensitivity Analysis of Energy Performance of Office Buildings' by J. C. Lam and S. C. M. Hui, Building and Environment Vol. 31, No. 1, pp. 27-39, 1996

Lawson 2006: 'How Designers Think – the design process demystified' by B. Lawson, Architectural Press/Elsevier, Great Britain

Living Architecture 2001: 'Living Architecture no. 18' by V. Udsen, Per Nagel, Denmark (more information available at http://www.livingarch.com/site/02/02_18.php august 2007)

Marsh, Lauring and Petersen 2000: 'Arkitektur og miljø – form, konstruction, materialer og miljø påvirkning' by R. Marsh, M. Lauring and E. H. Petersen, Arkitektskolens forlag, Aarhus, Denmark.

Mostaedi 2002: 'Sustainable Architecture Low Tech Housing' by A. Mostaedi, Gingko Press, Spain 2002, ISBN-10: 8489861781 and ISBN-13: 978-8489861787

Mostaedi 2003: 'Sustainable Architecture High Tech Housing' by A. Mostaedi, Gingko Press, Spain 2003, ISBN-10: 848986179X and ISBN-13: 978-8489861794

Nesbitt 1996: 'Theorizing a New Agenda for Architecture – an anthology of architectural theory 1965-1995' by Kate Nesbitt, Princeton Architectural Press, New York

Olgyay 1963: 'Design with Climate – a bioclimatic approach to architectural regionalism' by V. Olgyay, Princeton University Press, New York, USA.

Outhwaite 1996: ‘The Habermas Reader’ edited by W. Outhwaite, chapter 5 and 8

Owen Lewis 1999: ‘A Green Vitruvius: Principles and Practice of Sustainable Architectural Design’, edited by J. Owen Lewis, James & James (Science Publishers).

Popper 2002: Conjectures and refutations – the growth of scientific knowledge, by Karl R. Popper, Routhledge and Kegan Paul, London, page: 33-65

Powell 1999: “Rethinking the Skyscraper – The complete architecture of Ken Yeang” by Robert Powell, Thames & Hudson Ltd., London

Pregizer 2002, ‚Grundlagen und Bau eines Passivhauses’ by D. Pregizer, C.F. Müller verlag, Heidelberg, Germany.

prEN ISO 13790 (2005): ’Thermal performance of buildings – calculation of energy use for space heating and cooling (ISO/DIS 13790:2005)’, draft from May 2005 submitted to CEN-members by the European Committee for Standardization.

Roaf 2003: ‘Eco-house 2 – A design guide’ by S. Roaf, Architectural Press, 2nd Edition, Oxford, UK

Saltelli, Chan and Scott 2004: Sensitivity Analysis, Edited by: A. Saltelli and K. Chan, John Wiley & Sons Ltd (2000). Reprinted in 2004, Pages: 1-100 and 400-447

Saltelli, Tarantola and Campolongo 2000: ‘Sensitivity Analysis as an Ingredient of Modelling’ by Saltelli, A., Tarantola, S., Campolongo, F. Published in Statistical Science, Vol. 15, No. 4 pp. 377-395

Saltelli, Tarantola, Campolongo and Ratto 2004: ‘Sensitivity Analysis in Practice – A Guide to Assessing Scientific Models’ by A. Saltelli, S. Tarantola, F. Campolongo and M. Ratto, John Wiley & Sons, Ltd., 2004. Chapter 4 (The Screening Exercise).

SBi 2002: ‘Naturlig ventilation i erhvervsbygninger – beregning og dimensionering’ by K.T. Andersen, P. Heiselberg and S. Aggerholm. Danish Building Research Institute, Hørsholm, Denmark

Schmidt 2007: ‘The tectonic practice – in the transition from pre-digital to digital era’ by Anne Marie Due Schmidt, PhD thesis, Department of Architecture and Design, Aalborg University, Denmark.

Schnittich 2003: ‘Solar Architecture – strategies, visions and concepts’ edited by C. Schnittich, Detail – Review of Architecture and Birkhäuser – Publishers of Architecture, München, Germany and Basel, Switzerland.

Schön 1983: ‘The reflective practitioner – how professionals think in action’ by Donald A. Schön, Basic Books Inc., USA (ISBN: 0-465-06874-x, 0-465-06878-2).

Steele 2005: ‘Ecological Architecture – A Critical History’ by James Steele, Thames and Hudson Ltd, London

Steemers and Steane 2004: ‘Environmental Diversity in Architecture’ edited by K. Steemers and M. A. Steane, Routhledge, UK

Steen-Thøde M. et al 1997, Grundlæggende klimateknik og bygningsfysik (Fundamental climate technique and building physique), Aalborg University Department of Building Technology, Aalborg, Denmark

Thau 2006: 'Filosofi & Arkitektur i det 20. århundrede' edited by C. Thau, Kunstakademiets Arkitektskole Inst. I for Bygningskultur, Denmark

Valbjørn et al 2000: 'SBI anv. 196 Indeklimahåndbogen' by O. Valbjørn, S. Laustsen, J. Høwisch, O. Nielsen, P. A. Nielsen, Danish Building Research Institute, Hørsholm, Denmark

Wigginton and Harris 2002: Intelligent Skins by Michael Wigginton and Jude Harris, Oxford, UK, Architectural Press (isbn: 0 7506 4847 3)

Williamson, Radford and Bennetts 2003: 'Understanding Sustainable Architecture' by Terry Williamson, Anthony Radford & Helen Bennetts, Spoon Press, 2003, London and New York
Wines 2000: 'Green Architecture' by James Wines, Taschen, Köln

Wittgenstein 2001: 'Tractatus Logico-Philosophicus' by Ludvig Wittgenstein (original text 1922) p. 1-23, Routhledge.

Yeang 1994: 'Bioclimatic skyscrapers' by Ken Yeang, Artemis, London, England.

Yeang 1999: 'The Green Skyscraper: The Basis for Designing Sustainable Intensive Buildings' by Ken Yeang, Artemis, London, England.

World Wide Web
http://allergi.astma-allergi.dk/regado.jsp?type=page&id=143&domain=this August 2005
http://architecture.about.com/library/blmurcutt-ball-eastaway.htm July 2007
http://architecture.about.com/od/greenarchitecture/Ecology_and_Green_Architecture.htm February 2007
http://archnet.org/library/sites/one-site.tcl?site_id=1231 July 2005
http://dictionary.reference.com April 2006
http://en.wikipedia.org/wiki/Commerzbank_Tower June 2005
http://en.wikipedia.org/wiki/Epistemology September 2007
http://ing.dk/artikel/81337 September 2007
http://passivhus.aau.dk/ROOT/GetAsset.action?contentId=683842&assetId=687395 June 2005
http://rpbw.r.ui-pro.com/ July 2007
http://sundial.arch.hawaii.edu/sundial/vo/vitae98.html September 2007
http://usa.autodesk.com/adsk/servlet/item?siteID=123112&id=9485529 September 2007
http://www.aod.aau.dk September 2007
http://www.architektur.tu-darmstadt.de/powerhouse/db/248,id_122,s_Projects.en.fb15 date: October 2005
http://www.arct.cam.ac.uk/ArchIntranet/newsitem.aspx?rid=2293265&p=1&ix=92&pid=1&prcid=17&ppid=19 July 2007
http://www.arup.com/ July 2005
http://www.arup.com/aboutus.cfm September2007
http://www.assmannsalomon.de/N/down/1040222180_betonprisma_77.99.pdf July 2005
http://www.berliner-impulse.de/fileadmin/Steckbriefe/01_solidar_Marzahn_neu.pdf July 2005
http://www.britannica.com/eb/article-9106052/epistemology September 2007
http://www.builddesk.com/sw14887.asp July 2007
http://www.builddesk.com/sw51169.asp July 2007
http://www.builddesk.de/sw16591.asp July 2007
http://www.byggeplads.dk/grafiktekst/2001-3/1uforkortede/nykredit.htm July 2007
http://www.byggeri.dk September 2007
http://www.climatecrisis.net/ July 2007
http://www.dcue.dk/Default.asp?ID=330 June 2005
http://www.dietrich.untertrifaller.com/project.en.html July 2007
https://www.dong.dk/portal/page?_pageid=74,38341&_dad=portal&_schema=PORTAL June 2005
http://www.dr.dk/friland June 2007

http://www.ebst.dk/BR95 May 2007
http://www.ebst.dk/bygningsreglementer/0/91/0 July 2007
http://www.eca.ac.uk/ecalite/research_staff.cfml?nav2ID=16&nav3ID=100147&resintID=100147 September 2007
http://www.forbrug.dk/english/ September 2007
http://www.fosterandpartners.com/internetsite/Flash.html October 2005
http://www.gingkopress.com/_cata/_arch/sustarc.htm June 2007
http://www.gingkopress.com/_cata/ima2/sustar-0.htm June 2007
http://www.gingkopress.com/_cata/_arch/susthigh.htm June 2007
http://www.greatbuildings.com/buildings/Artists_House_in_N_Sydney.html July 2007
http://www.hydro.com/en/press_room/news/archive/2003_06/co2_trading_en.html June 2005
http://www.ibpsa.org/proceedings/BS2003/BS03_0421_426.pdf, July 2007
http://www.iea-shc.org/task23/ June 2006
http://www.iguzzini.com/html/en/431.html July 2007
http://www.infed.org/thinkers/et-schon.htm May 2007
http://www.ktp-architekten.de/gb_9222.htm July 2007
http://www.mapcruzin.com/news/cc071001a.htm November 2004
http://www.mesiniaga.com.my/web/mbsite.nsf/public/newsroom7.html July 2005
http://www.miljoeogsundhed.dk/default.aspx?node=5245 September 2007 http://www.msa.mmu.ac.uk/bioclimatic/proposit.html March 2006
http://www.nextroom.at/building_article.php?building_id=3843&article_id=7263 October 2005
http://www.peabody.org.uk/pages/GetPage.aspx?id=179 July 2007
http://www.passiv.de May 2007
http://www.passiv.de/07_eng/news/CEPHEUS_final_long.pdf August 2007
http://www.reference.com/search?q=multidisciplinary July 2007
http://www.reference.com/search?q=culture 2007
http://www.rps.psu.edu/unplugged/spring05/wines.html June 2007
http://www.sbi.dk/indeklima/simulering/aktuelle-projekter July 2007
http://www.sbi.dk/miljo-og-energi/miljovurdering/edb-verktoj-beat/generelt-om-beat July 2007
http://www.shef.ac.uk/architecture/main/people/p_pag/bl.html May 2007
http://www.shl.dk May 2007
http://www.statistikbanken.dk/statbank5a/default.asp?w=1280 (> byggeri og boligforhold > Boligforhold > BOL51) October 2005.
http://www.trhamzahyeang.com/project/skyscrapers/mesiniaga01.html July 2005
http://www.trhamzahyeang.com/project/skyscrapers/elephant-tower01.htm February 2007
http://www.trhamzahyeang.com/profile/company.html February 2007
http://www.unige.ch/cuepe/idea/_buildings/b_123/frm_obj.htm January 2005
http://www.units.muohio.edu/aisorg/pubs/issues1/restricted/042/paper.pdf July 2007
http://www.vandkunsten.com/show/skabelon1.asp?ID=311 July 2007
http://www.velfac.dk/ March 2007
http://www.vobs.at/hs-klaus//Texte/Klassen-Überblick.htm November 2006
http://www.zedfactory.com/bedzed/bedzed.html July 2005
http://193.163.166.189/step1.aspx August 2007

Study trips

Study trip 2005: participation in a passive house study trip to Austria and Switzerland arranged in September by 'Erhvervsnetværk Passiv Hus' at Aalborg University.

Study trip 2006: in February to the BedZED project in Hackbridge, London.

14 Illustrations

15 Enclosures

A: Tasks and issues identified in Part 1: Methodical approaches to sustainable architecture

The following tasks and *issues* were identified based on the design strategies and methodical process descriptions studied in Part 1 of this thesis.

Stage	***Tasks and Issues***
Inception	**Project brief** ***Background for the project*** Client's wishes for the building *Architectural references, if any? Purpose of new building? Iconic?Attitude towards the relationship between the building and the context, Client demands in general, Type of building, Type of user, Type of climate, Geographical placement; longitude and latitude* ***Objectives*** Client's description of user needs and user patterns *Comfort requirements, Description of the rooms and functions needed, Specification of the demands for the building technology and strategies, Environmental profile and performance targets* ***Internal and external influences*** Investigation of internal and external influences that may cause restrictions in the project **Economy** Set up of economic frame for the project *Estimate possible restrictions on the technical and aesthetical strategies in the building caused by the economic frame* **Process management** ***Set up design team*** ***Decide steps needed before selecting a contractor*** ***Time schedule for project and distribute responsibilities*** ***Contracts and safeguard financing*** ***Documentation*** Project definition report ***Decisions*** Design start up decision First project initiative **Building codes and regulations** ***Gathering the building codes and regulations that will apply for the building*** **Site** Selection of site and possibly alternative sites *Brownfield vs. Greenfield. (brown preferable to green in most cases), Logistics – transportation to and from site, Type of site (landscape vs. urban), Risk of previous contamination of site* **Building** Client's initial wishes for the architectural expression of the building *Architectural references, Visibility, and architectural expression.* Follow up on issues stated in the project brief *Influence on architectural expression and the technological possibilities* **Comfort** ***Type of climate*** ***Comfort demands stated directly and indirectly in the project brief***

Preliminary Studies	**Project brief** ***Detailing the project brief with findings in analyses and investigations*** ***Feasibility study*** Building programme requirement profile **Economy** ***Costs*** What is possible given the cost constraints? ***Rough cost estimate*** **Process management** Pre-design report Pre-design decisions ***Experts*** *Call in experts or jury* Set up design team Call in expert (e.g. jury) **Building codes and regulations** Consider building codes, regulations and industry standards **Comfort** ***Thermal comfort requirements*** Comfort temperatures *Area, Number of people, Activity level, Clothing resistance, Radiation from hot/cold surfaces, Ventilation rates* ***Atmospheric comfort requirements*** Smell (OLF) *People in the room, Smoke, Materials (building, furniture…), Adaptive comfort* $C0_2$ *People in the room* Ventilation *Ventilation rates are calculated for both OLF and* $C0_2$*. These are compared to the minimum requirements stated in the building code (if stated). The highest ventilation rate is chosen* ***Acoustic comfort requirements*** Reverberation *Reverberation time stated in building codes.* ***Visual comfort requirements*** Glare Colour of light ***Psychological comfort requirements*** Daylight Colours Shape of room	**Site** ***Site analysis (also performed for alternative sites if there are any)*** Investigation of urban integration, proportion and site development Soil conditions (for construction purposes as well as pollution from previous use) Vegetation and wild life Shelter, shade and isolation Logistics Materials applied in the area Vernacular architecture Orientation of the site Sun, wind, temperatures, precipitation etc. on site Previous utilisation of the site Investigation on urban integration, proportion and site development Analysis of site *Information about the site, architecture of the neighbourhood, topography, vegetation, sun, light and shadow, Predominant wind direction, access to and seize of the area and neighbouring buildings, Special qualities of the area* Urban development plans *Regional plans, municipality plans and local plans, building restrictions, Location in the city and relation to general urban plan, logistics, paths, future development plans* ***Site plan*** Diagrammatic sketches for the site plan Conceptual sketches *Daylight/shade, Shelter/exposure, Logistics, Terrain, Vegetation schemes* **Building** ***Function analysis*** Research the building type and find best practice examples Company profile (user profile) *Demands for space, functionality, logistics* Preliminary design approach *Functions, Space, Technological, Visual requirements for each function* ***Architectural expression*** Room programme Chart of functions Principles of energy consumption Principles for (natural) ventilation *Consideration of outdoor conditions, wishes for façade expression, purpose of the building and the demands for functionality* Indoor environment Construction General approach for energy supply and systems

Sketch Studies	**Building** Check interfaces; proportions, multi-functionality, flexibility General Dispositions (mass/functions), horizontal/ vertical development, building periphery Design alternatives Conceptual sketches *Plans; logistics in the building, furniture, orientation of different functions in relation to the comfort requirements of the different functions.Facades; shade vs. exposure, window areas, orientation of windows* ***Technological solutions*** Conceptual sketches *Daylight/shade, Shelter/exposure, Logistics, Terrain, Vegetation schemes* Building plan and section *Section height and depth, no. of floors and orientation to optimise daylighting, enable passive ventilation using the stack effect and to reduce heat loss.* Elevation *Broad proportions of fenestration, with effects of daylighting, ventilation, overheating (on east, west and south facades), external shading.* Solar access *Provide solar access to residential living spaces, Maximise daylight penetration using plan and section* Materials *Structural system and external envelope, and their environmental impact. Use thermal mass. Use locally produced materials* Consider water supply and waste handling methods Iterative studies of design concepts to assess performance Principles of construction Functional demands Comparison of different solutions *Calculation of the consequences of the technical choices by rather simple calculation methods.*	**Project brief** ***Update brief according to decisions and findings.*** ***Check that the overall project corresponds with the brief.*** Renewed/specified building programme performance profile **Process management** Set up/complete design team Call in expert **Site** Site layout/Plan *Protection and use of pre-existing site characteristics: vegetation, landscaping, topography, water, site disposition for isolation, shading and shelter, proportion of hard landscaping for water runoff conservation, vegetation and shelter, cold air drainage. Orientation, zoning and general disposition, with impact on energy consumption. Use passive solar strategies including daylight.* **Comfort** Principles for (natural) ventilation *Considering outdoor conditions, wishes for façade expression, purpose of the building and the demands for functionality* Principles of energy consumption and indoor environment Estimation of how the choices regarding form, plans, room programme, orientation of building, the construction of the climate screen influence the energy consumption in terms of heating, cooling, ventilation and daylight.

Pre-project	**Project brief** Demands and wishes for the building are met *For architecture, design, working environment and visual impact.For functions, construction, energy consumption and indoor environmental conditions.* Review goals and requirements, **Economy** Qualified cost estimation Cost *Consider factoring environmental life cycle cost into initial estimates. Where higher initial cost is proposed this may be for better performance, improved environmental quality, and/or lower life cycle energy cost. Design for re-cycling* **Process management** Specialist consultants *Presentations should indicate how environmental principles will be developed in the detailed design stage, and how proposals will be evaluated, with maximum us of passive systems* Concept design report Concept design decisions **Building codes and regulations** Administrative authorities *Consult about innovative propositions for fresh water supply, rain water disposal or reuse, grey and black water disposal. Discuss advantageous tariffs for low consumption with utilities. If the building generates electricity (PV panels, wind) discuss buy-back with the utility company as necessary* **Comfort/Climate** Principles of energy consumption and indoor environment Estimation of how the choices regarding form, plans, room programme, orientation of building, the construction of the climate screen influence the energy consumption in terms of heating, cooling, ventilation and daylight. Specify design criteria for services Calculate predicted building performances and assess against the targets	**Site** Site plan and external landscaping *Layout and orientation of building groups in relation to isolation and overshadowing. Size and location of hard surfaces in relation to desired sunlight and shelter. Use earth berms (volde) and shelter planting to create sheltered and protected areas.* Concept design approach **Building** Calculations, simulations, quantifications Design and gross design of system solutions Building performance *Building and energy system, spatial structure and construction, envelope, Daylighting, solar, Traffic and HVAC systems* Concept design approach Principles of construction Functional demands Comparison of different solutions *Calculation of the consequences of the technical choices by rather simple calculation methods.* Building plan and section *Drought lobbies at entrances and where necessary. Optimise use of daylight in habitable spaces. Use zoning in northern latitudes for sanitation, circulation, and storage orientated north. Include airflow paths for natural ventilation in plan (if the building is shallow) and section (perhaps employing the stack effect). Consider room heights for heating, cooling and daylighting* Elevation *Consider proportions of glazing to opaque façade for daylight distribution and passive heating and cooling. Control glare and overheating, particularly on the east and west facades and consider shading devices. Optimise proportion and distribution of external envelope openings with heating and lighting in mind (and cooling).* Materials *Consider use of structural thermal inertia to dampen internal heat fluctuations. (Thermal mass for building use pattern, intermittent or continuous?). Consider sustainability and environmental impact of materials on embodied energy, impact of habitats, toxic emissions and ease of recycling or re-use.* Technical principles *Consider combined heat and power to reduce primary energy use. Provide outline illustration of environmental performance, particularly through plan and section diagrams for passive and active energy flows; heating season day and night, cooling season night, and Sankey diagrams of energy flow.*

Basic Project	**Project brief** Centred requirements performance profiles **Process management** Design development report, building documents Definitive design decisions Complete design team Call in expert Specialist consultants *Consider long life and loose fit building structure and the adaptability of structure and services for different building use. Long-term adequacy of load-bearing capacity. Ensure accessibility to ductwork, pipes and wires with removable covers, demountable trunking. Size conduit drops in walls for easy rewiring.* Documentation of the final calculations regarding the climate screen (building envelope), energy calculations and (natural) ventilation etc. (all technical strategies) Documentation of how the aims and programme of the project are met ***Building Documents:*** Confirmed performance profiles Construction documents Environmental criteria and specs for tender Construction strategies Report(s) *Containing text, diagrams, façades, plans, architectural volumes, details and calculations(, as well as a documentation of the process and a process evaluation for learning purposes)* Drawings *façades, plans, sections, details* Models *Physical models* IT-visualisations *Computer presentation and animation (virtual model) of project* Posters *Containing drawings, text and renderings of virtual or photos of physical models* **Comfort** Indoor environment Technical Principles *Develop design of building services systems from the principles previously enunciated. Make calculations of building energy performance*	**Site** Finalise Layout (plans, sections, elevations) for statutory approvals; *Iimplications for daylight, ventilation, passive and active systems.* **Building** Modular tuning of space use, construction elements Life cycle cost analysis, cost calculation Detailed constructions, Simulation Optimise system solutions, final sizing, system operation System integration, selection of building components and materials Design development approach Final form in which the demands from the aims and programme are met *Architecture, architectural volumes, aesthetic, visual impacts, functional and technical solutions and qualities are created.* Synthesis is reached between; *Architectural expression, plans, visual impact, functionality, company profile, aesthetics, the space design, working environment, room programme, principles of construction, energy consumption and indoor environment technology.* Architectural and functional qualities Construction Energy consumption Select materials and construction materials *having regard to thermal mass, openings and shading, sourcing of materials.* Site and building plans *Confirm earlier decisions on site and building plans: siting and positioning for isolation and shelter, form for overshadowing, layout and extent of hard and soft landscaping. Consider disposal of surface water within site* *Consider treatment of polluted water from vehicle hard standings.* Section and elevation *Confirm floor to floor heights to maximise daylight and natural ventilation and avoid overheating. Confirm façade proportions, and provision and design of external shading to prevent overheating. Consider opening sections in windows for passive ventilation. Confirm previous decisions on sustainable materials*

Execution of Project	**Process management** Develop specifications for good workmanship and site management Specialist contractors *Make green design requirements explicit in all tender packages, especially in specialist packages for design and construct works. These requirements will include directives on the use of as-found material; on construction waste minimisation, handling and disposal; and on the use of environmentally-friendly cleaning materials.* **Site** Site plan *Specify rainwater soak-aways and ponds. Closed sewage treatment systems.* **Building** Detail for thermal performance, daylight, controlled ventilation Specify window and external door frames for environmental performance Consider internal and external finishes for environmental friendliness Consider environmental performance in selection of heating and cooling plant, radiators, controls Specify electrical lighting equipment and controls for lowest consumption Specify sanity fittings for low water consumption Section and elevation *Select glazing frames for best performance. Glazing to incorporate low-emission coatings. Use trickle ventilators and/or passive ventilation strategies. Use heat recovery where appropriate. Insulate beyond building regulation requirements in sustainable materials. Detail to avoid cold bridging.* Materials *Specify for long life and low embodied energy. Masonry components of local origin, roof finishes for long life, greater thickness of sheet flooring, timber boards of low formaldehyde content, lime-based plaster mixes and acrylic and/or water water-based paints are healthier. Monitor consultants to ensure strategy agreed at earlier stages is implemented.* Technical principles and application *Specify mechanical services components for good energy performance over long life, gas fired condensing boilers, best available thermostatic radiator valves, weather compensating heating system controls, underfloor low pressure hot water central heating, mechanical ventilation systems include heat recovery components, low energy lift installations, passive infrared light switching and compact fluorescent lighting, dual flushing WC cisterns, photoelectric cell operated urinals and wash basins, energy and resource efficient domestic appliances. Minimise hot water pipe lengths from storage to point of use.*
Tender procedure	**Process management** Explain the requirements of green design to tendering contractors Requirements upon builders and suppliers. Call for tender Bidding Negotiation Building contracts Building contract decisions Contracting **Project brief** Specify more demanding construction practices and tolerances **Site** Site plan *Limit contractor's working space to protect pre-existing natural features and vegetation. Specify to conserve re-use top soil. Give directions on materials handling and storage to minimise waste.*

Construction (Inspection/ supervision)	**Process management** Final commissioning Commission report certificate of building Building use/rent decisions Contractor should not substitute materials or components without architects approval Ensure acceptable methods for waste disposal **Site** Protect the natural landscape as much as possible **Building** Ensure completeness of insulation coverings and no thermal bridging at openings Check construction standards *Correct installation of insulation. Correct working of materials for health, cutting, spraying. Quality of external masonry. Weather tightness of opening elements. Sealing off openings around pipes penetrating the external envelope. Vapour control membranes. Low emissivity coatings on glazing. Correct disposal of toxic waste. Housekeeping regarding waste materials and recycling of package insulation.* Commissioning plan for energy related Construction works Operational, functional and energy performance checks Analyse and assess impact caused by project change Implementation of necessary changes Construction supervision, cost control, quality assurance Identify and eliminate deficiencies
Acceptance (and advice on building operation and maintenance)	**Process management** Make sure client and users understand building concepts and systems (provide maintenance manuals) Show how to get maximum value from the active system controls Correct building maintenance *Maintaining and renewing floor and wall finishes selected for health and environmental performance. Regular cleaning of windows and luminaries. Maintaining sanitary components to minimise water consumption. Maintaining internal and external planting. Use of suitable, non-toxic, biodegradable cleaning agents. Application of paint and thin film coatings in properly ventilated spaces. Annual inspection of active systems to check continued efficiency of boilers, cooling equipment, radiator valves, infrared switching, heating and cooling controls.* Operating energy management systems *Operating systems to prevent overheating in summer: moveable shading and night-time cooling. Operating ventilation systems: both mechanically assisted and passive: fans, natural ventilation, to optimise balance of ventilation, heating and cooling demand. Operating the building to maximise heat gain and in the heating season: control night-time ventilation, operating blinds to maximise insulation, closing internal doors to retain captured heat, opening shutters to promote desired ventilation. Illustrating the mechanical system controls such as programming time clocks, operating weather compensating controls, setting thermostatic radiator valves, seasonal manipulation of flow temperature in heating system. Operating electrical installations: correct placement of light fittings, discussion of switching on lighting and power, lighting sensors, power zoning. Operating to maximise the use of daylight and minimise use of artificial lighting. Avoiding peak electricity costs (typically at 7:30 to 17:30) by periodically shutting down large plant*

Defects Period (and monitoring environmental performance)	**Process management** Lease/use contract Management and maintenance plan Operation manuals Management, control, optimisation User/operation staff information and training **Building** Monitor active systems for actual as against projected performance Monitoring Environmental Performance *Check air infiltration as a result of drying out and shrinkage leading to poor air tightness. Investigate energy consumption through an entire heating and cooling season, by reference to utilities invoices or electricity, gas, other. These can be totalled over a year and consumption in kWh/m² readily derived. This can be compared with reference figures for an assessment of the overall performance of the building user's comfort, particularly in relation to overheating in the cooling season, where air conditioning is not provided and natural cooling methods are employed, and user satisfaction in relation to daylight availability. Questionnaires can be helpful in this regard. Monitor room temperatures, either by simple maximum/ minimum thermometers or by thermometer linked to computerised recording system, to establish the effectiveness of heating and cooling installations and help determine whether active installations are over-utilised. Water consumption, by monthly and yearly meter readings and a daily consumption in litres per head calculated from the number of building users. Data may be checked with reference to established benchmarks to establish the level of performance.* Occupation Operation strategies Operation Energy checks, monitoring Adjust energy performance to user demand Changes in building use Basics for retrofit design
Maintenance and Refurbishments	**Building** Use green finishes where these were originally applied Use environmentally-acceptable cleaning and sanitation materials Undertake energy audit prior to commencing project Survey the potential for upgrading of active services Survey for potential upgrading of envelope **Comfort** Consider indoor air quality and healthy building environment

C: Iterations in sensitivity analyses

This enclosure contains a description of the iterations between the input parameters and calculation parameters in the local and the global sensitivity analyses reported in chapter 9 of the thesis entitled ‘design strategy development experiment’.

Local sensitivity analysis

Building shape

- Average room height (2.5 to 4.5 m): changes made for the average room height in the building led to changes in the total wall area and the ventilation rates in the Be06 programme.

- Surface area of different shapes in a one storey building with the same total floor area (circle, square, half circle, rectangles with different width to depth ratios (1:2, 1:3, 1:4, 1:5 and 1:6): changes made for the surface area of the different shapes led to changes in the total wall area in the building, the length of the thermal bridges where the wall meets the fundament and thermal bridges at the corners in the building in the Be06 programme.

- Number of storeys (1 to 253): changes made for the number of stories in the building led to changes in the total wall area in the building, the area of windows and doors areas facing north/south/east/west, lengths of thermal bridges around openings and at the corners in the building, and in the heated floor area in the Be06 programme.

Shade

- Placement of window in the depth of the façade (0 to 500 mm): changes made to the distance between the outer edge of the façade and the window glass led to changes in the ‘Window hole %’ and the angle between the outer edge of the façade and the horizontal middle of windows and doors in the Be06 programme.

- Size of overhang (0 to 3000 mm): Changes made to the depth of the overhang led to changes in the angle between the overhang and the vertical middle of the windows and doors in the Be06 programme.

- Shade from surroundings (0 to 90°): Changes made to the shade from surroundings led to changes in the horizontal angle (the angle between the vertical middle of the window and the height of the shading object (e.g. a house or a tree) in the Be06 programme.

- External shade in front of windows (0 to 100% shade in all directions, north, south, east or west): Changes made to the external shade in front of windows led to changes in the shade factor[1] for the windows and doors (f_s) in the Be06 programme.

Window type

- Different types of VELFAC windows with no visual coating: Changes made for the window type led to changes in U-values for the entire window, in the values for the heat transmittance through the glass (g-value), in the glass to frame area ratio (Ff) in the Be06 programme

Window area, angle and orientation

- Different window to floor area ratios (0 to 100%): changes made for the window to floor area ratio led to changes in the window and wall areas in the Be06 programme.

- Different window area to orientation ratios: changes made for the window area to orientation ratios led to changes in the percentage distribution of the window area on the facades in the reference building.

- Rotation of the building (0 to 360°): changes made to the rotation of the building led to changing the rotation parameter in the Be06 programme. This is practically the same as changing the window area to orientation input parameter by rotating the building in the Be06 programme.

- Window angle (0° to 90°, 0 = horizontal, 90 = vertical): changes made for the window angle led to changes in the angle of the windows in the Be06 programme.

Insulation of the building envelope

- U-value walls (0.05 to 0.4 W/m^{2}K), U-value ground floor (0.05 to 0.4 W/m^{2}K), U-value roof (0.05 to 0.4 W/m^{2}K): changes made to the U-values of the walls, ground floor and roof led to changes in the U-values of the walls, ground floor and roof in the Be06 programme.

Thermal mass

- Heat capacity of the building materials (40 to 160 Wh/K m^2): changes made for the heat capacity of the building led to changes in the heat capacity of the building in the Be06 programme.

Ventilation

- Heat-recovery; 0 to 95% (mechanical all year, and mechanical in winter and natural in summer): changes made for the heat-recovery of the ventilation led to changes in the ventilation system from natural to mechanical ventilation, the specific electrical energy consumption used for air transport (SEL) and the heat-recovery percentage of the ventilation system in the Be06 programme.

- Comfort criteria for ventilation rates (0.23 l/s m^2 to 0.56 l/s m^2): changes made for the ventilation rates in relation to different comfort criteria led to changes in the air change rate in the Be06 programme in relation to different types of comfort criteria ($C0_2$ and OLF) for rooms with smoking and no-smoking.

- Ventilation rates winter (0.35 to 0.63 l/s m^2): changes made for the winter ventilation rates related to the analysis of the different room heights. This calculation was performed without changing the total wall area in order to gain an understanding of whether the changes caused in the energy consumption of the building by changing the room height were primarily due to changes in the surface area or the ventilation rates. The changes led to changes in the air change rates for winter situations only in the Be06 programme.

- Ventilation rates summer (0.42 to 2.14 l/s m^2): changes made for the summer ventilation rates led to changes in the ventilation rate of the summer situations only in the Be06 programme as a passive cooling strategy.

Use of the building

- Internal heat gain people (0.66 to 2.63 W/m^2): changes made to the internal heat gain from people led to changes in the internal heat gain from people in the Be06 programme.

- Internal heat gain appliances (210 to 840 W/m^2): changes made to the internal heat gain from appliances (installations) led to changes in the internal heat gain from appliances in the Be06 programme.

- Comfort temperature of user (18 to 26°C): changes made to the comfort temperature of the user led to changes in the dimensioning winter and summer temperatures in the Be06 programme.

- Hot water consumption (109 to 438 l/year m^2): changes made to the hot water consumption in the building led to changes in the hot water consumption in the programme.

Global sensitivity analysis
The input parameters selected for the global sensitivity analysis were:
Building shape
- Number of stories (1 to 6)
- Room height (2.5 to 3.0m).

Insulation of the building envelope
- Effective U-value of the non-transparent parts of the building envelope ($U_{eff, BE}$)(0.09 to 0.2)

Window type, areas and orientations
- Window to floor area ratio (20 to 40%)
- Window area to orientation ratio, window type ~Effective U-value windows (0.5 to -0.5)

Shade
- Depth of window (0 to 500 mm)

Ventilation
- Ventilation rate summer (0.42h^{-1} to 2.18 h^{-1})
- Heat-recovery winter (35 to 95%)

The changes in the Be06 programme caused by changes in the input parameters selected for the global analysis are the same as for the local analysis, the only difference in the global analysis case were that the parameters are changed at the same time, which means that the wall and window areas, lengths of thermal bridges, heated floor areas, ventilation rates and heat-recovery percentages are changed simultaneously in the Be06 programme. This means that when input parameters are changed that influence e.g. the wall and window areas in the building they need to be changed in a specific order in order to ensure that the correct wall and window areas are inserted in the programme.

Based on an analysis of which of the input parameters influences the same calculation parameters it was concluded that some of the selected input parameters should be changed in a specific order in the excel working document to end up with the correct values for the:
- Winter ventilation rates
- Window area to orientation ratios
- Wall and window areas

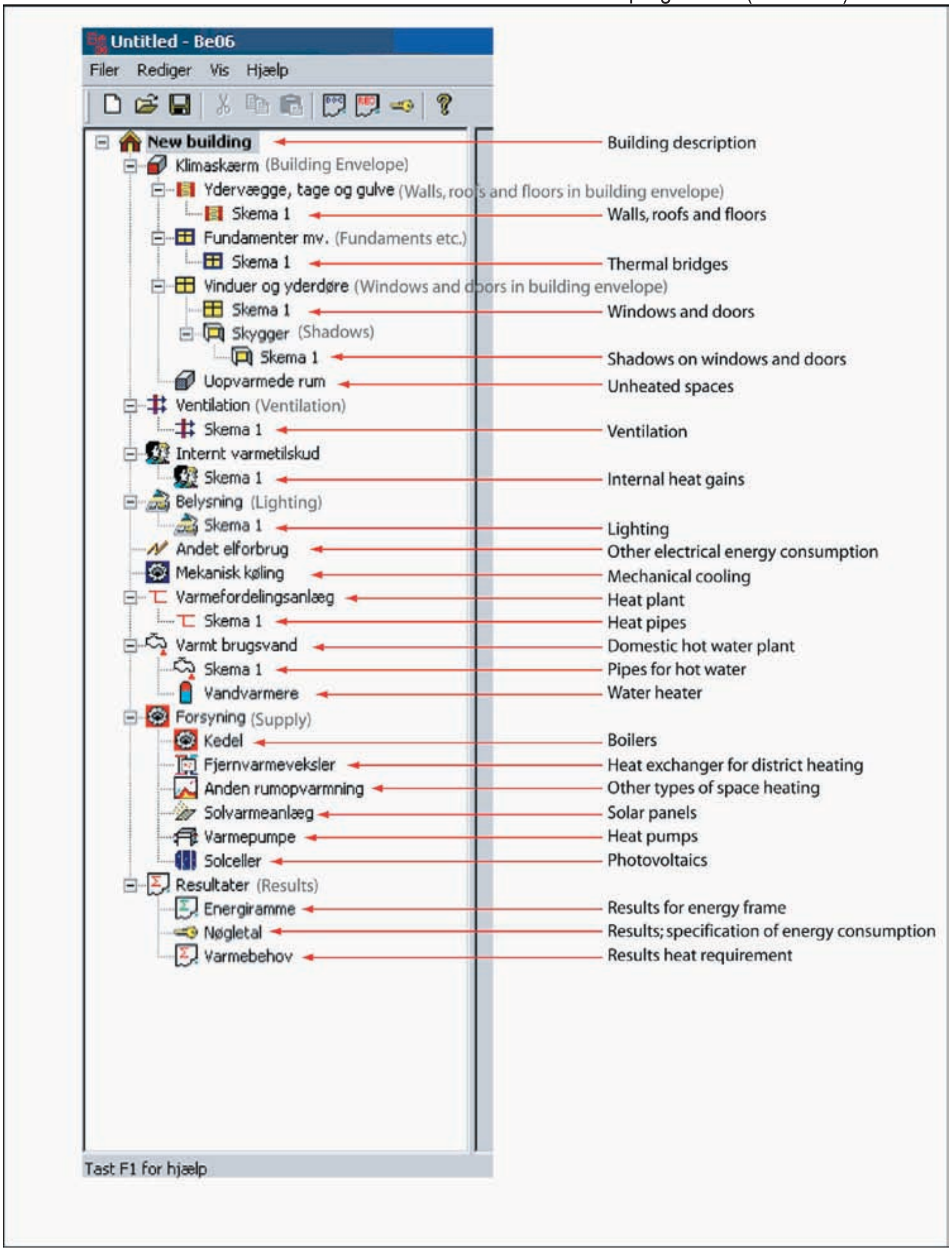
The input parameters were changed in the following order:
1) Heat-recovery winter
2) Ventilation rate summer
3) Depth of window in façade
4) Effective U-value non-transparent elements of the building envelope
5) Average room height
6) Window to floor area ratio
7) Window area to orientation ratio
8) Number of stories in the building

Of these it is especially the last four that are sensitive to the order of changes, while the first four can be changed at any time in the process. In other words; it is the last four parameters that are inter-dependent in relation to the winter ventilation rates, window area to orientation ratios, and wall and window areas. (Please refer to the working documents for the sensitivity analysis on the CD tor more information about this was carried out in the sensitivity analysis).

[1] The shade factor is used in the in the Be06 calculation for the calculation of the passive solar heat gain transmitted through the windows and doors.

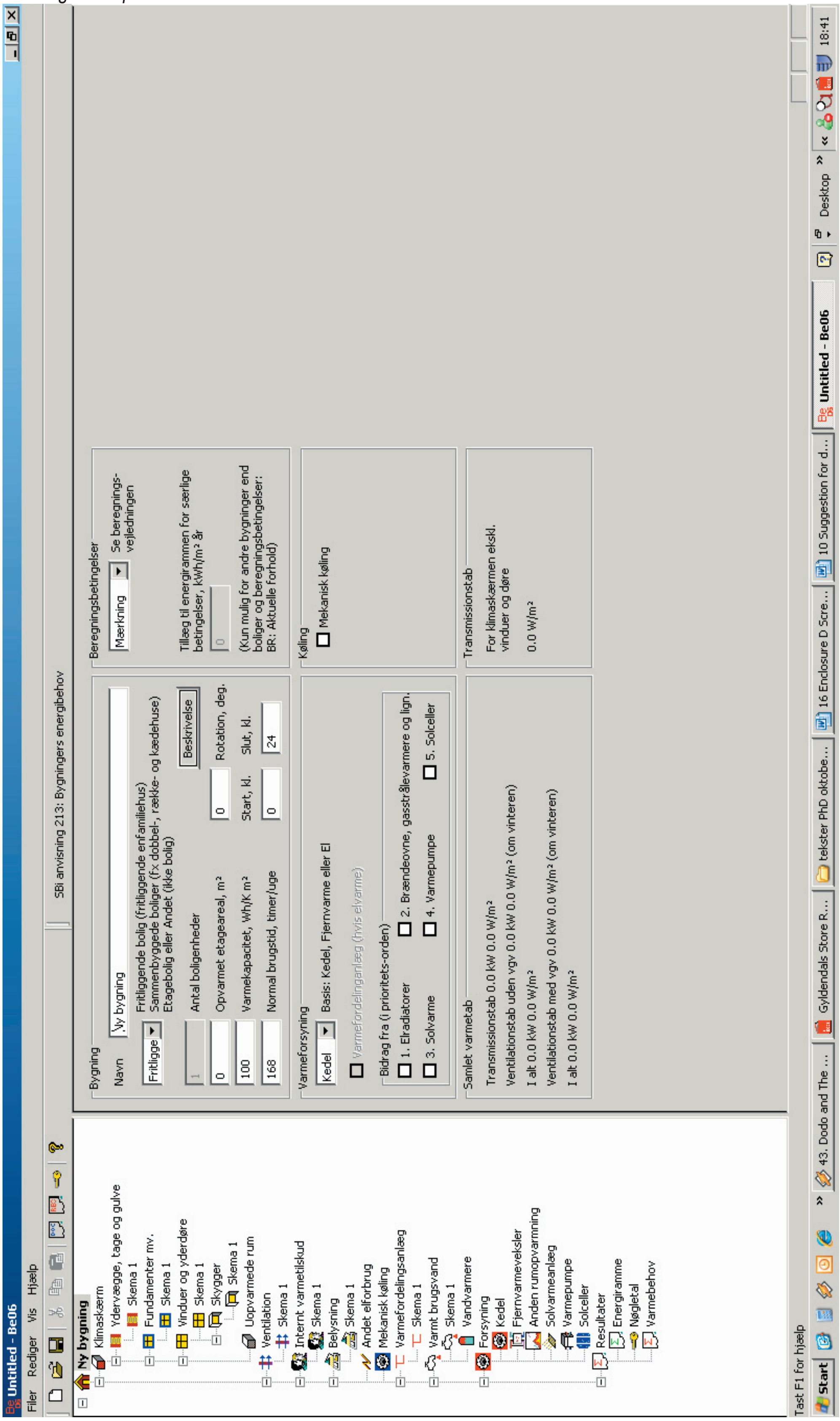
D: Screen shots of Be06 programme interface

This enclosure contains screen shots of the interface in the Be06 programme (in Danish).

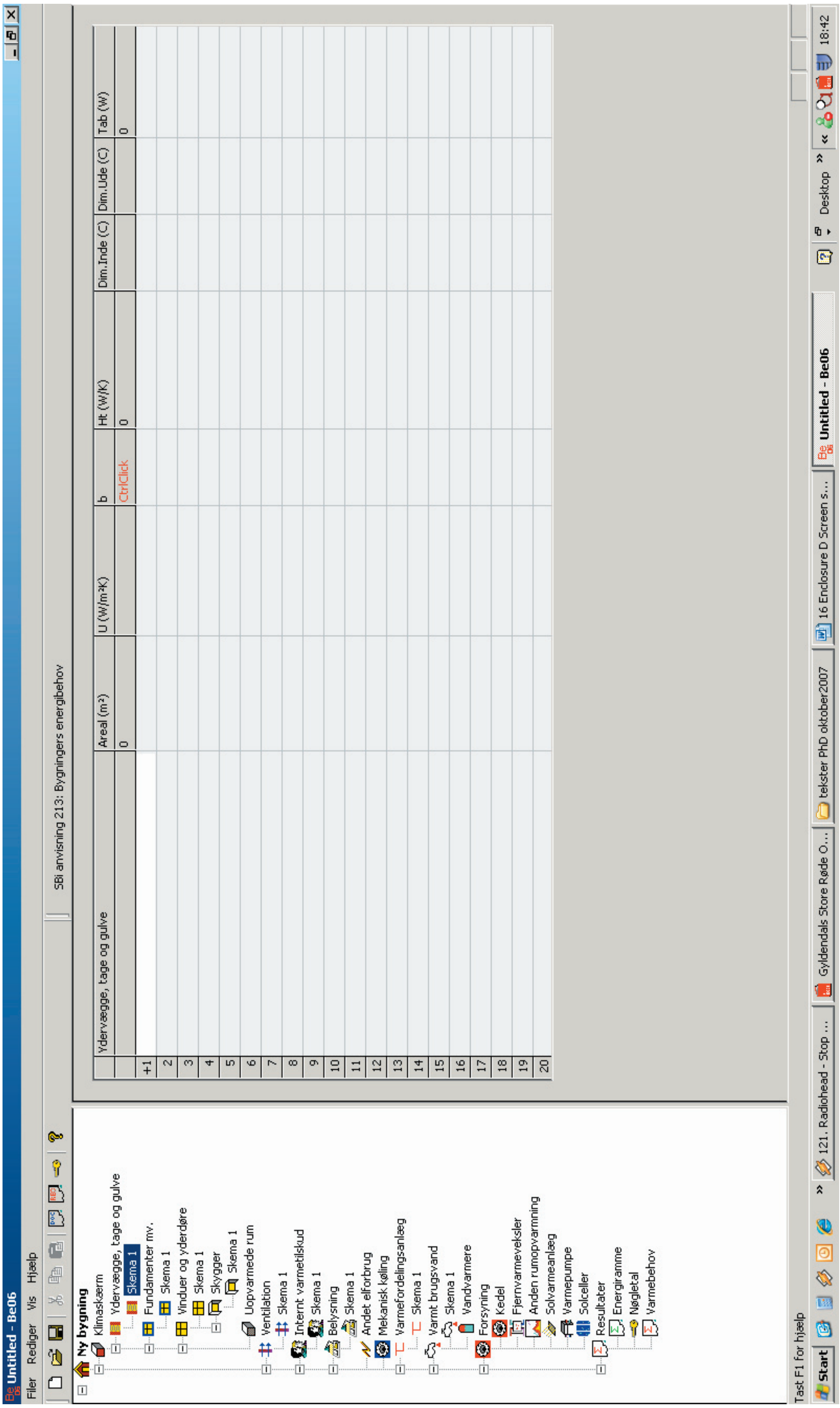


Illu.: Translation of the menu

Building description

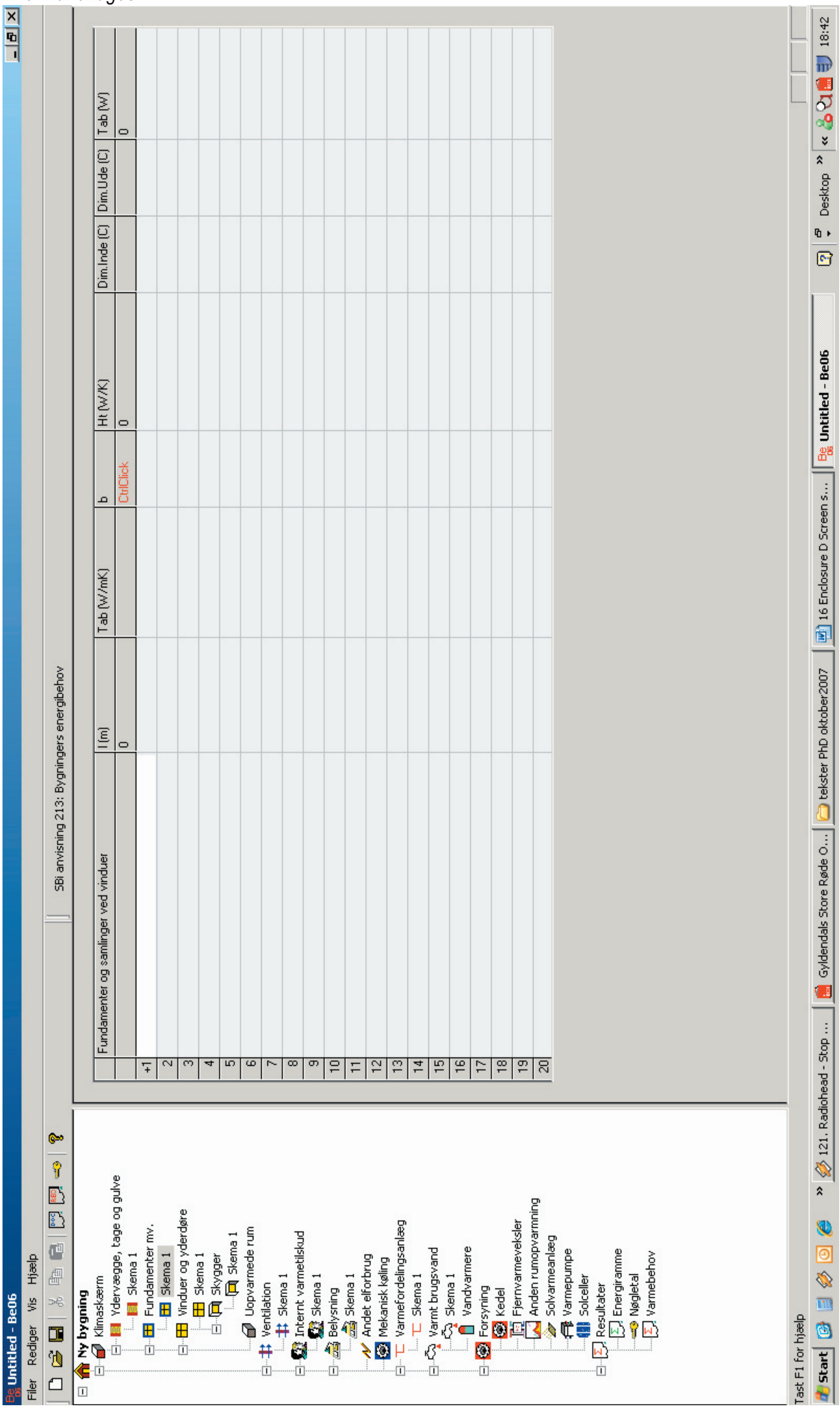


Walls, roofs and floors in building envelope

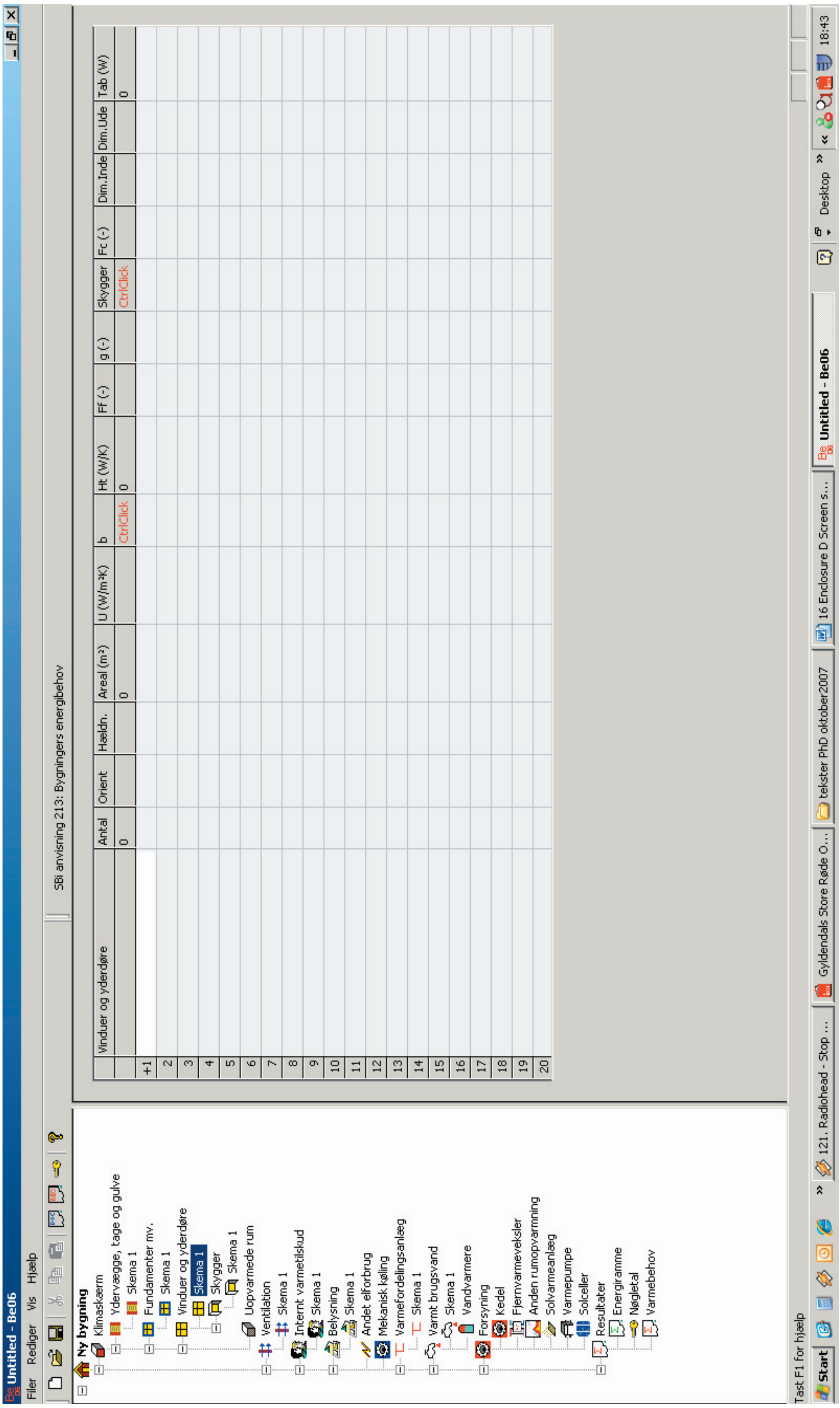


Untitled - Be06
Filer Rediger Vis Hjælp
SBi anvisning 213: Bygningers energibehov
Ny bygning
Klimaskærm
Ydervægge, tage og gulve
Skema 1
Fundamenter mv.
Skema 1
Vinduer og yderdøre
Skema 1
Skygger
Skema 1
Uopvarmede rum
Ventilation
Skema 1
Internt varmetilskud
Skema 1
Belysning
Skema 1
Andet elforbrug
Mekanisk køling
Varmefordelingsanlæg
Skema 1
Varmt brugsvand
Skema 1
Vandvarmere
Forsyning
Kedel
Fjernvarmeveksler
Anden rumopvarmning
Solvarmeanlæg
Varmepumpe
Solceller
Resultater
Energiramme
Nøgletal
Varmebehov
Ydervægge, tage og gulve
Areal (m²)
U (W/m²K)
b
Ht (W/K)
Dim.Inde (C)
Dim.Ude (C)
Tab (W)
CtrlClick
Tast F1 for hjælp
Start
121. Radiohead - Stop ...
Gyldendals Store Røde O...
tekster PhD oktober2007
16 Enclosure D Screen s...
Untitled - Be06
Desktop
18:42

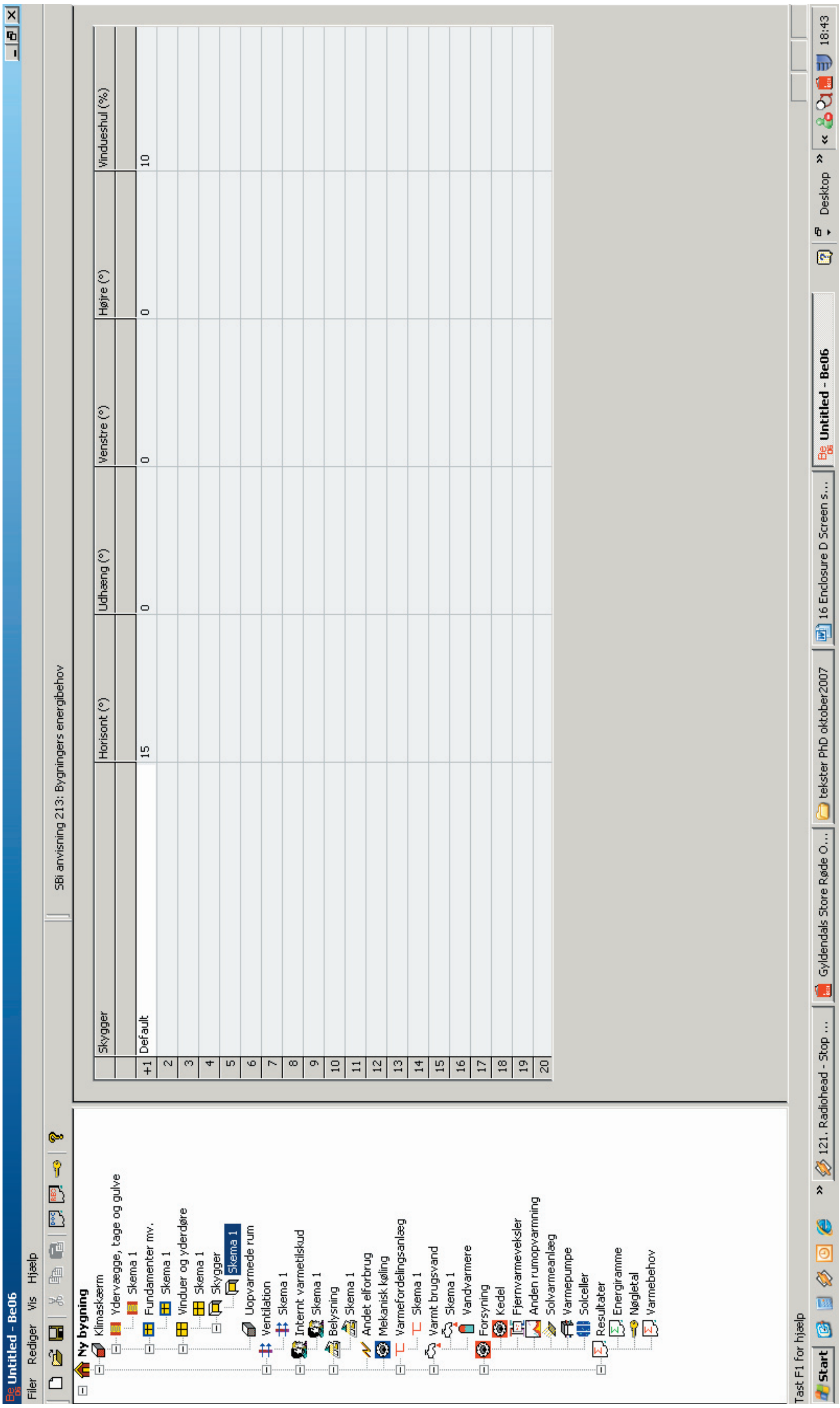
Thermal bridges



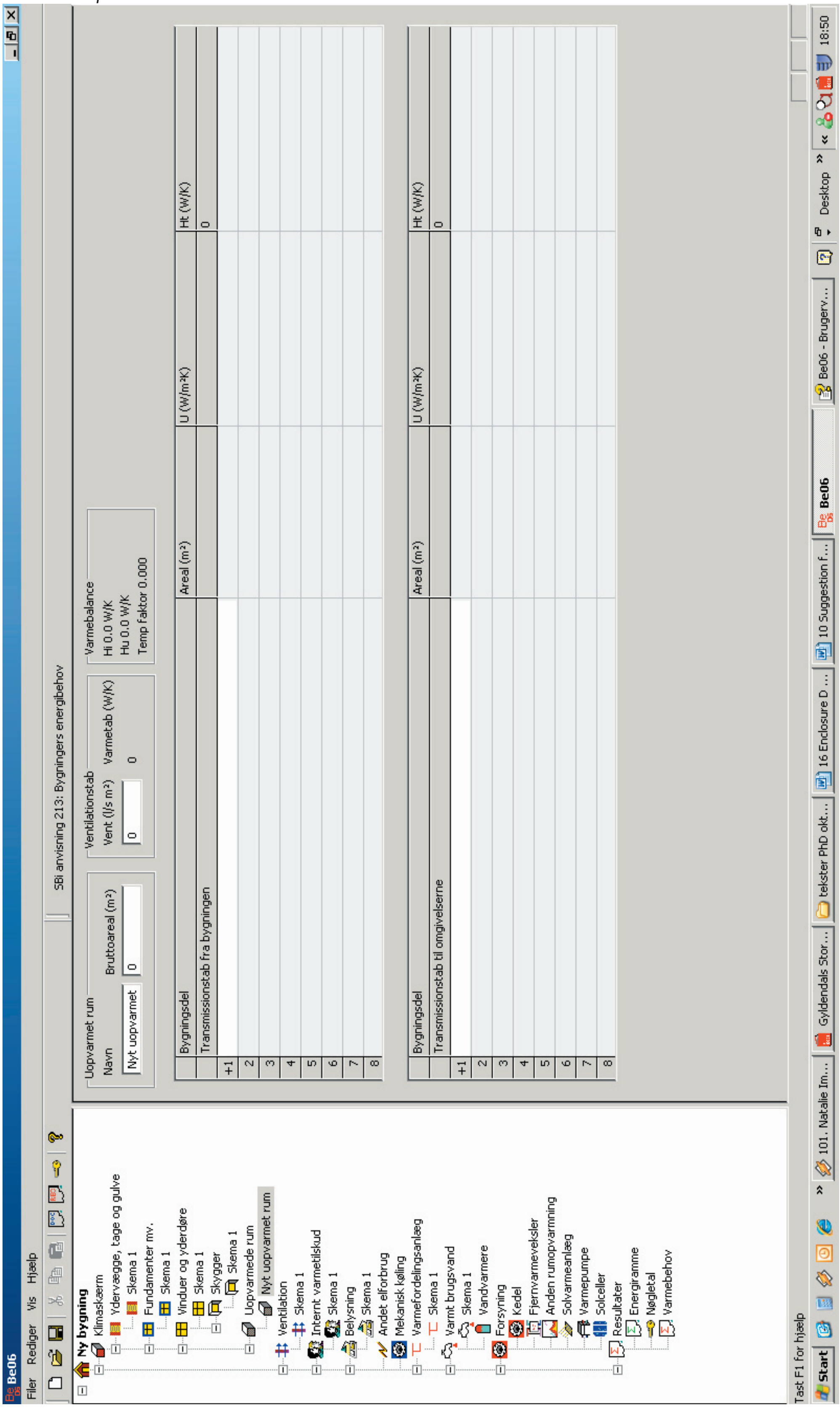
Windows and doors



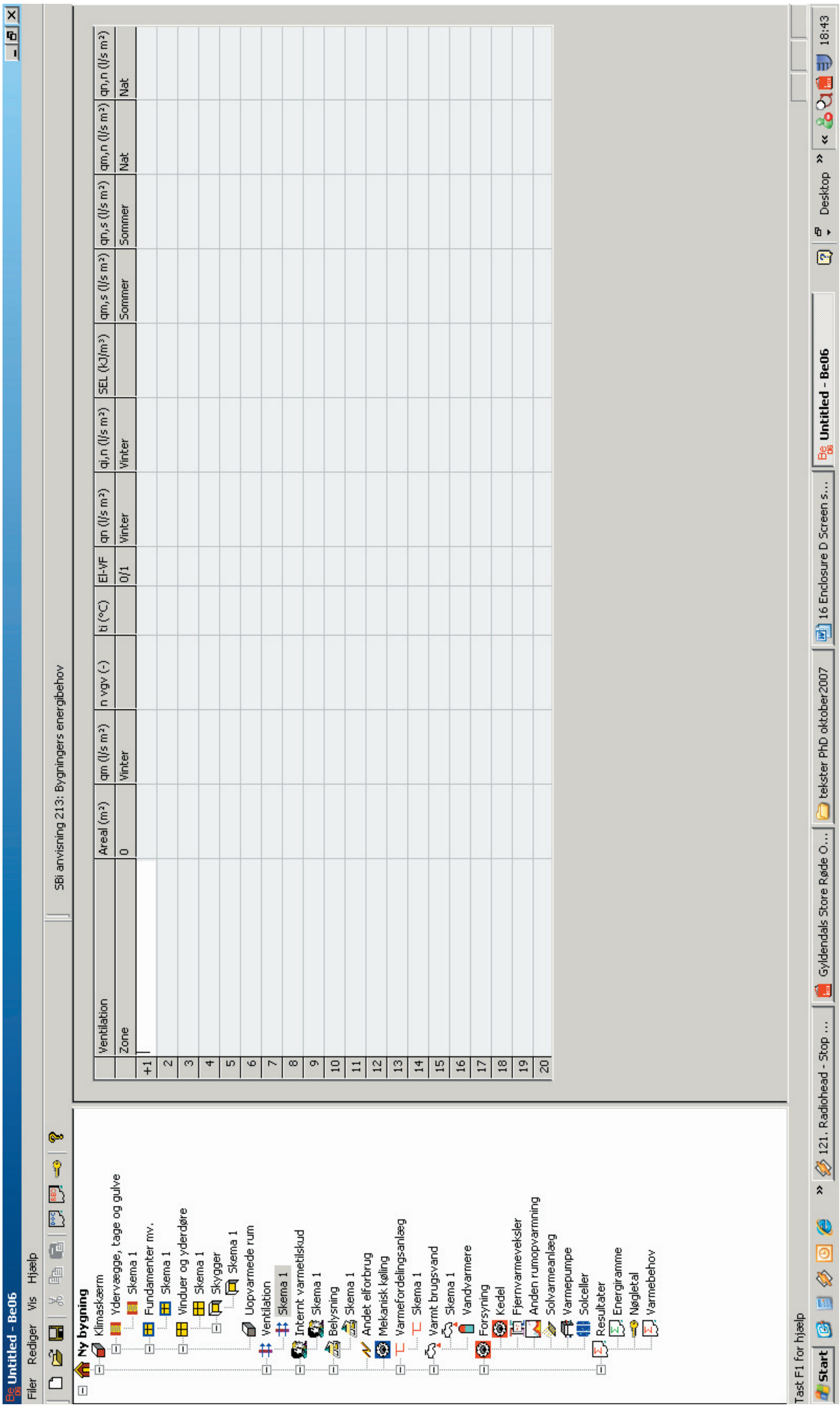
Shadows on windows and doors



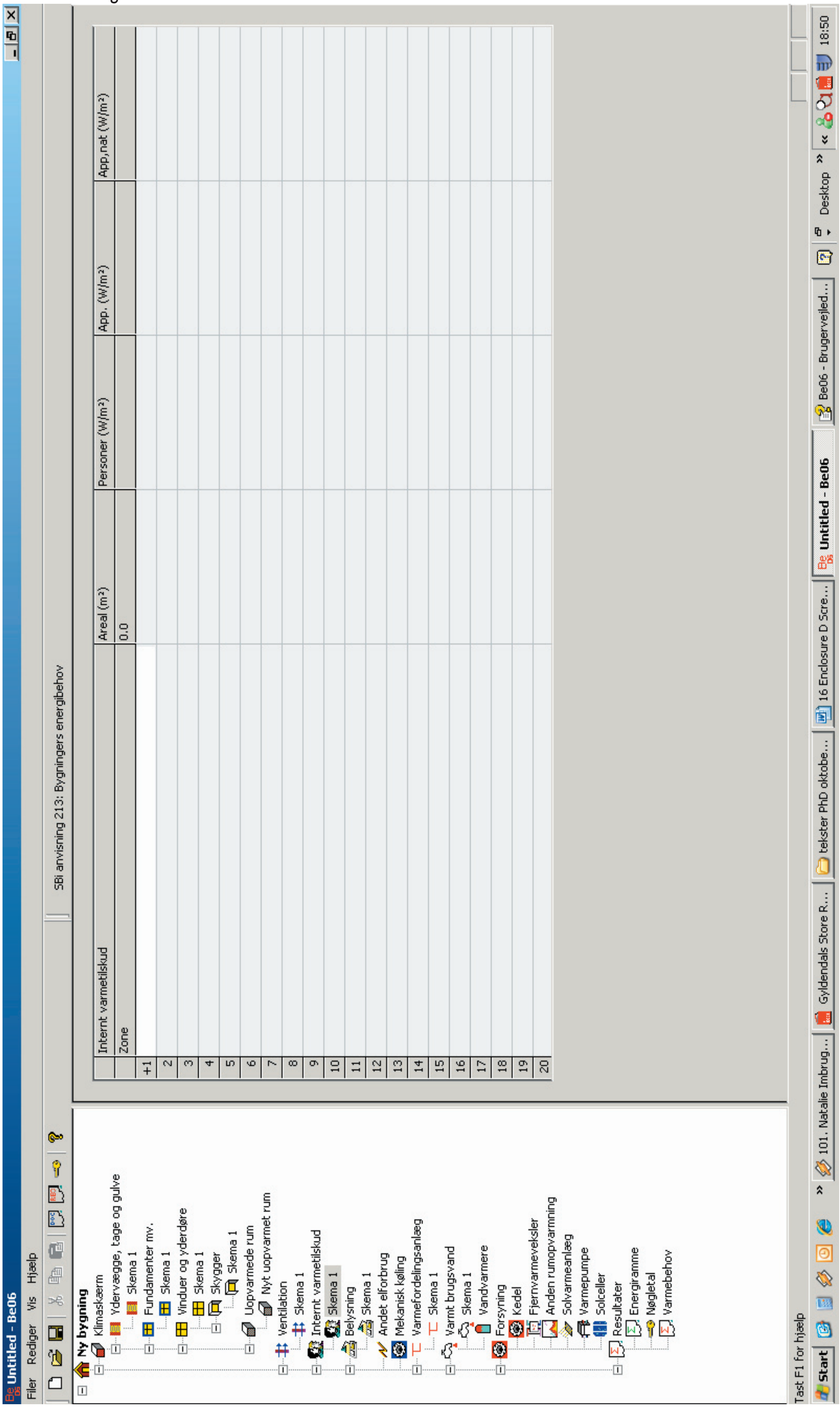
Unheated space



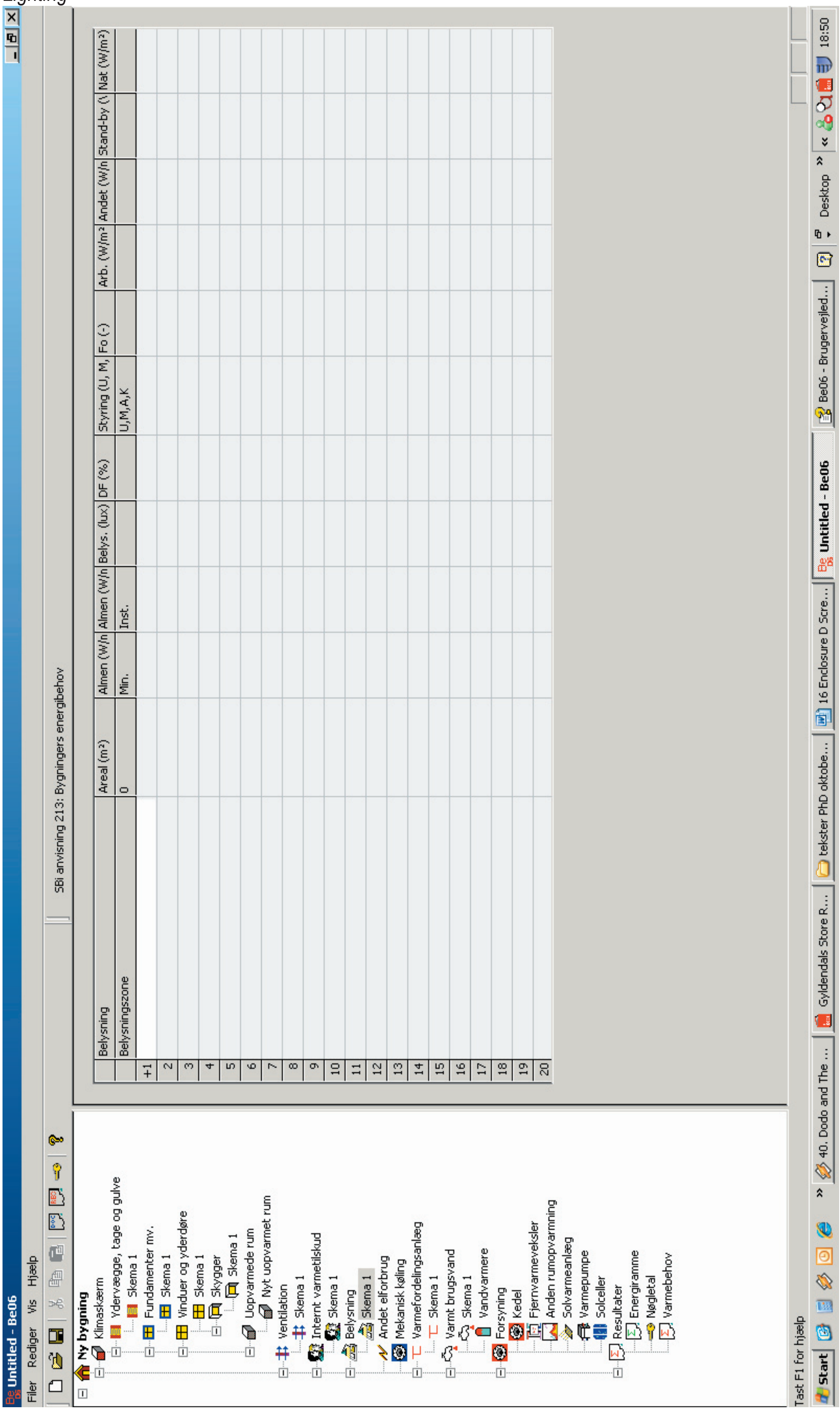
Ventilation



Internal heat gains

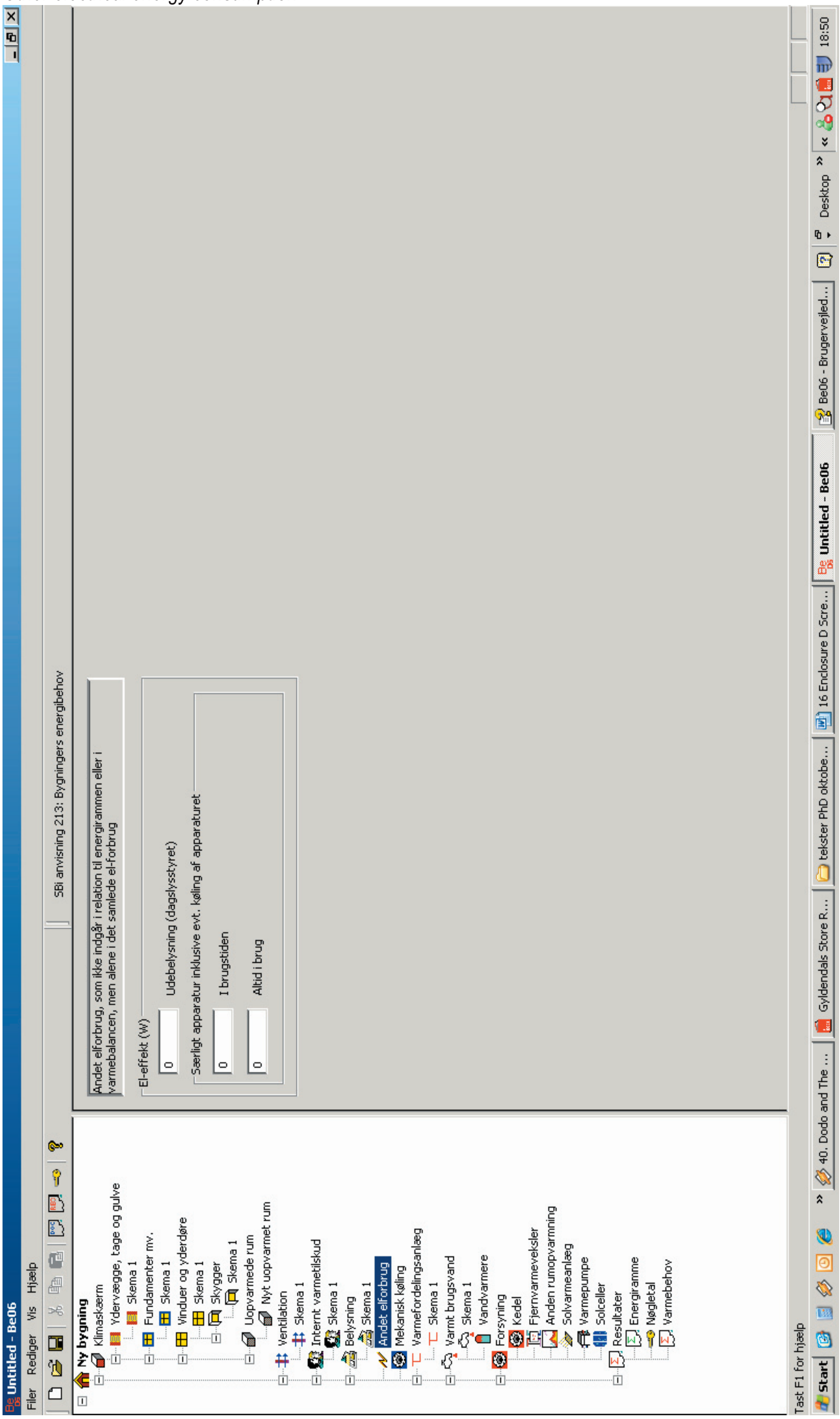


Lighting

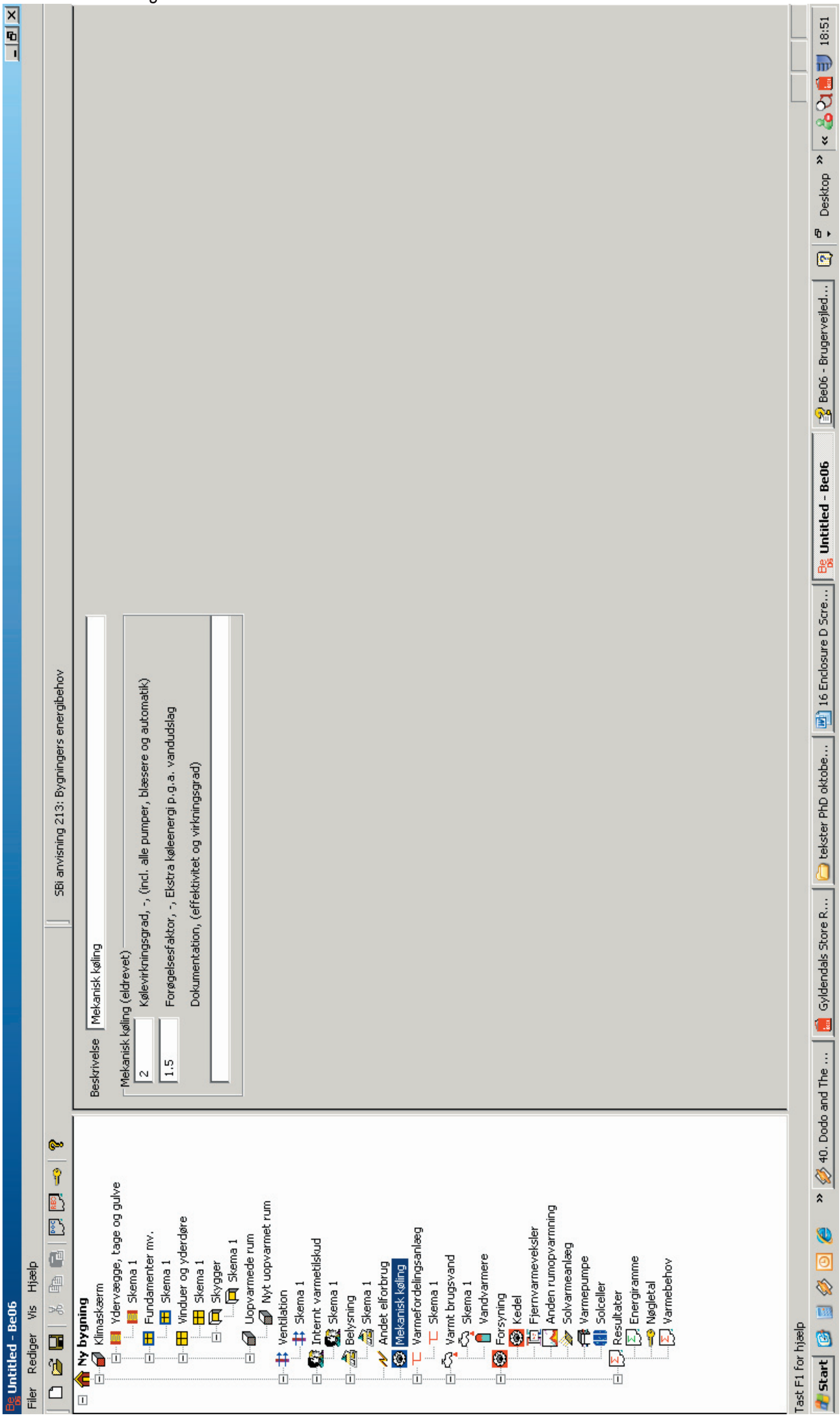


Untitled - Be06
Filer
Rediger
Vis
Hjælp
SBi anvisning 213: Bygningers energibehov
Ny bygning
Klimaskærm
Ydervægge, tage og gulve
Skema 1
Fundamenter mv.
Skema 1
Vinduer og yderdøre
Skema 1
Skygger
Skema 1
Uopvarmede rum
Nyt uopvarmet rum
Ventilation
Skema 1
Internt varmetilskud
Skema 1
Belysning
Skema 1
Andet elforbrug
Mekanisk køling
Varmefordelingsanlæg
Skema 1
Varmt brugsvand
Skema 1
Vandvarmere
Forsyning
Kedel
Fjernvarmeveksler
Anden rumopvarmning
Solvarmeanlæg
Varmepumpe
Solceller
Resultater
Energiramme
Nøgletal
Varmebehov
Belysning
Belysningszone
Areal (m²)
Almen (W/m
Min.
Almen (W/m
Inst.
Belys. (lux)
DF (%)
Styring (U, M,
U,M,A,K
Fo (-)
Arb. (W/m²
Andet (W/m
Stand-by (
Nat (W/m²)
Tast F1 for hjælp
Start
40. Dodo and The ...
Gyldendals Store R...
tekster PhD oktobe...
16 Enclosure D Scre...
Untitled - Be06
Be06 - Brugervejled...
Desktop
18:50

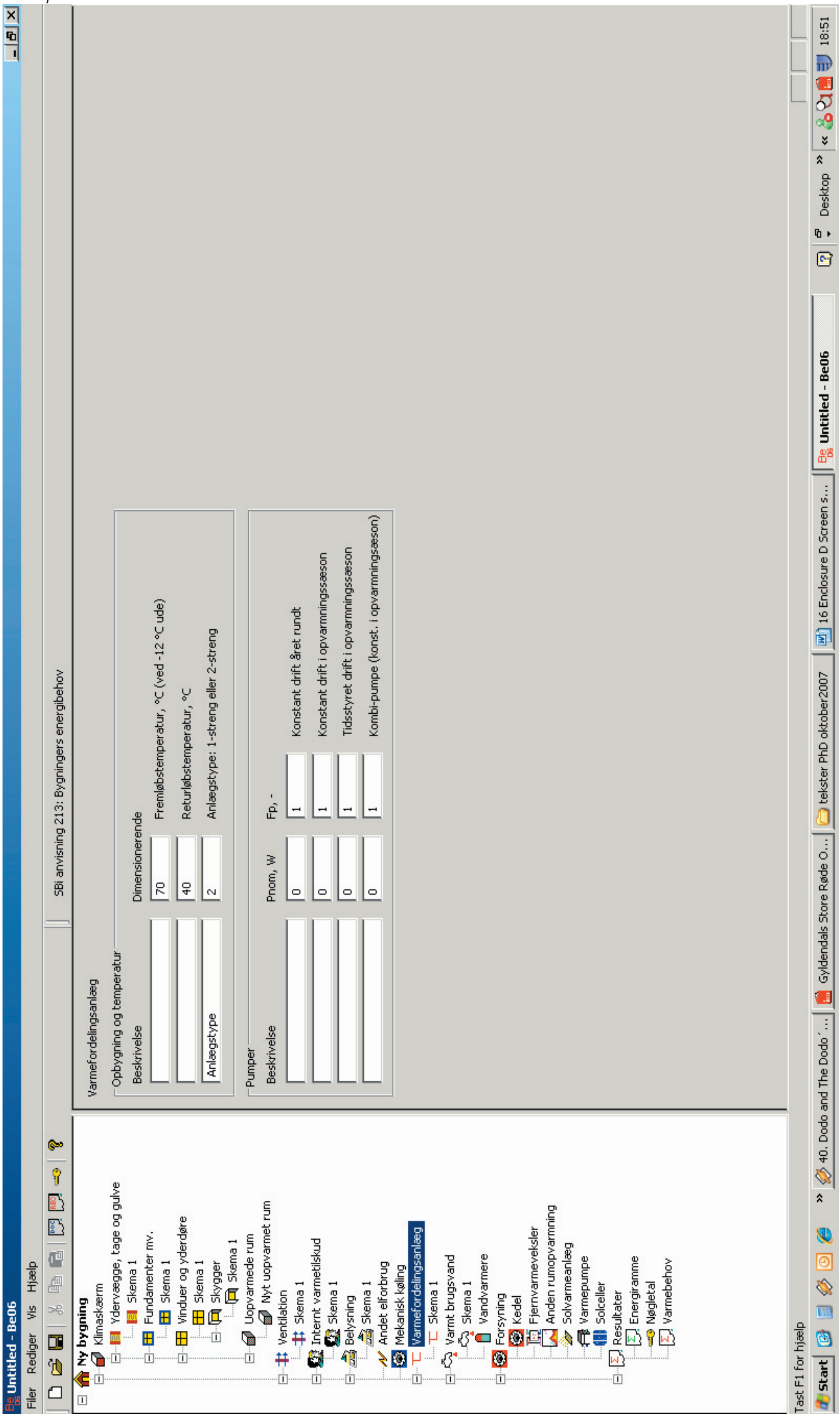
Other electrical energy consumption



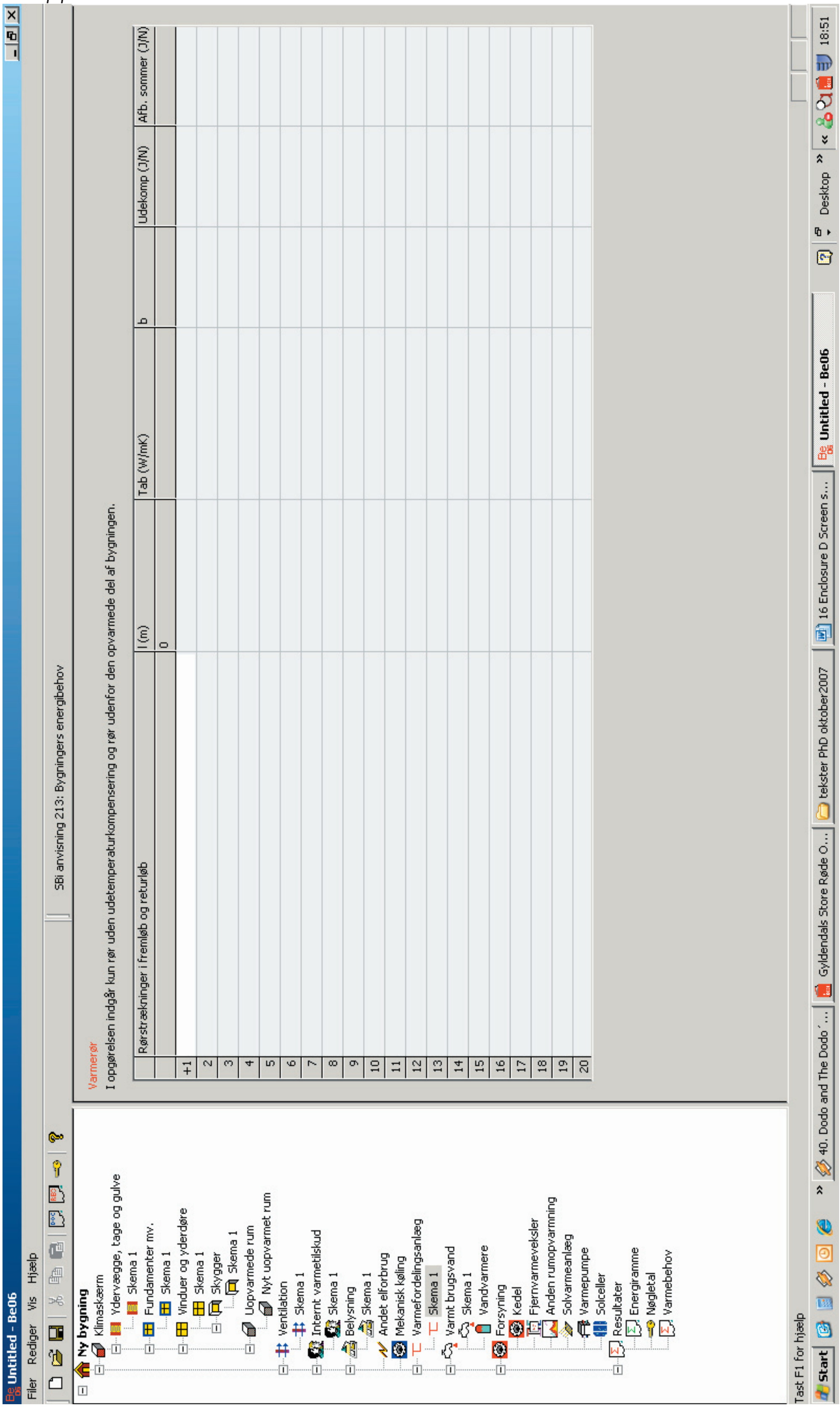
Mechanical cooling



Heat plant

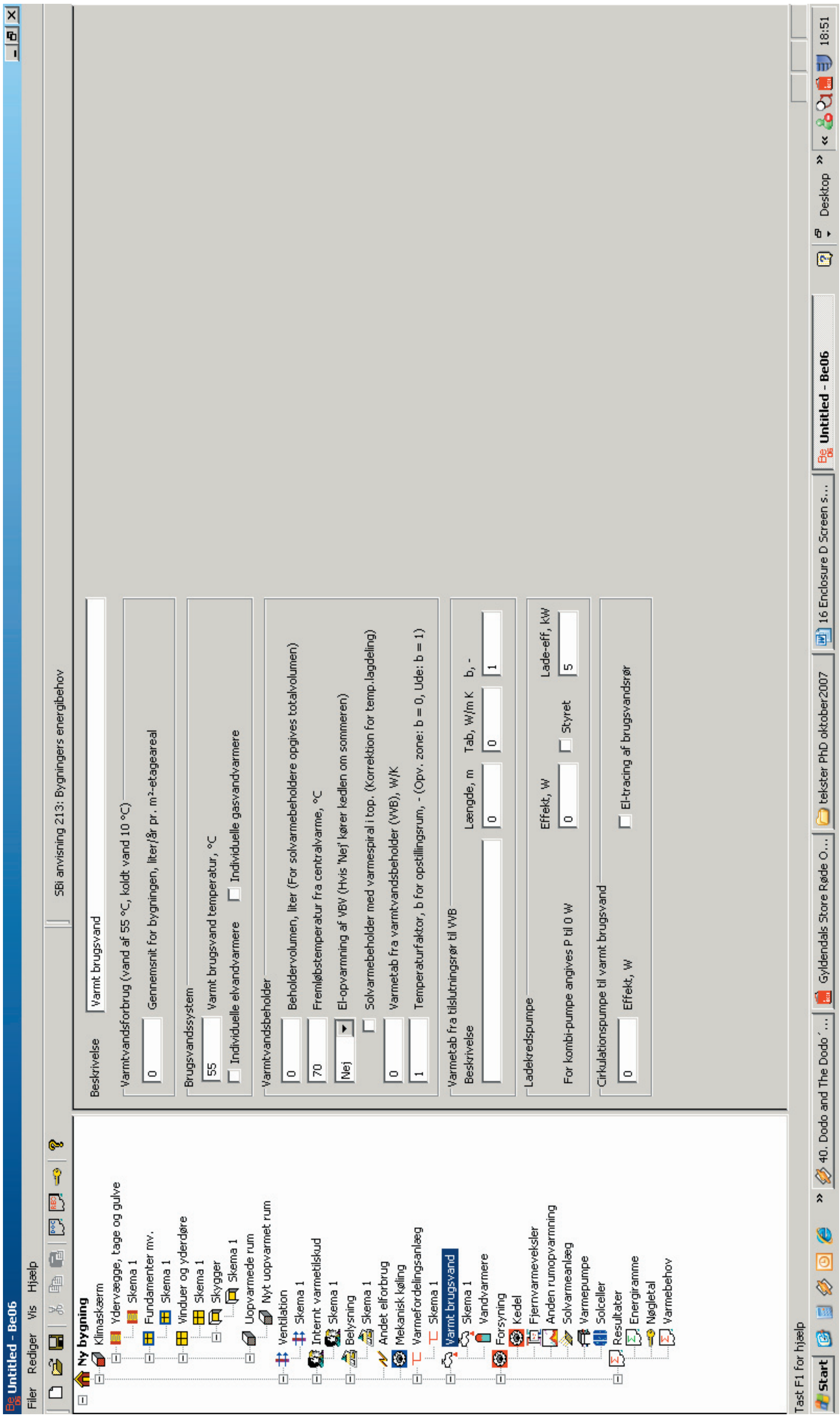

Untitled - Be06
Filer Rediger Vis Hjælp
SBi anvisning 213: Bygningers energibehov
Ny bygning
Klimaskærm
Ydervægge, tage og gulve
Skema 1
Fundamenter mv.
Skema 1
Vinduer og yderdøre
Skema 1
Skygger
Skema 1
Uopvarmede rum
Nyt uopvarmet rum
Ventilation
Skema 1
Internt varmetilskud
Skema 1
Belysning
Skema 1
Andet elforbrug
Mekanisk køling
Varmefordelingsanlæg
Skema 1
Varmt brugsvand
Skema 1
Vandvarmere
Forsyning
Kedel
Fjernvarmeveksler
Anden rumopvarmning
Solvarmeanlæg
Varmepumpe
Solceller
Resultater
Energiramme
Nøgletal
Varmebehov
Varmefordelingsanlæg
Opbygning og temperatur
Beskrivelse
Dimensionerende
70
Fremløbstemperatur, °C (ved -12 °C ude)
40
Returløbstemperatur, °C
Anlægstype
2
Anlægstype: 1-streng eller 2-streng
Pumper
Beskrivelse
Pnom, W
Fp, -
0
1
Konstant drift året rundt
0
1
Konstant drift i opvarmningssæson
0
1
Tidsstyret drift i opvarmningssæson
0
1
Kombi-pumpe (konst. i opvarmningssæson)
Tast F1 for hjælp
Start
40. Dodo and The Dodo´...
Gyldendals Store Røde O...
tekster PhD oktober2007
16 Enclosure D Screen s...
Untitled - Be06
Desktop
18:51

Heat pipes

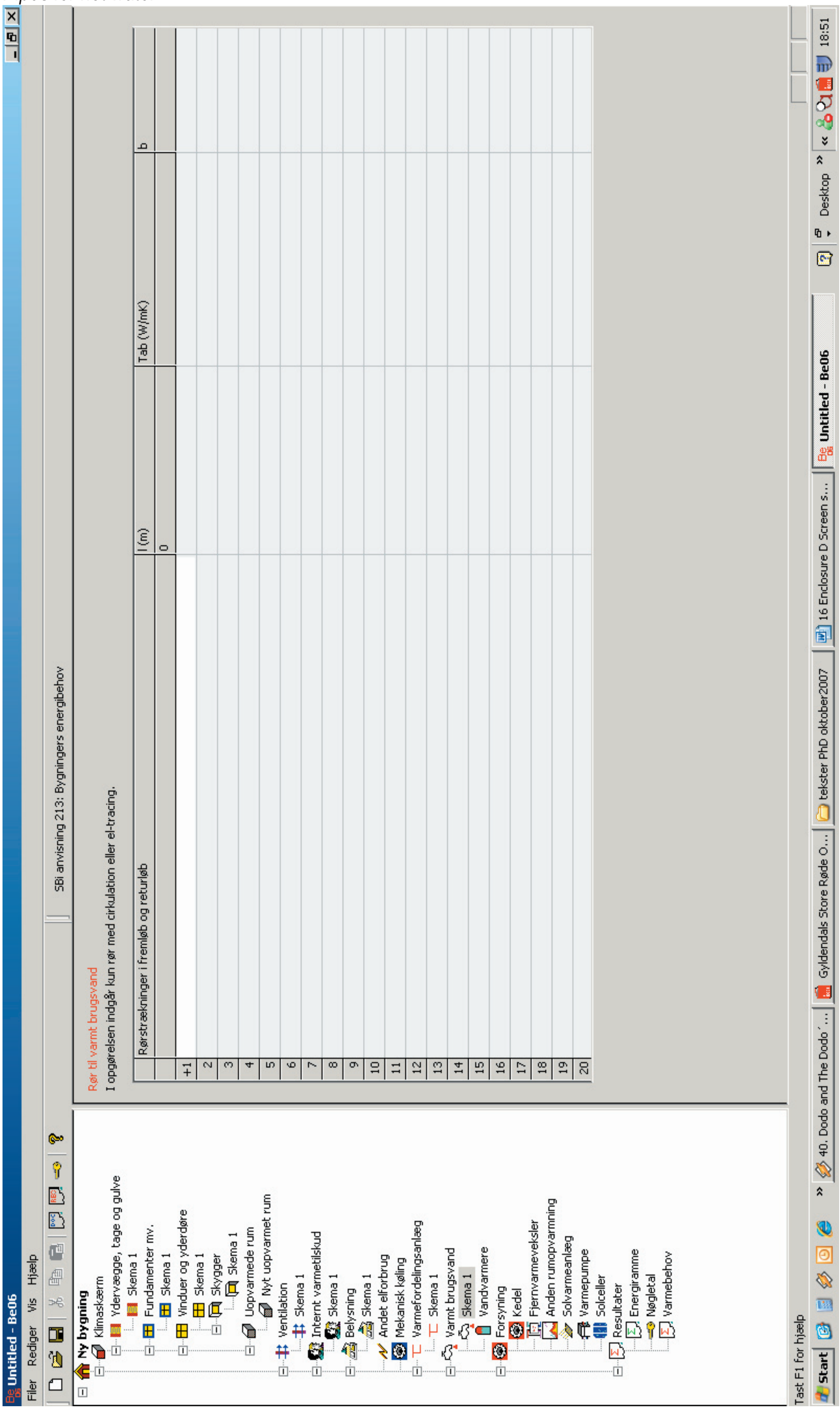


Untitled - Be06
Filer Rediger Vis Hjælp
SBi anvisning 213: Bygningers energibehov
Ny bygning
Klimaskærm
Ydervægge, tage og gulve
Skema 1
Fundamenter mv.
Skema 1
Vinduer og yderdøre
Skema 1
Skygger
Skema 1
Uopvarmede rum
Nyt uopvarmet rum
Ventilation
Skema 1
Internt varmetilskud
Skema 1
Belysning
Skema 1
Andet elforbrug
Mekanisk køling
Varmefordelingsanlæg
Skema 1
Varmt brugsvand
Skema 1
Vandvarmere
Forsyning
Kedel
Fjernvarmeveksler
Anden rumopvarmning
Solvarmeanlæg
Varmepumpe
Solceller
Resultater
Energiramme
Nøgletal
Varmebehov
Varmerør
I opgørelsen indgår kun rør uden udetemperaturkompensering og rør udenfor den opvarmede del af bygningen.
Rørstrækninger i fremløb og returløb
l (m)
Tab (W/mK)
b
Udekomp (J/N)
Afb. sommer (J/N)
Tast F1 for hjælp
Start
40. Dodo and The Dodo'...
Gyldendals Store Røde O...
tekster PhD oktober2007
16 Enclosure D Screen s...
Untitled - Be06
Desktop
18:51

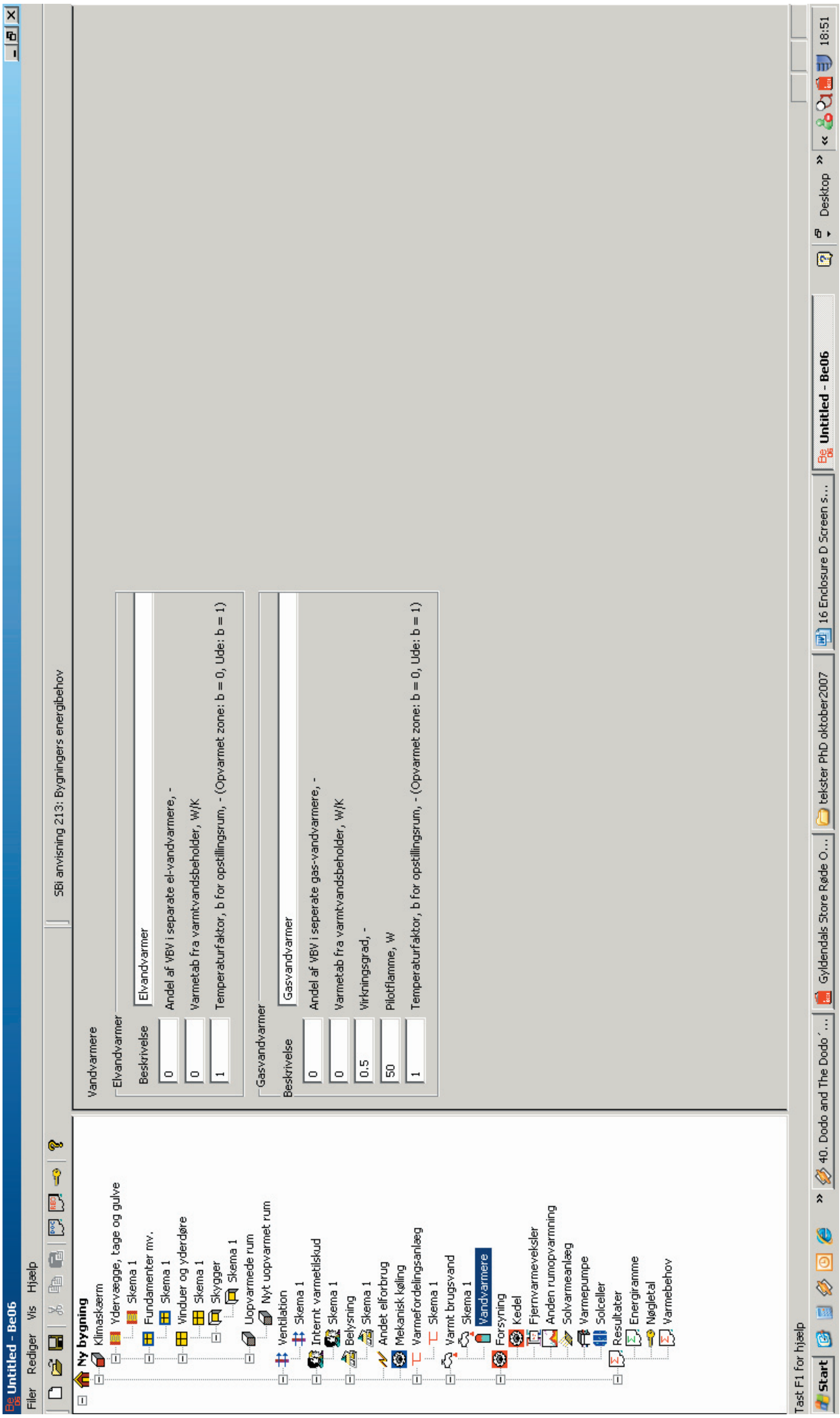
Domestic hot water



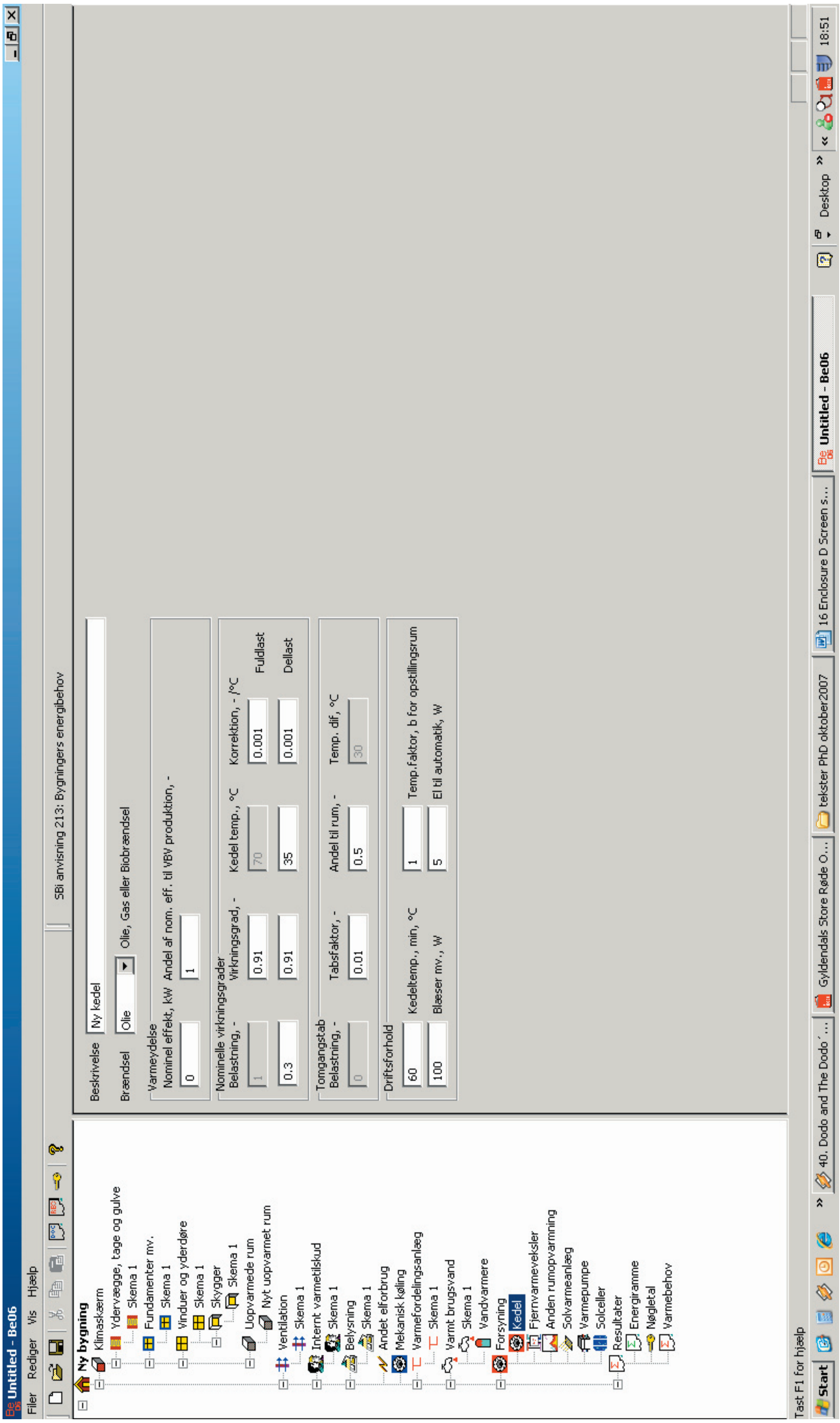
Pipes for hot water



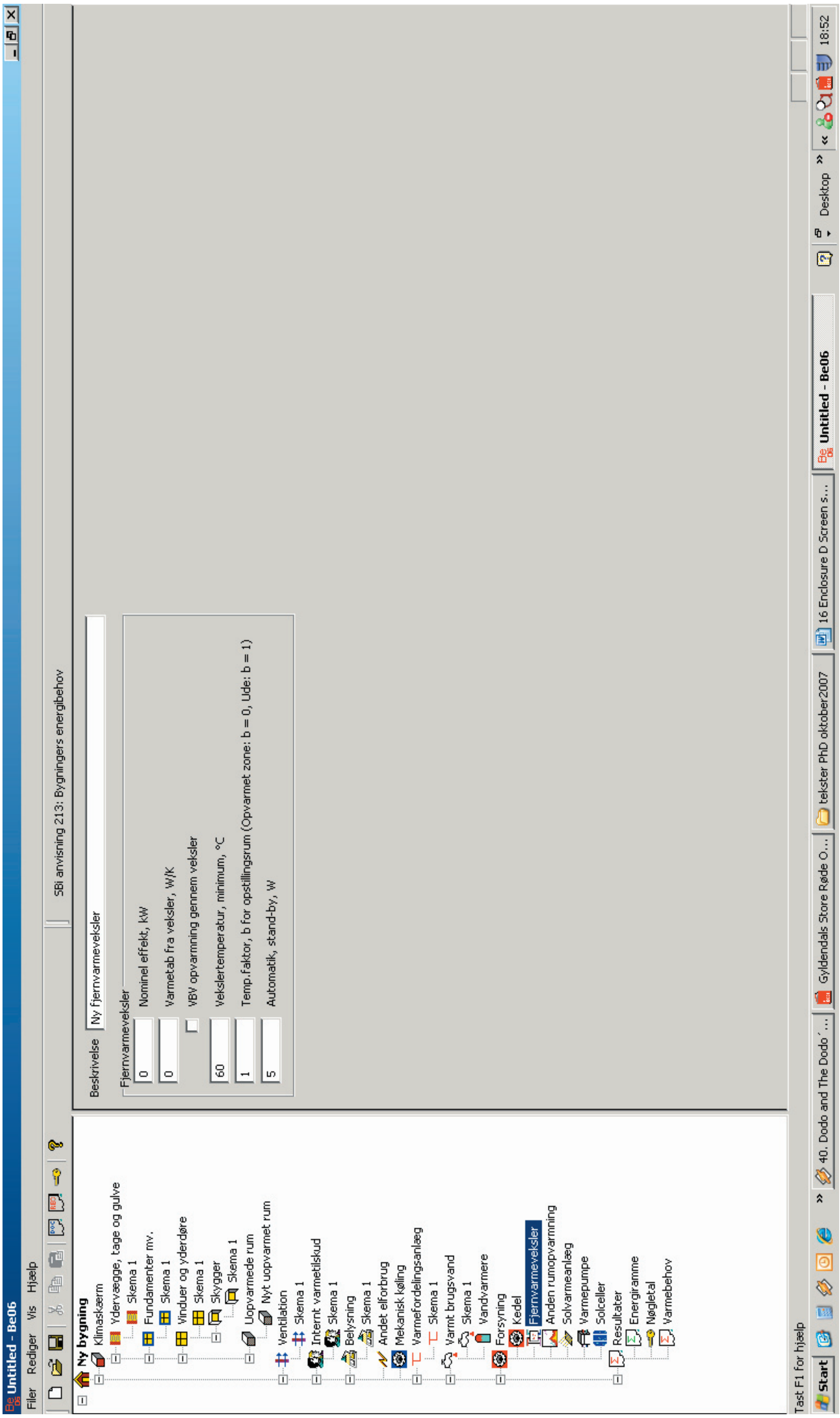
Water heater



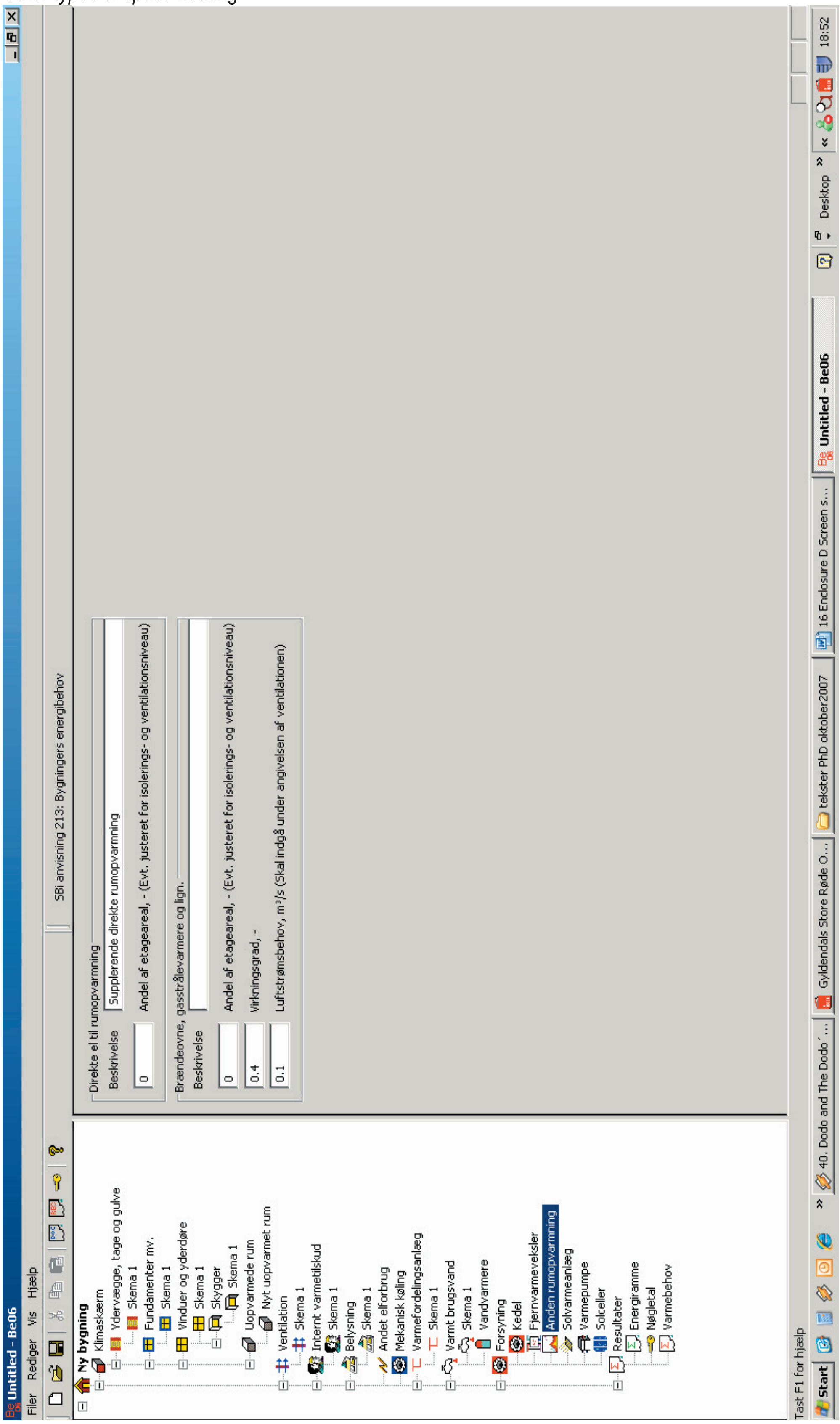
Boilers



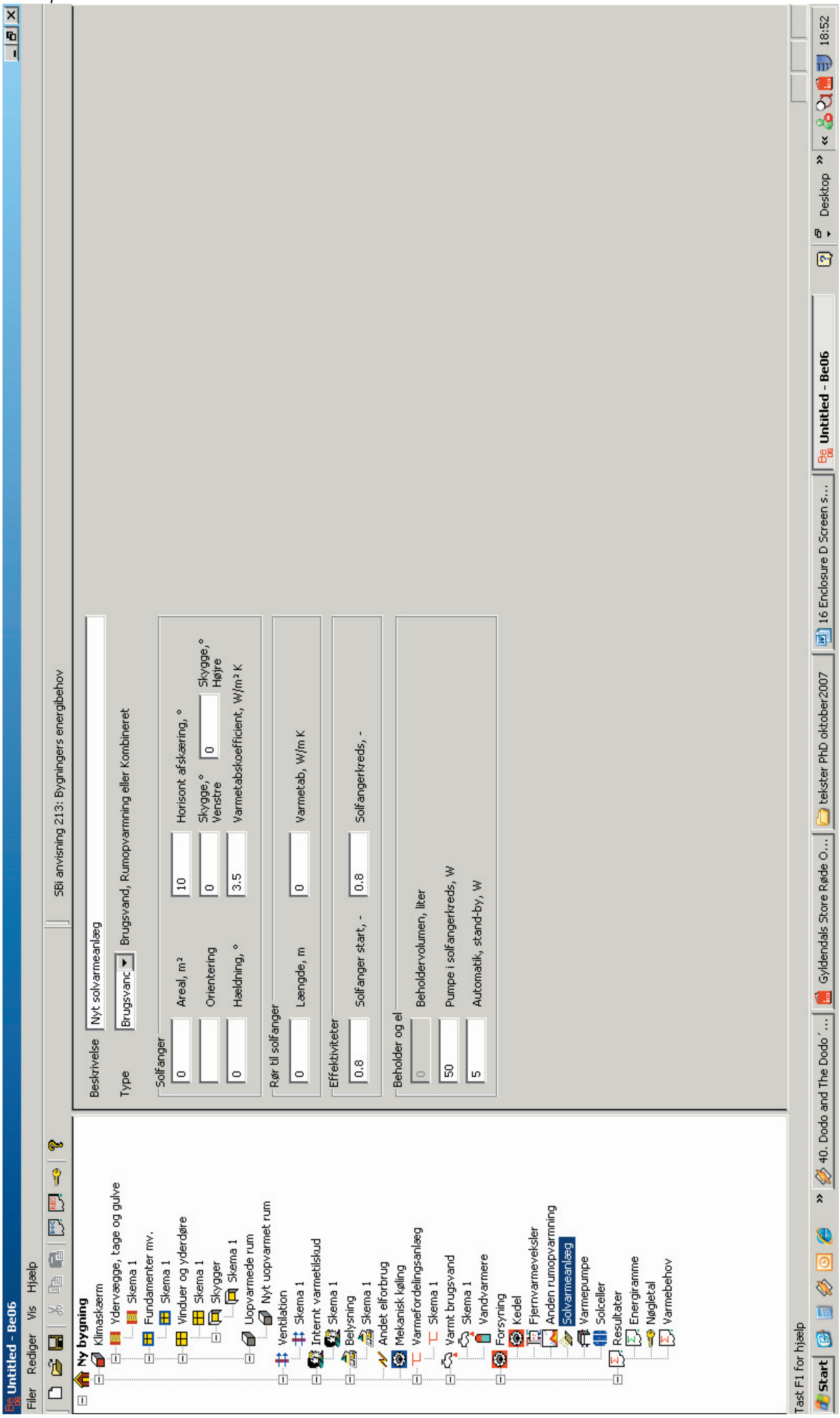
Heat exchanger for district heating


Untitled - Be06
Filer Rediger Vis Hjælp
SBi anvisning 213: Bygningers energibehov
Ny bygning
Klimaskærm
Ydervægge, tage og gulve
Skema 1
Fundamenter mv.
Skema 1
Vinduer og yderdøre
Skema 1
Skygger
Skema 1
Uopvarmede rum
Nyt uopvarmet rum
Ventilation
Skema 1
Internt varmetilskud
Skema 1
Belysning
Skema 1
Andet elforbrug
Mekanisk køling
Varmefordelingsanlæg
Skema 1
Varmt brugsvand
Skema 1
Vandvarmere
Forsyning
Kedel
Fjernvarmeveksler
Anden rumopvarmning
Solvarmeanlæg
Varmepumpe
Solceller
Resultater
Energiramme
Nøgletal
Varmebehov
Beskrivelse
Ny fjernvarmeveksler
Fjernvarmeveksler
0
Nominel effekt, kW
0
Varmetab fra veksler, W/K
VBV opvarmning gennem veksler
60
Vekslertemperatur, minimum, °C
1
Temp.faktor, b for opstillingsrum (Opvarmet zone: b = 0, Ude: b = 1)
5
Automatik, stand-by, W
Tast F1 for hjælp
Start
40. Dodo and The Dodo´...
Gyldendals Store Røde O...
tekster PhD oktober2007
16 Enclosure D Screen s...
Untitled - Be06
Desktop
18:52

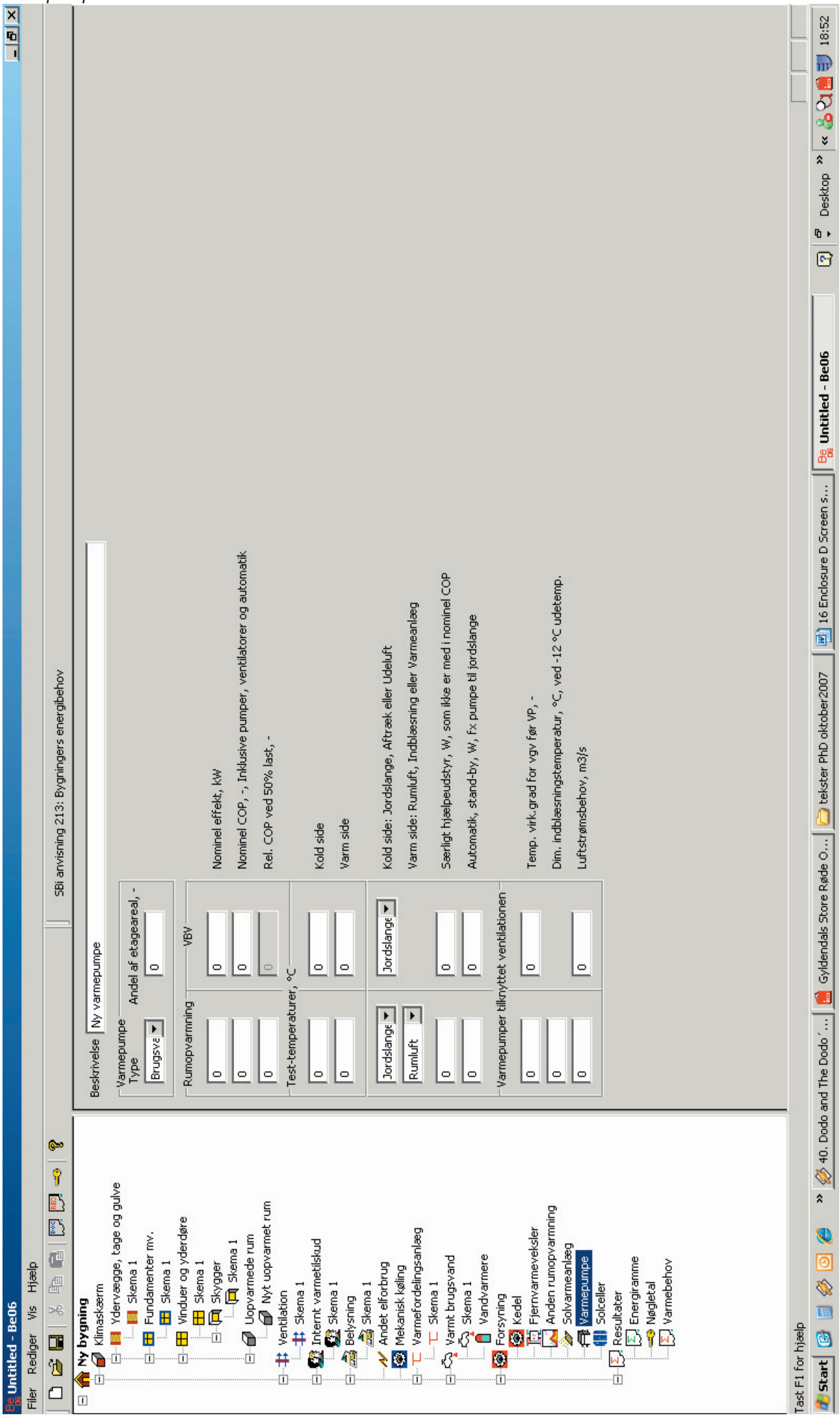
Other types of space heating

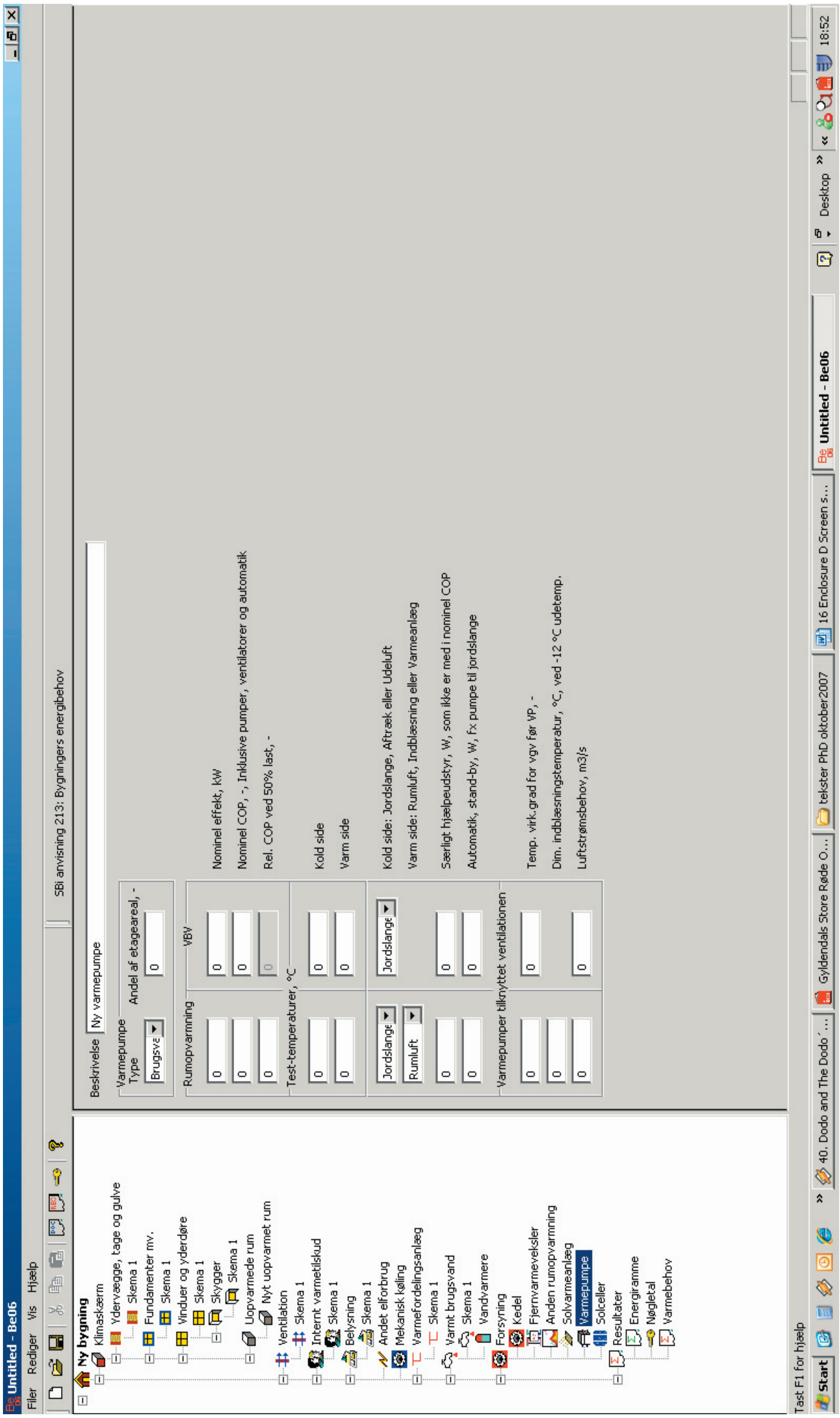


Solar panels

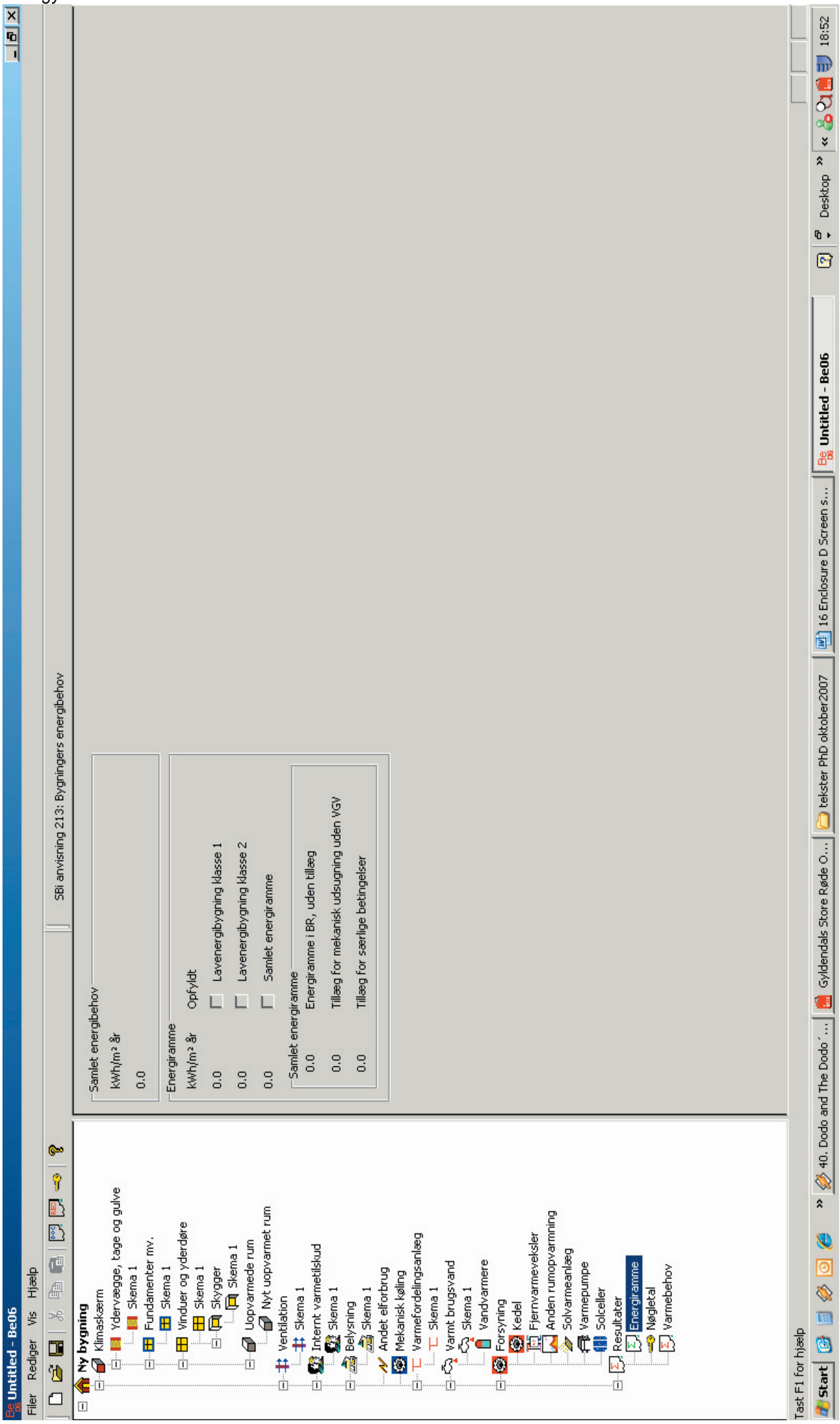


Heat pumps

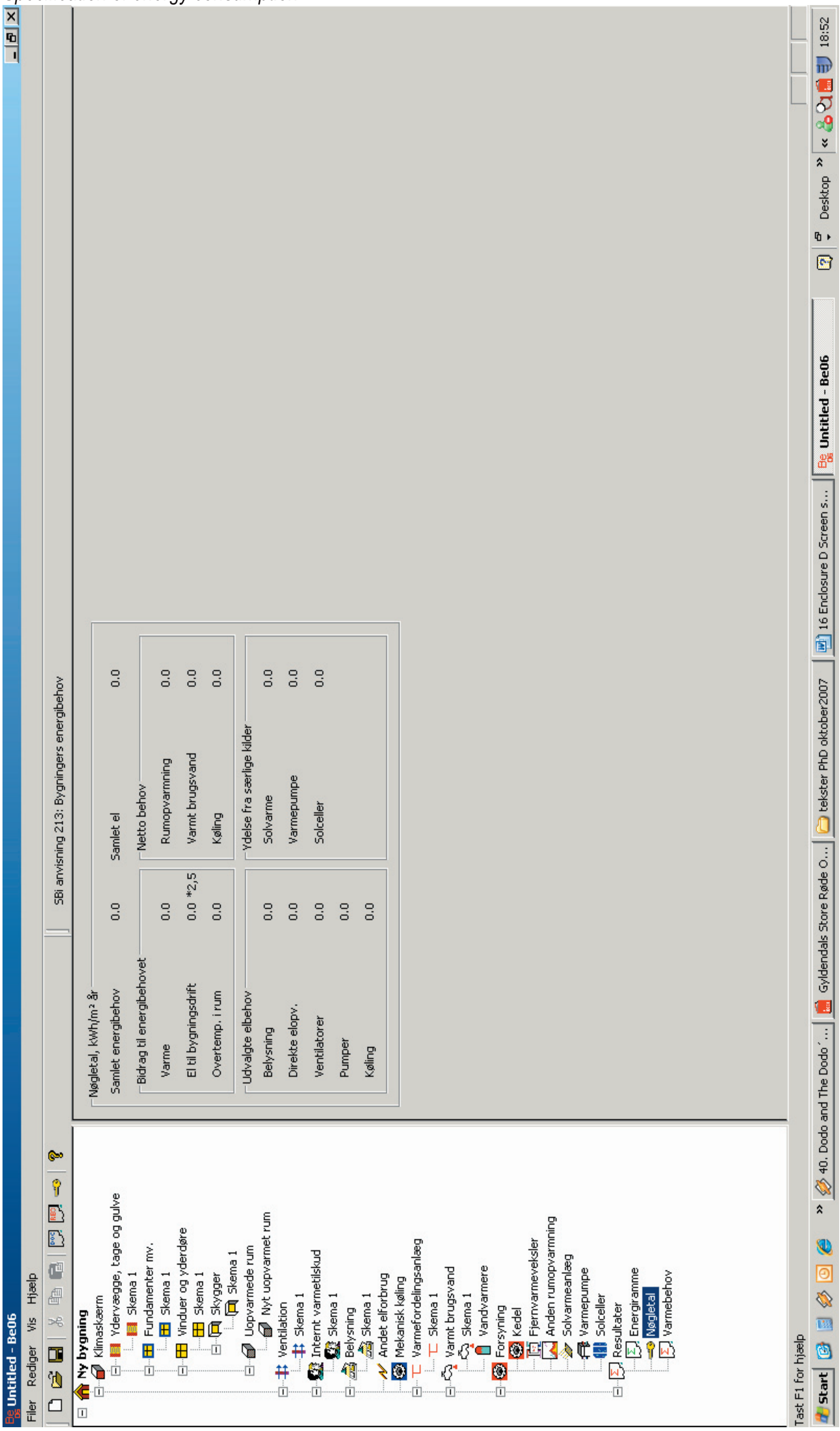

Untitled - Be06
Filer Rediger Vis Hjælp
SBi anvisning 213: Bygningers energibehov
Ny bygning
Klimaskærm
Ydervægge, tage og gulve
Skema 1
Fundamenter mv.
Skema 1
Vinduer og yderdøre
Skema 1
Skygger
Skema 1
Uopvarmede rum
Nyt uopvarmet rum
Ventilation
Skema 1
Internt varmetilskud
Skema 1
Belysning
Skema 1
Andet elforbrug
Mekanisk køling
Varmefordelingsanlæg
Skema 1
Varmt brugsvand
Skema 1
Vandvarmere
Forsyning
Kedel
Fjernvarmeveksler
Anden rumopvarmning
Solvarmeanlæg
Varmepumpe
Solceller
Resultater
Energiramme
Nøgletal
Varmebehov
Beskrivelse Ny varmepumpe
Varmepumpe
Type
Brugsva
Andel af etageareal, -
Rumopvarmning
VBV
Nominel effekt, kW
Nominel COP, -, Inklusive pumper, ventilatorer og automatik
Rel. COP ved 50% last, -
Test-temperaturer, °C
Kold side
Varm side
Jordslange
Rumluft
Kold side: Jordslange, Aftræk eller Udeluft
Varm side: Rumluft, Indblæsning eller Varmeanlæg
Særligt hjælpeudstyr, W, som ikke er med i nominel COP
Automatik, stand-by, W, fx pumpe til jordslange
Varmepumper tilknyttet ventilationen
Temp. virk.grad for vgv før VP, -
Dim. indblæsningstemperatur, °C, ved -12 °C udetemp.
Luftstrømsbehov, m3/s
Tast F1 for hjælp
Start
40. Dodo and The Dodo´...
Gyldendals Store Røde O...
tekster PhD oktober2007
16 Enclosure D Screen s...
Untitled - Be06
Desktop
18:52

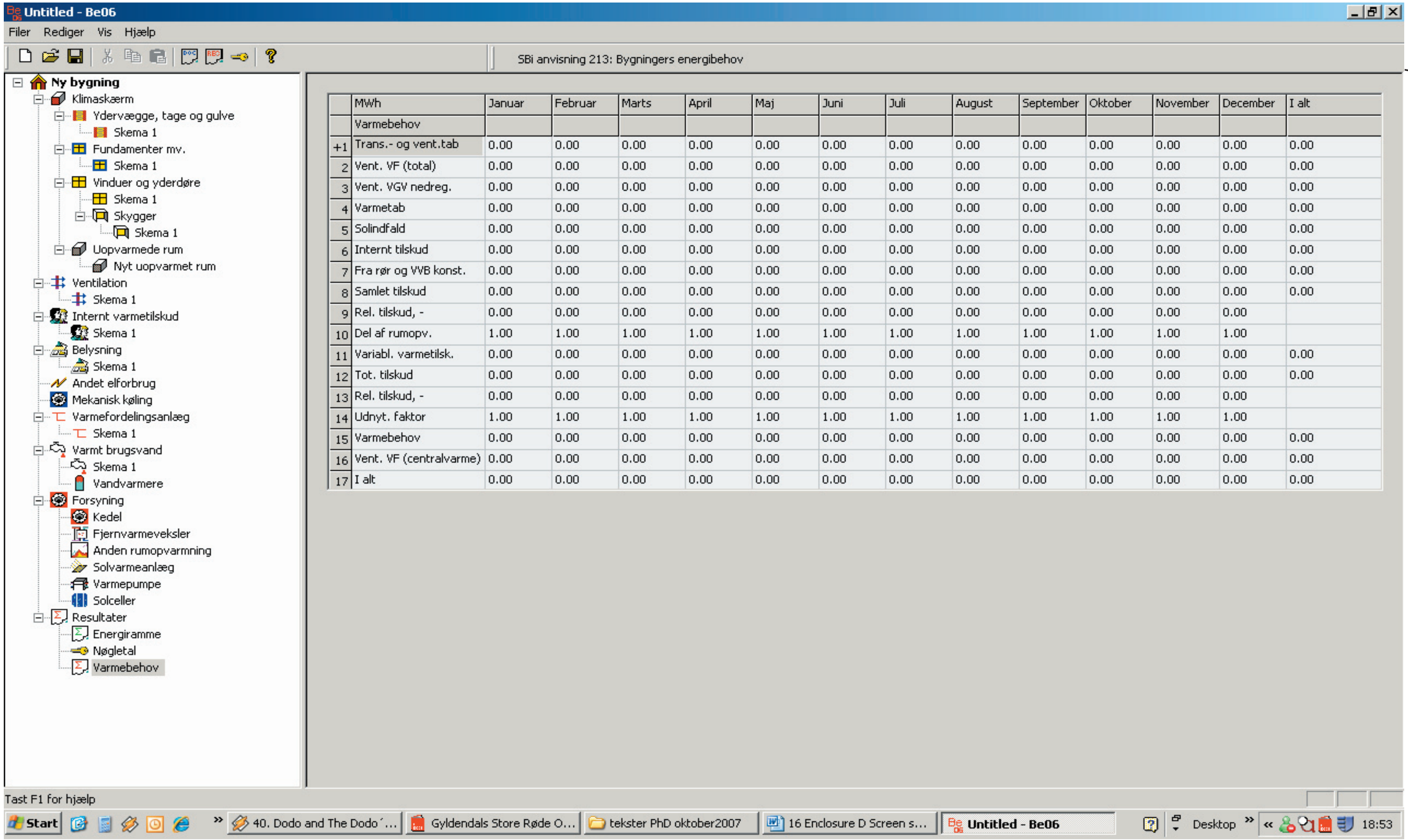

Untitled - Be06
Filer Rediger Vis Hjælp
SBi anvisning 213: Bygningers energibehov
Ny bygning
Klimaskærm
Ydervægge, tage og gulve
Skema 1
Fundamenter mv.
Skema 1
Vinduer og yderdøre
Skema 1
Skygger
Skema 1
Uopvarmede rum
Nyt uopvarmet rum
Ventilation
Skema 1
Internt varmetilskud
Skema 1
Belysning
Skema 1
Andet elforbrug
Mekanisk køling
Varmefordelingsanlæg
Skema 1
Varmt brugsvand
Skema 1
Vandvarmere
Forsyning
Kedel
Fjernvarmeveksler
Anden rumopvarmning
Solvarmeanlæg
Varmepumpe
Solceller
Resultater
Energiramme
Nøgletal
Varmebehov
Beskrivelse
Ny varmepumpe
Varmepumpe
Type
Brugsva
Andel af etageareal, -
Rumopvarmning
VBV
Nominel effekt, kW
Nominel COP, -, Inklusive pumper, ventilatorer og automatik
Rel. COP ved 50% last, -
Test-temperaturer, °C
Kold side
Varm side
Jordslange
Rumluft
Kold side: Jordslange, Aftræk eller Udeluft
Varm side: Rumluft, Indblæsning eller Varmeanlæg
Særligt hjælpeudstyr, W, som ikke er med i nominel COP
Automatik, stand-by, W, fx pumpe til jordslange
Varmepumper tilknyttet ventilationen
Temp. virk.grad for vgv før VP, -
Dim. indblæsningstemperatur, °C, ved -12 °C udetemp.
Luftstrømsbehov, m3/s
Tast F1 for hjælp
Start
40. Dodo and The Dodo´...
Gyldendals Store Røde O...
tekster PhD oktober2007
16 Enclosure D Screen s...
Untitled - Be06
Desktop
18:52

Energy frame



Specification of energy consumption





	MWh	Januar	Februar	Marts	April	Maj	Juni	Juli	August	September	Oktober	November	December	I alt
	Varmebehov													
+1	Trans.- og vent.tab	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	Vent. VF (total)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	Vent. VGV nedreg.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	Varmetab	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	Solindfald	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	Internt tilskud	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	Fra rør og VVB konst.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	Samlet tilskud	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	Rel. tilskud, -	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
10	Del af rumopv.	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
11	Variabl. varmetilsk.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	Tot. tilskud	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	Rel. tilskud, -	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
14	Udnyt. faktor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
15	Varmebehov	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	Vent. VF (centralvarme)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	I alt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Heat requirement