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Climate Change and Its Impact on the Operation and Maintenance of Buildings

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PhD Thesis

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Department of Civil Engineering
Technical University of Denmark

Climate Change and Its Impact on the Operation and Maintenance of Buildings

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Co-supervisor Stine Tarhan from Gentofte Building Department, Gentofte Municipality

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Preface

At some time or another, we have all probably thought:
"I would like to change the world,
But I don't know what to do
So I leave it up to you"
I hope this thesis provides some assistance in deciding "what to do"

Abstract

It is now accepted that some level of climate change is inevitable. Consequently, there is a need for tools to support designers and managers of buildings to model the potential effects of climate change on buildings. This thesis makes the following contributions towards this.

Contribution 1: Estimations of the future energy consumption of buildings are becoming increasingly important as a basis for energy management, energy renovation, investment planning, and for determining the feasibility of technologies and designs. Future weather scenarios, where the outdoor climate is usually represented by future weather files, are needed for estimating the future energy consumption. In many cases, however, the practitioner's ability to conveniently provide an estimate of the future energy consumption is hindered by the lack of easily available future weather files. This is, in part, due to the difficulties associated with generating high temporal resolution (hourly) estimates of future changes in temperature. To address this issue, I investigated if, in the absence of high-resolution data, a weather file constructed from a coarse (annual) estimate of future temperature change can provide useful estimates of future energy demand of a building.

Experimental results based on both the degree-day method and dynamic simulations suggest that this is indeed the case. Specifically, heating demand estimates were found to be within a few per cent of one another, while estimates of cooling demand were slightly more varied. This variation was primarily due to the very few hours of cooling that were required in the region examined. Errors were found to be most likely when the temperatures were close to the heating or cooling balance points, where the energy demand was modest and even relatively large errors might thus result in only modest absolute errors in energy demand.

Contribution 2: The way a particular function of a building is provisioned may have significant repercussions beyond just resilience. To address this issue, I considered how to couple and quantify resilience and sustainability, where sustainability refers to not only environmental impact, but also economic and social impacts. The goal was to develop a decision support tool for facilities managers. Within this context, I assumed an economist's perspective, i.e. that facility managers are rational and base decisions on economic criteria. As such, a risk framework was utilised to quantify both resilience and sustainability in monetary terms.

The risk framework permits coupling resilience and sustainability so that the provisioning of a particular building can be investigated with consideration of functional, environmental, economic and possibly social dimensions.
The method of coupling and quantifying resilience and sustainability was illustrated with a simple example that highlights how very different conclusion can be drawn when considering only resilience or resilience and sustainability. The method is generic allowing the method to be customized for different user communities.

Contribution 3: A third, more applied contribution of my thesis was to investigate a passive ventilation solution for historical buildings based on a ventilation window supported by chimneys, where the air supply is provided through the ventilation window and the air is naturally extracted through the existing chimneys.

An advanced natural ventilation system in existing double skin windows was installed in a historical case study building using the original features of the building. The passive natural ventilation is automatically controlled by internal and external top openings supported by passively extracted air through the chimneys. I investigated three ventilation strategies during the moderate period of a year. The CO_2 produced by the occupants was chosen as the trace gas to estimate the air exchange in the building with its conduits for ventilation such as windows and chimneys.

Studies showed that only one of the three strategies work as expected. The investigation showed that the ventilation system did not provide sufficient air change throughout the building during the mild spring and autumn weather conditions when the investigation was conducted.

Resumé

Det er nu alment kendt at klimaforandringer i en vis grad er uundgåelige. Derfor er der behov for nye værktøjer til professionelle i byggesektoren til lettere at modellere fremtidige klimapåvirkninger, og til at sikre at klimatilpasning og bæredygtig udvikling indgår i drift og vedligehold af bygninger. Denne Ph.D. afhandling er et bidrag til denne faglige udvikling.

Bidrag 1: Metode til estimering af fremtidigt energiforbrug
Estimering af det fremtidige energiforbrug i bygninger bliver stadig vigtigere som grundlag for energiledelse, energirenovering, investeringsplanlægning og til at afgøre hvilke energiforbedringer der bør gennemføres. At undersøge fremtidige vejrscenarier, hvor udendørsklima simuleres ved hjælp af fremtidige vejrdatafiler, er nødvendige for at estimere det fremtidige energiforbrug. I mange tilfælde er estimering af fremtidens energiforbrug forhindret, af manglen på lettilgængelige fremtidige vejrdatafiler. Dette er forbundet med vanskeligheder i at få adgang til fremtidens vejrdata i høj tidsopløsning (på time basis). For at løse dette problem i projektet blev der undersøgt, om fremtidens vejrdatafiler kan konstrueres ved hjælp af en grov tidsopløsningsvejrdata (på årlig basis). Tre type filer, omhandlende fremtidigt vejr, blev konstrueret ved at tilføje en fremtidig ændring af et vejrparameter (i dette tilfælde temperatur) til den nutidige vejrfil ved hjælp af tre forskellige tidsoplysninger: (i) høj(timebaseret) (ii) moderat (månedligtbaseret) og (iii) groft (årligtbaseret). Fremtidigt energiforbrug af tre forskellige type bygninger, blev estimeret ved hjælp af de tre nævnte vejrfiler. Estimeringen blev gennemført med både graddage metoden og dynamiske simuleringer. Eksperimentelle resultater afslørede, at estimeringen af fremtidens varmebehov for alle tre type fremtidige vejrfiler var inden for nogle få procents variationer. Hvorimod estimering af fremtidigt kølebehov var mere varieret. Denne variation skyldes primært de få timers nødvendig køling i den pågældende region, Denmark. Den største forskel blev fundet når temperaturen var tæt på opvarmnings- eller kølingsbalancepunkter. Energibehovet i disse balancepunkter var beskedne, og selv relativt store forskelle kan således resultere i beskedne absolutte forskelle i energiforbruget.

Bidrag 2: Planlægning af klimatilpasset og bæredygtig bygningsrenovering
Udformning og byggeteknisk tilstand af en bygning kan have betydelige konsekvenser for bygningens modstandsdygtighed og bæredygtighed.
I projektet foreslås det at koble og kvantificere både bæredygtighed af en bygning, og dens modstandsdygtighed overfor klimaforandringer.

Målet var at udvikle et beslutningsstøtte værktøj for ejendomsforvaltere med et entydigt økonomisk resultat. Værktøjet skulle vurdere ændringen i funktionspåvirkning af bygningens modstandsdygtighed. Denne ændring vil samtidig påvirke bygningens grad af bæredygtighed. I dette tilfælde refererer bæredygtigheden til både miljømæssige-, økonomiske - og sociale faktorer.

Der er anvendt en ramme for risikoanalyse til at kvantificere både modstandsdygtighed og bæredygtighed af et renoveringsprojekt.

Metoden til at koble og kvantificere modstandsdygtighed og bæredygtighed er illustreret med et simpelt eksempel, der fremhæver hvordan forskellige konklusioner kan drages, hvis man inddrager enten kun modstandsdygtighed, eller modstandsdygtighed og bæredygtighed af et renoveringsprojekt. Metoden er generel og tillader at tilpasse metoden til forskellige brugergrupper.

Bidrag 3: Eksperiment med naturlig ventilation i eksisterende bygning
Et tredje og mere praktisk bidrag var, at undersøge en passiv ventilationsløsning til historiske bygninger. Ventilationsløsningen var baseret på henholdsvis ventilationsvinduer og af eksisterende skorstene. Frisk luft til bygningen blev tilført passivt gennem de originale eksisterende dobbeltvinduer, og udsuget naturligt gennem de eksisterende skorstene. Den passive naturlige ventilation er automatisk styret af interne og eksterne topåbninger, der understøttes af passiv udsugning gennem skorstene.

Denne ventilationsløsning blev installeret i en historisk forsøgsbygning. For at undersøge om ventilationsløsningen virkede som planlagt, og kunne tilføje det nødvendige luftskifte blev tre ventilationsstrategier undersøgt under de milde årstider: forår og efterår. Estimering af luftskifte i bygningen blev baseret på CO_2-udånding fra brugerne. Undersøgelser påviste at kun en af de tre strategier virkede som planlagt. Samtidig viste undersøgelsen at bygningen ikke kunne tilføje den nødvendige luftskifte over alt i bygningen under det milde forår- og efterårsvejr.

Acknowledgment

I would first like to thank the Department of Civil Engineering and Management Engineering at the Technical University of Denmark together with Gentofte Municipality Building Department for supporting my Ph.D.

I am very grateful to number of people in Gentofte Municipality including my co-supervisor Stine Tarhan and her colleagues Henning Bakke Jensen, Søren Brink Schørring and Jeppe Zachariassen, who trusted in my recommendations for the renovation of Villa Bagatelle.

Thank you to my colleagues Toke Rammer Nielsen, Jørn Toftum, Arsen Kerikov Melikov and Christopher Just Johnston all from the Department of Civil Engineering at Technical University of Denmark who helped me to understand the complexity of natural ventilation as well as professors Michael Davies and Ben Croxford both from University College London who helped me to understand the principles of ventilation window.

I also thank the occupants of Villa Bagatelle for their patience and support in collecting the data, as well as the project manager of the building, Jeppe Zachariassen, for believing in my idea and all his assistance to install and investigate the performance of the system. I also benefited from the support of Windows Masters, especially Dennis Gudmannsen, in collecting the data for my experiments.

I especially thank Martin Olsen and Martin Drews of the Danish Metrological Institute who provided insight into future weather in Denmark and understanding of how the global and regional climate models are design and used. Thanks too to Hans Lund of the Department of Civil Engineering who explained how the Typical and Design Reference Year file was constructed.

Special thanks to my academic supervisors Carsten Rode from the Department of Civil Engineering and Susanne Balslev Nielsen of Management Engineering Department who believed in my ideas and provided support and encouragement when I needed it.

Finally, thanks to my husband and my children, Amalie and Harald, for their patience, support and encouragement.

Abbreviations

IPCC	The International Panel of Climate
RCM	Regional Climate Models
GCM	Global Climate Models
DMI	The Danish Metrological Institute
SER	IPCC future scenarios of the world
UKCIP	UK Climate Impact Programme
FM	Facilities Management
SD	Sustainable Development
DRY	Design Reference Year
TRY	Typical Reference Year
CQRS	Coupling and quantifying Resilience method
CO_2	Carbon dioxide concentration (ppm)

Table of content

1 Introduction

1.1. Aim and objective of research

Models of global warming predict not just an increase in average temperature across the globe. Increased temperatures may also lead to increases in sea level, and changes in local weather patterns, causing an increased number of extreme weather events [1] [2]. The consequences of these extreme weather events may have a high material cost on buildings and their occupants [3]. To reduce the risk of unexpected costs, building owners need to investigate cost effective options to adapt their properties to be more resilient to possible future environmental changes.

A building's resilience is a measure of how well a building continues to function during or after an event, and, if the function of the building has been affected, how fast the building can regain its function.

While climate change affects building, buildings have an effect on climate change. It has been estimated that buildings contribute up to a third of green house gas emissions [4] primarily through heating and cooling. Therefore adaptations of buildings to climate change should also consider including mitigation elements to reduce buildings' impact on climate, otherwise adaption strategies may contribute to further green house gas emissions. To avoid this, adaptation strategies also need to be sustainable.

A definition of sustainable development (SD) was formulated by the Brundtland Commission in 1987 as "development that meets the needs of the present without compromising the ability of future generations". This definition is often described as triple bottom line, because it considers environmental, economic and social consequences of development. In the context of the built environment, sustainability has been widely used to refer to methods of reducing the environmental impact of buildings. Thus, it is not required that a building be completely sustainable, i.e. will have no impact on the environment. Rather, sustainability is interpreted as a measure of the relative reduction in environmental impact compared to a baseline, such as the environmental impact of a building that only just satisfies associated building standards.
Adaptation is used through out the thesis as referring to the resilience of the building to changing climate, while mitigation refers to the sustainability of the building.

To be able to adapt new and existing buildings, the threats of climate change need to be quantified and data predicting future weather needs to be readily available. Though there are well-developed climate models over the globe that can predict the climate change in different global regions, sufficient information at the national and local level can be difficult for practitioners to obtain. Practitioners need local models of climate change to prepare existing buildings and design new building with capacity to adapt to and mitigate the changing climate. For, example to investigate adaption and mitigation strategies it is necessary to model and quantify newly designed and refurbished buildings not only with current climate models but also with future climate models. However, the data for the future weather that is available for practitioners is very limited, due to the complexity of generating the data and the expertise needed to work with it. In Paper I we investigated how to develop the future weather files for heating and cooling using limited data.

Another challenges that practitioners face when preparing buildings for climate change is how to prepare buildings to be both resilient and more sustainable. In general, most maintenance and operation strategies do not yet deal with climate change and the sustainability agenda, beyond simple energy savings that are tied to cost reductions and compliance with current building regulations. Those working with the conditions of current building stock seldom consider the risk, i.e. the expected cost based on the probability of an event occurring and the associated cost of the event, associated with changing climate. A reason for this could be a lack of management tools that enable calculations of costs and benefits in an integrated manner, as pointed out e.g. by [5]

New decision support tools are needed to achieve sustainable adaptive building designs through a strategy of using maintenance activities to gradually update a building or a whole building portfolio. Papers II and III discuss the need of addressing both resilience and sustainability simultaneously and Paper III proposes a management tool that considers both resilience and sustainability.

The building sector is responsible for a significant share, approximately 40% of overall energy demand in Europe [6] including electricity for appliances and lighting, ventilation, cooling and heating and 32% total global final energy use [4]. National building regulations are gradually requiring reducing heat losses from buildings' envelopes for the new and even for existing building. It is sometimes a challenge to achieve energy efficiency measures in existing buildings. This is especially true for historical buildings, usually because of architectural restrictions. Consider, for example, ventilation. The ventilation options that are often available are usually based on some form of mechanical ventilation, which requires space and piping in a building. However historical buildings often have internal and external restrictions, which limit the use of traditional mechanical ventilation.

From a climate change prospective, Lomas has argued that natural ventilation should be considered as a mitigation option in both new and refurbished buildings. Lomas argues that advanced natural ventilation, where air is not provided to a building directly by opening windows, but through air supply channels, is more resilient to increasing temperatures, requires less energy, and therefore emits less CO_2. [7]. In the Technical Report we investigate an advanced natural ventilation system in a case study based on an historical building.

The focus on adaption and mitigation of historical buildings is partly motivated by the partners in this Ph.D., which is supported by Gentofte Municipality, Gentofte Building Department (Gentofte Ejendomme). During the first year of my

Ph.D., I spent a day a week at Gentofte municipality and participated in the work of the climate adaption group. In the early stages of the Ph.D., a case study building was identified. The building provided an opportunity to be directly involved in analysing and designing energy efficiency improvements, design a passive ventilation strategy for the historical building, and investigate the resilience of such strategies to future changes in climate. The collaboration with Gentofte Building Department on the refurbishment of an historical building provided both opportunities for evaluation in the real world, and experience of the obstacles practitioners face during the process of preparing buildings for the climate change.

This thesis first considers how to quantify climate change threats with limited data. It then proposes a framework where both resilience and sustainability are included in a decision making tool. Finally, a passive ventilation system for an historical building is modelled and evaluated.

1.2. Scope

Climate change is not considered anymore as the technical problem that can be altered by improving energy efficiency or developing new technologies, but as a multi dimensional problem requiring tackling from different levels of society [8,9]. To investigate the impact of climate change on buildings a multidisciplinary approach is chosen integrating both natural and social science. Climate change also is an urgent problem that requires practical solutions her and now that can be integrated not only in designing new buildings but also upgrading the existing building stock.

The research for this thesis was carried out from a building manager's perspective to identify hurdles practitioners face when adapting a building to the changing climate. The thesis and the articles are built on a case study building in Denmark, using the Danish climate and a historical building as a reference. However, the findings are methodological findings and can be used for different types of buildings and in different countries.

The thermal comfort of a building depends on many different weather parameters such as outdoor temperature, relative humidity, wind speed and solar irradiation. However, only the change in the future outdoor temperature was considered, because, according to [10], the most significant weather parameter that has the strongest correlation with internal thermal comfort is the outside temperature during warm periods.

1.3. The structure of the thesis

This thesis is a collaboration between the Department of Civil Engineering and Management Engineering both at Technical University of Denmark, the Centre of Facility Management-Realdania Research, and Gentofte Building Department (Gentofte Ejendomme) at Gentofte Municipality. The project takes a practitioners perspective and investigates the challenges that the practitioners meet when they prepare buildings for climate change. The thesis is structured based on following main topics: (i) quantification of the impact of climate change on future heating and cooling demand of buildings, (ii) developing a decision making tool where both resilience and sustainability of the solution are included, and (iii) investigating an option to improve energy efficiency and provide natural ventilation in a case study building.

1.4. Hypotheses

The research to investigate the questions below is reported in the main body of this thesis and in 3 publications and a Technical Report, referred to in the text as Publication I-III and Technical Report. The publications are appended at the end of this thesis.

The main three topics, described above, are investigated in the thesis as three Research Questions (RQ).

The research question 1 (RQ1) is motivated by the need for practitioners to quantify the impact of climate change and provide them a tool to estimate the future energy consumption of buildings with limited available data.

RQ1: When building future weather files, what level of temporal resolution is needed to provide useful estimates of future energy demand?

RQ1 is answered in Publication I, which investigates whether in the absence of high-resolution (hourly) data, a weather file constructed from a coarse (annual) estimate of future outdoor air temperature change can provide useful estimates of future energy demand of a building. Experimental results based on both the degree-day method and dynamic simulations suggest that this is indeed the case. The paper is written in collaboration with Danish Metrological Institute (DMI), Climate Centre, Management Engineering and Department of Civil Engineering in Technical University of Denmark. The experiments were tested on the theoretical examples of 3 buildings, which were based on the case study building.

With the tool developed in Publication I the practitioners can develop the future weather files using annual temperature change, which is available in most regions, and can estimate the future heating and cooling demand. The future cooling demand can help to analyses the vulnerability of a building to an extreme weather event such as heat waves and then the solutions of increasing resilience of a building can be identified. However, only considering the resilience of the proposed solution the overall cost can increase. Therefore the second research question considers integration of both resilience and sustainability in the decision-making process.

RQ2. How can resilience and sustainability be quantified and integrated in order to produce a measure that can be used for decision-making process?

The RQ2 is addressed in both Publication II and III. The need of considering both sustainability and resilience in integrated manner was suggested in Publication II as well as a preliminary outline of the method for quantification. However, the idea of how to couple and quantify both resilience and sustainability was still not developed. That idea was finally developed in Publication III, which presents method Coupling and Quantifying Resilience and Sustainability (CQRS) and illustrates with a simplified example to demonstrate the line of thought. The emphasis of the paper was the decision support tool for facilities managers. The main idea of the Publication III is that the way a particular function of a building is provisioned may have significant repercussions beyond just resilience. To address this issue Publication III considers how to couple and quantify resilience and sustainability, where sustainability refers to not only environmental impact, but also economic and social impacts. Both Publications are result in collaboration with Gentofte Building Department at Gentofte Municipality, Management Engineering and Department of Civil Engineering in Technical University of Denmark.

Even though Publications I, II and III use the theoretical building models to investigate the research questions, the models are based on the case study building. The building was renovated in 2012-2013 and the passive ventilation system using ventilation windows and existing chimneys was installed. The effectiveness of the system is discussed in Technical Report, which answers the third research question:

RQ3. Can a passive ventilation system based on a ventilation window supported by chimneys provide adequate ventilation for an historical building?

The comfort of the building including air quality and thermal comfort was measured during the 3 periods after the renovation and the results are presented in the Technical Report. In the report we investigate a passive ventilation solution for historical buildings based on a ventilation window supported by chimneys, where the air supply is provided through the ventilation window and the air is naturally extracted through the existing chimneys. Technical Report is the result of collaboration with Gentofte Building Department at Gentofte Municipality and Department of Civil Engineering in Technical University of Denmark.

1.5. List of publications

Publications included in the thesis

I. Rimante A. Cox, Martin Drews, Carsten Rode, Susanne Balslev Nielsen
Simple future weather files for estimating heating and cooling demand
available online from May 2014 Building and Environment, and published Volume 83 January 2015 Pages 104-114
The article is cited in 3 articles and has been viewed or downloaded over 2000 times.

II. Rimante A. Cox, Susanne Balslev Nielsen *Sustainable Resilience in property maintenance: encountering changing weather conditions*, conference article published and presented in Proceedings of CIB Facilities Management Conference Using Facilities in an open world creating value for all stakeholders, 2014 page 329-339

III. Rimante A. Cox, Susanne Balslev Nielsen, Carsten Rode *Coupling and quantifying resilience and sustainability in property maintenance,* published in Journal of Facilities Management 2015 vol. 13 iss. 4

Technical Report – Rimante A. Cox *Description of the passive air supply system based on ventilation window supported by chimneys 2015*

Additional publication is also included in the thesis:

Rimante A Cox *Hvordan skal Facilities Management reagere på klimaforandringernes påvirkning af bygninger?* Published article in periodical journal of Facilities Management in Denmark FM Blad, June 2012 p.12-14, written in collaboration with Centre of Facilities Management - Realdania Research

1.6. Structure of the thesis

Chapter 1 introduces the motivation and outline of the thesis. Chapter 2 provides a review of climate change impact on buildings and further motivation for Papers I-III. Chapter 3 explains the connection between the three different topics investigated in this thesis and the methodologies used. Chapter 4 summaries the key findings of the thesis. Chapter 5 discusses the usability of the findings and Chapter 6 provides recommendations for future work.

4 Background

Despite international attempts to prevent climate change by reducing green house gas emission, it is now clear that global warming is now inevitable. The International Panel on Climate Change which is the scientific intergovernmental body that assesses scientific, technical and socio-economical relevant information defines climate change as*: "Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or* ***external forcings*** *such as modulations of the solar cycles, volcanic eruptions, and* ***persistent anthropogenic changes in the composition of the atmosphere or in land use****"* [11].

There is now strong scientific evidence that climate change is occurring across natural systems [12]. The latest IPCC 5 report removes any doubt whether human activities have an influence of changing climate: "*Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems"* [11].

Models of global warming predict not just an increase in average temperature across the globe. Increased temperatures also lead to increases in sea level, increase of flood and drought events [13], future winds [14] and changes in local weather patterns, causing increased numbers of extreme weather events [1] [11].

The modeling of future weather patterns uses IPCC 4 scenarios, which are described in Figure 1.

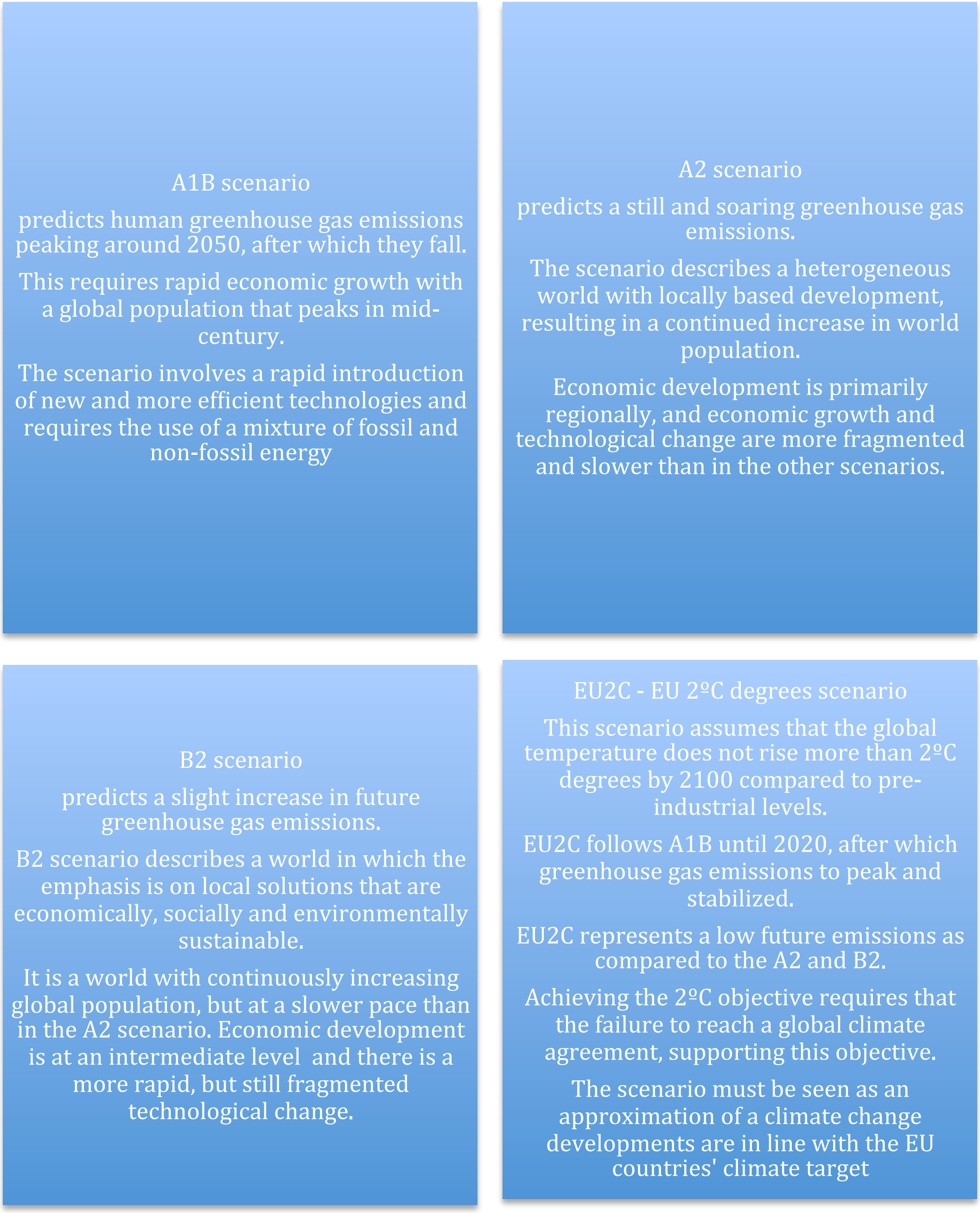

Figure 1 Description of the IPCC 4 scenarios taken from http://www.klimatilpasning.dk/daDK/service/Klima/klimascenarier/Sider/Forside.aspx)

The latest IPCC 5 report changed the scenarios. It is relevant to note that the work in this thesis as well as most of the literature review is based on the earlier assumptions of the scenarios shown in Figure 1 and 2, based on IPCC 4.

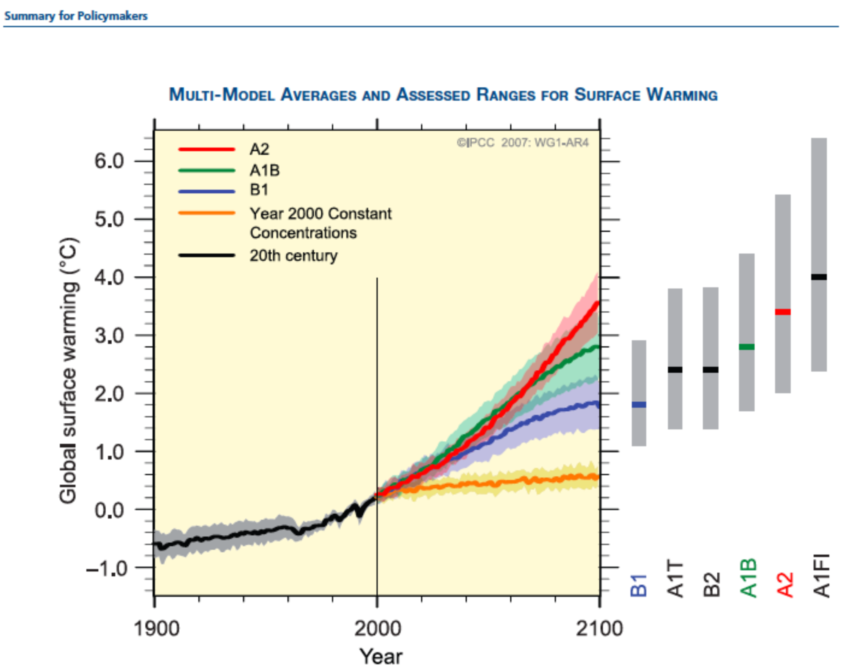

*Figure 2 Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the **likely** range assessed for the six SRES marker scenarios. The assessment of the best estimate and **likely** ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. Taken from IPPC report 4 [15]*

Different Global and Regional Climate Models (RCM) show that the patterns of extreme events will be more frequent and intense in the future. Some of the models show the correlation of occurrence of extreme weather events with the rise of greenhouse gases [16].

In the next section there is a short summary of predictions of climate change in Europe based on the earlier RCM models.

2.1 Summary of climate change predictions in Europe

An overview of the effects of climate changes in Europe was analysed by [1], which was based on PRUDANCE model data. The PRUDANCE model was a climate change downscaling experiment. The experiment created 55 simulations, which were based on 9 regional climate models (RCM) and one stretched global atmospheric climate model (GCM). The experiment included two periods: present from 1961-90 and future (2071-2100). The latest IPCC 5 report uses more recent data, which support the climate change predictions in PRUDANCE model. The results from the PRUDANCE experiment are summarised below as it gives a more clear idea of what will happen in Europe comparing with IPCC reports, which describes the global changes. The results of PRUDANCE experiment is also compared with other studies of future flooding, droughts and wind in Europe, such as Lehner B. et al., who used a global integrated water model WaterGAP to investigate future flooding and droughts in Europe, [13], (Jones 2001) who investigated the changing precipitation patterns in Europe, and Debernard J. et al., who investigated future wind, wave and storm surge in the North Atlantic [14].

2.1.1 Temperature

The PRUDANCE experiment included investigation of the changes in intensity and duration of summer heat-wave incidents. A heat wave was defined as a spell of at least six consecutive days with maximum temperatures exceeding 30°C [1].

The simulation results of PRUDANCE project showed that by the end of the twenty first century the summer climate zone would shift northward by at least 400-500 km. For example the mean number of days/years exceeding 30°C at the grid point nearest to Paris increased from 9 days under current climate (observations at the Paris Montsouris station give 6 days), to 50 days under future climatic conditions. The heat waves were restricted mostly to the summer period under current climate. However under future climate conditions heat waves would also occur outside of the summer period; the maximum number of consecutive days/year exceeding 30°C at Paris was predicted to increase from an average of 3.5 days (3.0 for observation at Montsouris station) to 18.9 days.

The mean duration of a heat wave increases by a factor between one and eight over most of Europe. Much higher of at least a factor of seven are predicted for Heat Wave Intensity, the mean number of heat waves and frequency of heat wave days changes nearly 10 times in south France and Spain.

Based on this study it is clear that "*the intensity of extreme temperatures increases more rapidly than the intensity of more moderate temperatures over the continental interior due to increase in temperature variability*" [1].

According to IPPC 5 the number of days of hot extremes will increase and the cold extremes will decrease [16].

2.1.2 Extreme precipitation

According to [1] heavy winter and summer precipitation would increase in central and Northern Europe, and will decrease in Southern Europe. For example, the experiment investigated extreme precipitation events and compared the results of current climate with a case study for Southern Germany. The results showed that precipitation in winter increases, and it was in line with the predictions of change for mean precipitation (Jones 2001), on the global scale.

Over most of north-western Europe, Scandinavian as well as Eastern Europe, the long lasting rains that could last up to 5 days increases in frequency 3 times. For example in winter - the long lasting participation with magnitude that only occurs every 15 years under current climate conditions will occur in the future as often as every 5 years in the simulation experiment.

According to PRUDANCE results of the simulation, the mean precipitation over Central Europe in summer time would decrease. However the mean summer maximum precipitation was projected to either increase or remain virtually unaltered. In northern Europe the projected change in summer, short but intensive precipitation, was positive in all the models, and ranged from 20 to 40%, and were mostly dependent on the models rather than the emission scenarios. For the summer mean precipitation in northern Europe the disagreement between different RCM was great and showed variations between increasing, decreasing or negligible change. The summer long lasting precipitation (lasting 5 days) was smaller but positive, revealing that the intensity of individual precipitation events increase more in northern Europe and decreases less in southern Europe.

In summer, the extreme value analysis showed a statistically decrease of 5% in magnitude of precipitation that occur every 5 years in Southern Europe and increased over Scandinavia and north-eastern Europe. In some parts of central and Eastern Europe the frequency of heavy precipitation increased, despite the overall decrease in mean precipitation. The decrease in frequency of mean precipitation was partly compensated for by an increase in precipitation intensity and the frequency of heavy events. However, there was a considerable variation in the quantitative change of these predictions between different RCM models that very much depended on the formulation of RCM and internal variability of climate, as well as the boundary conditions provided by GCM. The experiment also showed that even though the incidental heavy precipitation were not sensitive of the projected changes to emissions, the mean winter and summer precipitation were quite sensitive to the projected changes to emissions, as they vary with the different scenarios.

The simulation of European future flooding and drought using global integrated water model WaterGAP were investigated also by Lehner B. et al., who observed similar results [13]. Lehner B. et al. used definition of flooding as "floods through their daily peak flows, representing the state of maximum inundation or potential damage" and investigated period of 2070. Lehner B. et al. observed that flooding that occur every 100 years, would occur more frequent (every 40 years) in the northern and north eastern Europe and even in some parts of Portugal and Spain, where the general flooding would be reduced.

2.1.3 Drought

In PRUDANCE project the drought was defined as a continuous period of days with no precipitation, The experiment indicates considerable drying over much of Mediterranean and the most affected regions were observed to be Iberian peninsula, the Alps, the eastern Adriatic seaboard and south of Greece. For example, the drought over southern Iberia under the A2 scenario (described in Figure 1) will last over a month longer than at present, and under the B2 scenario 20 days longer than present [1]. Similar results were observed by Lehner B. et al. who investigated the frequency and magnitude of drought in Europe. Lehner B. et al. defined drought as a " persistent period where the river discharge stays below a reference minimum flow" [13].

2.1.4 Extreme wind storms

The simulation from PRUDANCE experiment showed that the wind speed during the winter period would increase 2.5% - 10% in European latitudes (45-55°N). The most positive changes were concentrated over the ocean, North Sea and western Europe (UK, France, northern Switzerland, Germany). Daily wind speed would decrease over UK, the North Sea, the Norwegian Sea and the Baltic, extending inland to France Germany and Scandinavia [1,17,18]. Debernard J. et al. investigated future wind, wave and storm surge in North Atlantic and forecasted similar results [14]. Debernard J. et al. investigated an earlier period 2030-2050. According to Debernard J. et al. the significant reduction in wind and waves were observed in north and west Iceland, and the significant increase in wind speed in the North Sea in north as well in the west of Atlantic Ocean. The reduction in wind speed was observed in the south west of British Isles in the autumn. The significant increase in seasonal sea level was observed by Debernard J. et al. in the Southwest part of North Sea [14].

2.2 Climate change in Denmark

The Danish Metrological Institute (DMI) [19] provides average seasonal and annual changes in Denmark based on IPCC SER scenarios [20,15], which are described in Figure 1 and shown in Figure 2. The DMI report uses a set of 13 regional models with different global circulation models to calculate the average annual and seasonal temperature change for IPCC scenarios A1B, A2 and B2 for the years from 2050 to 2100.

More recent forecasts of the changes in Danish Climate are listed in [21]. Here, the most significant changes in Denmark will be the increased precipitation and an increase in average temperature.

Denmark is already facing flooding threats due to sudden heavy rains, and coastal flooding due to storm surges. During the last three years Denmark experienced heavy rains in Copenhagen and other areas in Denmark where the cost of damage per event was close to 1 billion Euros [22]. The Danish government and municipalities are particularly interested in how to adapt their cities to the increasing threat of floods. There is on going work within the Danish scientific community to address the increasing risk of flooding [23], [24]. There is also an interest from the wind industry to have a clear understanding of future wind conditions [14], [25] as Denmark invests in offshore wind parks.

2.3 Climate change and its impact on buildings

The impact of climate change on society has gained increased interest. According to IPCC Report 5 by Working Group II, the number of scientific publications assessing the vulnerability and adaptation of societies to climate change impacts more then doubled in the period from 2005 to 2010 [11]. For example, there have been numerous studies of the possible consequences to health and wellbeing [26], [27], and the effect of climate change on agricultural production [28] and ecosystems. There is now significant research examining how countries can adapt to climate change [17].

Considerable research and development is now focused on ways to reduce carbon emissions through sustainable energy programmes such as solar, wind and tidal energy, and improving the energy efficiency of buildings. Consequently, there is a sustained interest in predicting the effects of expected future warming on societies, not only within academia but also in industry. This is particularly true with respect to expected impacts of climate change on the built environment and especially on buildings. For example, the impact of climate change on buildings was recently mapped by [29] and [30], identifying threats such as flooding, extreme winds and overheating. These extreme weather events can cause significant damage to buildings and infrastructure, as witnessed by the extreme precipitation in July 2011 in the Copenhagen region. Although extreme weather events are rare, the magnitude of the damage on building stock is increasing [31], [29] and is evident through increased insurance claims. [3]. According to Mills "*Climate change impacts in the buildings sector are the primary concern for property insurers, given the extent of insured value represented, and the vulnerability as compared with other infrastructure*".

Building owners are effected not only financially but also, "*with exposures ranging from damage to physical infrastructure to disruption of business operations to adverse health and safety consequences for building occupants)* [3].

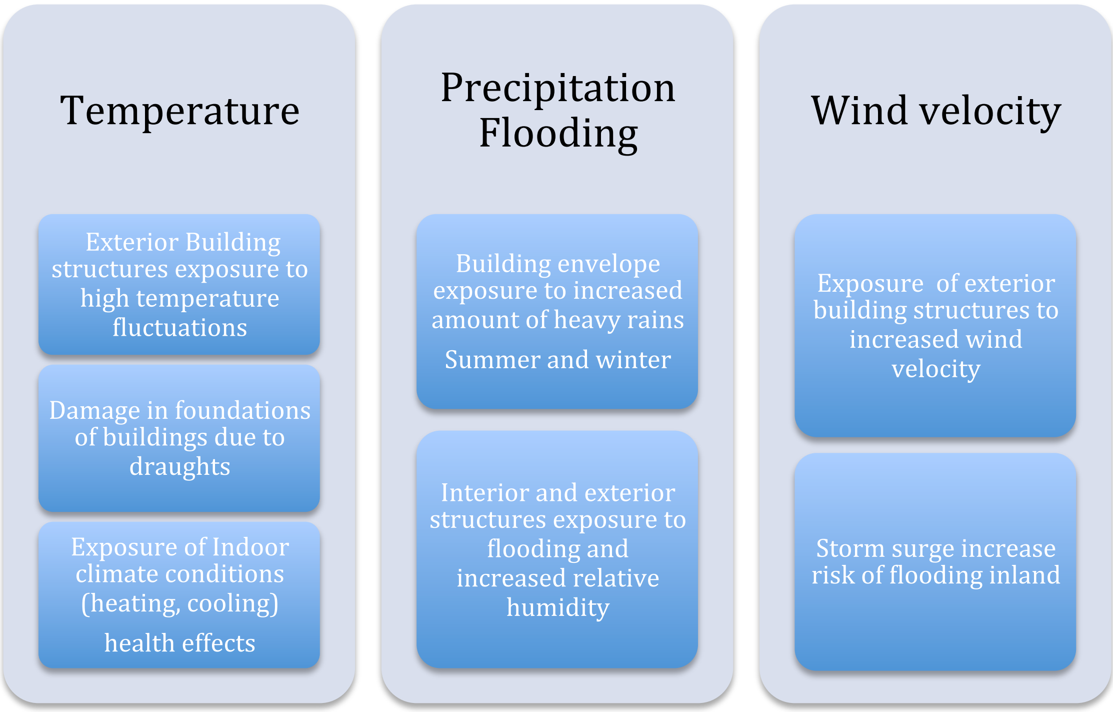

Figure 3 Extreme weather impacts on buildings

Mapping the threats is useful to identify the impact of climate change on buildings. However it is difficult to prepare the buildings for climate change if the threats are not quantified. In this thesis the focus is on tools to quantify the threats of climate change on buildings in Denmark.

The most significant affects of climate change on buildings have been identified as being due to (i) temperature, (ii) flooding due to precipitation or sea level rise, and (iii) wind. In this study we only considered temperature change as it will affect all buildings regardless of location, and can be both positive (heating demand decreases) and negative (cooling demand increases). To be able to predict future heating and cooling demand the new design buildings as well as major renovation of the existing building should be simulated not only with current weather files, but also with the future weather files. The future weather files similar as current weather files consist of different weather parameters, such as dry bulb temperature, relative humidity, solar irradiation, precipitation, wind direction, wind speed etc. on an hourly basis in a particular region.

In this study we only considered a single parameter, outside dry bulb temperature, of a future weather file. However, the work of [32] suggested that "*… with a +10% change in proposed future values for solar radiation, air humidity or wind characteristics, the corresponding change in the cooling load of the modelled sample building is predicted to be less than 6% for solar radiation, 4% for RH and 1.5% for wind speed, respectively".* Similarly, as noted in [10] even though the thermal comfort of a building depends on many different weather parameters, such as outdoor dry bulb temperature, relative humidity, wind speed and solar irradiation, the most significant weather parameter that has the strongest correlation with the internal thermal comfort is the outside temperature during warm periods. Also, Kershaw et al., who investigated internal temperatures and energy usage in buildings, pointed out that "*the external air temperature is a major driver of the internal temperature"* [33]. I therefore restrict further discussion to the impact of temperature change on buildings.

2.3.1 Impact of temperature change on buildings

A predicted overall increase in global warming of between 2 and 4 degrees in the next 50 years might not seriously affect buildings. However, climate change models also predict an increase in extreme weather events such as heat waves, persistent drought, and intense precipitation that often cause flooding, as well as storms and hurricanes.

Several researchers have pointed out that heat waves can have health effects and cause increased mortality in the most vulnerable members of society, especially the elderly and young children [34]. Hubler reviewed literature regarding the heat mortality in Europe during the summer of 2003. Significant cases of heat related mortality occurred among people above 75 years old: 85% of victims in England, 70% in France, 92% in Italy and 97% in Portugal. An earlier study by [35] investigated the relationship between outdoor temperature and mortality in Italy, and found a significant correlation. The study showed that an increase in mortality had statistical significance when the outdoor temperature exceeded $32C^{o}$.

Change in outdoor temperature effects buildings in two ways. First, indoor comfort is directly related to outdoor temperature, as discussed above. Second, since buildings shelter us from the surrounding climate, operation and maintenance of buildings can be significantly effected by increased heating, ventilation and cooling demands. If these demands are met using fossil based energy, then buildings can have a significant impact on natural environment through their contribution to global warming. For example, the energy used for heating, ventilation and cooling buildings represents approximately one third of total global final energy use*.* With increasing outdoor temperature, the heating, ventilation and cooling demand will change. It is estimated that the heating demand will be reduced by 10% and cooling demand will increase by 30% in Switzerland [36] in the UK [37], [38] and in Australia [39].

To be able to increase the resilience of building stock to different extreme weather events, it is important to investigate the vulnerability of building stock to these events. For example, heat waves, which are currently rare in Denmark, will mostly have consequences on the comfort of the building. The vulnerability of the building stock to heat waves will depend on the physical parameters of the building, location, orientation, the function of the building, as well as how the building is ventilated. Traditionally, buildings in Denmark, as in the rest of Europe are naturally ventilated.

According to [40] energy consumption for cooling in Europe has already increased 4.5 times within the domestic building stock in the last 20 years. Energy consumption of room air-conditioners increased from 1.6 GWh in 1990 to 44GWh in 2010. If the market for air-conditioning continues to grow at the same rate, future building stock will create more pressure on the environment by increasing the output of greenhouse gases due to the associated electricity consumption.

2.4 Current obstacles restricting preparation of buildings to climate change

Climate resilience has received a significant increase in attention and is an emerging topic in the facilities management (FM) research literature (e.g. [41] and [42]. However in practice, most maintenance and operation strategies do not yet deal with climate change and sustainability beyond energy savings.

One reason for this may be due to the lack of available data to quantify the risk of changing climate on buildings. To be able to estimated future heating and cooling demand of a building the building models can be simulated with a future weather file. However, the lack of readily available future weather data such as future weather files has been identified as a serious obstacle for practitioners and described in section 2.4.1.

Another reason for practitioners to ignore the climate change risk posed on buildings is limited decision making tools that helps building owners to (i) determining the resilience of a building (ii) identify the solutions and (iii) evaluate the sustainability these solutions which is described in the chapter 2.4.2.

2.4.1 Lack of data available for practitioners

Despite significant interest in climate change, there is evidence that future weather files are often not readily available in many regions. For example, Jentsch et al. "… *believe that one reason for this is the lack in availability of* *approved climate change weather files for simulation programmes*." [43]. This is supported by Jones and Thornton who write that "*The availability of weather data continues to be a serious constraint to undertaking many applied research activities … Nowhere is this more apparent than in agricultural impacts modelling, particularly in relation to utilizing the outputs of climate models to evaluate possible impacts of climate change*" [44].

The lack of available future weather files is, in part, due to the difficulty in acquiring future weather projections within a sufficiently localized region and at the hourly temporal resolution required by standard weather file formats. To produce such data typically requires downscaling global circulation models to regional levels, e.g. using regional climate models, followed by detailed analyses to assert the quality of the projections. This work requires expert knowledge of climatology and is typically conducted at dedicated research centres and national meteorological institutes. Such work has been done in UK where stochastically generated climate change weather files were produced by experts in climatology as part of the UKCIP UK Climate Impacts Programme (UKCP02 and UKCP09). These future weather files for different regions in UK are easily available for researchers and practitioners in UK.

As this project is the collaboration with practitioners we investigated how to estimate future heating and cooling demand when access to future weather files is limited. This is addressed in Paper I.

2.4.2 Lack of tools to incorporate resilience and sustainability in decision making processes

Resilience is increasingly used in the context of climate change and climate adaptation of the built environment. Most studies of resilience to climate change have been undertaken by (i) mapping threats such as the increased possibility of flooding, sea level rise or heat-waves [17], [18], [29], [42], (ii) investigating the vulnerability of a system to these threats [39], [30], and (iii) investigating how to adapt to these threats [7].

Similar sustainability is often used in the context of climate change as a way to mitigate climate change and to increase resilience of the built environment. Most common definition of sustainability in the built environment relates to a definition of sustainable development (SD), which was formulated by the Brundtland Commission. This definition is often described as triple bottom line, because it considers environmental, economic and social consequences of development.

Sustainability for Facilities managers' (FM) of buildings is becoming more important since maintenance and operation of buildings can make a significant contribution to a company's environmental impact. There is great potential to reduce environmental impact through FM, although this has not been well recognized as an important activity for environmental management of companies [45], [46]. However, while facilities management counts for only a small fraction of a company's budget, it can have a significant contribution to a company's environmental impact. For example, according to [45], [46], facilities management expenses account for 4-6% of a company's expenses, but operation and maintenance of buildings contribute 53-82% to a company's overall environmental impact, even when accounting for different types of companies, their sizes, locations and budgets. Thus, the application of sustainability in facilities management could be an option to reduce the overall environmental impact of a company and help promote the role of sustainability in the core business.

Both sustainability and resilience are important issues that should be considered during design or renovation of a building. New decision support tools are needed to consider resilience and sustainability in an integrated manner. This is discussed in Paper II.

Currently, it is commonly believed that sustainable solutions are more expensive than simply preparing a building to be more resilient. However, in Paper III we demonstrate that by only considering the resilience of the building, the solution can be more costly than solutions that take account of both resilience and sustainability.

3 Method and design of the thesis

As the research project is multi-disciplinary project involving partners from both natural and social sciences, as well as practitioners, the research methods are mixed. The practitioners' involvement in the research project from the early stages inspired me to take a practitioner's prospective. The subjects of research were chosen pragmatically [47] due to the structure of the research project and practical considerations. However the research approach for different areas followed the positivist research philosophy [47].

The research project involved three partners who funded the project: Building Department at Gentofte Municipality (Gentofte Ejendomme), the Department of Civil Engineering and the Centre of Facilities Management at the Technical University of Denmark. Early in the project the importance of climatology became clear and was incorporated into the project, with collaborations with the Danish Meteorological Institute and the Climate Centre at DTU.
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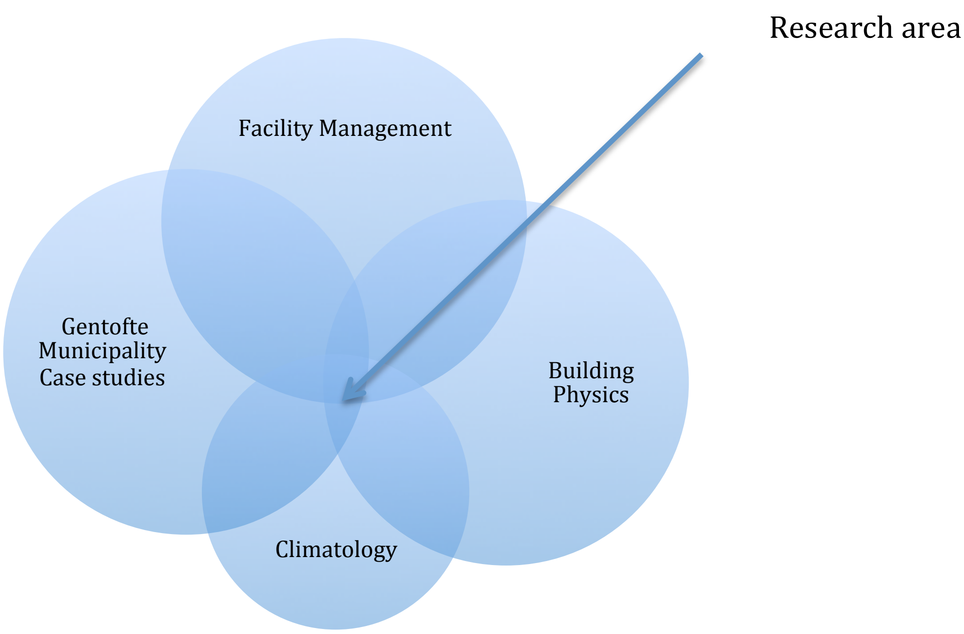

Figure 4 Research areas relevant to the thesis.

The thesis is focused at the intersection of these interests, as depicted in Figure 4. For example, a topic like mapping the threats of climate change is a general topic of climatology. However, only the parameters that have direct or indirect impact on buildings are within the scope of this thesis. For example, the most significant affects of climate change on buildings have been identified as being due to (i) temperature, (ii) flooding due to precipitation or sea level rise, and (iii) wind. However, the impact on precipitation or sea level rise will depend on the location of the building and not all buildings will be affected. In contrast, temperature change will affect all buildings regardless of location, and can be both positive (heating demand decreases) and negative (cooling demand increases). I therefore made the pragmatic decision to focus on temperature changes, as these are dominant.

Similarly, maintenance and operation of buildings, as part of Facilities Management discipline, has been identified to fall into the research area, because both climate change impact on buildings and buildings' impact on climate are using most energy during operational and maintenance phase.

From Building Physics perspective heating and cooling demand was identified to fall to the research area. Heating and cooling demand of the building differs from building to building and depends on the location and physical properties of the materials of the building, as well as form of ventilation. The heating and cooling demand of buildings usually dominates the energy used in buildings and represents the highest CO_2 outputs for a building [48].

As the research project takes the practitioners' perspective, an existing building, called Villa Bagatelle, Gentofte, Denmark was chosen as the research object of the thesis. The case study building, which is described in details in Technical Report, is used as an inspiration for the theoretical examples in the papers. The building is used to illustrate the considerations related to maintenance and operation process and identify the obstacles related to adaption of the buildings to climate change. The passive ventilation system based on ventilation windows and supported by chimneys was installed in the building in 2012 and tested in 2013.

The relationship between the 3 different research areas considered in this thesis, such as (i) develop simple future weather files with limited available data, (ii) incorporate sustainability and resilience cost in decision making process for property maintenance and (iii) effectiveness of passive ventilation system, is difficult to spot without understanding the relationship between buildings and climate, which was discussed in an article written by me for Facilities and Management magazine and attached in the end of the thesis. The relationship is illustrated in Figure 5 and is described below.

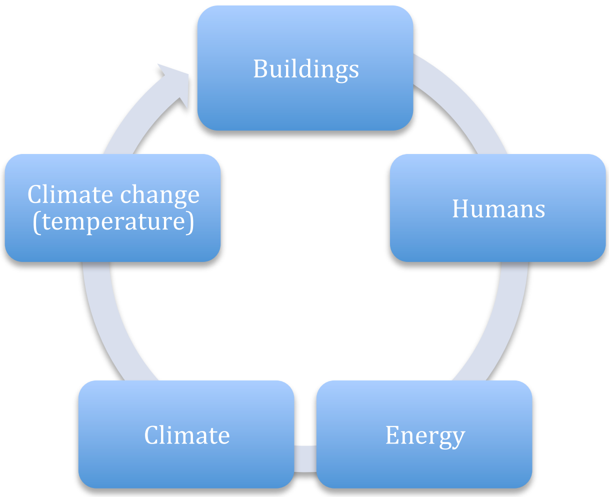

Figure 5 Relationship between buildings and climate change

Buildings protect humans from the surrounding environment, from weather and changing climate. Buildings are also products of human activities: the way we choose to design, operate and maintain our buildings have an impact on the surrounding environment. For example, most of the energy consumption used in buildings is derived from fossil fuels, which causes climate change.

In this thesis I make a distinction between adaptation and mitigation strategies. Adaption treats the symptoms of global warming, e.g. increased heat, but does not explicitly consider the underlying cause. For example, as average temperatures increase, an adaptation strategy (to improve resilience) might be to add additional air conditioning. Consequently, buildings will consume more energy for cooling. The increased energy demand, if provided by fossil fuels, exacerbates global warming, increasing average temperatures further. This, in turn, leads to further increases in energy consumption in order to cool the buildings. And a perpetual loop is created where the immediate solution subsequently makes the problem worse.

To avoid this unsustainable feedback loop, it is important to not just treat the immediate symptoms but also the underlying causes of climate change. More generally, a mitigation strategy (sustainability) is one that not only addresses the immediate problem, but also considers how proposed solutions may effect the future environment. Thus, a mitigation strategy for cooling buildings might try to install passive cooling, or ensure that the energy used for air conditioning is provided by sustainable, zero-carbon sources.

Even though research project is multi-disciplinary the positivist research philosophy is followed in I paper and Technical Report. The positivist epistemological research philosophy is mostly used in natural science and is described as "*working with an observable social reality and that the end product of such research can be law-like generalisations similar to those produced by the physical and natural scientists*" [47]. The case study building was measured, analysed based on the building structures and occupancy, and used to create a simulation model of the building. In Paper I the simulation model was then adjusted to represent the 3 types of buildings, where the 3 models of future weather files were tested. The results in Paper I are generalizable and can be used in any building and in any country. The Technical Report investigated the case study building and a passive ventilation solution for historical buildings where the air supply is provided through ventilation windows and the air is extracted through the existing chimneys. The building was first simulated using a dynamic simulation model and the installed system was tested in a natural environment during occupancy.

Papers II and III follow a more a pragmatic philosophy, which takes the "*a way of examining social phenomena from which particular understandings of these phenomena can be gained and explanations attempted* " [47]. The research approaches in both II and III paper are very much based on the values and thereby follows the pragmatic philosophy, which is frequently used in social sciences. The paper III analysis the ways the resilience and sustainability is measured and quantified and proposes a "*radical change*" how the prising of sustainability and resilience can be conducted "*in order to make fundamental changes to the normal order of things*" [47].

Table 1 summarises the method used in the papers I-III and Technical Report

	Paper I	Paper II	Paper III	Technical Report
Method	Relative Change based method to create future weather files Heating and cooling degree day method Dynamic simulation of the building	Reviewing method to quantify resilience and sustainability Risk analysis	Expanding risk analysis method where resilience and sustainability is expressed as risk	Metering and estimating air quality based on CO_2 concentration in the rooms using the mass balance theory. Estimating the air movements in and out of the building during 3 ventilation strategies
Results	3 future weather files based on different temporal resolution Comparison of future heating and cooling demand of 3 type of buildings with 3 types of future weather files	A conceptual tool to include resilience in property maintenance decision	A conceptual tool to include both resilience and sustainability in property maintenance decisions Illustrative example	The system could not provide sufficient air change for ground floor or 1st floor. The modification of the system was proposed, but not tested
Case	3 Theoretical models based on the case study building	Theoretical model based on the case study building	Theoretical example based on case study building	Case study building

Table 1 Different methods used in Papers I-III and Technical Report

4 Summary of results

This chapter summarizes the research results. A much more detailed description can be found in the corresponding papers.

4.1 Paper I - Simple future weather files for estimating heating and cooling demand

Practitioners need future weather files in order to predict the future energy demand of buildings. A common way to construct future weather files is to first estimate the expected change in temperature at some future time and then add these changes to a current weather file. Since current weather files provide temperature data at hourly intervals over a one-year period, the expected changes in temperature are also estimated at an hourly resolution. Providing such fine grain estimates requires sophisticated modelling that is usually performed by a meteorological institute. In many situations this data is not readily available. Paper I investigated the question of what level of temporal resolution is needed to provide accurate estimates of future energy demand? If future weather files constructed using much coarser estimates of changes in temperature, e.g. annual changes, still provide similar estimates of future energy demand, then practitioners can easily construct future weather files from existing weather files.

I investigated how estimates of a building's energy demand differ based on different future weather files constructed using coarse (annual), medium (monthly) and fine (hourly) temporal resolution data of temperature change. The construction of future weather files is described in Sections 4.1.1- 4.1.3. The degree-day method and a dynamic simulation model were used to assess the ability of different future weather files to estimate future energy demand and are described in section 4.1.4-4.1.5. The results are summarised in 4.1.6.

4.1.1 Current method of developing future weather files

In Paper I the current methods of constructing future weather files were categorised as (i) absolute or (ii) relative. In the former case, projections of weather parameters from climate simulations are used directly, while in the latter case projections of expected *changes* in weather parameters are used. The projected changes are then added to either a synthetic weather series derived from a weather generator, or to an existing (observational) weather series such as Typical Reference Year (TRY) or Design Reference Year (DRY), in order to produce the final future weather file. Both methods are described in Paper I.

4.1.2 Change-based method for developing future weather files

In Paper I we used a simple "change-based" method for constructing future weather files, e.g., adding an estimated annual increase in temperature to an existing weather file, and we then considered whether the results provide useful estimates of a building's future energy demand.

4.1.3 Construction of future weather files

The relative *change based* method was used in the research to construct three future weather files:

1. Annual offset method – adding the expected annual increase in temperature to a design reference year
2. Monthly offset method – adding the expected monthly increases in temperature to a design reference year
3. Hourly offset method – adding the expected hourly increases in temperature to a design reference year

Note that in all three cases, only the temperature parameter of the design reference year was changed. All other parameters of the weather file, e.g. wind speed, humidity, etc., were unaltered.

Weather data

To construct the three future weather files we considered an existing weather file consisting of *n* parameters, p_1, p_2 … p_n. For example P_1 can be dry bulb temperature, P_2 relative humidity, P_3 wind speed etc. Each parameter, p_i, is a vector of 8760 hourly values. We also considered a projection of changes to each of these parameters, denoted Δ_1, Δ_2 … Δ_n. Each parameter, Δ_i, is a vector. The dimensionality of the vector may be different from that of the corresponding parameter p_i. For example, in the case of dry bulb temperature, the predicted change might be (i) a single 1-dimensional projection of the average annual change in temperature, (ii) a 12-dimensional projection of the average monthly change in temperature, or (iii) a 8760-dimensional projection of the hourly change in temperature. Each parameter, p'_i, of the future weather file was then constructed by adding the projected changes, Δi, to the corresponding parameter values, p_i, in the existing weather file.

4.1.4 Current method to predict heating and cooling demand

Two common methods for estimating energy demand for a building are (i) the degree-day method and (ii) dynamic simulations of a building.

Degree-day method

Heating and cooling demand are generally functions of various weather parameters, including outside dry bulb temperature, humidity, solar irradiation, wind spend and direction, etc. The degree-day method on the other hand only considers the outside dry-bulb temperature. Nevertheless, it is commonly used as a convenient method for estimating heating and cooling demand in a building. The principle behind the degree-day method is that heating and cooling demand are proportional to the area below or above a balance point temperature. For a particular building a heating balance point temperature is defined as the temperature below which heating is required to maintain a comfortable temperature. Similarly, for a particular building, a cooling balance point is defined as the temperature above which cooling is required to maintain a comfortable temperature. These two balance points are usually different. The degree-day method is a convenient way to examine the effect of different weather files on estimates of the energy demand of buildings [36]. Despite this advantage, the degree-day method has a number of disadvantages as noted in, for example [49]and [50]. Guan argues that some of the limitations of the degree-day method are (i) that it requires that building use and heating and cooling systems are constant, and (ii) that it is only appropriate in climates where humidity is not an issue. To address these concerns regarding the degree-day method, I also provide experiments using dynamic building simulations, which do not have these limitations.

Dynamic building simulation

A dynamic building simulation can also be used to estimate a building's energy demand. Using a dynamic simulation, the energy performance of a building is calculated based on the building's location, construction type, form of ventilation, occupancy and weather parameters at the location of the building. Dynamic simulations address some of the limitations of the degree-day method as the heat losses and heat gains are calculated (i) based on the particular building's thermal properties and internal gains on an hourly base, (ii) and take into account other weather parameters, which could affect the annual energy demand, such as solar gains, wind, humidity etc. Based on outputs from a dynamic simulation model, the heating and cooling balance point can be calculated for the specific building. Dynamic building simulations are commonly used to analyse the performance of the envelope of new buildings, and the performance of different passive and active heating and cooling systems [43], [51]], [39], [52]. Examples of dynamic building simulation programs include TAS[1], BSim[2], IES[3], IDAICE[4] or Energy Plus[5].

A dynamic building simulation requires both (i) a detailed model of the building and it's heating and cooling elements, and (ii) a weather file that represents the typical weather conditions at the location of the building. To investigate the impact of climate change on buildings, a dynamic building simulation must be carried out using a future weather file incorporating climate change projections.

Dynamic simulation programmes typically require weather files to have an hourly temporal resolution.

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[1] TAS (Thermal analysis simulation) software developed by a company Environmental Design Solution Limited (EDSL), UK mostlyused in UK
[2] BSim (Building Simulation) is an integrated PC tool for analysing buildings and installations developed by the Danish Building Research Institute SBI, now part of Aalborg University, that is mostly used in Denmark
[3] IES (Integrated Environmental Solutions), mostly used in the UK, USA, France, Germany
[4] IDAICE – IDA Indoor Climate and Energy is a building simulation tool developed by EQUA Solutions that is mostly used in Sweden, Finland, Germany, Switzerland and UK.
[5] Energy Plus –is a whole building simulation program developed by the US Department of Energy

Degree day method balance points

We assume that the balance point for heating is 17°C, which is typically used for estimating the heating degree days in Denmark and the balance point for cooling is 25°C, above which "active" cooling is required. We assume that natural cooling can be obtained between 17 and 25°C.

Building simulations

For comparison and to address the limitations of the degree-day method a dynamic thermal simulation model in TAS was constructed for a case study building, which is an existing, historic, naturally ventilated building in the Gentofte municipality near Copenhagen. In addition to exploring its present-day appearance, I considered two types of modifications to the building, which have different energy efficiency consequences, and different types of ventilation systems, to evaluate the dependency of the results on the particular choice of building.

Thus there are three building models:

1. "Existing" based on description [53]
2. "Improved-NV", where the building's leakage was reduced by tightening the windows and doors, and the thermal performance of the windows in all occupied spaces was improved by adding a 3rd layer of K-coated glazing on the inner frame and improve the U-value to 0.8 W/m^2K. Natural ventilation was also established through carefully chosen top windows for the air supply using existing chimneys to extract the air. After renovation of my case study building, which is evaluated in Technical Report.
3. "Improved-MV", is the same as 2, except that the passive ventilation system was replaced with a mechanical ventilation system, in which heat-recovery could be applied. However, I did not include heat-recovery in the present comparison. A more detailed description of the three building models is provided in Paper I.

4.1.5 Results of Paper I

Experimental results using both the degree-day method and dynamic simulations of three buildings with very different thermal properties are summarised in Tables 2 and 3. The results indicate that even coarse annual estimates of temperature change produce useful estimates of energy demand. We observe that for the heating balance point, the differences in estimated energy demand using different weather files are very small, typically less than 1%. Table 2 enumerates both the number of hours and the area under the curve, i.e. total hours or heating or cooling, for a range of heating and cooling balance points.

	Number of hours			Area below balance point Degree-hours		
	Hourly	Monthly	Annual	Hourly	Monthly	Annual
Above 25	92	87	98	191	167.51	189.71
		95%	107%		95%	107%
Above 26	60	55	62			
		92%	103%			
Above 27	37	33	37			
		89%	100%			
Below 17	7706	7713	7630	7,7100	7,7100	7,7300
		100%	99%		100%	99%

Table 2 **Number of hours when outside temperature is above or below heating and cooling base line in 4 different weather files. Percentages are relative to the hourly data.**

The result from the heating degree method (Table 2) is in line with the heating estimates made for all three building models below using dynamic simulations (Table 3). I observed that there is almost no difference in the predicted heating demand when using the three different future weather files. However, I observed greater percentage differences across the weather files for the cooling balance points. This can be explained by the fact that the number of hours above these cooling thresholds is actually quite small, e.g. there are only 92 hours out of 8760 in the weather file where the temperature exceeds 25^{o}C based on the hourly-change weather file, and only 37 hours where the temperature is expected to exceed 27^{o}C (Table 2). Thus, even a small change, i.e. a single hour difference, results in a 1% or 3% (1 in 37) change respectively.

	Heating				**Cooling**			
	Present	Hourly	Monthly	Annual	Present	Hourly	Monthly	Annual
	Existing building							
Total kWh	76547	67128	67331	67641	1556	2265	2197	2387
Percentage			100%	101%			97%	105%
	Improved NV							
Total kWh	18877	16056	16145	16321	2776	3540	3485	3684
Percentage			101%	102%			98%	104%
	Improved MV							
Total kWh	11126	9256	9311	9502	7981	9174	9130	9398
Percentage			**101%**	**103%**			**100%**	**102%**

Table 3 ***Annual heating and cooling demand for the three buildings with three future weather files in comparison to the fine temporal resolution (hourly). Shaded columns present the present heating and cooling demand for the buildings***

It is assumed that the area under the curve, i.e. the total number of heating or cooling hours, is directly proportional to the energy demand. Note that in all weather files we have only changed the temperature, and all other weather parameters were kept the same. Consequently, if this area is approximately the same for all three weather files, then all three weather files result in very similar estimates of energy demand. In this case it is exactly the same, because the annual and monthly change was calculated based on hourly changed.

The results empirically show that future weather files constructed using only a coarse annual estimate of temperature difference can provide useful estimates of a building's future energy demand. However, it is straightforward to construct examples of hourly temperature changes and corresponding annual temperature change that would give very different results. Paper 1 describes the limitations of the method and under what conditions accurate estimates can be expected and considers cases when by adding annual or hourly change can cause different results.

Clearly, the energy demand of buildings is also sensitive to weather parameters other than temperature, such as wind, solar gain or precipitation, as well as cross-correlations between parameters. None of these have been investigated here and should be addressed in a future study. However, once again, we note that previous work by [32] suggests that the effect of these parameters could be relatively small (less than 10%).

The practical implication of our results is to recommend that in cases with limited access to high temporal resolution weather data, using the annual change in temperature may produce close estimates. Moreover, the coarse resolution weather file is, from an energy simulation point of view, simple to construct.

4.2 Paper II and III - Risk framework for quantifying of resilience and sustainability in property maintenance

A building's resilience is a measure of how well a building continues to function during or after an event, and, if the function of the building has been affected, how fast the building can regain its function.

While climate change affects building, buildings have an effect on climate change. It has been estimated that buildings contribute up to a third of green house gas emissions [4] primarily through heating and cooling. Therefore adaptations of buildings to climate change should also consider including mitigation elements to reduce buildings' impact on climate, otherwise adaption strategies may contribute to further green house gas emissions. To avoid this, adaptation strategies also need to be sustainable. As noted in the Introduction, adaptation is used through out the thesis as referring to the resilience of the building to changing climate, while mitigation refers to the sustainability of the building.

Papers II and III investigate the question of how resilience and sustainability can be quantified and integrated in order to produce a measure that can be used for decision-making process? In Paper II the need of such approach was identified, and an outline of a method to incorporate both resilience and sustainability was proposed. Paper III significantly extended this outline, to describe a comprehensive framework that is illustrated with a simplified example.

4.2.1 Coupling resilience and sustainability

To couple resilience and sustainability, I proposed determining the expected cost (risk) to a company of providing a function of a building in a particular manner, where the cost considers functional (resilience), as well as environmental, economic and possibly social dimensions (sustainability).

This is very different from resilience alone. Consider, for example, the function of cooling a building. Resilience only considers under what conditions the cooling system will fail, and the expected cost associated with resilience is only due to the costs associated with a loss of function. If there is no loss of function, resilience is perfect and there is no expected cost. In contrast, resilience and sustainability considers not only the cost associated with loss of function, but also costs associated with environmental sustainability and economic sustainability. Thus, the expected cost associated with resilience and sustainability, of say cooling, may be high, even when there is no loss of functionality, if providing this function has environmental, economic or social repercussions.

4.2.2 Quantifying resilience and sustainability

In order to meet the expressed need of measuring and quantifying engineering solutions and to allow multi-criteria comparisons of alternative solutions we integrate both the risks associated with resilience and sustainability to derive the expected cost, in monetary terms. The expected cost explicitly includes environmental, economic and social costs that are incurred by provisioning a function of a building in a particular way.

I assumed an economist's perspective that facility managers are rational and base decisions on economic criteria. Thus, it is imperative that a monetary cost be associated with sustainability, or the lack thereof. Such costs can be either direct or indirect costs. For example, the carbon output of a building may have a direct cost if a carbon tax is imposed. Alternatively, the carbon output of a building may have an indirect cost in the absence of a carbon tax. This indirect cost may manifest itself as a reputational cost that must be determined based on a company's public appearance. A company that promotes itself as "green" may suffer significant reputational loss if it is found to be a major polluter of greenhouse gases. This loss in reputation will have a financial impact on its revenues. Clearly the cost due to loss of reputation is non-deterministic, and even direct costs such as carbon taxes may vary over time. However, once again risk can be used to determine the expected cost.

Based on the Brundtland Commission's definition, sustainability has three key dimensions, environmental, economic, and social. We can quantify each dimension separately using a risk framework, to determine the environmental risk, R_e, economic/business risk, R_b, and social risk, R_s.

The expected cost associated with resilience and sustainability is simply the sum of the expected functional, environmental, economic and social costs as shown in equation 1. That is,

$$R_{rs} = \sum_{f=1}^{n} P_f * C_f + \sum_{e=1}^{m} P_e * C_e + \sum_{b=1}^{l} P_b * C_b + \sum_{s=1}^{k} P_s * C_s$$

Equation 1

where C_f is the estimated cost of loss of function, P_f is the probability of loss of function and n is the number of functions under consideration. The other symbols are defined similarly. The first summation measures the functional cost, i.e. the cost associated with loss of function of the building, the second summation measures environmental cost, the third economic cost and the fourth social cost.

Thus, resilience, together with a risk analysis, helps to identify what improvements are required of a building. Resilience coupled with sustainability helps identify how changes in resilience are provided, based on explicit modelling of environmental, economic and social costs. The concept is illustrated in Paper III with a simple example.

4.2.3 Results Paper III

Paper III describes a conceptual method called Coupling and Quantifying Resilience and Sustainability (CQRS). It is primarily theoretical. The conceptual study draws on current literature on sustainability and resilience to propose how they should be coupled.

The CQRS method consists of seven steps:

1. Determine the resilience of the building to the disturbance(s), i.e. at what temperature the building's functions will be compromised.
2. Determine the costs associated with both the loss of building functionality and the building's current sustainability.
3. Determine the corresponding probabilities associated with each cost.
4. Determine the expected cost associated with the current resilience and current sustainability of the building using risk analysis.
5. Determine capital and operational costs of each remedial solution.
6. For each remedial solution, determine the expected cost associated with the proposed resilience and proposed sustainability of the building using risk analysis.
7. Select (or not) a solution based on cost benefit analysis.

I used an example of an architect office building to illustrate the methodology and the expected risk (cost) of two alternative solutions to a maintenance problem. The illustrative example was used to highlight a number of points. First, using a risk framework, the example showed how reputational and environmental costs could be evaluated and a monetary value placed on them. Second, by so doing, the example showed that a solution that only considered resilience could be more expensive than a solution that also consider sustainability. Third, we proposed some simple means for estimating some of the probabilities required in the calculations.

4.3 Technical Report - Passive air supply system based on ventilation windows supported by chimneys

The Technical Report investigates a passive ventilation solution for historical buildings based on a ventilation window supported by chimneys, where the air supply is provided through the ventilation window and the air is naturally extracted through the existing chimneys. The case study building has been investigated based on the dynamic simulation model and a passive ventilation solution based on a ventilation window supported by chimneys was proposed and installed in the case study building. The Technical Report investigates how the installed passive ventilation system works in the reality.

As part of the collaboration with Gentofte Municipality, villa Bagatelle was chosen as a case study building, which is a historical building from 1920. The building was built as a residential building, but now is used as daycare centre for children between 0.6 -2.8 years. The daycare centre was established in 2011 and with the change of use of the building, the council required documentation that the building provides the required ventilation rates to the occupants. The municipality was planning to install a mechanical ventilation system in the building. However, due to the historical value of the building, the client (Gentofte Municipality) wanted to investigate other options that did not require the installation of central mechanical ventilation and mechanical ventilation and system, nor changing internal or external appearance of the building.

From the perspective of my research, the building was interesting as a case study building to study the alternative ways to ventilate a building by passive means. The building offered an opportunity to evaluate whether passive ventilation could be used as an option to provide fresh air to historical buildings without using electricity to move air around the building and without creating drafts for the occupants.

From a climate change prospective the proposed passive ventilation option can be a mitigation option, as it does not increase the usage of the electricity, which is typically powered by fossil fuels, and would require less maintenance compared with a typical mechanical ventilation system. The passive ventilation option could also be an adaptive option, as it can provide ventilation and cooling during a power failure, though in this case the system must be manually operated.

The disadvantage of a natural ventilation system is that the system is difficult to design to provide a sufficient airflow, as the air movements and flows are difficult to control and measure. The system can also increase the heating demand of a building, as heat recovery is difficult to obtain. The dynamic simulation models can predict the heating demand of the building and fluid dynamic models (CFD) can predict the air movements. In the Technical Report we investigated the system in a natural environment.

4.3.1 Description of the proposed passive ventilation system

To be able to assess indoor air quality and thermal comfort of the building, the building was investigated by (i) measuring the internal temperature during the coldest period of the year, February 2012, (ii) determining infiltration by carrying out a blower door test and (iii) calculation of the building's ventilation requirements. Based on the measurements and the actual energy usage (83.000kWh/year) before the renovation, the energy rating was calculated to energy performance class "F" or 387kWh/m^2. [53].

The passive natural ventilation was installed in the case study building and was automatically controlled by internal and external top openings supported by passively extracted air through the chimneys.

The installed passive ventilation system was assumed to provide fresh air through 9 ventilation windows shown in Figure 6 and passively extracted by the chimneys 1 and 2. The windows located closest to the chimneys, were assumed to work as air sources, and chimneys 1 and 2 as extractors. The window 1.1 on the ground floor on the east façade, as well as window 5.1 on the west façade were assumed to work both as supply and extract due to their distance from the chimneys.

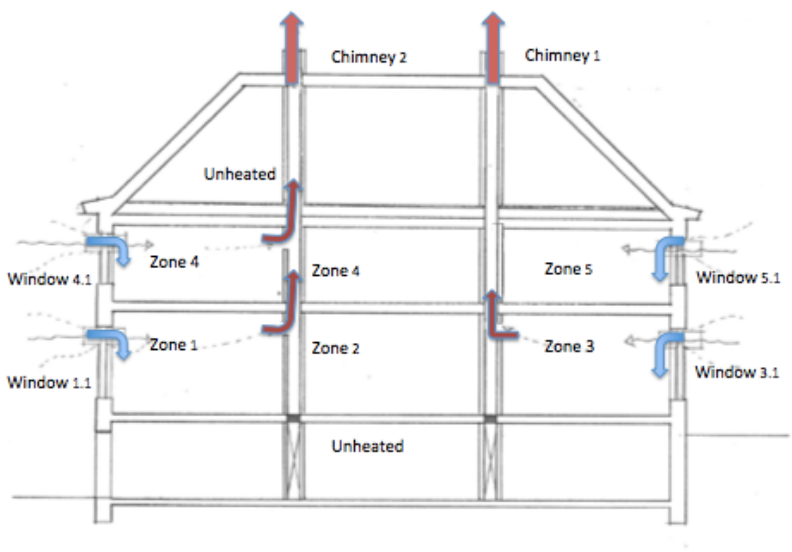

Figure 6 Diagram showing the fresh air supply through the window and extracts from the chimneys

A ventilation window or air supply window typically consists of an external and internal frame with an air gap in between. In such windows the air supply is provided through the lower part of the external frame. The air is then preheated as it moves up the gap between the external and internal glazing. This upward motion is driven by the stack effect. The preheated air then enters the building through the opening at the top of the internal frame. [54].

The blower door test result showed that the air leakage around the windows provided a sufficient air amount, at 1.68 ach during normal conditions (4Pa calculated) and it was higher than the calculated ventilation requirement of 1.4ach on the ground floor and 1.1 ach on the 1st floor. We therefore decided to ventilate the building with "controlled" infiltration [53].

It was proposed to reduce the air leakage of the building by sealing all the internal windows and doors, and improve the thermal performance of the windows in all occupied spaces. This was achieved by adding a 3rd layer of K-coated glazing on the inner frame, which sealed the inner window frame and improved the U-value to 0.8 W/m^2K as shown in Figure 7. Adding the 3rd layer glass did not visually changed the internal or external look of the building. The required air to the building during the cold periods of the year can be provided via the external frames, which were leaky (we assumed approximately 1mm around the perimeter of the window frame).

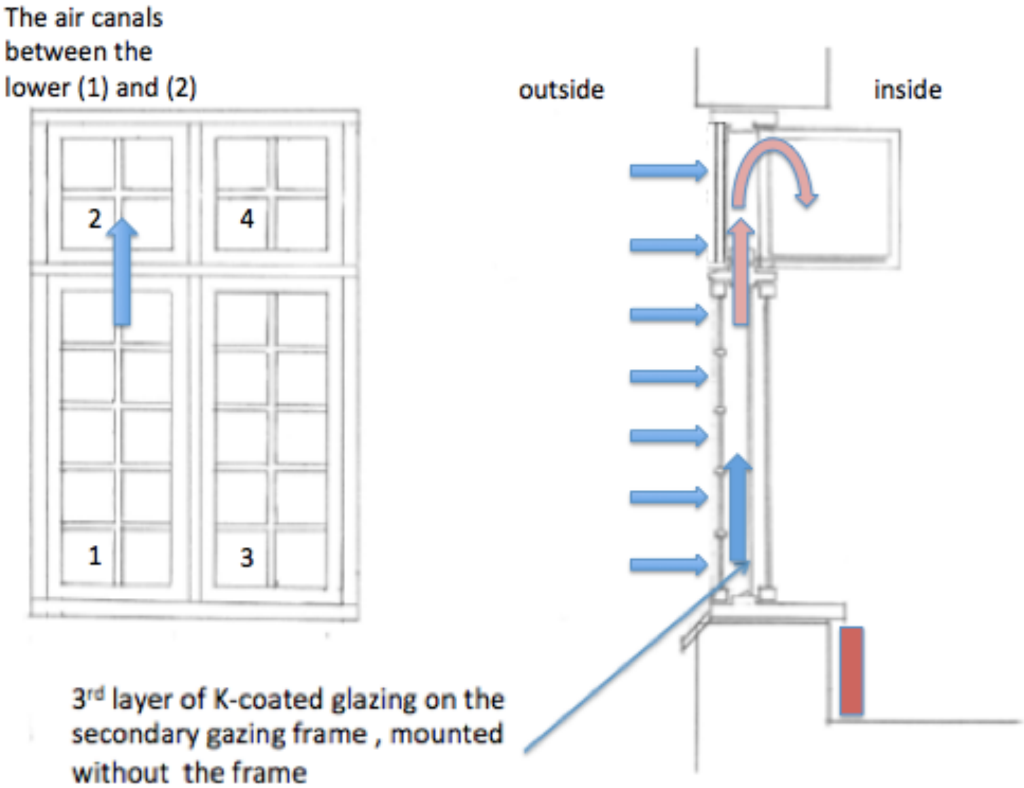

Figure 7Diagram showing the incoming air during the coldest periods of the air (winter)

Even though there was uncertainty as to whether the system could provide sufficient airflow to the building, the client and the building council accepted the proposal described above. The building was upgraded in 2013 based on the proposal.

4.3.2 Investigation of the air quality and thermal comfort in the building

The passive natural ventilation is automatically controlled by internal and external top openings supported by passively extracted air through the chimneys. We investigated three ventilation strategies during the moderate period of the year:

Experiment 1 – pulse ventilation
Experiment 2 – stream ventilation
Experiment 3 - ventilation window

The CO_2 produced by the occupants was chosen as the trace gas to estimate the air exchange in the building with its conduits for ventilation such as windows and chimneys. The air quality and thermal comfort of the building were investigated based on:

1. Automatic recordings of CO_2 meters installed in every zone provided by the supplier of the system;
2. External temperature, internal temperature, wind speed and wind direction around the building during the investigated periods, recorded by the supplier of the system
3. CO_2 and temperature readings in the ventilation windows and chimneys installed during the periods of the investigation
4. Air change was estimated based on the CO_2 readings and the number of occupants, where the occupants were recorded entering and leaving the room for longer than 15 min.

4.3.3 Results of evaluation of the passive ventilation system

There were three main purposes of the study: (i) to investigate whether our solution provided sufficient fresh air to the occupants of the building, (ii) whether air supply was provided through the "ventilation window" and extracted through the chimneys, as assumed, and (iii) how the system worked in a real building during usage. More detailed analysis of the results can be found in the Technical Report.

Does the system provide sufficient fresh air?

All three window opening strategies **could not provide the required air change of 1.4 ach.**

As the occupancy in the building during all 3 experiments was lower than designed, all three strategies provided nearly sufficient fresh air to the ground floor:

- Experiment 1 –according to the actual number of the occupants the system should provide a minimum of 0.7ach. However the system provided only 0.6 ach.
- Experiment 2 - according to the actual number of the occupants the system should provide minimum of 1.1 ach. However the system provided only 0.74 ach
- Experiment 3 - according to the actual number of the occupants the system should provide minimum of 0.98 ach. However the system provided only 0.87 ach

None of the three window opening strategies provided sufficient air change to the 1st floor. The reason for this could be that the pressure difference due to the stack effect was sufficient for the ground floor and not sufficient to the 1st floor.

- Experiment 1 –the actual number of the occupants was not available, and therefore we could not estimate the air change
- Experiment 2 – there were no occupants on 1st floor during the analysed day

- Experiment 3 - according to the actual number of the occupants during the experiment 3 the system should provide minimum of 1.04 ach. However the system provided only 0.4 ach

The results of our investigation showed that the proposed ventilation system as installed was not sufficient to provide the adequate ventilation to the upper floor and requires modification.

Did the system worked as predicted?

The idea of the installed system was to use the existing windows as ventilation windows, where the air in the building is provided by the natural leakage of the external frames. Only in Experiment 3 were the 9 windows controlled as ”ventilation windows”. During the Experiment 3 the air supply was additionally added by “pulse ventilation” in a similar manner as in experiment 1.

During experiment 2 the stable flow in the chimneys and the windows close to the chimneys was observed. However, as the internal and external windows were open in the same side, the window worked as a simple opened window and not as a predicted “ventilation window” and no preheating effect was observed. Even with constantly open external windows there was not sufficient air for the 1st floor.

During experiment 3 the CO_2 concentration was lower in the windows close to the chimney, which we interpreted as indicating that the windows worked as the air supply, albeit with some fluctuation.

The preheating effect was observed in the windows, which could be due to the solar radiation in the window gap as well escaping air from the room.

The assumption that the external wind can be ignored using ventilation window system proved to be incorrect.

Options for improvement

The experiments 1-3 showed that the leakage of the external frame was not able to provide sufficient airflow during the occupied hours. Experiment 2 showed that if the external windows would be slightly open during the occupied hours the flow in the chimney and in the windows close to the chimneys would be stable, but without the preheating effect. Some suggestions for achieving the preheating effect and providing the required airflow include:

(i) The whole window frame should be used for ventilation purposes. In this case the external window opening can stay as it was during the Experiment 1-3 (the top window (2) as shown on the Figure 8 is automatically controlled by supplier) and the internal window should be closed on the top window. The internal window on the opposite side (4) as show in Figure 8 should be open. At the bottom of the frame, an air passage must be established between (1) and (3) as well as an air passage between (4) and (3) as shown in the Figure 8. The fresh air should then come in through the open external window (2), then forced to travel down to box (1) and through the passage to box (3) and extracted into the room by the internal open box (4). The chimney should have a stable flow and the windows close to the chimney should work as the air supply. By having open external windows wider on the 1st floor than on the ground floor (4:1).

(ii) The air quality in Zone 5 was worse than in other zones as there were no direct connection to the chimney. To improve the air quality in Zone 5 a connection to chimney 1 should be established.

(iii) The occupants in Zone 6 kept the window shut due to a draft from the window. By improving the window design as described in (i) the draft problems may be reduced.

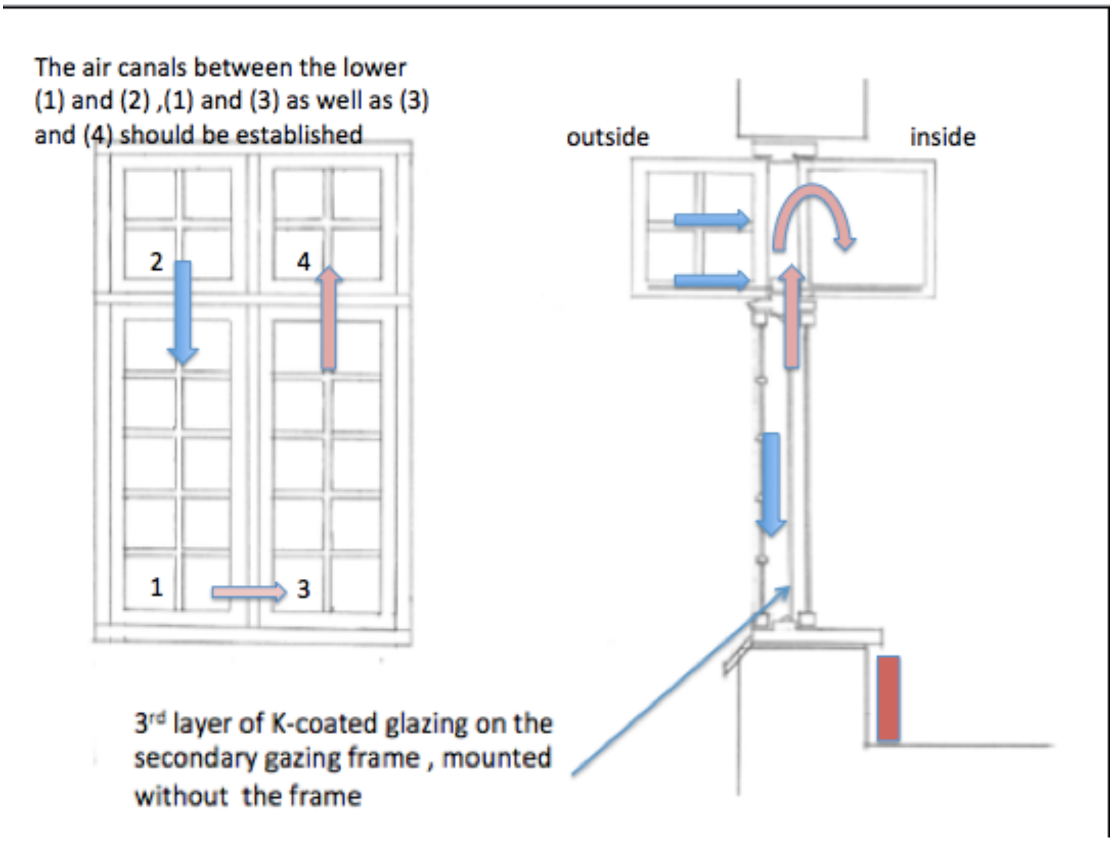

Figure 8 Suggestion for improving the system

Further experiments are needed to confirm that the suggested improvements works as expected.

4.3.4 Summary of the results of passive ventilation system provided by ventilation window and supported by chimneys

In a natural ventilated building the driving force for the ventilation is the pressure difference between the inside and outside. The pressure difference can be due to the temperature difference or the wind forces around the building. Our investigation of the performance of the ventilation window ignored the wind forces around the building. The assumption that the external wind can be ignored using ventilation window system was incorrect. The wind influence was mostly visible during the experiment 3 where the system was operated in the correct mode.

Experiments 1-3 investigated the system using three different ventilation strategies. The system as installed did not provide sufficient airflow to the ground floor or to the 1st floor. During the investigated period the building did not reached the full occupancy and therefore the air supply was moderate for the ground floor and bad for the 1st floor.

The installation of the internal and external automatically controlled windows on the same side was also incorrect. When both external and internal window were open the window worked as a simple window. To be able to make the window work as “ventilation window” automatically controlled openings should be installed on the opposite side of the window and air passages should be established between the boxes so that the air is forced to move down to the lower part of the window and extract through the top part of the opposite box. The preheating effect would also be better when all the window frames are used for ventilation purposes.

During the project we used simplified estimates to calculate the measured CO_2 levels in the building. The system should be investigated with dynamic calculation models and more detailed readings of the airflow in the building and more detailed registration of the movements of the occupants.

5 Conclusion

Despite international attempts to reduce CO_2 outputs from human activities, global greenhouse gasses are still increasing. For example, the atmospheric CO_2 concentration was 310ppm in 1955 and reached 399 ppm in December 2014[6]. There is a scientific consensus that the increase in CO_2 is mainly due to the human activities and that the increased CO_2 emissions in the atmosphere is causing climate change with increasing global temperature, sea level rise and an increasing number of extreme weather events occurring all around the world.

While technological and political efforts continue to try to avert climate change, some level of climate change is now inevitable. Consequently, building maintenance and operations practitioners now need tools to assess the impact of possible climate change scenarios on buildings. Practitioners are also acknowledging that buildings can contribute to climate change. They are therefore interested in tools to as assess the viability of remedial solutions that consider both the resilience and sustainability of the solution.

The impact of climate change is much broader than a single thesis can encompass. Thus, in this thesis I limited the research area to:

Climate change threats – temperature
Facilities management – maintenance and operation
Building physics– cooling and heating demand
Practitioners – naturally ventilated existing building in the real environment

A key requirement of practitioners is the need to estimate the future energy demand of buildings. To do so, requires a future weather file. Previous work had highlighted the fact that future weather files are not always readily available and often require sophisticated metrological modelling.

Paper I examined whether future weather files constructed with coarse temporal resolution data of expected annual changes in temperature could provide useful estimates of heating and cooling demand. Experimental results using both the degree-day method and dynamic simulations indicated the even a single annual estimate of expected change in temperature can provide very similar estimates of energy consumption to those obtained using fine, hourly temperature change estimates. In particular, heating demand estimates were within 3% and cooling demand estimates were within 5% of one another. The Paper supplemented the empirical investigation with a theoretical discussion of the conditions under which this method fails, i.e. weather files based on annual changes give significantly different results to those based on hour change estimates. The discussion showed that failure conditions occur when the temperature is close to the heating or cooling set point. Under these conditions, there may be large

[6] The world's most current data for atmospheric CO_2 measured at the **Mauna Loa Observatoy** in Hawaii the http://co2now.org

percentage differences. However, in absolute terms, the errors are likely to be small, since energy demand in the vicinity of the set points is small.

A limitation of this study is that we only change one weather parameter, temperature, while all other parameters remain unchanged. This is sufficient if we are only using the degree-day method. However, when using a dynamic simulation method, all weather parameters are important, and therefore some errors are expected. In general, the proposed simplified method to construct future weather files should only be used in the absence of absolute future weather files, and not instead of.

Our findings are significant, since there is evidence [43], [44] that many practitioners have difficulty obtaining future weather file data. While better data is always preferable, our study reveals that the in the absence of high temporal resolution data, a coarse annual estimate of the expected change in annual temperature may be a pragmatic and more accessible way when estimates of future energy demand is requested.

With a simple method to construct a future weather files using annual temperature change, the future energy demand can be estimated by the methodology proposed in Paper I. After doing so, the most *cost effective solution* to improve a building's resilience to climate change can be identified. However, in Paper II and III the way we understand *cost effectiveness* is questioned. I assume that any heating or cooling solution should ideally not contribute to further global warming. That is, a solution that improves the resilience of a building should also be a sustainable solution that minimizes future impact on the environment. The contribution of Paper III is to propose a methodology, which I refer to as Coupling and Quantifying Resilience and Sustainability (CQRS) that quantifies these concepts in monetary terms. The choice of a monetary dimension is based on the economic assumption that practitioners are rational agents whose decisions are based on maximising their return on investment. Paper III considers how to couple and quantify resilience and sustainable, where sustainability refers to not only environmental impact, but also economic and social impacts. We do so in the context of developing decision support tools for facilities managers. As such, we utilise a risk framework to quantify both resilience and sustainability. The risk framework allows us to couple resilience and sustainability so that the provision of a particular building can be investigated with consideration of functional, environmental, economic and possibly social dimensions.

The proposed CQRS method was illustrated with a simple example that highlights how very different conclusions can be drawn when considering only resilience or coupled resilience and sustainability. The methodology is generic allowing the method to be customized for different user communities. However, the example also illustrates the difficulty in deriving the costs and probabilities associated with particular indicators.

In the case study building I investigated a passive ventilation system for historical buildings. The idea was that the proposed passive ventilation option could be a mitigation option, as it does not increase the usage of the electricity, which is typically powered by fossil fuels, and would require less maintenance compared with a typical mechanical ventilation system. The passive ventilation option could also be an adaptive option, as it can provide ventilation and cooling during hot periods of the year and can also operate during a power failure.

First I investigated the indoor air quality and thermal comfort of an existing naturally ventilated historical building before a renovation and proposed a solution for providing ventilation by passive means based on dynamic simulation model of the building. A passive ventilation solution based on ventilation windows supported by chimneys was installed in the case study building. Technical Report investigated how the installed passive natural ventilation system worked in the reality.

The experiments conducted and described in Technical Report confirm that the natural ventilation system is difficult to design and operate as the air movements and flows are difficult to control and measure. Technical Report conducted three experiments, which investigated the system using 3 different ventilation strategies. All three strategies failed to provide sufficient airflow to the ground floor and to the 1st floor. During the investigated period the building did not reached the full occupancy and therefore the air supply was moderate for the ground floor and bad for the 1st floor. The modification of the system was proposed, but not tested.

6 Future work

When I started this thesis I did not realise how great a threat climate change is. It is probably the greatest threat currently facing mankind. When I began, I thought that climate change only required a technological solution. However, during the course of my Ph.D., I have realised that technology will form only part of a solution. Government public policy, economics, and behavioural science must all play a part.

"This human response to climate change is unfolding as a political tragedy because scientific knowledge and economic power are pointing in different directions. The knowledge of the reality, causes and implications of human-caused climate change creates a moral imperative to act, but this imperative is diluted at every level by collective action problems that appear to be beyond our existing ability to resolve. This challenge is compounded by collectively mischaracterising the climate problem as an exclusively environmental issue, rather than a broader systemic threat to the global financial system, public health and national security" [55].

I hope this thesis is a contribution to the technological dimension of a future solution to climate change. Despite the enormity of the problem, I am reminded of the saying "The journey of a thousand miles begins with one step". Below I briefly outline a few further steps.

Regarding Paper I, more work is needed to test the methods proposed on different type of buildings and for different type of solutions. Further work is needed to investigate whether other parameters, such as wind, precipitation, cloud cover or humidity can be treated similarly using a change-based method or whether more detailed future weather files developed using a weather generator are required. Likewise, further work is needed to determine the sensitivity of energy demand estimates to the correlations between parameters and to take into account the inherent uncertainties of climate model projections.

Regarding Papers II and III, more sophisticated probabilistic models could be considered - future costs could be discounted to reflect inflation and the net present value of money, costs such as carbon taxes could incorporate variation in taxation across years. Further research is needed to translate this theoretical framework to a practical tool for practitioners and to evaluate the CQRS method in practice. In industries where risk analysis is routinely used, such as the life insurance industry, actuarial life tables provide probabilities of life expectancy. There is a need for similar tables to be developed at national and regional levels that allow practitioners to easily determine the probabilities necessary to complete the risk calculations needed to couple and quantify resilience and sustainability. Where practical, similar tables should also be developed to provide corresponding costs of, for example, possible future carbon taxes.

Practitioners also need a user-friendly software suite that incorporates these tables and user provided data to calculate a building's sustainable resilience.

More work is needed to investigate different passive ventilation options in the real environment. There is also a need to develop a better understanding of natural ventilation systems and to develop improved simplified models to estimate the expected airflows in a building.

Appendix I – summary of the report Villa Bagatelle

Appendix I summarizes the report "Villa Bagatelle" [53]. The report investigated options to renovate the listed building, considering both requirements due to the historical details of the building, and the desire to reduce the overall environmental impact of the building.

The report investigated the actual building, villa Bagatelle, located on the Jægersborgs alle 147, Gentofte, Denmark, which has been used as a case study building for the thesis.

The primary goal of this case study building was to investigate passive ventilation options to provide a comfortable thermal environment for the building's occupants and comply with current building regulations. From the climate change prospective the suggested improvements were considered to be as passive as possible to reduce the overall environmental impact of the building and to be easy to operate and maintain with the minimal running cost.

1.7. Description of the building

The case study building was a 2-story building with unheated basement and unheated attic spaces. The building was heated by district heating with a heated area of 279 m^2 and a total area of 571m^2. Before the renovation, the building was naturally ventilated, except for the bathrooms, which had mechanical extracts. In 2009 the building was upgraded by adding 300 mm of insulation between the 1st floor and the unheated attic. The U-value of such a construction is typically 0.13 W/m^2K. The cavities of the external facades on the ground floor and 1st floor were insulated with 170mm and 130mm of cavity insulation respectively. The U-values of such constructions are typically 0.16 W/m^2K and 0.21 W/m^2K respectively. The original wood framed windows had secondary glazing placed 120mm from the external window frames (4x120x4). The U-value of such a construction is typically 2.8W/m^2K.

The indoor thermal comfort of the building was investigated by (i) measuring the internal temperature during the coldest period of the year, February 2012, (ii) determining infiltration by carrying out a blower door test and (iii) calculation of the building's ventilation requirements. Based on the measurements and the actual energy usage, the energy rating was calculated to energy performance class "G". The results of this investigation can be found in the Report villa Bagatelle [53].

The measured temperature in the day-care 1st floor was between 16 -22^{o}C with the highest temperatures occurring during times when the external temperature or the number of occupants is highest. This was the room where the occupants spend most of their time. The average temperature was 19.5^{o}C, which is lower than the temperature accepted as comfortable, which is between 21-23°C. The relative humidity during the measured period was between 20-40%.

Even though the energy efficiency of the building was upgraded in 2009, the annual energy usage for the building was still high, specifically 83.000kWh/year or 417kWh/m^2. The major problem for the building was the high infiltration rates, estimated at 1.68 ach during normal conditions (4Pa calculated) or 7.88 ach or 6.42 l/s/m^2 under 50 Pa pressure, which was measured with a blower door test before the renovation. The infiltration mostly occurred around the windows and doors.

1.8. Options for improvement

Based on the measurements and the building construction documentation, a dynamic simulation model of the building was created in TAS, which predicted very similar results to the actual energy usage. The model was used for further investigation of possible thermal improvements to the building and to propose passive ventilation strategies for the building [53].

The options of improving energy savings were simulated in the dynamic simulation model of the building and are summarized in the Figure 1 below:

(i) Improved window U-value;
(ii) Insulation of the external façade;
(iii) Insulation of the basement;
(iv) Reducing the infiltration.

The results showed that the reduction of the infiltration provided by far the most saving. However, the tightening of the building required adding ventilation to provide required fresh air to the occupied spaces.

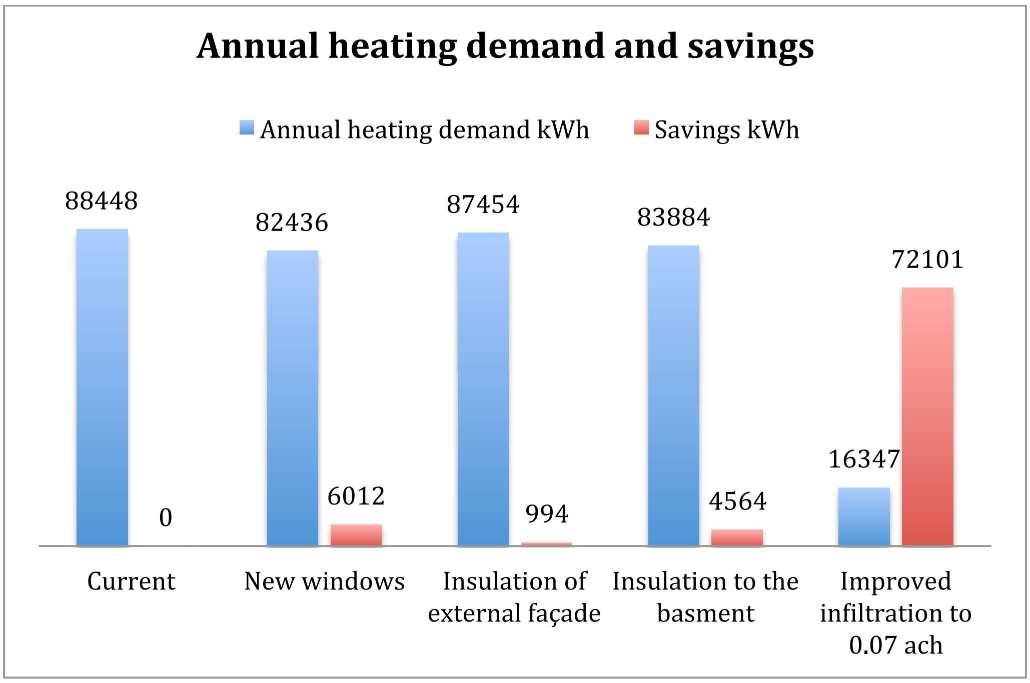

Figure 9 Annual heating demand and savings by improving building's fabric and reducing infiltration

Different form of ventilation were considered and summarized in Figure 2:

(i) non-uniform ventilation with heat recovery (mechanical ventilation),
(ii) non-uniform ventilation without heat recovery
(iii) uniform ventilation(natural ventilation) with heat recovery and
(iv) uniform ventilation without heat recovery,
(v) coupled infiltration and natural ventilation,
(vi) coupled infiltration and natural ventilation in only occupied spaces.

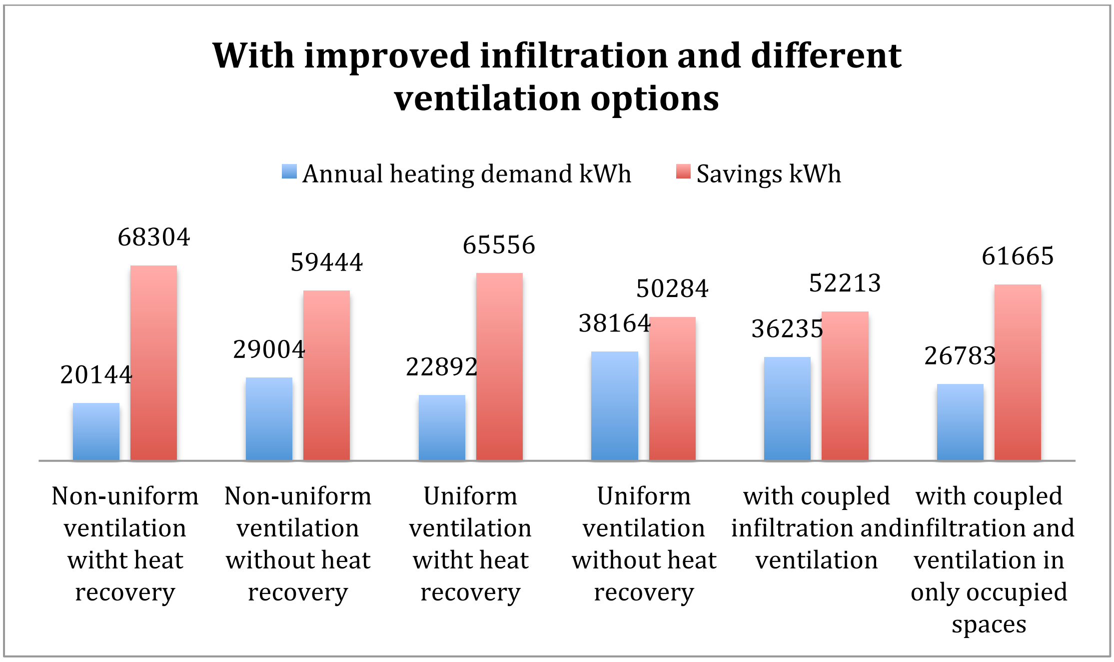

Figure 10 Annual heating demand and savings with the improved infiltration and different options of ventilation

The simulations showed that by applying coupled infiltration and reduced ventilation the heating demand can be reduced to 26,783kWh.

1.9. Proposed passive ventilation system

The passive options of improving the building's fabric were investigated and it was decided that the most cost efficient option was to reduce infiltration of the building by tightening of windows and doors and improve the windows U-values. The tightening of the building provided not only significant energy savings but will also improved thermal comfort for the occupants. However, tightening of the building required that the building be ventilated. Non-uniform (mechanical) ventilation with heat recovery would be the most energy effective, but would require ducting. To avoid ducting, uniform ventilation (natural) was suggested.

As infiltration provided sufficient fresh air for the building's occupants before the renovation, it was proposed to establish a passive ventilation system that would not change the appearance of the building either internally or externally, and would provided the required fresh air.

The investigations showed that a combination of chimneys and windows would provide the most effective ventilation system for the building.

It was proposed to install a natural ventilation system, where the supply air is provided through "ventilation windows" supported by the existing chimney as shown in Figure 3.

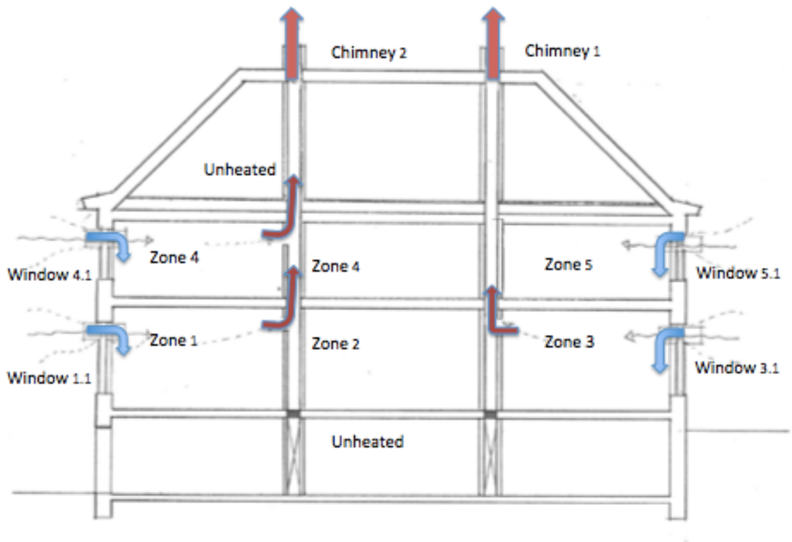

Figure 11 Diagram showing the fresh air supply through the window and extracts from the chimneys

During no occupancy all internal windows and the chimneys would be closed with very little infiltration, which is the reason for calling such system a "controlled infiltration". We assumed that the natural infiltration was reduced to 0.07 ach at 4Pa (normal conditions), when all windows were closed.

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8 Paper I

Simple future weather files for estimating heating and cooling demand

Rimante A. Cox, Martin Drews, Carsten Rode, Susanne Balslev Nielsen

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http://www.sciencedirect.com/science/article/pii/S0360132314001024

9 Paper II

Sustainable Resilience in property maintenance: encountering changing weather conditions,

Rimante A. Cox, Susanne Balslev Nielsen

Proceedings article published and presented in Proceedings of CIB Facilities Management Conference Using Facilities in an open world creating value for all stakeholders, page 329-33

10 Paper III

Coupling and quantifying resilience and sustainability in property maintenance,

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http://www.emeraldinsight.com/doi/pdfplus/10.1108/JFM-04-2015-0012

11 Technical Report

Description of the passive air supply system based on ventilation windows supported by chimneys

Rimante A. Cox June 2015

12 Article in periodical journal FM Blad

Hvordan skal Facilities Management reagere på klimaforandringernes påvirkning af bygninger
Rimante A. Cox June 2012