

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



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Cox

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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’d love to change the world, written by Alvin Lee of the band Ten Years After
1971)

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 CO₂ 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 (månedligt-baseret) og (iii) groft (årligt-baseret). 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, Danmark. 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 CO₂-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.

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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)

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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 CO₂. [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 here 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 summarizes 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 greenhouse 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.

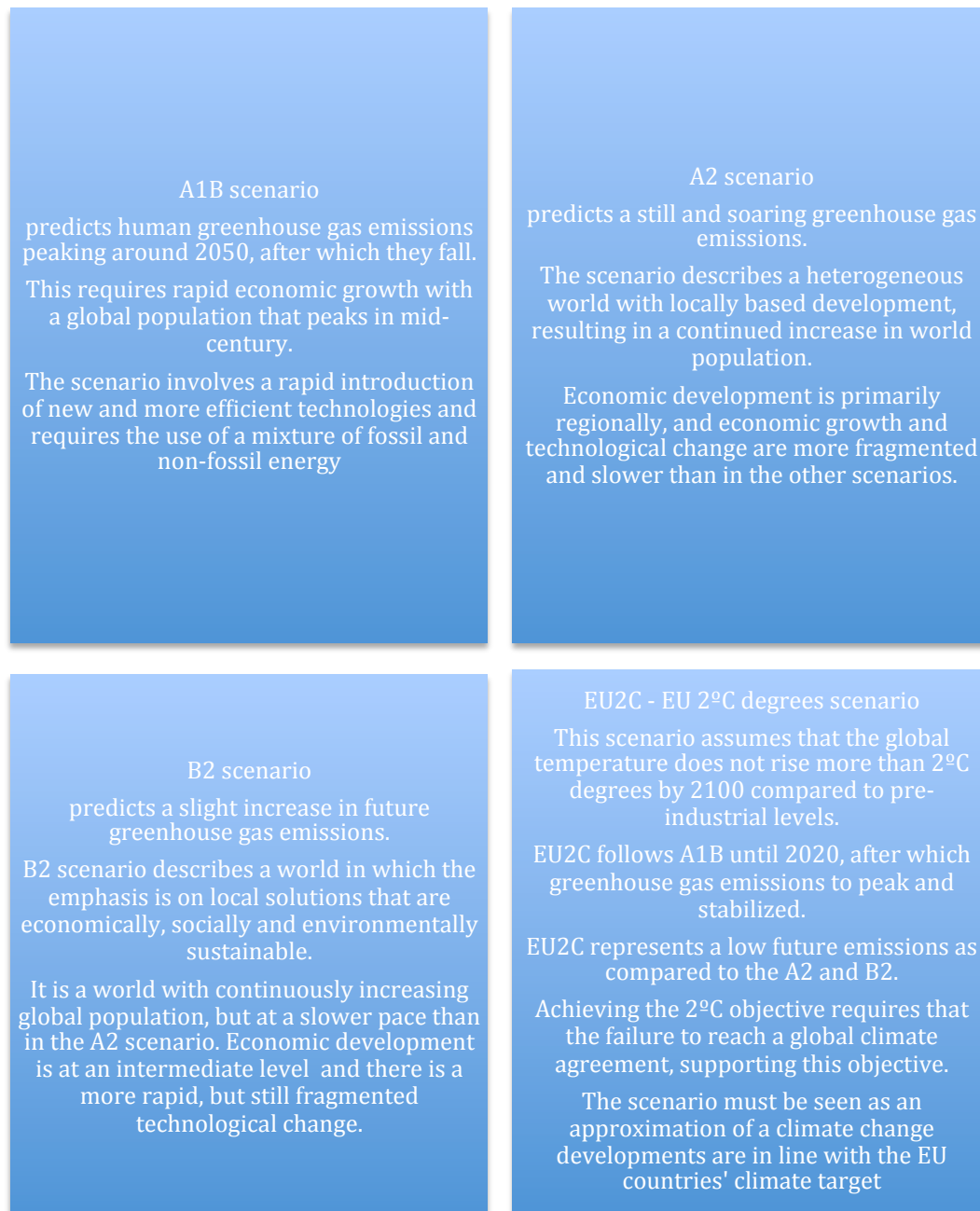


Figure 1 Description of the IPCC 4 scenarios taken from <http://www.klimatilpasning.dk/daDK/service/Klima/klimascenarier/Sider/Forside.aspx>

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.

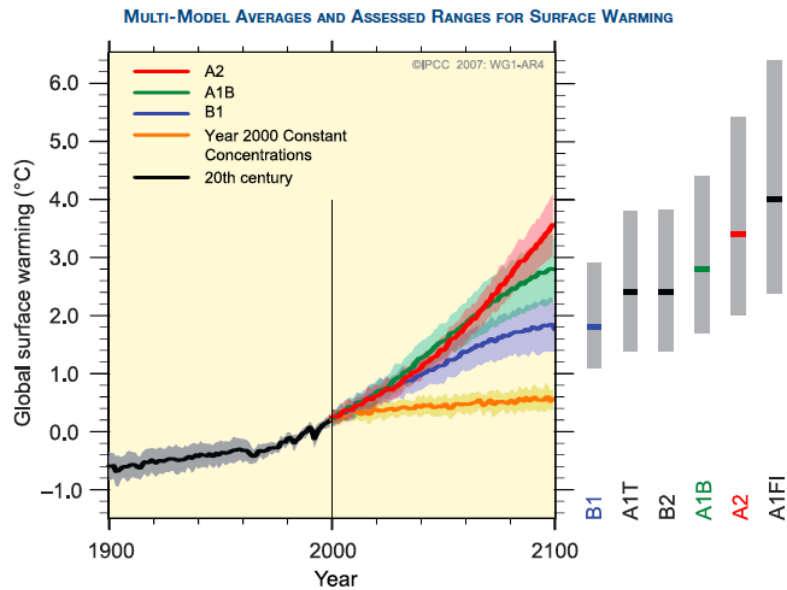


Figure 2 Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ± 1 standard deviation range of individual model annual averages. The orange line is for the experiment 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 IPCC 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 than 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].

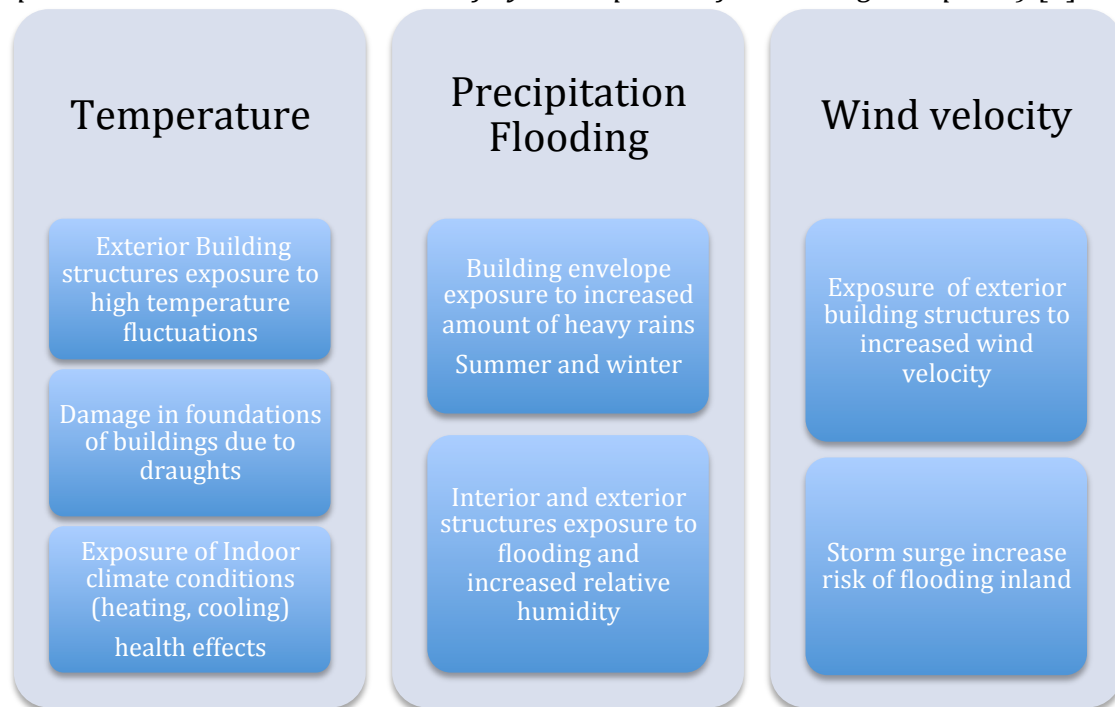


Figure 3 Extreme weather impacts on buildings

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°.

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.

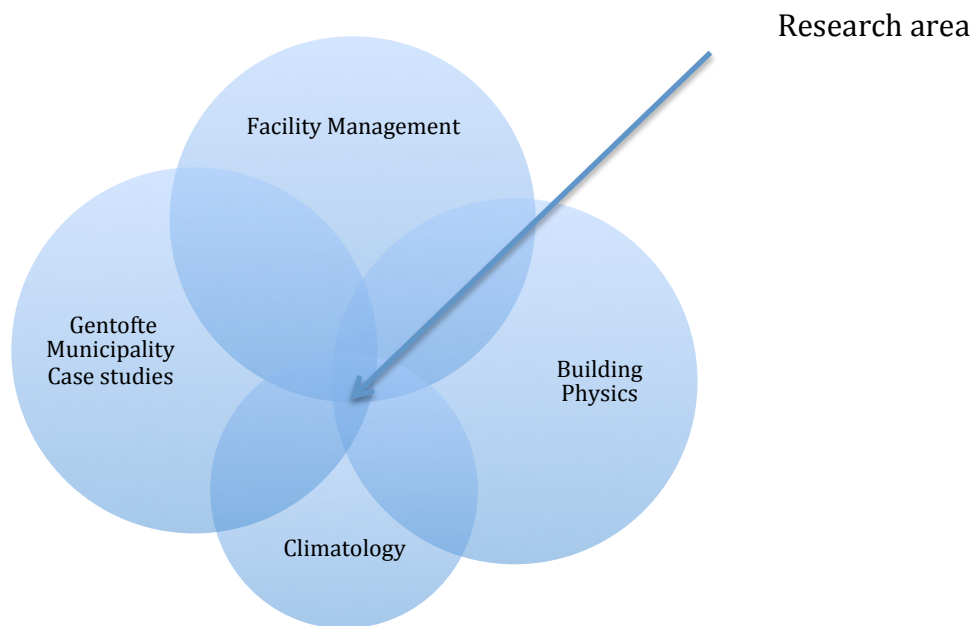


Figure 4 Research areas relevant to the thesis.

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 CO₂ 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.

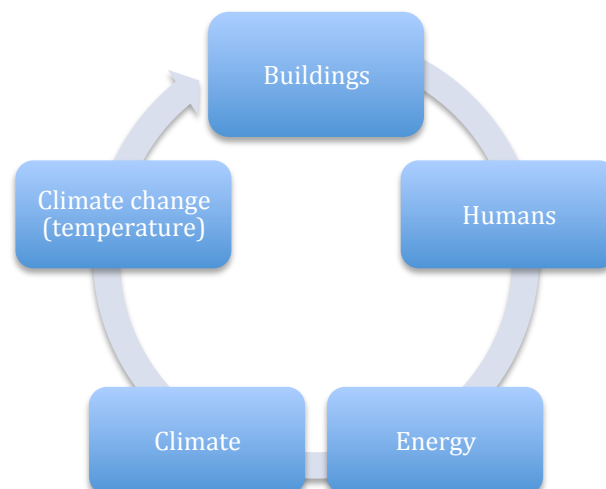


Figure 5 Relationship between buildings and climate change

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. Adaptation 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 1 st 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, $p_1, p_2 \dots p_n$. 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 $\Delta_1, \Delta_2 \dots \Delta_n$. 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, Δ_i , 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 speed 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 TAS¹, BSim², IES³, IDAICE⁴ or Energy Plus⁵.

A dynamic building simulation requires both (i) a detailed model of the building and its 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.

¹ TAS (Thermal analysis simulation) software developed by a company Environmental Design Solution Limited (EDSL), UK mostly used 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/m²K. 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°C based on the hourly-change weather file, and only 37 hours where the temperature is expected to exceed 27°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/m². [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.

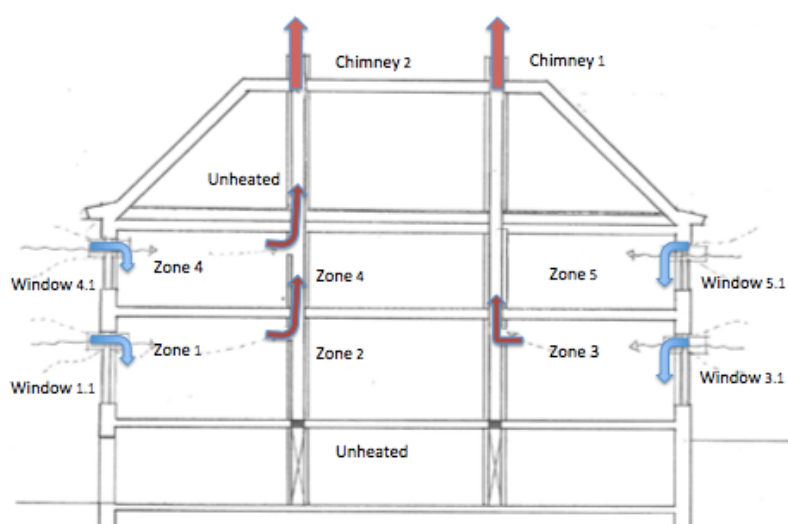


Figure 6 Diagram showing the fresh air supply through the window and extracts from the chimneys

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/m²K 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).

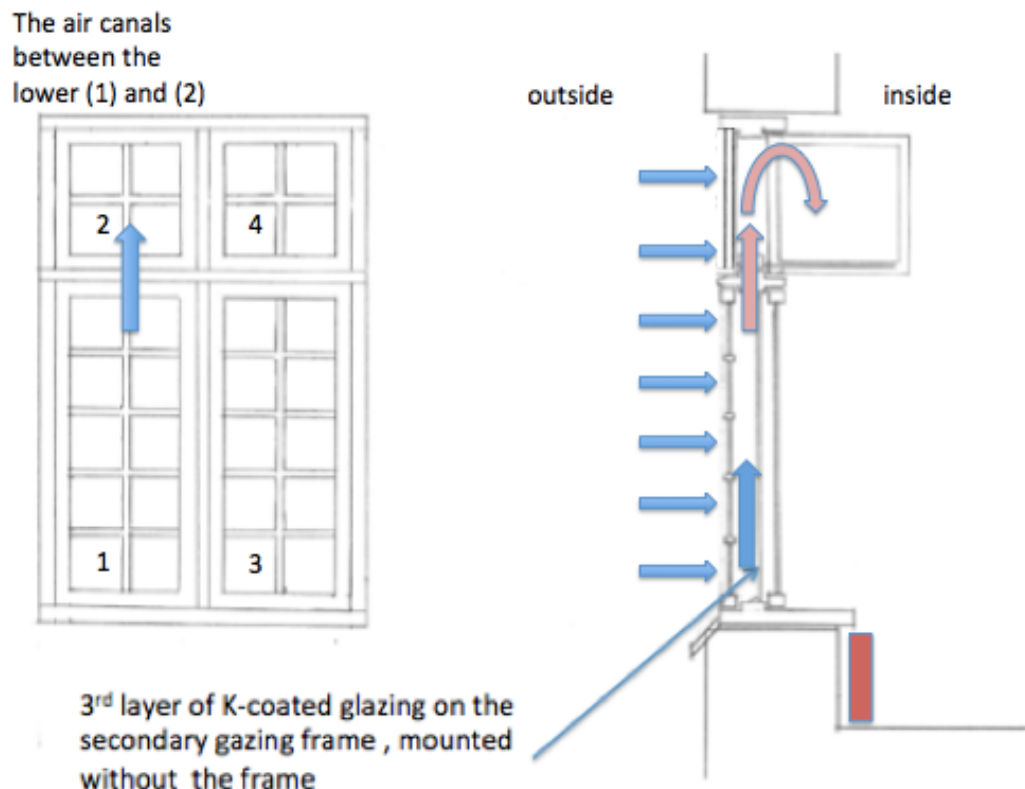


Figure 7 Diagram showing the incoming air during the coldest periods of the year (winter)

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 CO₂ 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 CO₂ 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. CO₂ and temperature readings in the ventilation windows and chimneys installed during the periods of the investigation
4. Air change was estimated based on the CO₂ 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 CO₂ 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.

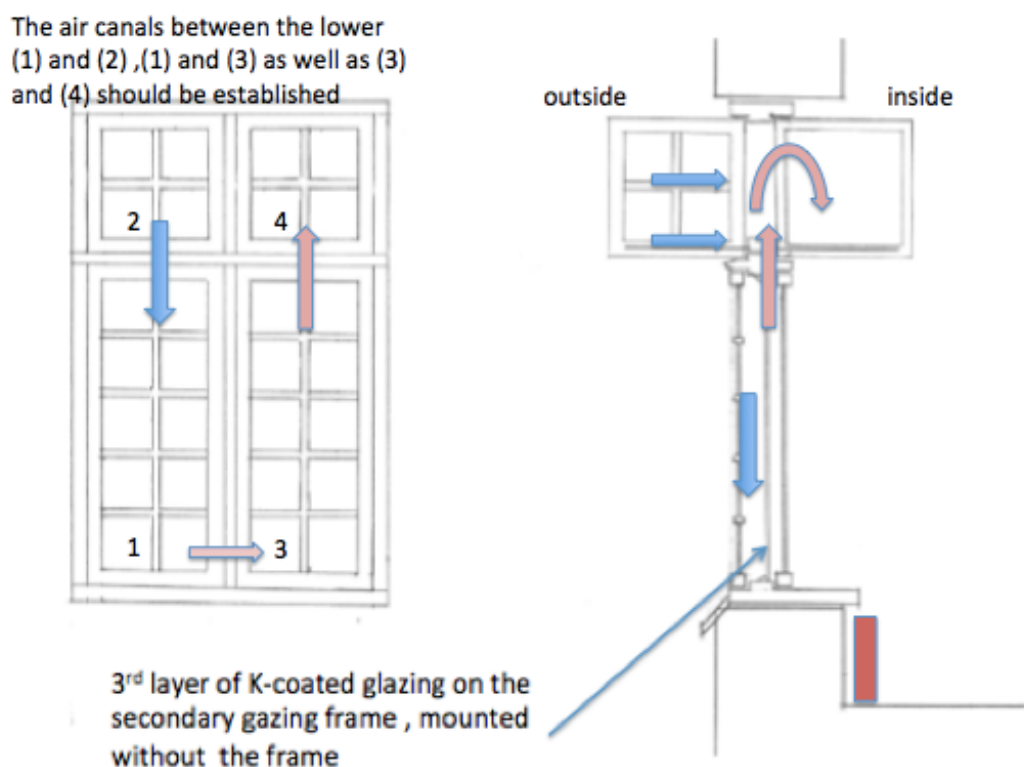
The assumption that the external wind can be ignored using ventilation window system proved to be incorrect.

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

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.



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 reach 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 CO₂ 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 CO₂ outputs from human activities, global greenhouse gasses are still increasing. For example, the atmospheric CO₂ concentration was 310ppm in 1955 and reached 399 ppm in December 2014⁶. There is a scientific consensus that the increase in CO₂ is mainly due to the human activities and that the increased CO₂ 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 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 CO₂ measured at the **Mauna Loa Observatory** 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 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 m² and a total area of 571m². 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/m²K. 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/m²K and 0.21 W/m²K 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/m²K.

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°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°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/m². 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/m² 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.

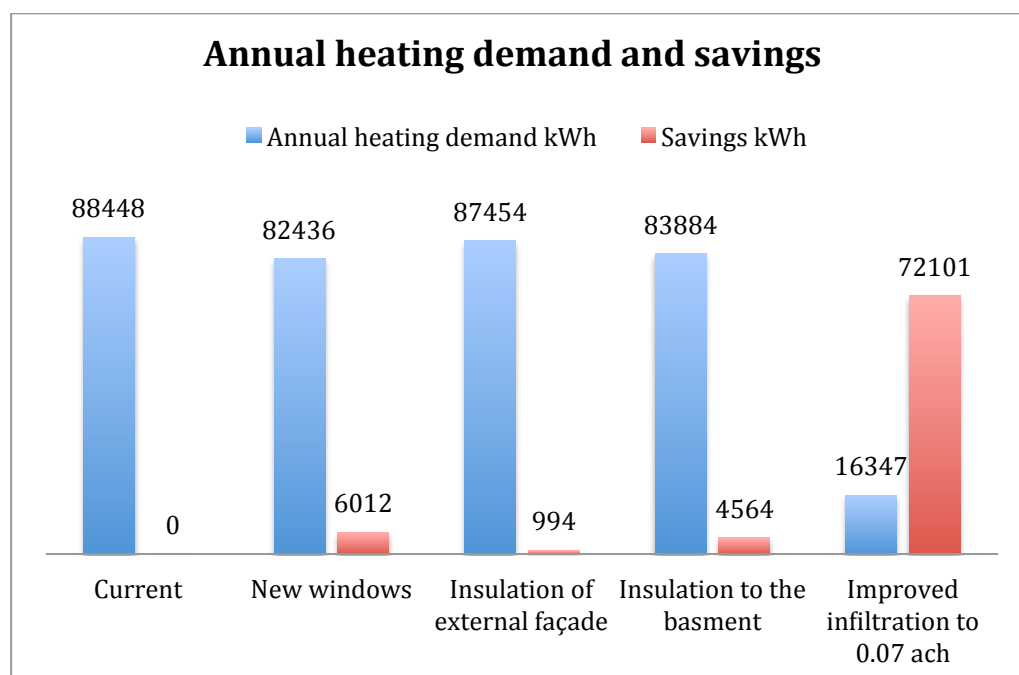


Figure 9 Annual heating demand and savings by improving building's fabric and reducing infiltration

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.

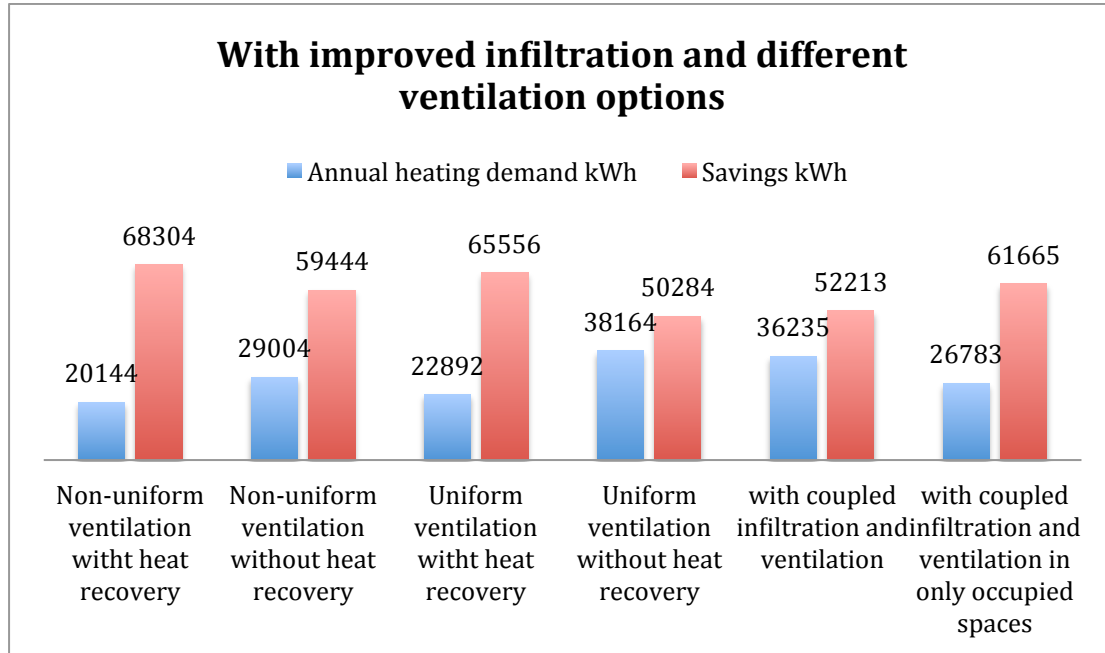


Figure 10 Annual heating demand and savings with the improved infiltration and different options of ventilation

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.

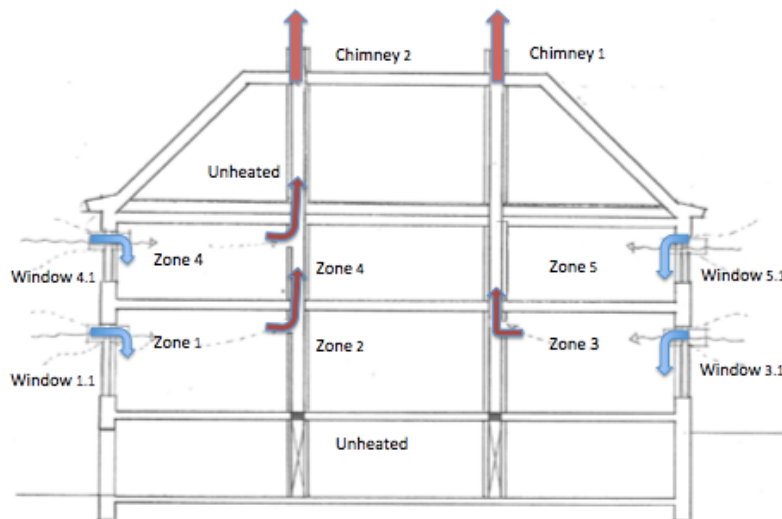


Figure 11 Diagram showing the fresh air supply through the window and extracts from the chimneys

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

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Simple future weather files for estimating heating and cooling demand

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ABSTRACT

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 air temperature. To address this issue, we investigate if, in the absence of high-resolution data, a weather file constructed from a coarse (annual) estimate of future 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. 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 air 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.

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1. Introduction

Global warming is apparent and there is general consensus that even by dramatic reductions in the global anthropogenic emissions of greenhouse gasses, adaptation action will be necessary to address those impacts that are already unavoidable. While substantial reductions in CO₂ emissions can be achieved from optimized energy use in buildings, present and future constructions require to be taken into account the changing climate conditions, including increased risk and intensity of extreme events such as floods, strong winds and heat waves. Unsurprisingly, there is a strong interest in predicting the effects of the expected future climate warming on the built environment in terms of developing appropriate adaption and mitigation strategies [1–3]. In this

context, there is a particular need from property owners and facilities managers for estimates of the future energy demand for heating and cooling [4].

The energy demand of buildings, both now and in the future, can be quantified in a variety of ways. Common methods utilize (i) Heating Degree Days (HDD) and Cooling Degree Days (CDD) from which fuel consumption is directly inferred [5–7], (ii) total energy consumption or heating and cooling demand [8,9], (iii) relative changes in energy demand [10,6], or (iv) CO₂ emissions, which are a function of energy consumption and supply source [10]. Other factors directly related to buildings' thermal performance can be quantified by metrics as suggested by de Wilde [11], i.e. (i) peak demand of a building [12] (ii) peak demand on the grid [13] (iii) and the overheating risk in different types of buildings [14–16]. In this article we consider the relative change of the energy demand using both a degree day method and a dynamic simulation tool.

To determine the annual energy demand of a building, we require a weather file that describes the typical weather

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conditions at the building's location, as well as information on the structure and usage of the building. A typical weather file is usually constructed from real, measured data, the details of which are discussed in Section 2.1. To determine the *future* annual energy of a building requires a future weather file, i.e. a projection of the weather at some time of interest in the future. Research in constructing future weather files has received significant interest recently, and this work is summarized in Section 2.2.

Despite the significant interest, there is evidence that future weather files are often not readily available in many regions. For example, Jentsch et al. note the lack of availability of approved climate change weather files for simulation programmes [15]. This is supported by Jones and Thornton who also comment that the lack of availability of weather data is a serious impediment to undertaking climatic modelling to assess the impact on agriculture [17].

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 assess the quality of the projections. This work requires expert knowledge of climatology and is typically conducted at dedicated research centres and national meteorological institutes. A wide range of global and regional climate projections provided by different climate modelling groups may be extracted from international multi-model inventories like the CMIP5 (Coupled Model Intercomparison Project) and CORDEX (Coordinated Regional Climate Downscaling Experiment) data centres, however, typically at coarse temporal (daily) and spatial resolutions (25–50 km).

In this study we investigated the implications of temporal resolution on future simulations of buildings' energy demand. To address this issue we used a simple "change-based" method for constructing future weather files, e.g., adding an estimated annual increase in air temperature to an existing weather file, and we then considered whether the results provide useful estimates of a building's future energy demand. We 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 air temperature change. In this study we only considered a single parameter, outside dry bulb temperature, of a future weather file, i.e. other parameters such as humidity, solar irradiation, precipitation and wind speed were not considered. However, we note that the work of [18] 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 Ref. [19] 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 air 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 [16].

The emphasis of the present work was to investigate how well a future weather file was able to predict future energy demand, whereas broadly speaking, previous work has been concerned with how "realistically" a future weather file models the expected

weather. Thus, our focus in this paper was on the application of future weather files rather than on climate modelling. Of course, we expect more "realistic" future weather files to provide accurate estimates of energy demand. However, as we previously discussed, the creation of these files can be difficult or at least impeded by the lack of available data. If simpler future weather files can produce very similar estimates of a building's energy demand, this will facilitate the modelling of future energy demand by practitioners.

In the following we first briefly review how historical weather files are created (Section 2.1) and categorize different methods to construct future weather files. Three common ways are discussed for constructing future weather files with annual, monthly and hourly temporal resolution (Section 2.2). In Section 2.3 we describe the commonly used methods to estimate the energy demand of a building, such as the degree-day method and dynamic building simulations. In Section 3 we investigated the sensitivity of a building's energy demand to three different methods of calculating a future weather file, where the calculations were based on the abovementioned coarse (annual), medium (monthly) and fine (hourly) estimates of future air temperature changes obtained from a regional climate model. We used the degree-day [20] analysis, which is independent of any specific building model, and the sensitivity is measured based on the change in the number of heating and cooling degree-days resulting from the analyses. For comparison we also investigated the sensitivity of three dynamic simulation models to the differently constructed future weather files. These three building models were (i) an existing naturally ventilated historical building, (ii) the same building renovated to have an air tight envelope, windows with improved thermal properties and naturally ventilated and (iii) the same building renovated as (ii), where the ventilation is provided by mechanical ventilation, and the heat-losses due to ventilation are recovered. Section 4 discusses the experimental results. Finally, Section 5 summarizes our findings and discusses some possible lines of future research.

2. Construction of weather files

This section outlines how current weather files are constructed based on historical observations of weather parameters as well as how future weather files are constructed and used to provide estimates of the energy demand of buildings.

2.1. Historical weather files

A weather file consists of a variety of parameters that vary with the type of weather file. The most common weather files are (i) the Example Weather Year (EWY) developed by Chartered Institution of Building Services Engineers (CIBSE) [21] and mostly used in UK, (ii) the Typical Meteorological Year (TMY) developed in 1978, which is mostly used in the USA, (iii) the International Weather Year for Energy Calculation (IWYEC) developed and used by ASHRAE in the USA and other global locations, (iv) the Test Reference Year (TRY) and Design Summer Year (DYS) developed by the CIBSE and used in Europe, and (v) the Design Reference Year (DRY) developed by Ref. [22] and used in Denmark and 20 other countries.

In this paper we used data from a Design Reference Year (DRY), which comprises 25 parameters. The DRY was chosen as the base line for our experiment mainly because of our knowledge of how the files were created as well as availability. Each parameter is assigned hourly values for a period of one year, i.e. the temporal resolution is hourly, and thus a DRY file contains 8760 values for each parameter. The construction of data in a DRY file is similar to

the construction of data for other weather files. The basic steps in constructing a weather file are:

- (i) Collect real weather data over a period of years. The DRY file is constructed using weather data for the 15 year period of 1975–1989.
- (ii) Compute the average year, i.e. determine the average value of each parameter over the 15 year period.
- (iii) For a given interval, e.g. 1 month, compare the monthly means with each of the 15 actual months and select the actual month that is closest to the average. The selected month then becomes part of the weather file. Repeat this process for all intervals in the year [22].

Thus, a weather file is not the average of weather parameters over some period. Rather, it consists of samples of real weather files taken from this period, where the samples are chosen for their similarity to the average of the weather parameters. The measure of similarity can change across methods, but typically considers various factors, including both monthly and seasonal mean values and occurrence of cold, warm, sunny and overcast days. The true correlation between different parameters such as air temperature, solar irradiance, cloud cover and wind is preserved. Note that the sampling of real weather files ensures that the variance or standard deviation of values in the weather file is approximately the same as for an actual year. In contrast, the variance of the average year is much lower, being reduced by the square root of the number of years.

2.2. Constructing future test reference years

The Special Report on Emission Scenarios (SRES) [23] developed by the International Panel on Climate Change (IPCC) defines a family of possible emission scenarios for the next 100 years, based on economic, social, technological and environmental assumptions. Specifically, this paper considers scenario A1B [24], which represents an intermediate scenario, and which has been used in a number of different climate model experiments. Climate data from coupled atmosphere-ocean Global Circulation Models (GCM) are typically available at a temporal resolution of a month and a coarse spatial grid resolution of 150–300 km. These projections may be further refined using Regional Climate Models (RCM) to provide climate projections at a grid resolution of typically 10–50 km. The temporal resolution of the regional projections is generally available from data centres at a temporal resolution of days or hours.

As noted earlier, climate projections vary in both spatial and temporal resolution. Here we will not consider the variability of spatial resolution. Rather, given an existing weather file and corresponding projections of future changes in these weather parameters, we investigate whether the temporal resolution has a significant effect on estimates of a building's energy consumption.

Projections of future weather conditions can be broadly categorized 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 either to a synthetic weather series derived from a weather generator, or to an existing (observational) weather series, in order to produce the final future weather file. Both methods will be described below.

2.2.1. Category 1 – absolute

One general method used to construct future weather files is to obtain the absolute values directly from regional climate models. This method has been used by Refs. [8,9]. As mentioned above,

regional climate model simulations are governed by Global atmosphere-ocean Circulation Models (GCM), typically at spatial resolutions of ~200 km, and produce finer scale projections at a spatial resolution of 10–50 km. The advantages of using direct input from climate models are that the physical correlations between the weather parameters are preserved (as well as they are captured by the models) and that data is, in principle, available at hourly resolution, as required by dynamic building simulation models. Unfortunately, for practical purposes only 6-hourly time series data are generally stored by international data centres, and since 1-hourly data is not stored locally by all modelling groups, the availability of such data may be sparse. Moreover, the complexity of the models usually requires collaboration with climate modelling experts to ensure proper use of such data.

Recently, the “absolute” approach has been extended to create future weather files that are based on a probabilistic weighting over a number (ensemble) of climate model realizations. For example [15,14,25,26] use a set of stochastically generated climate change weather files produced by experts in climatology as part of the UKCIP climate change scenarios for the UK (UKCP02 and UKCP09). A stochastic weather generator was used to generate statistically plausible weather data, based on actual observations and a Regional Climate Model (RCM) with a spatial grid resolution of 25 km. The weather generator yields daily and hourly data at a 5 km spatial resolution. In Ref. [25] this method was compared to a relative method, described below, in which predicted *changes* are added to an existing reference year weather file. The weather generator method was found to produce more realistic projections¹ of the future weather than the relative method. However, national weather generators are not available in all countries, which limits their application.

2.2.2. Category 2 – relative

Relative methods are provided with projections of *changes* in weather parameters rather than the absolute values from climate models, typically calculated as the difference between a future (scenario) time period and a control period. These relative changes are then incorporated into a current reference year weather file based on observations in order to produce the future weather file. When used to analyse historical time series data, climate models generally exhibit systematic biases, which carry over and may even be more emphasized in future projections. Systematic biases can be attributed to errors in the model formulation, such as shortcomings in the parameterization of sub-grid processes, and more fundamentally to the deficiencies in accurately representing the climate system, e.g. the climate sensitivity, due to our lack of knowledge. As noted in Ref. [6] “... this means that even the present day climate [predictions] may be biased, for example warmer than measured. It is generally assumed that any changes to the climate caused by anthropogenic forcing are then biased by the same amount so that the changes in climate are correct. It is for this reason that climate change scenarios generally quote changes rather than absolute values”.

Projected changes can be incorporated into a present-day weather file in a variety of ways, depending on the climate parameter in questions (e.g. air temperature), as discussed in Ref. [6] and include (i) directly adding the change (shift), (ii) multiplying the present-day data by a scaling factor (stretch) that controls the variance of the parameter and (iii) a combination of (i) and (ii).

¹ There are a variety of ways researchers have quantified whether projections are realistic. For example, Eames [25] considers (i) intervariable relationships, (ii) statistical plausibility as measured by mean and variance, and (iii) minimum and maximum air temperatures.

The predicted changes may have different temporal resolutions. For example [7,15,6] used monthly predictions [27], used seasonal mean changes, and [28] discussed annual changes.

The work of [6,28] are particularly relevant to the work described here. The focus of [6] was to produce design weather data for buildings thermal simulations that account for future change to climate. Their main aim was to develop a practical method by adjusting present-day weather data based on predicted changes in climatic parameters that produced meteorologically consistent data at a fine spatial resolution of 25 km (RCM). The authors compare their “morphing” method with data derived directly from a regional climate model. To do so, they looked at the change in the number of heating degree-days, observing that this provides a means of comparing the present morphing method with the changes to the degree day computed directly from the regional climate model. While this is similar to what we describe here, there is an important distinction. While Belcher et al. used the degree-day method to partially validate the quality of their constructed future weather file, in contrast, we used the degree-day method to assess the ability of different future weather files to estimate future energy demand.

The work of [28] focuses on developing a framework for producing future weather files that is able to deal with different levels of available climate change information, while retaining the key characters of a “typical” year weather data for a desired period. The different levels of available information included predicted changes at different temporal resolutions. However, once again, the focus was on constructing realistic weather files, not on their application, and there was no investigation of the effect that different resolution has on estimates of a building’s future energy demand.

2.3. Methods to estimate energy demand

Here we briefly discuss two common methods for estimating energy demand for a building: (i) degree day method and (ii) dynamic simulations of a building.

2.3.1. Degree-day method

Heating and cooling demand are generally functions of various weather parameters, including outside dry bulb temperature, humidity, solar irradiation, wind speed and direction. 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 assumes a linear relationship between energy demand and the degrees above (below) the cooling (heating) balance point temperature. If t_{bh} is the heating balance point, then the energy demand for heating, Q , is

$$Q_{\text{net},h} \propto \frac{\sum_i^{8760} \max(0; t_{bh} - t_i)}{24} \quad (1)$$

where t_i is the hourly outside temperature at hour i provided by a weather file.

Similarly, we can calculate the energy for cooling. If t_{bc} is cooling balance point, then the energy demand for cooling, Q , is

$$Q_{\text{net},c} \propto \frac{\sum_i^{8760} \max(0; t_i - t_{bc})}{24} \quad (2)$$

where t_{bc} is the cooling balance point.

The degree-day method is a convenient way to examine the effect of different weather files on estimates of the energy demand of buildings [20]. As noted earlier, the number of degree-days above a balance point temperature is independent of the specifics of a building – it is the constant of proportionality needed in Equations (1) and (2) that is building specific and which converts degree-days into energy demand. Despite this advantage, the degree-day method has a number of disadvantages as noted in, for example [29,28]. 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, we also provide experiments using dynamic building simulations, which do not have these limitations.

2.3.2. 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 the dynamic simulation programmes the heating and cooling balance point can be calculated for the specific building.

Dynamic building simulations are becoming commonly used to analyse the performance of the envelope of new buildings, and the performance of different passive and active heating and cooling systems [15,25,10,30]. Examples of dynamic building simulation programs include TAS,² BSim,³ IES,⁴ IDAICE⁵ or Energy Plus.⁶

A dynamic building simulation requires both (i) a detailed model of the building and its heating and cooling elements, and (ii) a weather file that represents the typical weather conditions in 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.

3. Methodology

To determine whether the temporal resolution of future weather files affects estimates of a building’s energy demand, we

² TAS (Thermal analysis simulation) software developed by a company Environmental Design Solution Limited (EDSL), UK mostly used in UK.

³ 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.

⁴ IES (Integrated Environmental Solutions), mostly used in the UK, USA, France, Germany.

⁵ 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.

⁶ Energy Plus – is a whole building simulation program developed by the US Department of Energy.

constructed three future weather files based on the relative methods described in Section 2.2.2. In the following we refer to the three weather files as Annual, Monthly and Hourly offset methods:

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

Note that in all three cases, only the air temperature parameter of the design reference year was changed. All other parameters were unaltered.

3.1. Weather data

To construct the three future weather files we considered an existing weather file consisting of n parameters, $p_1, p_2 \dots p_n$. Each parameter, p_i , is a vector of 8760 hourly values. We also considered a projection of changes to each of these parameters, denoted $\Delta_1, \Delta_2 \dots \Delta_n$. 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 air temperature, (ii) a 12-dimensional projection of the average monthly change in air temperature, or (iii) a 8760-dimensional projection of the hourly change in air temperature. Each parameter, p'_i , of a future weather file is constructed by adding the projected changes, Δ_i , to the corresponding parameter values, p_i , in the existing weather file. In this paper, we only considered the parameter of air temperature. All other parameters were left unchanged.

Mathematically, for case (i) we have:

$$p'_i = p_i + \Delta_{ia} \quad (3)$$

where Δ_{ia} is a scalar constant predicting the average annual change in air temperature. This value is added to each of the 8760 values of p_i to produce the final hourly projections, p'_i .

For case (ii) we need to convert the 12-dimensional vector of monthly average changes to a 8760-dimensional vector of hourly projections. To do so, we simply add each of the 12 values by the number of hours in the corresponding month. Given the resulting vector, Δ_{im} , we then have:

$$p'_i = p_i + \Delta_{im} \quad (4)$$

For case (iii) we have:

$$p'_i = p_i + \Delta_{ih} \quad (5)$$

where Δ_{ih} is a 8760-dimensional vector predicting the expected hourly changes in air temperature. These values are added to each of the corresponding 8760 values of p_i to produce the final hourly projections, p'_i .

The DRY weather file used in this study is based on actual rather than interpolated weather data for our region of interest, and the fact that it covers the period from 1975 to 1989, which falls within the normal period of 1961–1990 commonly used by the meteorological community.⁷

⁷ Note, that the DRY format is not compatible with some dynamic simulation programs, such as TAS. We therefore converted the DRY formatted data to an Energy Plus format (EPW).

Table 1
Monthly changes calculated from HIRHAM5-BCM.

Monthly change	
Month	Monthly change $T^\circ\text{C}$
January	1.35
February	1.42
March	1.93
April	1.60
May	0.95
June	1.18
July	1.06
August	1.02
September	1.07
October	1.13
November	1.30
December	1.87

Annual, monthly and hourly climate projections were investigated for Gentofte, a suburb of Copenhagen, Denmark. Hourly data from a transient regional climate simulation at a spatial resolution of 25 km was provided by the Danish Meteorological Institute (DMI). The obtained data covers the control period of 1961–1990 and a future scenario period of 2021–2050 using the IPCC A1B scenario. The climate simulation was carried out using DMI's HIRHAM5 regional climate model, forced by the BCM GCM (Bergen Climate Model) and was part of the EU-ENSEMBLES project [31]. The choice of the scenario period 2021–2050 is somewhat arbitrary, and was chosen based on the fact that the components such as HVAC systems of new and refurbished buildings are currently expected to have a lifetime of 20–30 years.

To extract the weather data (in this case only air temperature) for the Gentofte region, the Climate Data Operator (CDO) [32] software was used, specifically the REMAP operator.⁸

To generate the projected hourly changes in air temperature, a 8760-dimensional hourly offset Δ_h was computed by taking the difference between the average regional climate model projections for the period 2021–2050⁹ and subtracting the corresponding average regional climate model projections for the control period 1961–1990.

Picking out individual years in a climate simulation is not meaningful, since climate models provide both a projection of the statistical properties of the weather based on the prescribed concentrations of greenhouse gasses and atmospheric aerosols overlaid with natural climate variability. Due to natural variability, the usual best practice in climate science, which we adopt here, is to consider averages of typically 20 or 30 years rather than individual years (30-year averages has been the de facto best practice for many years, corresponding to the iconic meteorological normal period 1961–1990, whereas 20-year averages have been the norm in the last two IPCC reports).

The projected hourly changes in air temperature, a 8760-dimensional hourly offset, Δ_h is given by

$$\Delta_h = \hat{Y}_{2021-2050} - \hat{Y}_{1961-1990} \quad (6)$$

where Δ_h is a 8760-dimensional vector of hourly differences and $\hat{Y}_{2021-2050}$ is given by

$$\hat{Y}_{2021-2050} = \frac{1}{30} \sum_{i=2021}^{2050} y_i, \quad (7)$$

⁸ The input parameters to CDO are the longitude and latitude for Gentofte, i.e. lon = 12.67/lat = 55.63 (bicubic interpolation between grid cells i.e. REMAPBIC).

⁹ in the obtained model data year 2047 is missing.

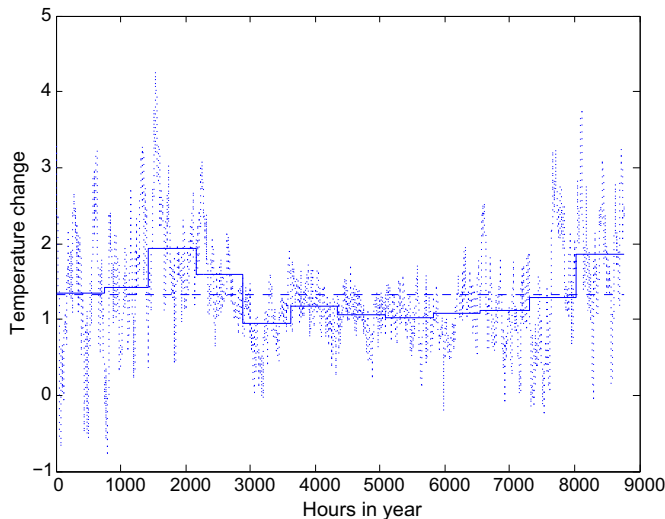


Fig. 1. Annual (dashed), monthly (solid) and hourly (dotted) projections of air temperature changes for the period 2021–2050.

and

$$\hat{y}_{2021-2050} = \frac{1}{30} \sum_{i=2021}^{2050} y_i, \quad (8)$$

and y_i is a 8760-dimensional vector of hourly air temperatures for year i .

In order to assess the quality of the regional climate model simulation, we note that the expected annual and seasonal changes in Denmark for different weather parameters based on 13 simulations from the ENSEMBLES multi-model experiment are summarised in Ref. [33]. Assuming the IPCC A1B scenario, the mean annual air temperature change in Denmark based on this ensemble of model projections is estimated at approx. 1.2 °C for the period 2021–2050 as compared to the control period (1961–1990). Conversely, the annual change in air temperature for the same period in Gentofte, Copenhagen area, based solely on the hourly HIRHAM5-BCM data set is approximately 1.32 °C. This seems to be consistent with the more robust ensemble estimate, bearing in mind that we are comparing one model to many and many grid points to a single grid point. In the following experiments all quantities (annual, monthly, hourly changes) were calculated using HIRHAM5-BCM data, ensuring that the only observed difference were due to differences in temporal resolution. The monthly changes are enumerated in Table 1 below.

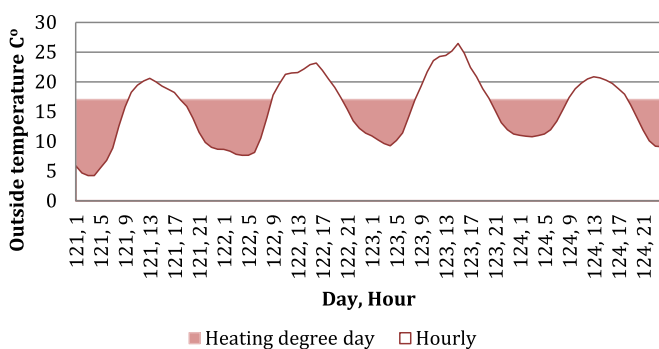


Fig. 2. Temperature profile for a 4-day period in May (day numbers 121–124) for the hourly weather file. The x-axis label, d, h refers to day d and hour h in that day. The shaded area represents the days when energy is needed for heating.

Table 2a

Number of hours when outside temperature is above or below heating and cooling base line in 3 different weather files.

	Number of hours above (below) cooling (heating) balance points				
	Hourly	Monthly		Annual	
		Number of hours	Percentage of hourly	Number of hours	Percentage of hourly
Above 25	92	87	94.6%	98	106.5%
Above 26	60	55	91.7%	62	103.3%
Above 27	37	33	89.2%	37	100.0%
Below 17	7706	7713	100.1%	7630	99.0%

Percentages are relative to the hourly data.

The annual and monthly future weather files were constructed based on Equations (3)–(5), respectively. Fig. 1 illustrates the corresponding annual (horizontal line dashed), monthly (solid) and hourly (dotted) changes.

3.2. 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.

3.3. Building simulations

For comparison and to address the limitations of the degree-day method a dynamic thermal simulation model in TAS was constructed for an arbitrary existing, historic, naturally ventilated building in the Gentofte municipality near Copenhagen. In addition to exploring its present-day appearance, we consider two types of modifications, which have different energy efficiency consequences and different types of ventilation systems, to assert the dependency of our results on the particular choice of building. A detailed setup of the three models may be found as [Supplementary Information](#) and outlined below.

The reference building is an old residential building from 1920, which is now used as a day-care centre for children between 6 months and 3 years of age. The building is a 2-story building with unheated basement and unheated attic space. The building is heated by district heating with a heated area of 279 m² and a total area of 571 m². The building is naturally ventilated, except for the bathrooms, which have mechanical extracts. The building has recently been 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/m²K. The cavities of the external facades on the ground floor and 1st floor were recently (2009) insulated with 170 mm and 130 mm of cavity insulation

Table 2b

Area represents the heating degree days, that can be expressed as the energy demand required for cooling or heating, when outside temperature is above or below cooling or heating base line in 3 different weather files.

	Area representing the energy required for heating or cooling				
	Hourly	Monthly		Annual	
		Area	Percentage of hourly	Area	Percentage of hourly
Above 25 (Cooling)	191	167.51	87.7%	189.71	99.3%
Below 17 (Heating)	7706	7713	100.1%	7630	99.0%

Percentages are relative to the hourly data.

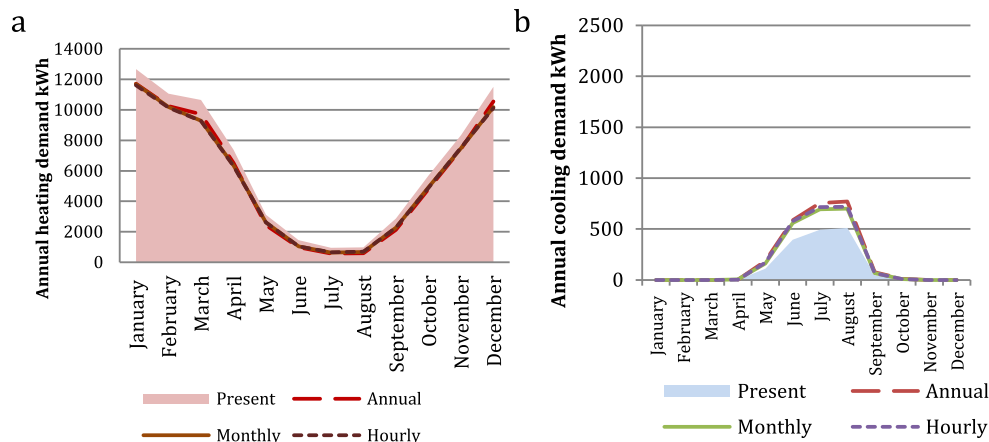


Fig. 3. a. Annual heating demand for the “existing” building for weather files based on present (shaded), annual (dashed), monthly (solid) and hourly (dotted) changes. b. Annual cooling demand for the “existing” building for weather files based on present (shaded), annual (dashed), monthly (solid) and hourly (dotted) changes.

respectively. The U-values of such constructions are typically $0.16 \text{ W/m}^2\text{K}$ and $0.21 \text{ W/m}^2\text{K}$ respectively. The original wood framed windows now have secondary glazing placed 120 mm from the external window frames. The U-value of such a construction is typically $2.8 \text{ W/m}^2\text{K}$.

Comparison of the simulation results with the actual energy usage and measured temperature of the building was used to validate the accuracy of the model.

Two other models, which are variations of the existing building, were also created with different types of ventilation. Thus we have three building models:

1. “Existing”,
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 $0.8 \text{ W/m}^2\text{K}$. Natural ventilation was also established through carefully chosen top windows for the air supply using existing chimneys to extract the air.
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, we did not include heat-recovery in the present comparison. A more detailed description of the three building models is provided in [Appendix 1](#).

4. Results

We considered the number of hours each of the three weather files is above or below a balance point temperature. For a particular weather file, we plotted the outside temperature as a function of time, and examined the area between the curve and the balance point, as shown in [Fig. 2](#).

By assuming that this area is directly proportional to the energy demand, noting that in all weather files we have only changed the air temperature, whereas other weather parameters were kept the same. This means that other parameters such as solar gains, which may influence the energy demand, were not considered here.¹⁰

¹⁰ We note that the work of [\[18\]](#) suggests 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”.

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.

[Table 2](#) enumerates both the number of hours and the area under the curve for a range of heating and cooling balance points. We observe that for the heating balance point, the differences across weather files are very small, typically less than 1%. This result is in line with the heating estimates made for all three building models below. In contrast, we observe 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 thresholds is actually quite small, e.g. there are only 92 h out of 8760 in the weather file where the air temperature exceeds 25°C based on the hourly-change weather file, and only 37 h where the air temperature is expected to exceed 27°C . Thus, even a small change, i.e. a single hour difference, results in a 1% or 3% (1 in 37) change respectively.

[Fig. 3](#) (a) and (b) shows the estimated annual heating and cooling demand for the “existing” building based on a TAS simulation using the three different weather files (annual, monthly, hourly) where again the weather files differ only in their air temperature parameter, i.e. all other parameters, e.g. humidity, wind speed etc. are identical. [Figs. 4a and b and 5a and b](#) show the same for the “Improved-NV” and the “Improved-MV building models respectively. Note that the vertical scales are different for heating and cooling. [Table 3](#) summarises the results.

We observed that there is almost no difference in the predicted heating demand when using the three different future weather files. In particular, for the “existing” building the heating demand estimated using the future weather files based on annual and monthly changes differ by no more than 1% with respect to the hourly-change weather file. The same is true for the “Improved-NV” building model, despite the very different thermal properties of the building, which drop total heating demand from approximately 67 MWhours to 19 MWhours. For the “Improved-MV” model, the differences in the estimated heating demand across weather files is only slightly larger, 3% (annual) and 1% (monthly) with respect to the hourly-based weather file. Once again, there is a very significant difference in the thermal properties of the “Improved-MV” model, with the total heating demand dropping to about 10 MWhours.

The differences in the predicted cooling demand, when using the three different future weather files, is slightly larger. We observe that the cooling demand estimated based on the annual change is between 2% and 5% greater than for the hourly estimated.

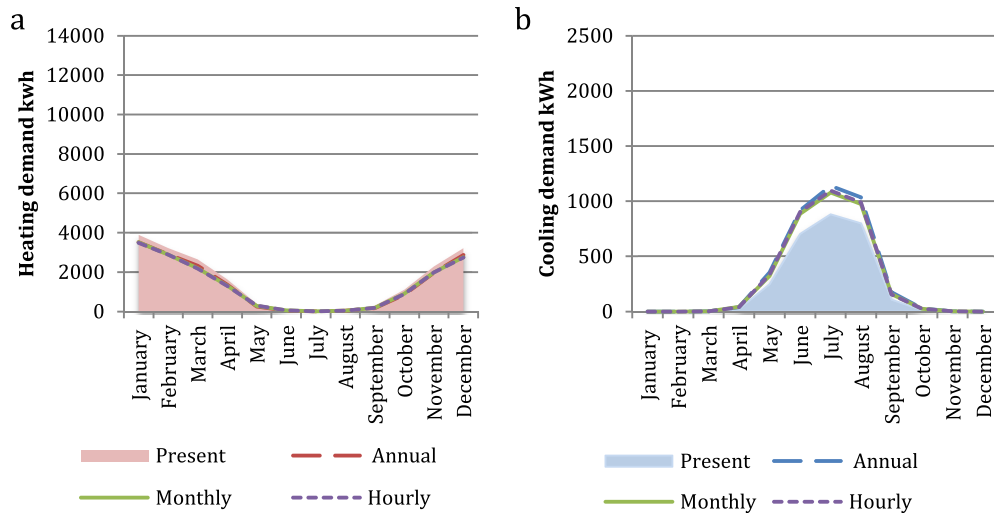


Fig. 4. a) Annual heating demand for the “improved NV” building for weather files based on present (shaded), annual (dashed), monthly (solid) and hourly (dotted) changes. b) Annual cooling demand for the “improved NV” building for weather files based on present (shaded), annual (dashed), monthly (solid) and hourly (dotted) changes.

Conversely, we observe that the cooling demand estimated based on the monthly change is between 0 and 3% less than for the hourly estimated.

5. Discussion

Experimental results using both the degree-day method and dynamic simulations of three buildings with very different thermal properties seem to indicate that even coarse annual estimates of air temperature change produce useful estimates of energy demand. This result is not obvious as it is easy to construct examples of hourly air temperature changes and corresponding annual air temperature change that would give very different results. For example, consider Example 1 in Fig. 6 in which the hourly differences are all zero except during the summer period where the differences are large, say 10°C (dotted). The average annual change is then estimated to be 2.5°C (dashed). Now consider a hypothetical real weather file, describing a location where heating is required throughout the year, as even

during the summer period, the measured air temperature is usually about 1°C below the heating balance point. When we add the two temperature difference curves of Fig. 6 to baseline temperature curve (solid), we obtain two future weather curves, depicted in Fig. 6 (dotted and dashed). The curve based on a single annual change remains below the heating balance point. However, the curve based on hourly changes now requires almost no heating during the summer period. We believe that such a pathological example is very unlikely in practise.

Conversely, it is also easy to construct an example where the hourly and annual air temperature differences will give the same result. Consider an arbitrary hourly air temperature difference curve, as illustrated in Fig. 7. The horizontal line is the average annual air temperature change calculated from this hourly data. Thus, by definition, the area under the horizontal line is equal to the area under the hourly curve. We refer to this area as A.

Now, consider a weather data curve of Fig. 8, where all air temperatures are below the heating balance point, i.e. heating is

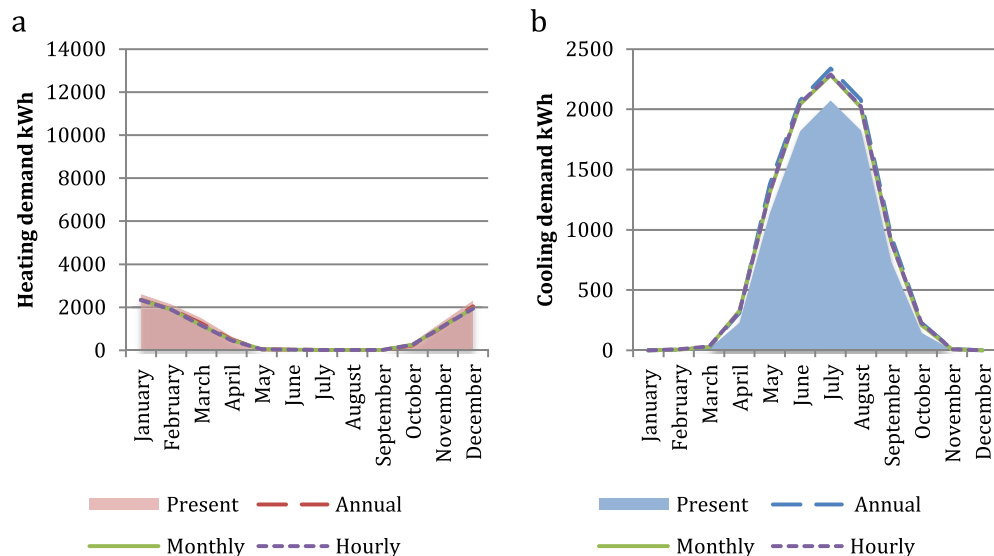


Fig. 5. a) Annual heating demand for the “improved MV” building for weather files based on present (shaded) annual (dashed), monthly (solid) and hourly (dotted) changes. b) Annual cooling demand for the “improved MV” building for weather files based on present (shaded) annual (dashed), monthly (solid) and hourly (dotted) changes.

Table 3a

Annual heating demand for the three buildings with three future weather files in comparison to the fine temporal resolution (hourly). Shaded columns present the present heating demand for the buildings, which will decrease in the future.

Annual heating demand					
Present	Hourly	Monthly		Annual	
kWh	kWh	kWh	Percentage of hourly	kWh	Percentage of hourly
Existing building					
76547	67128	67331	100.3%	67641	100.8%
Improved NV					
18877	16056	16145	100.6%	16321	101.7%
Improved MV					
11126	9256	9311	100.6%	9502	102.7%

required at all time. Thus, based on the degree-day method, the heating energy is proportional to the area between the air temperature curve and the horizontal line representing the balance point. We refer to this area as area B. When we add a temperature difference curve to the weather data, we obtain a new curve and the future heating demand is given by the area, $C=B-A$, i.e. we obtain exactly the same degree-days whether hourly changes or an annual change are used.

A discrepancy between hourly and annual air temperature changes only manifests itself when the future weather air temperature curve intersects the heating balance point, as depicted in Fig. 9. In this illustrative example, both the hourly and annual future weather files do not contribute to heating degree-days for points above the heating balance point temperature. The hourly estimate of the heating demand is proportional to the area between the hourly curve and the horizontal balance point line and similarly for the annual estimate of heating demand. Thus, the error is the difference in these two areas. In practice, an air temperature curve may cross the balance point multiple times, which complicates any more general analysis.

We observe from Fig. 1 that the actual hourly air temperature changes predicted for the Copenhagen region are generally smaller during the summer period and largest during the winter period. However, Fig. 10, which shows the DRY file used in Section 3.1 reveals that when the predicted air temperature changes are largest, the temperature curve is usually very far from the heating balance point and thus the hourly or annual predicted air temperatures seldom exceed the heating balance point temperature. Thus the annual and hourly heating energy estimates are close. Conversely, for cooling demand, we observe that (i) there are very few hours in the DRY file that exceed the cooling balance point, and (ii) these point are close to the threshold. Thus we would expect the error to be larger between the hourly and annual

Table 3b

Annual cooling demand for the three buildings with three future weather files in comparison to the fine temporal resolution (hourly). Shaded columns present the present cooling demand for the buildings, which will increase in the future.

Annual cooling demand					
Present	Hourly	Monthly		Annual	
kWh	kWh	kWh	Percentage of hourly	kWh	Percentage of hourly
Existing building					
1556	2265	2197	97.0%	2387	105.4%
Improved NV					
2776	3540	3485	98.4%	3684	104.1%
Improved MV					
7981	9174	9130	100.5%	9398	102.4%

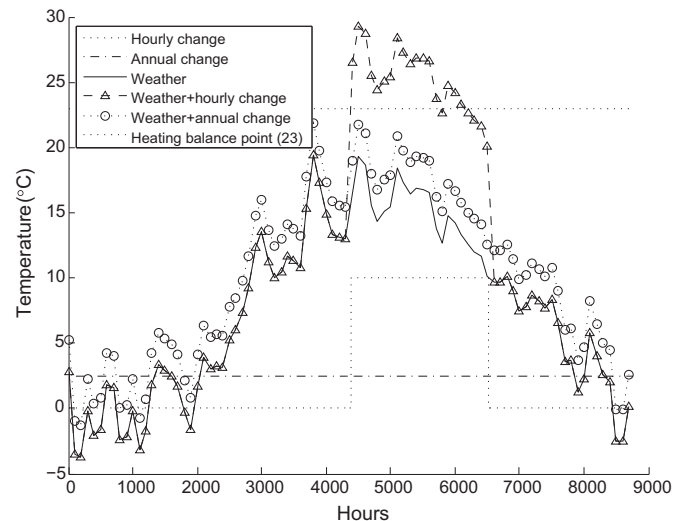


Fig. 6. Weather data smoothed using a moving 1-week average for illustrative purposes (solid), annual change (dashed), hourly change (dotted), Weather + annual change (circle + dotted), Weather + hourly change (triangle + dashed), balance point for heating degree day (dotted).

predictions, and this is supported by experiments. In general, we would expect the relative error between coarse (annual) and fine (hourly) temporal predictions of air temperature changes to be large when the actual weather file data is close to a balance point. However, while the relative error may be large, the absolute error in energy may still be small, since, when the air temperature is near a balance point, much less energy is needed to heat or cool a building.

Clearly, the energy demand of buildings is also sensitive to other weather parameters than air 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 Ref. [18] 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,

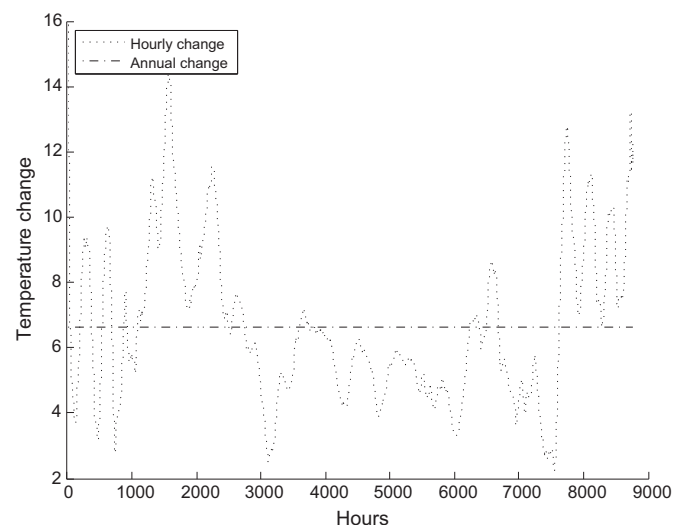


Fig. 7. Hourly air temperature change smoothed using a moving 1-week average for illustrative purposes (dotted) and average annual change (dashed).

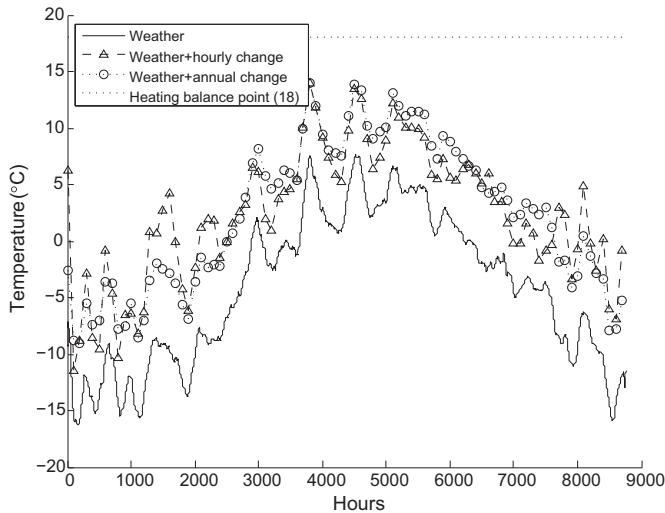


Fig. 8. Weather data smoothed using a moving 1-week average for illustrative purposes curve (solid), added hourly change curve (triangle + dashed), added annual change curve (circle + dotted) and heating balance point temperature at 18 °C (dotted).

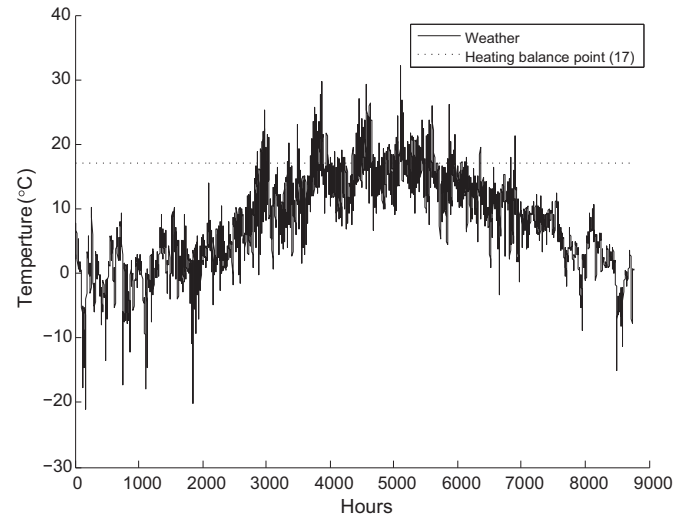


Fig. 10. DRY temperature (solid) and heating balance point at 17 °C (dotted).

using the annual change in air temperature may produce close estimates. Moreover, the coarse resolution weather file is, from an energy simulation point of view, simple to construct.

6. Conclusion

This paper examined whether future weather files constructed with coarse temporal resolution data of expected changes in air 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 estimate of expected annual change in air 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 4% of one another.

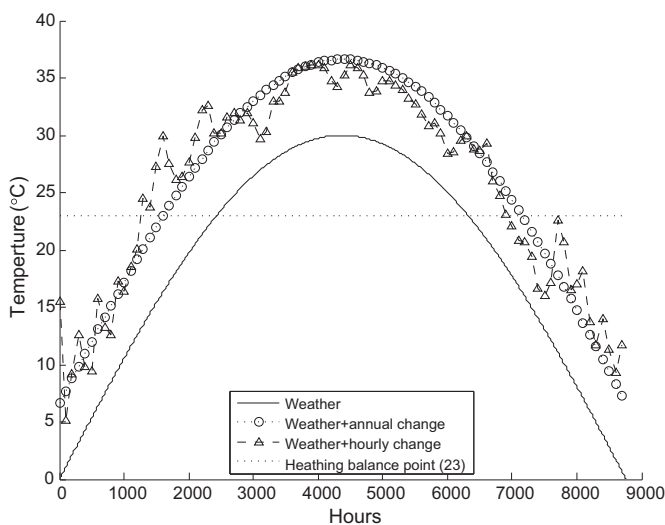


Fig. 9. Synthetic weather data (a sinusoid curve) (solid), added annual change (circle + dotted), the hourly change added (triangle + dashed), heating balance point (23 °C) (dotted).

Arguably, large relative errors are most likely when the air temperatures are close to the heating or cooling balance points. However, energy demand in these regions is modest and even relatively large errors may only result in modest absolute errors in energy demand.

A limitation of our investigation is that it only considers the change in the dry bulb temperature. Further work is needed in order to confirm whether other parameters, such as wind, precipitation, cloud cover or humidity can be treated similarly. 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.

In this paper we only present results for one location, i.e. Gentofte, which is used here to illustrate some of the technical challenges, practitioners face. In that context our findings are significant, since there is evidence [15,17] that many practitioners have difficulty obtaining future weather file data. While better data is always preferable, our study reveals that in the absence of high temporal resolution data, a coarse annual estimate of the expected change in annual air temperature may be a pragmatic and more accessible way when estimates of future energy demand is requested. Clearly, more research is needed in order to test strengths and weaknesses of the methodology comprehensively, e.g. under different climate conditions and for different building types. This was however beyond the scope of this study, e.g. in terms of data availability. In the future, we intend to extend our work to assess the methodology for other climatic regions as well.

This paper has examined whether future weather files constructed using coarse temporal resolution data could provide useful estimates of future energy demand. Future weather files can and are used to estimate other factors and future work is needed to evaluate whether the methodology proposed here is useful for other factors such as estimating future thermal comfort.

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Appendix 1. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.buildenv.2014.04.006>.

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9 Paper II

Sustainable Resilience in property maintenance: encountering changing weather conditions,

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SUSTAINABLE RESILIENCE IN PROPERTY MAINTENANCE: ENCOUNTERING CHANGING WEATHER CONDITIONS

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ABSTRACT

Purpose: The purpose of the study is to develop a methodological approach for project management to integrate sustainability and resilience planning in property maintenance as an incremental strategy for upgrading existing properties to meet new standards for sustainable and climate resilient buildings.

Background: Current maintenance practice is focused on the technical standard of buildings, with little consideration of sustainability and resilience. There is a need to develop tools for incorporating sustainable resilience into maintenance planning.

Approach: The study is primarily theoretical, developing the concept of sustainable resilience for changing weather conditions.

Results: The paper suggests a decision support methodology that quantifies sustainable resilience for the analytical stages of property maintenance planning.

Practical Implications: The methodology is generic and expected users are FM organisations with responsibility of property maintenance, and consultants offering property management planning as a service.

Research limitations: The methodology is conceptual and has not been tested. However the concept is to be further developed in dialogue between the authors, the Danish local authority Gentofte Properties and other potential users.

Originality/value: The paper suggests a new methodology to explicitly integrate sustainability and resilience planning in property maintenance planning.

Keywords

Sustainable FM, climate adaptation, guideline, planned maintenance, property management.

1 INTRODUCTION

Every day property managers around the globe plan the maintenance tasks ahead of them, either as part of a periodic inspection and planning process, or as emergent maintenance because an acute problem has occurred. This paper investigates how opportunities for upgrading the existing building stock can be executed in a way that also includes the perspective of sustainable development and climate resilient cities in an integrated way. 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. Here we are primarily concerned with extreme weather events, but our general framework is applicable to other events, e.g. power failure. Climate resilience has received a significant increase in attention due to predictions that climate change will cause more extreme weather events (Beniston M. et al., 2007).

Climate adaptation and resilience is no longer only an issue at a political level but is also an emerging topic in the FM research literature (e.g. Warren 2010 and Carthey et al., 2009). However, in general, we believe that most of the maintenance and operation strategies in practice do not yet deal with climate change and the sustainability agenda, beyond simple energy savings. Those working with the conditions of current building stock do not consider the risk associated with changing climate.

Typically the maintenance and operation strategies are based on the current condition of the building stock and can be simplified into two types of maintenance: emergent or planned (Flores-Colen I. et al., 2010). The better the building owner knows the condition of his building stock, the easier for him/her it is to plan the cost of maintenance and repairs. In such a portfolio the budget for emergency cost is expected to be small and the planned maintenance cost budgets are distributed through a number of years so the owner is comfortable with his spending. Together with a repair plan, the owner can incorporate the upgrading of the building elements, which will reduce the maintenance or operational cost of the building in the future. However, even a well-managed building portfolio can be disturbed by extreme weather events, which increase emergent maintenance cost and possibly place the owner of the building in financial difficulty. To reduce the risk of unexpected costs, building owners must investigate cost effective options to adapt their properties to possible future environmental changes whose consequences are yet unknown. As Bosher et al., observed, *“Well-designed buildings, properly protected from the hazards associated with climate change, will be easier to sell or let and could also command higher prices. Opportunities are therefore available for organisations to position themselves as market leaders in the climate-related ‘future-proofing’ of buildings, thereby presenting a means of attracting new customers and gaining a competitive edge.”* (Bosher L. et al, 2007).

Numerous methods have been proposed for measuring both resilience and sustainability, separately. Often the investment needed to make a building more resilient or sustainable is not easy to express in monetary terms, which can then be compared with the investment. This is because many of definitions of resilience or sustainability are difficult to measure, and as such provide insufficient information with which to make investment decisions, as most investment decisions are determined by economic models such as return of investment. To address this issue we investigate a method of quantifying the sustainable resilience of buildings, which can be applied in a decision making process of everyday maintenance strategies. In this paper we discuss how risk management tools familiar to some building owners, facility manager, architects, and other decision makers, can be used to quantify resilience, and facilitate the decision process for selecting between remedial solutions with varying degrees of sustainability.

The paper has the following structure. In Section 2, we first review previous work on resilience, sustainability, and sustainable resilience. Section 3 then summarizes how risk management can and has been used to quantify resilience. Ultimately we see resilience and risks as two sides of the same coin: the higher the risk, the less resilient a building is. We then discuss how sustainable solutions can be incorporated into the risk framework through the economic concept

of externalities. Section 4 provides an illustrative example of how the framework can be used. Finally Section 5 provides a discussion of future work

2 BACKGROUND

Resilience is becoming increasingly used in the context of climate change and adapting built environment. Most resilience studies on climate change have been undertaken by mapping threats such as the increased possibility of flooding, sea level rise or heat-waves (Beniston et al., 2007), (Biesbroek et al., 2010), (Bosher L. et al., 2007), (de Wilde et al., 2012), (Snow et al., 2011), investigating the vulnerability of a system to these threats (Guan 2012), (Camilleri et al., 2001), (Jentsch et al., 2008), or investigating how to increase a capacity to adapt (Lomas 2009).

2.1 Definition of Resilience

We are interested in resilience to extreme weather events, although the framework is applicable to other events as well. Given the possibility of an extreme weather event, e.g. a heat wave, resilience seeks to determine how well a building or system continues to function during and after the event. As such, we broadly follow the definition of Nelson that “*System resilience refers to the amount of change a system can undergo and still retain the same controls on function and structure ...*” (Nelson et al., 2007), although we acknowledge a number of other possible definitions of resilience depending on various perspectives. (Manyena S.B., 2006), (Folke C. et al., 2002), (Bosher L. et al., 2007). (Carpenter S. et al., 2001; Christenson M. et al., 2006; Cole R.J., 1998; Cox R.A et al., 2014), (Holling C.S., 1996), (Pimm 1984)

While such measures are valuable, particularly in the context of understanding the ecology of a region, we believe such measures are of limited value in supporting the process to decide whether remedial action should be taken to improve a building’s resilience. For example, knowing that a building is resilient to average daily temperatures of up to say 30C is useful, but any investment decision must also consider both the cost of failure when daily temperatures exceed 30C and the probability of such weather events occurring. The latter probability is necessary to arrive at an overall expected cost that can be directly used to prioritize investments. Assigning an economic cost to resilience can be handled using well-known risk measures, which are discussed in the next section. However, before doing so, we next discuss sustainability.

2.2 Definition of sustainability

The definition of sustainable development (SD) was defined by Brundtland Commission in 1987 as “development the 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 ecological, economic and social consequences of development. According to this definition the environmental, social and economic needs are defined as equal and “*must deliver prosperity, environmental quality and social justice*” (Ding G.K.C., 2008). We argue, that the Brundtland definition is very broad, without a clear understanding of the limits of the natural cycle of a limited area. This definition of sustainability is difficult to quantify. To be able to quantify and measure sustainability we view sustainability as “the ability of our own human society to continue indefinitely within natural cycles of the earth” K. Baxter, A. B. (2010). By doing that we could identify the natural cycles of the limited geographical area, such as a country, a city, a company, a project or even a building.

As resilience can be quantified using risk analysis, similar the sustainability can be measured by quantifying a building's impact on environment. However the impact on environment is more difficult to quantify as some of metrics such as different greenhouse gasses (GHG) are quantitative and well defined and can be compared globally, and other impacts such as overall impact on environment can only be quantified qualitative by "awarding points for presence or absence of desirable features" (Cole R.J., 1998). Most of building sustainability assessments tools such as BREEAM, LEED or DGNB etc. are well defined tools for a specific type of building in specific geographical area and taking into account both qualitative and quantitative metrics (Ding G.K.C., 2008). Most of the building assessment tools are based on a scoring system, which is defined and weighted by either (i) all criteria's are weighted equally, or (ii) weighting coefficients were determined by questionnaire survey of users of the system such as designers, building owners, operators, and can be modified to suite the local conditions.

From the facility managers' perspective there is still missing a method to evaluate smaller refurbishment projects where only one or two components of the building are to be replaced as part of maintenance. In such projects the environmental impact should to be expressed in monetary terms to be able to feed in to the traditional Cost Benefit Analysis (CBA). The CBA is a well-respected tool where everything is converted into monetary terms and decisions are based on highest net value (Ding G.K.C., 2008). As we already discussed, the environmental impacts are not always possible to express in monetary values. We investigate how the environmental impacts can be included in CBA.

2.3 Definition of sustainable resilience

The idea of merging both sustainability as a mitigation option and resilience as the adaptation option has been suggested by (Mills E. et al., 2003), (Bosher L. et al., 2007) and (Camilleri M. et al., 2001), (Folke C. et al., 2002). However, the authors only discussed a need of coupling the sustainability and resilience without suggesting how to quantify them.

3 APPROACH

The study is primary theoretical as it draws on current literature on sustainability and resilience to develop the concept of sustainable resilience. However it builds on the example of property maintenance in the Danish Municipality Gentofte, and illustrates how Gentofte and other property managers can innovate their property maintenance planning practice to meet new political strategic goals of sustainable resilient properties.

Risk and resilience are seen as two sides of the same coin and therefore the developed guideline adopts a risk management approach. (Jones 2012) has a similar approach when suggesting a framework for risk assessment for extreme climate change challenges. The difference between Jones and this paper is primary that we integrate traditional building technical maintenance not only with extreme climate change risks, but also with the sustainability profile of the building.

This study could be done in a qualitative way to illustrate the line of thinking. But in order to meet the expressed need of measuring and quantifying engineering solutions to demonstrate a value and to allow multi-criteria comparisons of alternative solutions and total cost/value evaluations, we aim for quantifications of each indicator. We also assume an economist's

perspective that facility managers are rational and base decisions on economic criteria, i.e. facility managers are asked to create as much value as possible out of a given budget.

The paper presents work in progress and is therefore not fully developed in terms of suggesting specific measures for sustainable resilience.

3.1. Quantification of resilience

In summary the resilience can be measured by (i) defining most significant indicators, or (ii) using risk analysis. The risk (R) is defined as the expected consequences associated with a given activity (Faber M.H., 2012). Risk can be described by a function of probability (P_i) of an event, i , occurring, together with the consequence (C_i). If there are n possible events, then the risk is defined as

$$R = \sum_{i=1}^n P_i * C_i$$

From the facilities management point of view there are several advantages for using risk assessment for quantification of resilience:

- a. To be able to calculate the risk assessment the object or system whose resilience we are investigating must be well defined: resilience of what, and resilience to what. Thus, to quantify the resilience of a building, we need to split the building as a system into different problem areas: for example if we are investigating the resilience to overheating we are only looking into the indoor temperatures and not other parameters such as degradation of the external materials.
- b. By calculating the risk of failure it is possible to express the failure in monetary terms. How much it will cost if the system will fail and how much it will cost to prevent that failure.

However the disadvantage of only taking the risk assessment into account is that the overall resilience of the building will be difficult to assess and the environmental impact of the proposed solution is not evaluated.

To be able to include the environmental impact of the solution we also require to look at the sustainability assessment methods that are described below.

3.2 Quantification of sustainability

The quantification of sustainability of buildings can be measured by:

- (i) Different sustainability indicators covering all 3 aspects of sustainability (ecological, economical and social) and are usually defined from project to project
- (ii) Environmental assessment tools, which are based on the awarded points, and are weighted by the overall impact on buildings and is often a 5 level system, where 5 is the most desirable environmental performance of the building. The advantage of such system is that the evaluation of the building's environmental performance becomes more comparable within the same scheme and within the regions. The disadvantage is that it does not take economic cost nor resilience into consideration (at least not directly)

- (iii) Sustainability index where different alternative solutions can be calculated and compared to each other by including not only the economic cost of a solution but also the Benefit Cost Ratio (BCR), Energy Consumption (EC), External Benefits (EB) and Environmental Impact (EI). This has the advantage of considering economics but not resilience.

3.3 Quantification of sustainable resilience

The first attempt to quantify both the sustainability and resilience was proposed by Camilleri using Climate Change Sustainability Index (CCSI), (Camilleri M. et al., 2001). The author proposed to establish a scoring system rating from -2 to +5, where the scores are given based on Annual Exceedence Probability (AEP).

- (iv) Climate change sustainability index, which rates a building's adaptation performance by using the probability of return of extreme event, which will affect the performance of the building. The method proposed ranking a building from -2 to 5 (where 0 represents no risk at present, but the risk is already occurring in the adjacent properties).

4 RESULTS

The focus of the paper is how to quantify sustainable resilience as input to maintenance planning. In the following we use risk and incorporate additional costs to non-sustainable solutions. These costs are often referred to as externalities within economics such as: carbon costs, water consumption, public relations etc. These costs allow a return on investment (ROI) to be calculated for both resilient and sustainable resilient solutions. The general approach is to define risk and introduce the basic concepts, e.g. probability of an event and cost of event and compare it with the expected cost of the maintenance project.

To illustrate the methodology we investigate how resilient a historical naturally ventilated building is to changing weather conditions. We restrict our investigation to only one changing parameter – external temperature and investigate the building's resilience, i.e. ability to maintain its function during the extreme high temperatures. We consider the spatial area of Denmark and the time periods of current climate, 2050 and 2100.

4.1 A 6 step approach to measuring sustainable resilience:

Given (i) a building and (ii) a disturbance, e.g. temperature

1. Determine the resilience of the building to temperature, i.e. at what temperature will the building's functions be compromised?
2. Determine the cost associated with the loss of building functionality.
3. Determine the probability of the event/disturbance occurring.
4. Apply risk analysis to determine the expected cost associated with the current resilience of the building, (existing conditions).
5. Determine cost of remedial solutions as well as period when the solution is required
6. Apply cost benefit analysis to select (or not) a solution

To incorporate sustainability, step 5 is expanded as following;

- a) Determine capital and operating costs, as before
- b) Determine direct/indirect ecological costs, e.g. carbon tax, etc.
- c) Determine intangible costs to say, reputation

d) Add (a)-(c) to determine total cost, then go to Step 6

The steps for investigating sustainable resilience, described above, are used to illustrate the example below. The example investigates the resilience of a naturally ventilated building to heat waves in Denmark, as an illustration of the principles of the method.

Step 1. Determine the resilience of the building to temperature

The resilience of building stock depends on the type of extreme weather events, which will have different consequences. Increased temperature will reduce heating demand, but increase cooling demand and will increase the risk for overheating (Christenson et al. 2006) (Jentsch et al. 2008).

In the context of the risk of overheating in a naturally ventilated building, we define the Limit State Function (LSF) as the event when the naturally ventilated building (i) fails to provide a comfortable thermal environment, which can result in loss of productivity, (ii) must be closed due to overheating, and (iii) becomes a risk to human life.

Table 1: The threshold for different LSF in naturally ventilated building

Stages of failure	Internal temperature °C
No impact (G_0)	$21 < t < 25$
Loss of productivity (G_1)	$25 < t < 30$
Loss of function (G_2)	$30 < t < 32$
Risk of mortality (G_3)	$32 < t$

Step 2 Determine the cost associated with the loss of building functionality

The cost associated with the loss of buildings function will be different for different stages of failure G_1 , G_2 , G_3 . The risk of mortality G_3 will not be discussed further as the building will be closed before the risk will occur. Therefore the risk of loss of function G_2 will be expressed as the loss of function during periods where the external temperature exceeds 32°C . The cost of productivity is most relevant for this case and is discussed in detail below.

A review of the literature investigating the relationship between indoor temperature and productivity is provided by (Seppanen et al. 2004), who observed a strong correlation between temperature (t) and productivity when the temperature is above or below the comfort zone ($21-25^\circ\text{C}$).

Based on the analysis the author develops a model to calculate productivity loss based on internal temperature, which we have adapted to calculate the productivity loss in our building. As we assume that our case study building is an office, we calculate productivity loss L , measured as a percentage and expressed by

$$L = 2 * t - 50, \quad 25^\circ\text{C} < t < 32^\circ\text{C}$$

$$L = 0, \quad 21^\circ\text{C} < t < 25^\circ\text{C} \quad (2)$$

The loss of productivity or function depends on the building. As our case study is an office we calculate the loss of productivity and function based on salaries of employees.

The cost of an employee is based on the assumptions that (i) the annual salary of an employee is 350.000 DKK, (ii) the salary overhead is 2 and (iii) the number of working hours in a year is 2500. Then, the hourly cost per employee is

Hourly Cost per employee = $350.000 * 2 / 2500 = 350 \text{kr}$.

We assume that the cost of loss in productivity C_i can be calculated as following:

$$C_i = \sum_{i=25}^{32} N_e * C_{he} * N_{di} * L_i \quad (3)$$

where i is a temperature from 25...32°C

N_e - number of employees

C_{he} -hourly cost of employee in Dkr

N_{di} - number of hours between i and $i+1$.

L_i – productivity loss of employee for a threshold i in %

Similar, we can calculate the cost of loss of function when the building will be required to be shut down (G_2), and the cost of mortality of the occupants (G_3).

Other factors such as high humidity, which could influence the productivity of the occupants, can be included. However, in this example we restrict ourselves only to the temperature change.

Step 3 Determine the probability of the event/disturbance occurring

The resilience of a building to, for example heat waves, depends on a building's physical properties (location, orientation, building physics and ventilation type), the function of the building, and the climate in the particular location. To define the resilience for the particular building to a particular risk, in this case overheating, the resilience was investigated by applying a dynamic simulation for a model of the building first with a current weather file.

To investigate the building's performance for the future periods 2050 and 2100 we use a simple method to create a future weather file using annual change, based on (Cox R.A et al., 2014), where 5 future scenarios are created: one for 2050 and four for 2100. Then we simulate the building with these different future scenarios to determine the number of hours above the thresholds.

The predicted annual change for these 5 scenarios has been calculated by the Danish Metrological Institute (DMI) (Olsen M. et al., 2012) and based on IPCC SER scenarios (IPCC, 2011). The 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.

Table 2 Probability of increased temperature for current and future weather

	Current DRY	A1B 2050	A1B 2100	A2 2100	B2 2100	E2 2100
ΔT °C	0	1.32	2.9	3.2	2.5	2
Probability	100	90%	25%	25%	25%	25%

Step 4 Apply risk analysis to determine the expected cost associated with the current resilience

The expected costs can be calculated on the basis of the cost of building new, but recent extreme weather events are providing new statistical data about costs in cases of e.g. storms and flooding. We expect that in the future there will be a more developed basis for estimating expected cost.

Step 5 Determine cost of remedial solutions

The remedial solution is the solution that the property owner suggests based on current practices which focus on the technical standard of the building.

To incorporate sustainability, step 5 is expanded as following;

- Determine capital and operating costs, as before
- Determine direct/indirect ecological costs, e.g. carbon tax, etc
- Determine intangible costs to say, reputation
- Add (a)-(c) to determine total cost, then go to Step 6

Step 6 Apply cost benefit analysis to select (or not) a solution

The last step of the evaluation is to compare alternative solutions in a cost benefit analysis based on a set of indicator which are chosen based on the organisation policy, a building standard (BEAM, LEED etc.) or both.

Table 3 Comparison total cost for of different remedial solutions

Solution	Current conditions	Remedial solution A	Remedial solution B	Remedial solution C
Capital and operating costs				
Direct/indirect costs				
Intangible costs				
Total cost				

5 DISCUSSION AND CONCLUSION

The aim of the paper is to suggest a methodology that can measure the sustainable resilience of specific maintenance project, and to form a basis for evaluating if a specific solution (a

maintenance project) is making the building more or less resilience to existing extremes and future extremes, i.e. how the proposed solution is more or less sustainable now and in the future.

We have suggested a 6 step approach to measure sustainable resilience to respond to a need for quantifying resilience and sustainability for maintenance planning. Our perspective is to link maintenance planning done by to FM organisation to meet the political agendas of resilient, sustainable and well maintained cities in the way property management is executed. To some extent this can be done in a qualitative way, but in order to become more mainstream we have investigated how sustainable resilience can be expressed quantitatively, i.e. in monetary terms, to be able to be easily incorporated within the decision making process.

The paper reports work in progress and future studies have to be made to test the methodology and to co-develop it with property owners like Gentofte Property. However, the paper outlines the idea of our approach and supplements other studies (Jones 2012 and Jones et al 2013).

The 6 steps are explained but the first four steps are described more thoroughly than the last two. In the final version all 6 steps should be explained with same emphasis and tested. Currently there is a lack of data and agreed guidelines for quantifying sustainable resilience. However we expect that much more information will be available in the next few years due to current research and practice experiments.

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10 Paper III

Coupling and quantifying resilience and sustainability in property maintenance,

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Coupling and quantifying resilience and sustainability in facilities management

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Abstract

Purpose – The purpose of this paper is to consider how to couple and quantify resilience and sustainability, where sustainability refers to not only environmental impact, but also economic and social impacts. The way a particular function of a building is provisioned may have significant repercussions beyond just resilience. The goal is to develop a decision support tool for facilities managers.

Design/methodology/approach – A risk framework is used to quantify both resilience and sustainability in monetary terms. The risk framework allows to couple resilience and sustainability, so that the provisioning of a particular building can be investigated with consideration of functional, environmental, economic and, possibly, social dimensions.

Findings – The method of coupling and quantifying resilience and sustainability (CQRS) is illustrated with a simple example that highlights how very different conclusions can be drawn when considering only resilience or resilience and sustainability.

Research limitations/implications – The paper is based on a hypothetical example. The example also illustrates the difficulty in deriving the costs and probabilities associated with particular indicators.

Practical implications – The method is generic, allowing the method to be customized for different user communities. Further research is needed to translate this theoretical framework to a practical tool for practitioners and to evaluate the CQRS method in practice.

Originality/value – The intention of this research is to fill the gap between the need for increasing sustainability and resilience of the built environment and the current practices in property maintenance and operation.

Keywords Climate adaptation, Sustainability, Facilities management, Risk analysis, Building's resilience

Paper type Conceptual paper



1. Introduction

A building's resilience is a measure of how well a building continues to function, e.g. internal cooling during and after an event, e.g. heat wave, and if the function has been affected, how fast the building regains function. Resilience can be very important. The consequences of loss of function of a building can be very serious, resulting not just in large financial losses, but even in loss of life (Ballester *et al.*, 1997). It is increasingly clear, however, that the way a particular function of a building is provisioned may have significant repercussions well beyond those of resilience. For example, customers increasingly care about how a product or service is provided, and not just the product or service itself. Provisioning a building function must therefore consider not just the resulting resilience but also the resulting sustainability, where sustainability broadly refers to social, environmental and financial repercussions.

This paper considers resilience and sustainability of a building in the context of climate change. Climate resilience of buildings has received a significant interest (Biesbroek, 2010; Boshier *et al.*, 2007; Camilleri *et al.*, 2001) due to predictions that climate change will cause more extreme weather events (Beniston *et al.*, 2007). Climate adaptation and resilience are no longer just political issues but are also emerging topics in facilities management (FM) research (Warren, 2010; Jones, 2014).

At a practitioner level, most maintenance and operation strategies do not yet deal with climate change and sustainability, beyond simple energy savings, the latter being tied to cost reductions and compliance with current building regulation. One reason for this may be a lack of management tools to support calculations of costs and benefits in an integrated manner, as pointed out by Oeyen and Nielsen (2009). New decision support tools are needed to support new building designs and renovations that consider resilience and sustainability in an integrated manner. The intention of this research is to fill the gap between the need for increasing sustainability and resilience of the built environment and the current practices in FM.

Numerous methods have been proposed for measuring both resilience and sustainability, separately. Further, many definitions of resilience and/or sustainability are difficult to quantify and as such provide insufficient information with which to make investment decisions. As almost all investment decisions are determined by economic models such as return of investment, we believe that quantifying, in a monetary sense, resilience and sustainability is necessary. Currently, there is no generally agreed understanding of how to couple resilience and sustainability.

Our proposal to couple resilience and sustainability for buildings is motivated by a need to provide decision support tools to facilities managers, who are responsible for property maintenance. To do so, we assume an economist's perspective that facility managers base their decisions on economic criteria, i.e. facility managers are asked to create as much value as possible out of a given budget. Under this assumption, it is imperative that costs be associated with resilience and sustainability. To address this issue, we show how risk management tools, familiar to some building owners, facility managers, architects and other decision makers, can be used to quantify resilience and sustainability, and facilitate the decision process for selecting between remedial solutions with varying degrees of sustainability.

The paper has the following structure. In Section 2, we first review previous work on resilience and how risk management can and has been used to quantify resilience. Ultimately, we see resilience and risk as two sides of the same coin: the higher the risk,

the less resilient a building is. In a similar way, we review sustainability and methods to quantify it, and then review the literature on coupling resilience and sustainability. In Section 3, we discuss how sustainable solutions can be incorporated into the risk framework through economic concepts that quantify the loss of function (resilience) and cost of environmental damage and loss of reputation (sustainability). Then we describe our proposed method for coupling and quantifying resilience and sustainability (CQRS). Section 4 provides an illustrative example of how the CQRS method can be used. Finally, Section 5 provides a discussion of the method, and Section 6 concludes and suggests directions for future work.

2. Background

Section 2.1 reviews prior work on resilience. 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:

- mapping threats such as the increased possibility of flooding, sea level rise or heat waves (Beniston *et al.*, 2007; Biesbroek, 2010; Boshier *et al.*, 2007; de Wilde and Tian, 2011; Snow and Prasad, 2011; Jones, 2014);
- investigating the vulnerability of a system to these threats (Guan, 2012; Camilleri *et al.*, 2001; Jentsch *et al.*, 2008); and
- investigating how to adapt (Lomas, 2009).

Section 2.2 then briefly outlines how a risk framework (Faber, 2012) can be used to economically quantify resilience. Section 2.3 reviews prior work on sustainability, and Section 2.4 proposes how to couple resilience and sustainability within a risk framework that can be expressed in monetary terms.

2.1 Definition of resilience

A number of studies exploring the definition of resilience in different contexts have been recently undertaken, including Hassler and Kohler (2014), Vale (2014), Tainter and Taylor (2014) and Anderies (2014). Boshier (2014) distinguishes four categories of resilience, specifically:

- (1) resistance/robustness/absorptions;
- (2) recovery/“bouncing back”;
- (3) planning/preparing/protecting; and
- (4) adaptive capacity.

In this paper, we focus on planning/preparing/protecting, as we investigate how to improve resilience in an existing building during planned maintenance work.

Resilience seeks to determine how well a building or system continues to function during and after the event. As such, we broadly follow the definition of Nelson *et al.* that “System resilience refers to the amount of change a system can undergo and still retain the same controls on function and structure [...]” (Nelson *et al.*, 2007), although we acknowledge a number of other possible definitions of resilience depending on various perspectives (Manyena, 2006; Folke *et al.*, 2002; Boshier *et al.*, 2007; Carpenter *et al.*, 2001; Holling, 1996; Pimm, 1984).

Carpenter *et al.* (2001) highlighted the importance of specifying “Resilience of What to What”, which reflects the practitioners’ need for practical methods to quantify resilience. In this paper, we focus on resilience to extreme weather events such as heat wave, although the framework is applicable to other events as well. Holling (1996) defines resilience as the magnitude of a disturbance, e.g. temperature that a system can tolerate and still remain in a desired state. Thus, we might say that a building is resilient to average daily temperatures of up to T degrees. A contrasting definition by Pimm (1984) defines resilience as that rate at which a system returns to its desired state after a disturbance. Thus, under Pimm *et al.*’s definition, a building may lose functionality for some period before becoming operational again. The shorter this period of lost functionality, the higher the rate of return to the desired state, and thus the higher a building’s resilience is. While we acknowledge that the rate of recovery is important, we do not explicitly consider this in our subsequent work. Rather, for simplicity, we rely on the definition of Nelson, previously given, and define resilience as such:

A building’s resilience is a measure of how well a building continues to function, e.g. internal cooling during and after an event e.g. heat wave, and if the function has been affected, how fast the building regains the function.

While such measures of resilience are valuable, we believe such measures are of limited value in supporting the process of deciding whether remedial action should be taken to improve a building’s resilience. For example, knowing that a building is resilient to average daily temperatures of up to say 32°C is useful, but any investment decision must also consider both the cost of failure when daily temperatures exceed 32°C and the probability of such weather events occurring. The latter probability is necessary to arrive at an overall expected cost that can be directly used to prioritize investments. Assigning an economic cost to resilience can be handled using well-known risk measures, as discussed next.

2.2 Quantification of expected cost associated with a level of resilience

The cost associated with a particular resilience can be measured using risk analysis. The risk (R) is defined as the expected monetary cost associated with a given activity (Faber, 2012), as shown in equation (1). Risk can be described by a function of the probability (P_f) of a failure event, f , occurring, together with the corresponding consequence (C_f) of failure, measured in monetary units. If there are n possible events, then the risk is defined as:

$$R_f = \sum_{f=1}^n P_f * C_f \quad (1)$$

From the FM perspective, there are several advantages to using risk assessment to quantify resilience. First, risk analysis requires facilities managers to clearly define *resilience of what to what*. Thus, to quantify the resilience of a building, we need to split the building system into different problem areas: for example, if we are investigating the resilience to overheating, we need consider only the indoor environment, for example temperature, and not other parameters, such as degradation of the external materials. Second, by calculating the risk of failure, it is possible to express the failure in monetary terms. Knowledge of this cost allows a facilities manager to determine whether there is

a cost-effective solution to improve resilience. This is often accomplished using well-known methods such as cost benefit analysis (CBA). CBA is a well-respected tool where everything is converted into monetary terms and decisions are based on highest net value (Ding, 2008).

We note that Jones, who proposed to identify climate change threats using future weather files and suggested methods to improve the resilience of a building to such threats, quantified the resilience using risk assessment. However, the method does not explicitly include sustainability (Jones, 2014).

A limitation of resilience is that it only considers the cost associated with the loss of function of the building. However, it is increasingly recognized that a building's systems can and do have other associated costs, particularly environmental and reputational, that indirectly affect the financial viability of a company. We see the concept of sustainability as addressing these other costs.

2.3 Definition of sustainability

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 a triple bottom line, because it considers environmental, economic and social consequences of development. According to this definition, the environmental, social and economic needs are defined as equal and "must deliver prosperity, environmental quality and social justice" (Ding, 2008).

However, the Brundtland Commission definition is not well-understood. For example, Detwiller argues that definitions of sustainability and SD are used in too many different contexts and have many different meanings without a clear consensus (Detwiller, 2014). Bossel argues that the definition of sustainability as "maintaining a system" cannot be used literally, as "human society is a complex and adaptive system and is embedded in a natural environment system, and both systems continuously change" (Bossel, 1999). Bossel argues that the ability for change and evolution must be maintained if human society is to be able to cope with a changing environment. Baxter *et al.* suggested "sustainability is the ability of our own human society to continue indefinitely within natural cycles of the earth" (Baxter *et al.*, 2010).

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.

A number of methods have been developed to assess the environmental impact of a building. These include different sustainability indicators covering all three aspects of sustainability (environmental, economic and social). Typically, sustainability indicators vary, are specific to a particular project (Bossel, 1999) and are more useful for larger systems such as organizations, communities or countries. The disadvantage of the method is that it is very generic and difficult to apply to a single building. For that purpose, different environmental assessment tools have been developed to evaluate the overall environmental impact of buildings such as:

- Building Research Establishment Environmental Assessment Methodology (BREEAM), established in UK in 1990 by the Building Research Establishment and most widely used environmental assessment methodology in the world.
- Leadership in Energy & Environmental Design (LEED), developed by Green Building Council launched in 1993 in the USA and also used world-wide.
- German environmental assessment tool, developed by Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) in 2007, which is the newest environmental assessment tool and most popular in Europe.

These tools as well as other less known environmental assessment tools are usually based on awarded points, which are weighted to estimate the overall environmental impact of the building. The advantage of such methods, e.g. BREEAM, LEED and DGNB, is that the environmental performance of buildings becomes more comparable within the same method and within similar geographic regions (Cole, 1998). A disadvantage of point-based methods is that they do not explicitly consider economic cost or resilience.

Quantifying sustainability in monetary terms was considered by Ding (2008) in the context of the construction industry. Ding proposed a sustainability index where different alternative solutions can be calculated and compared to each other by including not only the economic cost of a solution but also the benefit cost ratio, energy consumption, external benefits and environmental impact. The method takes into account absolute quantities of resources and energy flows during the whole lifetime of the building and includes embodied and operational energy. The method expresses sustainability of the solution in monetary terms, and, as such, has some similarity with our proposal. However, the method does not consider the resilience of the solution, and it is not clear how resilience could be integrated into their proposal. Furthermore, the methodology is not based on a risk framework.

2.4 Integrating resilience and sustainability

The idea of merging both sustainability as a mitigation option and resilience as an adaptation option has been suggested by Mills (2003), Boshier *et al.* (2007) and Folke *et al.* (2002). Boshier defines “built in resilience” for a built environment that considers sustainability as:

[...] should be designed, located, built, operated and maintained in a way that maximises the ability of built assets, associated support systems (physical and institutional) and the people that reside or work within the built assets, to withstand, recover from, and mitigate for, the impacts of extreme natural hazards and human-induced threats (Boshier, 2014).

To identify the risk associated with failure of energy systems and its impact on the environment was proposed by McLellan *et al.* (2012). McLellan *et al.*'s and Boshier *et al.*'s proposals highlight the connection between sustainability and resilience, but do not suggest how to quantify the cost.

The first attempt to quantify sustainability and resilience was by Camilleri *et al.*, who proposed the Climate Change Sustainability Index (Camilleri *et al.*, 2001). The method proposed by Camilleri *et al.* is designed to both:

- rate the impact of climate change on a building, to identify the most vulnerable buildings; and
- to assess the impact of the building on the environment.

The method consists of two separate numeric ratings:

- (1) one for impact on buildings; and
- (2) another for greenhouse gas emissions, the latter being a measure of environmental sustainability.

Camilleri *et al.* use a risk assessment to identify the most significant climate change threats on buildings and quantify the vulnerability of the buildings to these threats. The method addresses both concepts separately, but does not couple resilience and sustainability. The idea of coupling both resilience and sustainability was briefly discussed by [Cox and Nielsen \(2014\)](#), but their article did not propose how to couple and quantify resilience and sustainability.

The next section considers how to couple resilience and sustainability.

3. Methodology

Based on the literature review above, in Section 3.1, we explain the purpose of coupling resilience and sustainability. In Section 3.2, we describe how to couple and quantify both using a well-known risk management tool, and in Section 3.3, we propose the conceptual method of CQRS.

3.1 Coupling resilience and sustainability

To couple resilience and sustainability, we propose 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 consider 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.

3.2 Quantifying resilience and sustainability

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.

As we assume an economist's perspective that facility managers are rational and base decisions on economic criteria, 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 .

Thus, environmental damage may be estimated as environmental risk R_e with associated probability P_e of environmental cost C_e , due to a number of m events, as shown in equation (2). Some of these costs are referred to as externalities within economics such as environmental taxes, carbon costs and water consumption.

$$R_e = \sum_{e=1}^m P_e * C_e \quad (2)$$

Similarly, the expected cost for economic/business sustainability R_b is expressed in equation (3):

$$R_b = \sum_{b=1}^l P_b * C_b \quad (3)$$

where l is the number of events associated with economic sustainability, e.g. reputational risk; P_b is the probability of the cost to occur; and C_b is the cost of loss of reputation.

The expected cost for social sustainability R_s can be determined similarly in equation (4):

$$R_s = \sum_{s=1}^k P_s * C_s \quad (4)$$

where k is the number of events associated with social sustainability, e.g. loss of employment; P_s is the probability of such an event to occur; and C_s is the cost associated with such an event.

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 (5). That is:

$$R_{rs} = \sum_{f=1}^n P_f * C_f + \sum_{e=1}^m P_e * C_e + \sum_{b=1}^l P_b * C_b + \sum_{s=1}^k P_s * C_s \quad (5)$$

where 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 measures the economic cost; and the fourth measures the 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 modeling of environmental, economic and social costs.

3.3 *The conceptual method of CQRS*

The CQRS method 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 will the building's functions 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 CBA.

We use an example of a small office building to illustrate the methodology and its valuation of two alternative solutions on a maintenance problem. In the example, we follow Baxter's definition of sustainability where the proposed sustainable solution, e.g. upgrading the air conditioning system, is the solution, where the electricity used for the system is provided by the locally installed PV system.

4. An illustrative example

Consider the hypothetical architectural company, Green, Greener and Greenest (GG&G), which specializes in the design and refurbishment of environmentally sustainable buildings. The offices of GG&G are located in an urban environment and consist of a single, detached, three-storey building originally constructed in the 1920s. The building provides office space for 30 employees. It is centrally heated and has a small central air conditioning unit. In the previous year, GG&G experienced a number of days where the building was uncomfortably hot, due to an unusually warm summer period. During this period, the air conditioning system was not capable of sufficiently cooling the building. The company lost 100 person-hours. As a result of this, the company decided to investigate their sustainable resilience to heat waves. GG&G followed the seven-step process outlined above.

4.1 *Determine the resilience of the building to the disturbance(s), i.e. at what temperature will the building's functions be compromised*

GG&G determined, based on a dynamic simulation model of their building, that the interior temperature will exceed 26°C when the exterior temperature exceeds 28°C. The central air conditional cooling unit is responsible for 8.4 t/year CO₂ emissions.

4.2 Determine the costs associated with both the loss of building functionality and the building's current sustainability

For simplicity, we only consider three types of associated costs: failure costs, environmental costs and economic costs. We do not consider social costs, but these can, in principle, be included.

4.2.1 Failure costs. When the building's interior temperature exceeds 26°C, GG&G estimated that productivity will drop by 5 per cent, resulting in a loss of \$150 per hour per person. Column 2 in Table I summarizes the cost of loss of function due to loss of productivity for each of n periods, where n is a number of hours above 26°C occurring during a one-year period. In addition, GG&G estimated that the air conditioning system consumed \$0.36 per hour to operate and used 10,000 kWh a year for cooling.

4.2.2 Environmental costs. GG&G assumed that the environmental costs are mainly due to CO₂ emissions generated as a by-product of electricity consumption. The company consumes 10,000 kWh a year for cooling. It is further assumed that this environmental cost may result in a carbon tax on the company and that the electricity produces 0.84 kg CO₂/kWh. While there is currently no such tax, GG&G expects a carbon tax to be introduced in the near future. For simplicity, the probability of a carbon tax is assumed to be linearly increasing during the five-year period of interest, with a probability of 0 currently and a probability of 1 at Year 5. The tax is assumed to be \$50/tonne (Luckow, 2013) and, for simplicity, is assumed to be constant over the five-year period. Column 2 in Table II shows the cost associated with environmental sustainability. We assumed that the cost of carbon is the same for all five years.

No. of hours above 26°C n	Cost of loss of function C_f	Probability of loss of function P_f	Expected cost of loss of function R_f
109	24,525	0.0015	36
108	24,300	0.0038	92
107	24,075	0.0087	210
106	23,850	0.0180	429
105	23,625	0.0332	784
104	23,400	0.0547	1,280
103	23,175	0.0807	1,870
102	22,950	0.1065	2,444
101	22,725	0.1258	2,859
100	22,500	0.1330	2,993
99	22,275	0.1258	2,803
98	22,050	0.1065	2,349
97	21,825	0.0807	1,761
96	21,600	0.0547	1,181
95	21,375	0.0332	709
94	21,150	0.0180	381
93	20,925	0.0087	183
92	20,700	0.0038	79
91	20,475	0.0015	30
Total			22,473

Table I.
Cost of loss of
function in a year

4.2.3 *Economic cost.* GG&G assumed that the main economic cost would be due to loss of reputation. Loss of reputation is assumed to cost 10 per cent of revenue, i.e. \$1,000,000. For simplicity, GG&G further assumed that once the reputational cost was incurred, it would persist for the remainder of the five-year period, i.e. if loss of reputation occurred in year i , then the total cost is $\$(5-i) \times 1,000,000$.

Column 2 in Table III shows the cost associated with economic sustainability during the five-year period.

4.3 *Determine the corresponding probabilities associated with each cost*

We now consider the associated probabilities. We consider the probabilities associated with each of the functional, environmental and reputational losses in turn.

4.3.1 *Functional probabilities.* To determine the expected cost, we also need the probability, $P_f(n)$, that the temperature will exceed 26°C, for n hours. For simplicity, we assume that $P_f(n)$ has a Gaussian distribution with a mean, $\mu = 100$, and a variance σ of 3, where n is the number of hours above 26°C. Thus $P_f(n)$ is given by equation (6):

$$P_f(n) = \frac{1}{\sigma * \sqrt{2\pi}} e^{-\frac{(n - \mu)^2}{2\sigma^2}} \tag{6}$$

For simplicity, we chose to only consider $90 < n < 110$, as values outside this range have very small probability and do not significantly affect the cost. Column 3 of Table I enumerates the probabilities over this range.

4.3.2 *Environmental probabilities.* GG&G assume that the probability of a carbon tax is linearly increasing from 0 in the current year to 1 in Year 5. Thus, the probability of a carbon tax in year y is shown in equation (7):

Table II.
Cost of loss due to
environmental cost
and carbon taxes in
five years

No. of years n	Cost C_e	Probability P_e	Expected cost R_e
0	420	0	0
1	420	0.2	84
2	420	0.4	168
3	420	0.6	252
4	420	0.8	336
5	420	1	420
Total			1,260

Table III.
The cost due to loss
of reputation over a
five-year period

No. of years l	Economic reputational cost C_b	Economic probability P_b	Expected economic cost R_b
1	500,000	0.1000	50,000
2	400,000	0.0900	36,000
3	300,000	0.0810	24,300
4	200,000	0.0729	14,580
5	100,000	0.0656	6,561
Total			131,441

$$P_e(y) = \frac{(y-1)}{4} \quad (7)$$

where $1 \leq y \leq 5$. Column 3 of Table II enumerates these probabilities.

4.3.3 Economic probabilities. GG&G assumed that the probability of loss of reputation P_b in any one year is constant and equal to 0.1. As GG&G assume that a loss of reputation in year l persists for the remaining years, then the probability of the loss of reputation occurring in year y is the product of the probability of the loss not occurring in the preceding $(l-1)$ years times the probability of the loss of reputation occurring in year l . Thus, the probability $P_l(1)$ of a loss of reputation in Year 1 is simply 0.1. The probability of a loss of reputation in Year 2 is the probability of no loss of reputation in Year 1 times the probability of a loss of reputation in Year 2, i.e. in equation (8):

$$P_b(2) = (1 - 0.1) * 0.1 = 0.09 \quad (8)$$

In general, the probability in year l is shown in equation (9) and is:

$$P_b(l) = (1 - 0.1)^{(l-1)} 0.1 \quad (9)$$

Column 3 of Table III enumerates the probabilities of loss of reputation in every year.

4.4 Determine the expected cost associated with the current sustainable resilience of the building using risk analysis

Steps 1-3 provide the basis for calculating the expected cost. We consider the expected functional, environmental and economic costs in turn.

4.4.1 Expected functional costs. The expected costs, R_f , due to loss of function is given by equation (10):

$$R_f = \sum_{y=1}^5 \sum_{n=100-3\sigma}^{100+3\sigma} P_f(n) C_f(n) = 5 \sum_{91}^{109} P_f(n) C_f(n) \quad (10)$$

where n is the number of hours above 26°C occurring during a one-year period.

Column 4 of Table II shows the calculation of annual expected costs for the loss of function. The expected cost due to loss of function over a five-year period is $22,473 \times 5$. Thus:

$$R_f = \$112,000.$$

4.4.2 Expected environmental costs. The expected costs, R_e , due to environmental issues is given by equation (11):

$$R_e = \sum_{m=1}^5 P_e(y) C_e \quad (11)$$

From Column 4 in Table II, we see that the expected environmental costs over the five-year period is \$1,260.

4.4.3 *Expected economic cost (loss of reputation).* The expected costs, R_b , due to loss of reputation is shown in equation (12):

$$R_b = \sum_{l=1}^5 (1 - 0.1)^{(l-1)} 0.1 C_b(l) \tag{12}$$

From Column 4 in Table III, we see that the expected reputational cost over the five-year period is \$131,000.

4.4.4 *Total expected cost.* The total expected cost, R_{rs} , associated with the current resilience and sustainability of the building is simply the sum of these individual costs, i.e. as shown in equation (13):

$$R_{rs} = \sum_{f=1}^n P_f(n) C_f(n) + \sum_{e=1}^m P_e(y) C_e + \sum_{b=1}^k P_b(k) C_b(k) \tag{13}$$

The expected cost of resilience (loss of function) over the five-year period is \$112,000.
The expected cost of environmental sustainability (carbon taxes) over the five-year period is \$1,260.
The expected cost of economic sustainability (reputation) over the five-year period is \$131,000.
The operational cost due to electricity consumption over the five-year period is \$18,000.
The total expected cost for the company for not upgrading the system is therefore \$263,000.
Note that the expected cost when only considering resilience is \$130,000.

4.5 *Determine capital and operational costs of each remedial solution*
GG&G considered two remedial solutions.

4.5.1 *Solution 1 upgrades the air conditioning system.* The capital cost is \$100,000. The new system consumes 12,000 kWh. The annual running cost is estimated to be \$4,320. The new air conditioner completely eliminates the risk of loss of function. The capital and operational cost for Solution 1 is \$122,000, during the five-year period, when only resilience of the building is considered, as shown in Column 3 in Table IV.

4.5.2 *Solution 2 upgrades the air conditioning system and adds onsite photovoltaic electricity generation.* While the new system consumes 12,000 kWh, all this energy is provided through the onsite photovoltaic system. The capital and operational cost is \$100,000 + \$30,000 + \$0 = \$130,000, as shown in Column 4 in Table IV.

Table IV.

Expected cost for the company over five-year period when only resilience is considered

Traditional cost-benefit method	Existing (\$)	Cost of solution 1 (\$)	Cost of solution 2 (\$)
Cost of failure	112,000	0	0
Running cost of a/c	18,000	21,600	0
Capital cost of a/c	0	100,000	100,000
Capital cost of PV	0	0	30,000
Total	130,000	121,600	130,000

4.6 For each remedial solution determine the expected cost associated with the proposed resilience and proposed sustainability of the building using risk analysis

The capital and operational cost for Solution 1 for five years is \$122,000. However, the risk from environmental issues increases from \$1,260 to \$1,510. Moreover, the probability of loss of reputation is assumed to increase from 10 per cent to 15 per cent of revenue due to the increased output of greenhouse gases. Thus, the expected reputational cost increases from \$131,000 to \$185,000. The total expected cost over the five-year period is then \$308,000, as shown in Column 3 in [Table V](#). Note that this expected cost is actually higher than the expected cost for not upgrading the system, despite the fact that the risk of loss of function was eliminated. The capital and operational cost for Solution 2 is \$130,000. Consequently, all three risks, function, environment and reputation, are eliminated. Then the total expected cost of the Solution 2 for the five-year period is only the capital cost, which is \$130,000, as shown in Column 4 in [Table V](#).

4.7 Select (or not) a solution based on CBA

If only the risk due to functional loss is considered, then Solution 1 is preferred. This is because Solution 1 will cost \$121,000 and Solution 2 will cost \$130,000, as is shown in [Table IV](#). However, when sustainability factors are considered, Solution 1 actually increases the overall expected risk and Solution 2 is preferred, as shown in [Table V](#).

5. Discussion

The example above illustrates how resilience and sustainability can be coupled and quantified within a risk framework that considers environmental, economic and social costs as well as the traditional cost associated with loss of function. For illustrative purposes, the example is simplified. In particular, 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 and temperature predictions could utilize future-weather files based on climate modeling, as proposed by [Cox et al. \(2014\)](#). These and many other more realistic assumptions can be supported within this framework, but are beyond the scope of this paper.

The simplified example only considers one element of resilience, namely, resilience to heat waves. We note that it is common to partition a building into separate subsystems that can, for the most part, be treated independently. Most environmental assessment methods, such as BREEAM and LEED, do so. It is straightforward to apply the same methodology to other subsystems and other elements of resilience, such as flooding. We

Coupling resilience and sustainability	Existing (\$)	Solution 1 (\$)	Solution 2 (\$)
Capital cost of a/c	0	100,000	100,000
Capital cost of PV	0	0	30,000
Expected annual cost due to loss of reputation	131,000	185,000	0
Expected annual cost of carbon tax	1,260	1,512	0
Loss of function	112,000	0	0
Running cost of a/c	18,000	21,600	0
Total	262,260	308,000	130,000

Table V.
Expected cost for the company over a five-year period when both resilience and sustainability are considered

also note that where two or more subsystems/elements interact, the methodology can easily integrate all risks and costs to allow practitioners to optimize their planned maintenance strategy.

The purpose of the simplified example is to illustrate how very different conclusions can be reached depending on whether only resilience, i.e. risk of loss of function, or resilience and sustainable are considered. In particular, it is interesting to note that while a traditional resilience analysis would consider a building to be perfectly resilient to an event if there is no loss of function, even a perfectly resilient building may not be sustainable, as the example above illustrates. Thus, when coupling both resilience and sustainability, changing the way a building's function is provisioned may be cost-effective even when the building is considered perfectly resilient.

Our proposed CQRS method is generic and therefore accommodates variations in requirements for a maintenance management tool across user groups. For example, we do not fix the set of sustainability indicators, as is commonly done in BREEAM, LEED or DGNB. Rather, the methodology can support any indicators that a user community feels is appropriate. However, we also acknowledge that this strength is also a weakness in that it is often unclear how to map a particular indicator to a monetary value. It is also difficult to determine appropriate corresponding probabilities.

6. Conclusion

The way a particular function of a building is provided may have significant repercussions beyond just resilience. To address this issue, this paper considers how to couple and quantify resilience and sustainability, 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. Within this context, we assume an economist's perspective, i.e. that facility managers are rational and base decisions on economic criteria. As such, we utilize 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 seven-step method of CQRS consists of:

- (1) determining the resilience of the building to a disturbance;
- (2) determining the costs associated with both the loss of building functionality and the building's current sustainability;
- (3) determining the corresponding probabilities associated with each cost;
- (4) determining the expected cost associated with the current resilience and sustainability of the building using risk analysis;
- (5) determining the capital and operational costs of each possible remedial solution;
- (6) for each remedial solution, determining the expected cost associated with the proposed resilience and proposed sustainability of the building using risk analysis; and
- (7) selecting a solution based on a CBA.

The proposed CQRS method is 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.

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.

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11 Technical Report

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

Rimante A. Cox June 2015



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

Rimante Andrasiunaite Cox
Technical Report

Department of Civil Engineering
Technical University of Denmark
2015

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

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

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Abstract

Most historical buildings were originally designed with passive ventilation systems, which are often forgotten, not in-use, or are now used in a non-passive manner. In this 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.

An advanced natural ventilation system in existing double skin windows has been 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. The building was designed as a residential building in 1920, but now used as a day care centre for children between 0.6-2.8 years. 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 CO₂ 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 have been investigated based on:

- (i) Automatic recordings of CO₂ meters installed in every zone provided by the supplier of the system;
- (ii) External temperature, internal temperature, wind speed and wind direction around the building during the investigated periods, recorded by the supplier of the system
- (iii) CO₂ and temperature readings in the ventilation windows and chimneys installed during the periods of the investigation
- (iv) Air change was estimated based on the CO₂ readings and the number of occupants, where the occupants were recorded entering and leaving the room for longer than 15 min.

The results of our investigation showed that the proposed ventilation system “as installed” was not sufficient to provide required ventilation to the upper floor and requires modification. A modification of the system was proposed, but not tested.

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1 Introduction

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 center for children between 0.6 -2.8 years. The daycare center 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. Most historical buildings have been designed with natural ventilation, which are often not in used. The building offered an opportunity to evaluate whether passive advance 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.

There are three main purposes of the study: (i) to investigate whether our solution provides sufficient fresh air to the occupants of the building without creating drafts for the occupants, (ii) whether air supply is provided through the “ventilation window” and extracted through the chimneys, as assumed, and (iii) how the system works in a real building during usage.

This report consist of following sections: section 2 describes the building before renovation and after renovation, section 3 describes the methods of analysis of the building during 3 periods with 3 different strategies, section 4 describes how the building behaves compared with proposed strategies and section 5 discusses the results and conclusion as well suggestions for future work.

2 Background

This section describes the building and its usage as well as the installed ventilation system.

2.1 Description of the building

The case study building is a 2-story building with unheated basement and unheated attic spaces. The building is heated by district heating with a heated area of 279 m² and a total area of 571m². 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/m²K. 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/m²K and 0.21 W/m²K 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/m²K.

As the building was upgraded in 2009 with improved thermal efficiency of the external and internal wall, we first investigated the indoor thermal comfort of the building.

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, the energy rating was calculated (iv) to energy performance class "F". The results of this investigation can be found in (R.A.Cox, 2012).

Even though the energy efficiency of the building was upgraded in 2009, the annual energy usage for the building was still high 83.000kWh/year or 387kWh/m². 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/m² under 50 Pa pressure, which was measured with a blower door test before the renovation. The infiltration mostly occurred around the windows and doors.

Based on the measurements we proposed improving the windows' thermal efficiency to reduce leakage and to establish a passive ventilation system that would not change the appearance of the building neither internally no externally.

2.2 Occupancy of the building

The building is used as daycare center for children between 0.6 -2.8 years. The building is a 2-storey building. On the ground floor there is a support daycare center occupied by up to 6 adults and a variable number of children (up to 25 children). During normal working hours from 7AM to 5PM the ground floor is occupied in zones 1-3, as shown on Figure 1. The parents arrive through the door on the east side of the building and deliver their children to the teachers in Zone 1. The arrival of the children is between 7-9AM. The children with their teachers are playing in Zone 1 and 2. Zone 3 is mostly used as an eating area, with all occupants gathering for lunch at 11-11.30AM. The other intermediate eating periods such as morning snack between 8.30-9AM and afternoon snack 14-14.30 AM vary in the number of occupants due to the nature of delivery and pick up of the children. Most children have an afternoon nap outside from 12-14AM. The parents collect their children between 14-17PM.

Zone 1, 2 and 3 have double doors between the rooms which are always open and the occupants move between these spaces, as shown in Figure 1. The children are taken to the afternoon nap through the terrace door 1, which is also

used to ventilate the space during that time. The door between zone 2 and the staircase is also partly open.

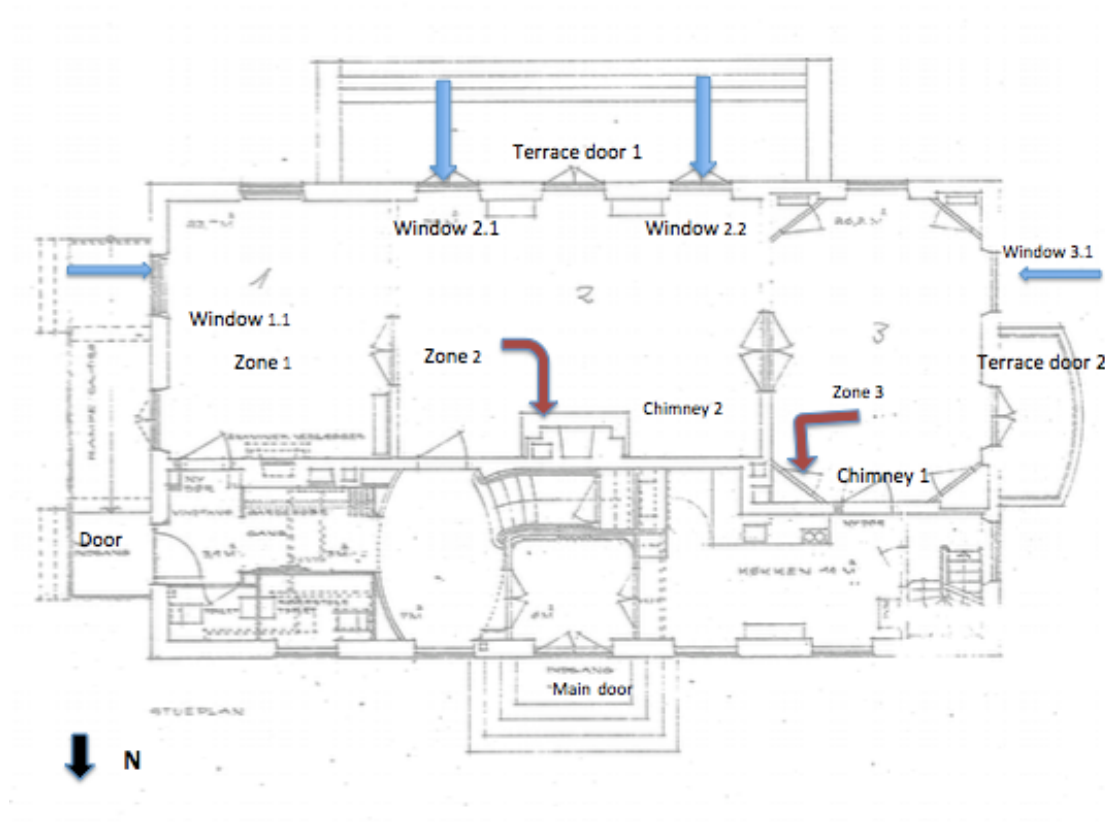


Figure 1 Diagram showing location of the windows and zones on the ground floor and assumed air movements through the window openings and chimneys.

Zone 4 and zone 5 on the 1st floor, as shown in Figure 2, are used as the daycare playroom area, where the local childminders with their children meet and spend the day together. The first floor is occupied with different adults and children nearly every weekday, with a maximum number of 5 adults and 15 children. Similar to the ground floor, the occupancy is between 7AM-5PM. Depending on the weather, the occupants spent some morning hours or afternoon hours outside on the playground. Some of the children have an afternoon nap between 12-14PM outside and some inside in Zone 5. During occupancy Zone 4 is used as a playing and eating area.

The door to the stairs is closed most of the time. Zone 6 is used as an office and a meeting room. The number of occupants in the office is mostly 1 or 2, but can be 4-5 during a meeting.

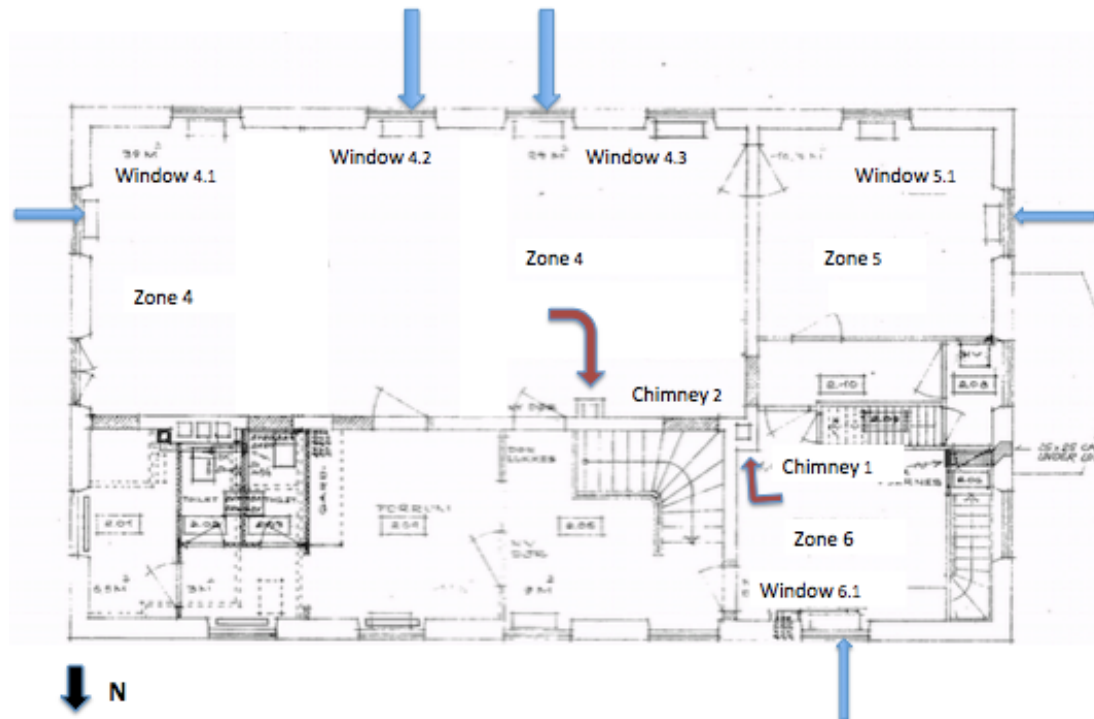


Figure 2 Diagram showing the location of the windows and zones on the 1st floor and assumed air movements through the window openings and chimneys.

2.3 Proposed passive ventilation system

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 to evaluate possible thermal improvements to the building and to propose passive ventilation strategies for the building (R.A.Cox, 2012).

As 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 on the 1st floor, we decided to ventilate the building with “controlled” infiltration.

In our simulation we assumed that the air leakage of the external frame provided enough air to the gap when the external temperature was below 5°C and only internal top windows were opening during the occupancy to provide ventilation, which we assumed to be equal to the measured infiltration before the renovation. When the external temperature was above 5°C, the external windows started to open (R.A.Cox, 2012, pp. 29-30). During no occupancy all internal windows and the chimneys were 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.

The “controlled infiltration” was achieved by improving the leakage and thermal efficiency of the windows. As the existing windows in the building were double skin windows, 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.

A “ventilation 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.

The performance of ventilation window has been investigated by McEvoy et al 2003, who conducted a study investigating the effect of the cavity width, ventilation rate in the window gap as well as the position of the low -E coating on the glazing, (M.E.McEvoy, 2003), by Diomidov et al 2002 who investigated the performance of ventilation window to increase the inner pane temperature (Diomidov M.V., 2002), by Carlos et al 2010, who investigated preheating effect of ventilation window for the windows with different positions of the triple glazing, (Carlos J.S., 2010) and (Kalyanova O., 2009), who investigated how to measure air flow rate in a naturally double skin façade. All these studies have been conducted in control environment. In this report we investigate performance of ventilation window in a natural environment, in a case study building which is use.

In our case we assumed that all external frames of ventilation window are leaky (1mm around the perimeter of the window frame) and can provide the required air to the building during the cold periods of the year. Our assumption was based on the blower door test described in (R.A.Cox, 2012). During moderate periods additional air supply should be provided by opening the external windows as well.

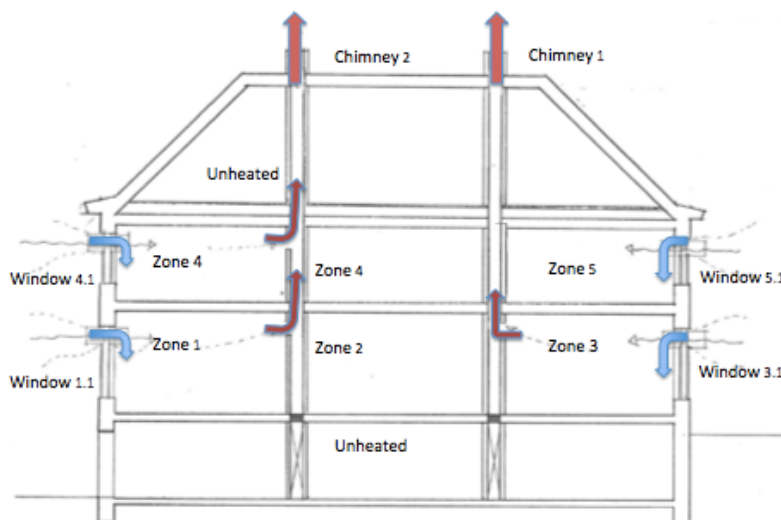


Figure 3 Diagram showing the fresh air supply through the window and extracts from the chimneys

The installed passive ventilation system is assumed to provide fresh air through 9 ventilation windows shown in Figure 1, 2 and 3, and passively extracted by the

chimneys 1 and 2. The windows located closest to the chimneys, such as windows 2.1, 2.2 and 3.1 on the ground floor and 4.2, 4.3 and 6.1 on the first floor, were assumed to work as air sources, and chimneys 1 and 2 as extractors. The window 1.1 (Figure 1) on the ground floor on the east façade, as well as window 5.1 (Figure 2) on the west façade were assumed to work both as supply and extract due to their distance from the chimneys.

As dynamic simulation programs cannot easily simulate these “ventilation windows”, we decided to investigate the air movements in the building using CO₂ produced by the occupants as the trace gas.

The investigation of the thermal improvements and ventilation strategies are described in the report (R.A.Cox, 2012), which was used for obtaining building permit to the natural ventilation in the property. Even though there was uncertainty as to whether the system can provide sufficient airflow to the building, the client and the building council accepted the proposal described below. The building was upgraded in 2013 based on the proposal.

2.4 Installed passive ventilation system

We proposed to reduce the building’s leakage by sealing the 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 (Figure 4), which sealed the inner window frame and improved the U-value to 0.8 W/m²K as shown in Figure 2. Adding the 3rd layer glass did not visually changed the internal or external look of the building.

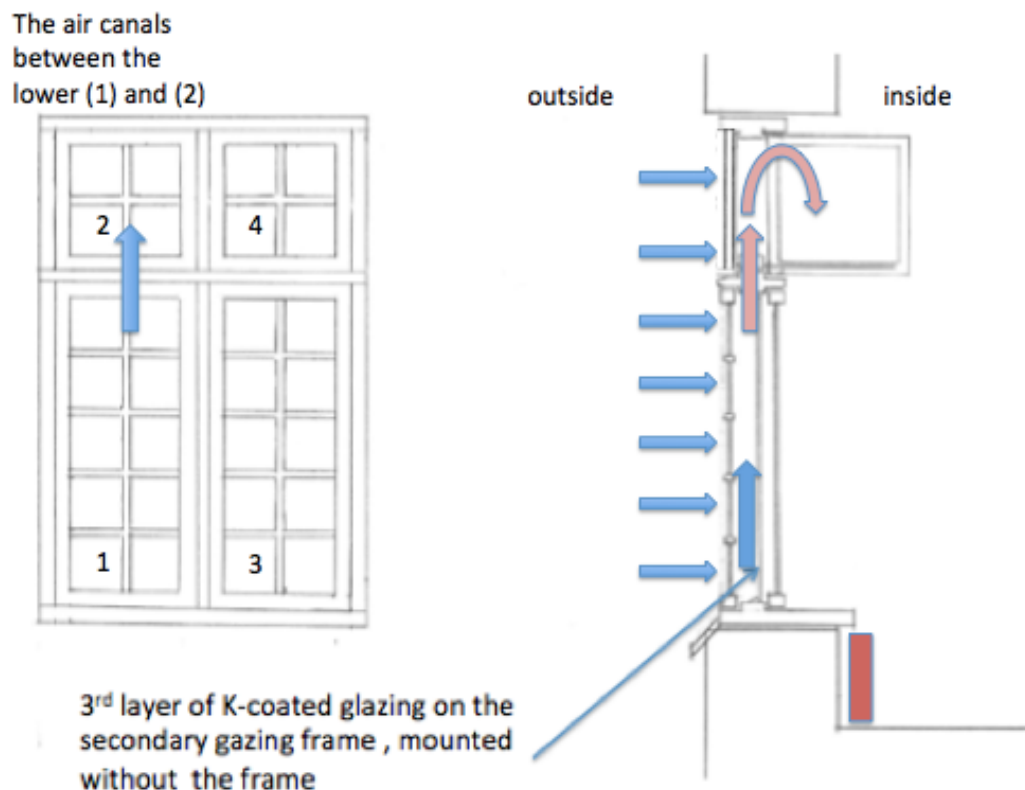


Figure 4 Diagram showing the incoming air during the coldest periods of the air (winter)

During the coldest period of the year the external frames (2) were closed and the internal frame (2) was open as shown in Figure 4. It was assumed that the external frame had leakage through a 1mm gap around the perimeter of the frame (1 and 2). The canals between the lower parts (1) and top parts (2) of the windows in the middle frames were established to ensure that the incoming fresh air through the natural leakage of the external frame of both part (1) and part (2) were working as supply air canals. The canals between part (1) and (2) also allow the air in the gap to move upwards due to the preheating effect of solar radiation or the escaping heat loss from the window, and enter the room slightly warmer than the external temperature. The parts (3) and (4) were not connected to parts (1) and (2) and are therefore not currently used for ventilation.

The openings of the windows, as well as the dampers in chimneys were controlled automatically. Even though the system was automatically controlled by opening and closing the windows, the air movements were only driven by passive means, such as buoyancy-driven or wind driven.

As the air leakage of the external frame depends on the temperature difference between inside and outside, the air to the building was proposed be provided according to 4 strategies, depending on the external temperature:

- (i) Cold (winter), where the external temperature is below 5°C (and shown in Figure 3),
- (ii) Moderate where the external temperature is between 5-12°C and shown in the Figure 1,
- (iii) Warm (summer) where the external temperature 12-25°C,
- (iv) Hot (heat wave) when the external temperature is between 25-32°C.

During strategies (ii), (iii) and (iv), the external windows must be partly open during the occupancy and the airflow should be controlled by the degree of opening of the internal windows.

In this report we only tested the moderate period - strategy (ii), where the temperature is between 5-12°C. This period is most complicated, because of the difficulty to determine degree of the opening of the windows. If the windows will be open too much the airflow will be sufficient, but the comfort for the occupants will be compromised as well as increased heat losses. However if the windows will be open for shorter period or with limited area of the windows opening the airflow cannot be sufficient. To determine which way of opening of the windows is most sufficient we investigated three opening of the windows strategies.

3 Methodology

To be able to determine whether the proposed system provides enough fresh air into the building, we measured the air quality of the building during the moderate period (5-12°C) of the year with 3 different windows opening strategies:

- (i) **pulse ventilation**, - Experiment 1;

- (ii) **stream ventilation** – Experiment 2;
- (iii) **ventilation window**, –Experiment 3.

3.1 Measuring the air flow

Measuring passive ventilation airflow through the windows in a natural environment is complicated, because of the stochastic nature of wind, low airflow and non-uniform and dynamic flow conditions.

As the incoming air is only driven by buoyancy-driven or wind driven sources, we had a challenge not only to calculate, but also to measure the air flows in the windows or even in the chimneys, because the air flows are very low (0-0.5 m/s and were difficult to measure with equipment usually used for mechanical ventilation systems. Another challenge was to investigate the natural ventilation system in a natural environment as the measurements were taken during normal occupancy, which also restricted the choice of gases used in the experiments. The third challenge was that occupancy not only varied from hour to hour but also between the zones.

The most common ways of measuring airflow in an opening are (i) the trace gas method, or (ii) measuring the velocity profiles in an opening and calculating the airflow from these measurements (Kalyanova O., 2009).

As the airflow velocity method was not possible in the case study building, the CO₂ produced by the occupants was chosen as the trace gas in the experiments. We conducted a set of experiments to examine the air quality and how the air is moving in the building.

3.2 Air quality based on the CO₂ concentration in the rooms

For experiments 1-3, the air quality (CO₂ concentration), external temperature and internal temperature on the ground floor and the 1st floor were automatically recorded by Windows Master in 1 hour or 10 min intervals. Windows Masters is the company who provided and installed the automatically controlled windows opening system in the building. The external temperature and wind velocity as well as wind speed were recorded by the local weather station on the roof of the building. Internal temperature, relative humidity and CO₂ concentration were automatically recorded by the meters installed in each zone, which were also used to control the opening of the windows by the Windows Masters system. The occupants were able to overrule manually the windows opening in each zone. Figure 5 and 6 shows the location of the automatically recorded meters as well as the ventilation windows.

To investigate the air quality of the rooms, the CO₂ concentration was compared with the number of occupants, where the occupants were recorded entering and leaving the room for longer than 15 min.

The infiltration during no occupancy was calculated using the mass balance theory decay case, where the C_t was used as the CO₂ concentration at 5PM, when the occupants leave the building, and the C_o was used as the CO₂ concentration at 12AM.

The CO₂ concentration $C(t)$ was calculated using the mass balance theory, build-up case during one hour period (11-12PM), where the number of occupants was most stable. To calculate the CO₂ concentration produced by the occupants, it was assumed that the average female height was 1.70m and weight 70 kg with an activity (MET) of 1.4. It was further assumed that the average child weighed 10 kg and was 0.9 m in height, with an activity of (MET) 1.4. The calculation was performed in Excel. Figure 5 shows an example of the calculation sheet.

To be able to use the balance theory the assumption was made that the air in the zones were well mixed and only had the interaction with the outside, but not with the other zones in the building.

	n=G/(CxV)		C=	993.6666667	corrected by outdoor CO2 conc. 400pp	
			G=	110.5	593.6666667	
ACH=	0.707715339		V=	263	110499	mL/h

Figure 5 Calculation of the CO₂ production by occupants

The 3 rooms on the ground floor are connected with openings in between, and users move free between the spaces. Therefore the average of CO₂ was calculated of the three zones, with the common volume of the room of 263m³.

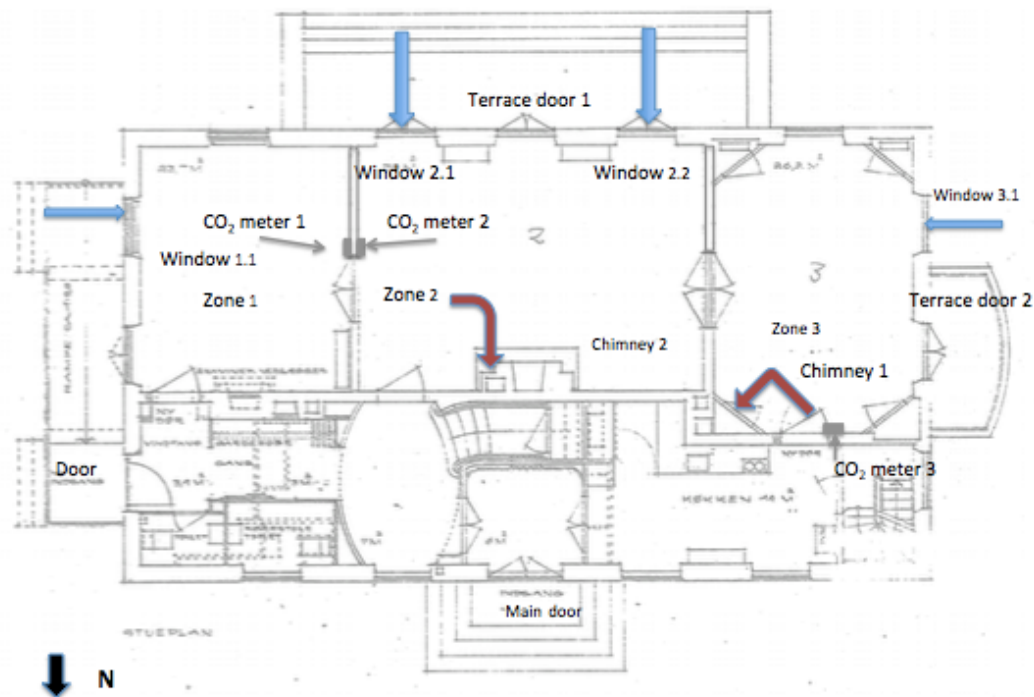


Figure 6 The grey arrows show the location of the CO₂ meters, automatically recorded by Windows masters on the ground floor

On the 1st floor, zone 4 and 5 were also connected with the openings in between. However zone 5 is used mainly as a sleeping area for children during the period of 12 to 2pm, and therefore the air change was calculated for the each zone separately. The volume of zone 4 was 145m³ and for zone 5 was 36 m³.

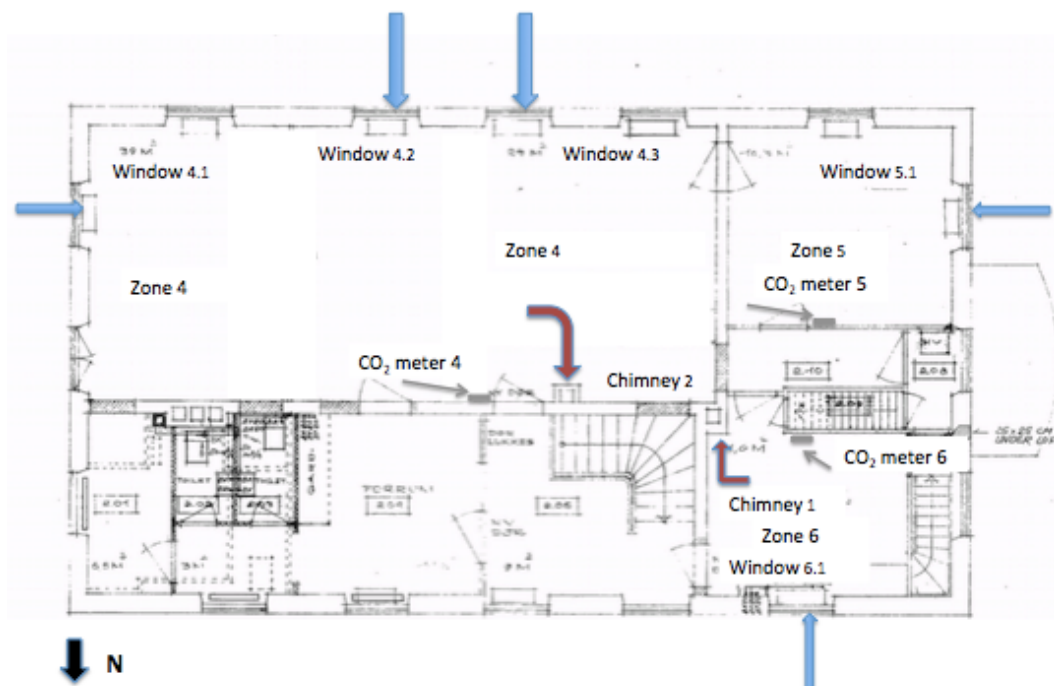


Figure 7 The grey arrows show the location of the CO₂ meters, automatically recorded by Windows masters on the first floor

The air quality of the room was considered (i) **good** if the CO₂ concentration did not increased above 1000ppm, (ii) **moderate** when the CO₂ concentration was between 1000-1500ppm, and **bad** if the CO₂ concentration was above 1500ppm.

3.3 Analysis of air movements based on additional meters located in the chimneys and ventilation windows

To verify whether the ventilation in the building behaves as predicted using the simplified calculation model described earlier, a set of experiments was carried out in the spring and autumn of 2013.

Automatic recordings of CO₂ levels and internal temperature were not sufficient to show whether the air was coming in through the windows and extracted by the chimneys. Therefore, additional CO₂, temperature and relative humidity meters were installed in all 9 ventilation windows and chimneys. The locations of the additional meters are shown in Figure 8. On the ground floor two meters were used per window: (i) in the gap of the top of the window where both internal and external openings of the window were located, and (ii) in the gap at the bottom of the window, where there were no openings except from the additionally added holes in the window frame between upper and lower part of the window, as shown earlier in Figure 4 and in Figure 9.

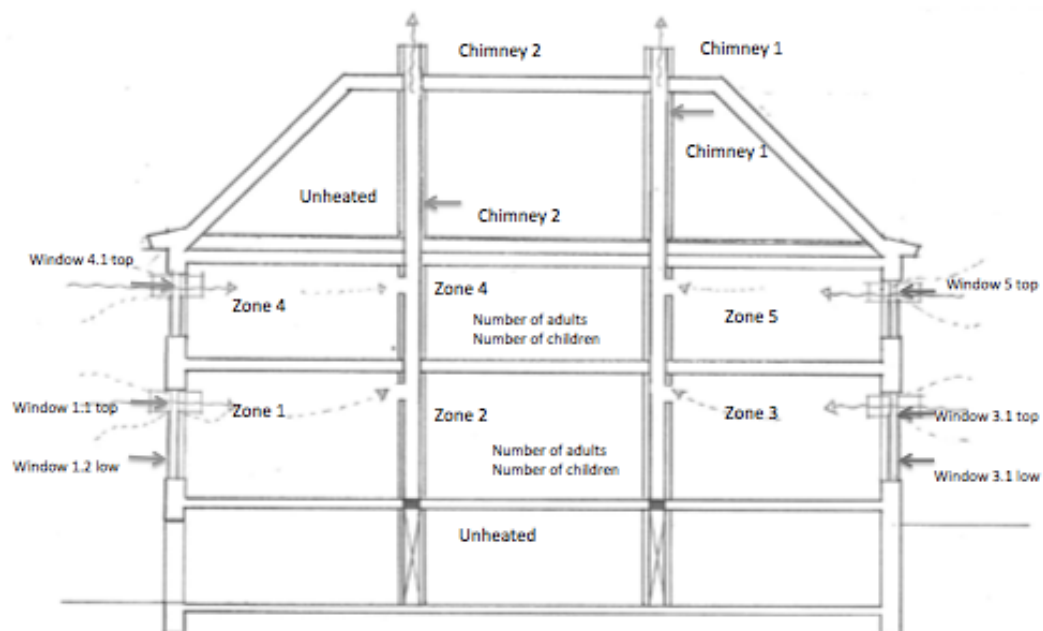


Figure 8 Location of the additional meters installed in all ventilation windows and chimneys during experiments 2 and 3.



Figure 9 Location of the additional meters in the gap between external and internal frame: on the left is the meter located in the top of the window and on the right the meter is located in the bottom of the window.

On the 1st floor only one meter was installed in the top of the windows.

3.4 Ventilation strategies tested in experiments 1-3

To be able to determine whether the proposed system provides enough fresh air into the building, we measured the air quality of the building during the moderate period of the year with 3 different ventilation strategies:

- (i) where fresh air was provided by **pulse ventilation**, (every hour both external and internal windows are open 30 cm (100%) for a 6 min period) during the occupancy and closed during no occupancy - Experiment 1;
- (ii) where fresh air was provided by **stream ventilation** through the external windows, which were constantly open 3cm (10%) and the internal windows were open 30 cm (100%) during the occupant hours and closed during no occupancy – Experiment 2;
- (iii) where fresh air was provided by the **ventilation window**, (the external windows are closed and only the leakage of the external windows frames provides the fresh air and the internal windows are open 30 cm (100%) –Experiment 3. During experiment 3 the external windows were open each hour for a 3 min period.

4 Results

This chapter describes the set up and results of experiments 1-3.

4.1 Pulse ventilation strategy - Experiment 1

Experiment 1 investigated the pulse ventilation strategy and was conducted during 27April - 14 May 2013.

4.1.0 Ventilation set up for experiment 1

During the period of the experiment the natural ventilation was automatically controlled by the Windows Masters program. Both top windows (internal and external) in our ventilation windows were opened 30cm, which is determined by the max length of the motor (100%) for 3 minutes every hour.

The measurements were collected at an hourly rate by Windows Masters.

The number of occupants in the building was only counted on the ground floor.

4.1.1 Results of experiment 1

The experiment showed that the air quality on ground floor was good most of the time. During the 16 day period, the CO₂ levels on the ground floor exceeded 1000ppm for a total of 5 hours, on as shown in Figure 10. The CO₂ levels on the first floor exceeded 1000ppm for a total of 14 as shown in Figure 11.

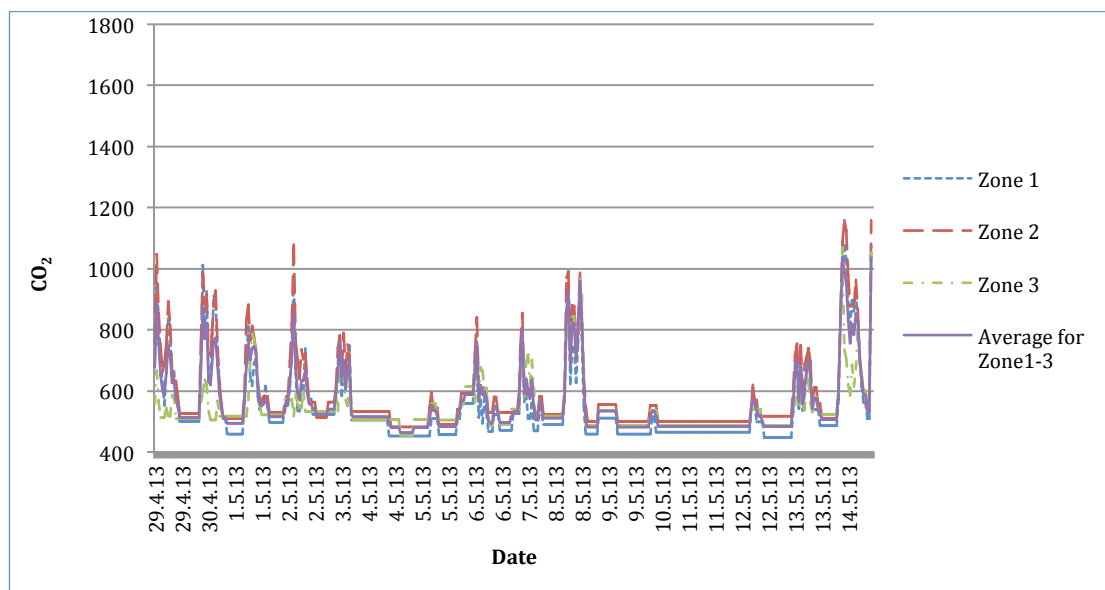


Figure 10 CO₂ concentration on the ground floor during the experiment 1, (27April - 14 May 2013)

The max CO₂ level on the ground floor were recorded at 1159 ppm in the Zone 2 on the 14 of May 2013 between 10-13.

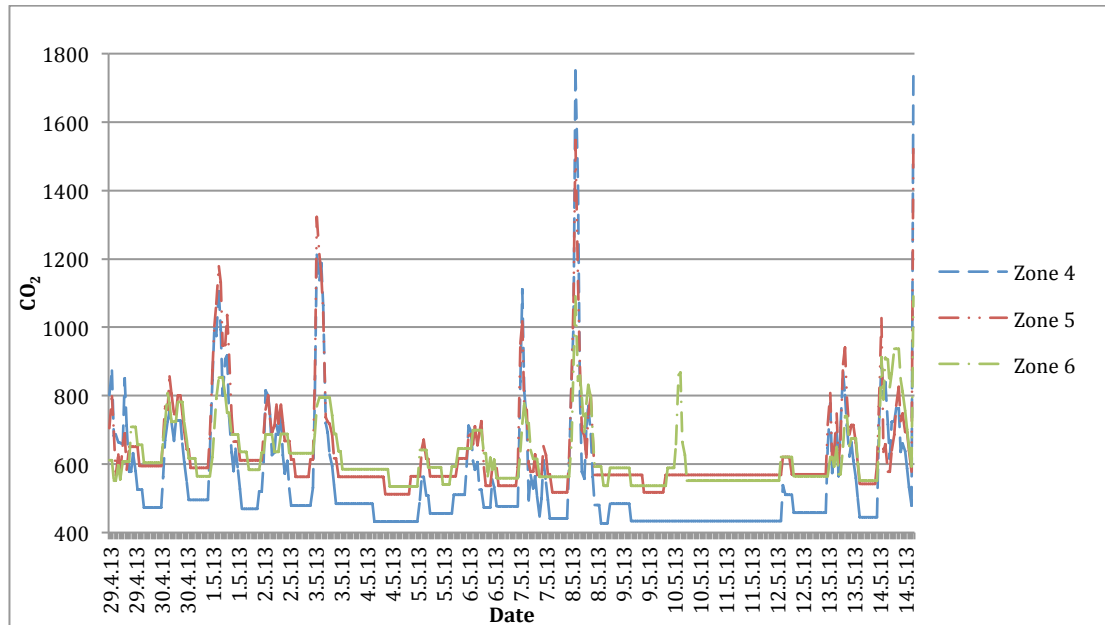


Figure 11 CO₂ concentration on the first floor during the experiment 1 (27April - 14 May 2013)

The max CO₂ level on the 1st was recorded at 1751ppm on the 8 of May 2013.

The highest CO₂ levels on the ground floor was recorded on the 14 of May 2013. We therefore investigated in detail the air change per hour during that day.

4.1.1.1 External conditions for experiment 1

The average external temperature on 14 of May between 10-12 am was 10.5°C with the wind speed of 3m/s and an internal temperature of 21.5°C.

The infiltration was calculated during the 7pm-12am on 14 of May. The external temperature was 15-12°C higher in the afternoon and cooling down during the evening, and the wind speed 3-2m/s changing from south west to south east during the evening. The infiltration was calculated using the decay method to be 0.0029 ach/h.

4.1.1.2 Analysis of the concentration of CO₂ in the occupied rooms

The most stable number of the occupants is usually between 11-12am. During this two-hour period there were 7 children and 5 adults in zones 1-3, on the ground floor. It was calculated that the occupants produced a total of 110.5 CO₂ emissions in an hour.

Figure 12 shows the CO₂ concentration on the ground floor during 14 of May 2013.

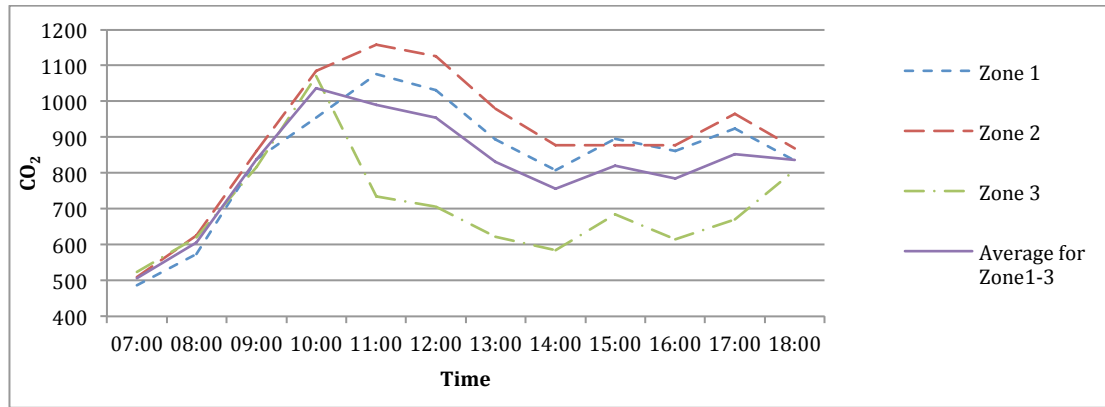


Figure 12 Hourly CO₂ levels on the ground floor 14 May 2013

To be able to keep the CO₂ levels below 1000ppm, the air change should be 0.7 ach. The measured average CO₂ concentration for 1-3 zones was 1103 ppm, which is considered moderate. Using the actual concentration, it was calculated that the actual air change was 0.6 ach, which is lower than required.

4.1.1.3 Summary of the results of Experiment 1

Experiment 1 recorded the average hourly CO₂ concentration in the room and the number of occupants and provided a rough estimate of the air quality in the room.

Summary of experiment 1

- (i) Experiment 1 confirmed that the air quality in the room was good most of the time on the ground floor and moderate on the 1st floor. However we were not able to estimate whether the ventilation strategy used during experiment 1 had reduced thermal comfort for the occupants by increasing draughts. There was insufficient data to calculate the air change on the 1st floor, as the number of occupants was not recorded.
- (ii) The data collected from Windows Masters during experiment 1 were hourly recordings, (an average of CO₂ concentration during 1 hour period). It means that CO₂ concentration could be higher for a shorter period of the time say 10 min, but not recorded and therefore was not sufficient to provide accurate air quality in the rooms.
- (iii) We used a simplified assumption that the room has well mixed air and the air exchange was only to the outside. However, our measurements showed that the air in the three zones is not well mixed as the CO₂ concentration differed from 100 to 250ppm from room to room.
- (iv) In experiment 1 the “ventilation windows” worked as simple windows, where the fresh air passed through the external frame and directly through the secondary frame to the room.

- (v) During experiment 1 we were not able to estimate how the air moved in the room and whether the air was entering from the windows and extracted from the chimneys as predicted.
- (vi) Experiment 1 did not show whether the gap between the windows internal and external frame had any influence on the air quality or the temperature of the incoming air.

4.2 Stream ventilation – Experiment 2

To analyze whether the air in the building was indeed entering the room through the top of the ventilation windows and extracted through the chimneys, as shown in Figure 1-3, the **stream ventilation** strategy was investigated in Experiment 2 conducted during the 7 day period of 17 - 25 October 2013.

4.2.1 Ventilation set up for experiment 2

During the period of experiment 2 the natural ventilation was set up such that all external ventilation windows were constantly open 3cm (10%) and the internal windows were open 30cm (100%) during occupancy. Only internal windows were manually regulated by occupants. The CO₂ concentration in 10 min intervals was collected from Windows Masters data. The air change was calculated the same way as in experiment 1.

In addition to the CO₂ concentration, temperature and relative humidity in ventilation windows and chimneys were recorded at 1 min intervals.

4.2.2 Results of experiment 2

Experiment 2 revealed that the air quality in the building was partly unsatisfactory (above 1000ppm) during the occupancy on the ground floor and worse on the 1st floor. During the 4 occupied days the CO₂ levels on both floors exceeded 1000ppm, for 9 hours on the ground floor and for 14 hours on the 1st floor. The max CO₂ level on the ground floor was 1409 ppm (for 10 min) and around 1300ppm on the 22 of October between 12-14, as shown in Figure 13.

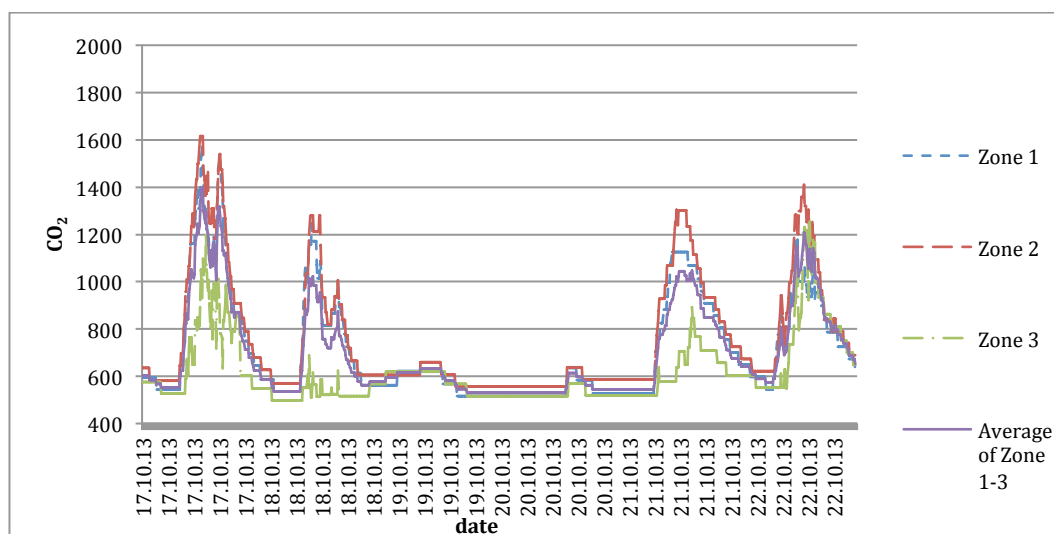


Figure 13 CO₂ concentration on the ground floor during experiment 2 (17 -22 October 2013)

The max CO₂ level on the first floor was 2275 ppm in zone 6 (office) and around 2000ppm for nearly an hour on the 21 of October between 10.30-11.30, as shown in Figure 14. We did not analyse data from the office (zone 6) because the occupants overruled the automatic settings of the ventilation system. The window was closed most of the time during the occupancy.

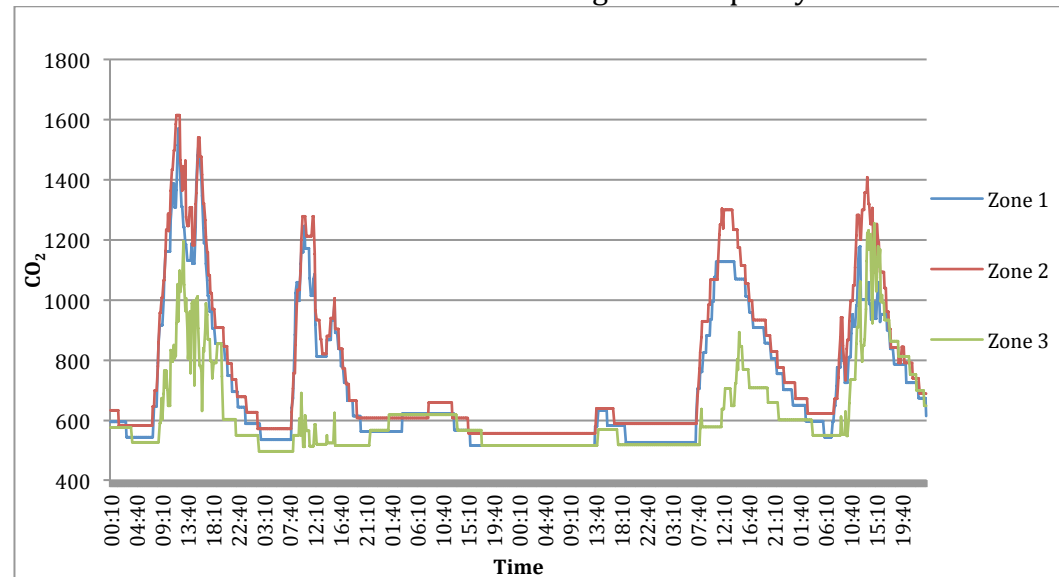


Figure 14 CO₂ concentration on the first floor during experiment 2 (17 -22 October 2013)

The highest recorded CO₂ levels in Zone 4 and 5 were 1852 and 1862 respectively.

4.2.2.1 Analysis of the concentration of CO₂ in the occupied rooms

Only one day, the 21th of October, was analysed, because the other days were missing some of the key measurements. For example, the meters in the chimneys were using batteries, which went flat and were not able to record data from the 22nd of October 2013. By accident some of the meters were turned off by the occupants. The number of occupants was only recorded from the 21th of October 2013.

The measurement results showed that the average quality of the air in the rooms was moderate, where the average of the CO₂ concentration was below 1000 ppm most of the time, as shown in the Figure 15. The highest concentration was recorded in Zone 2, where the extraction to the chimney is placed.

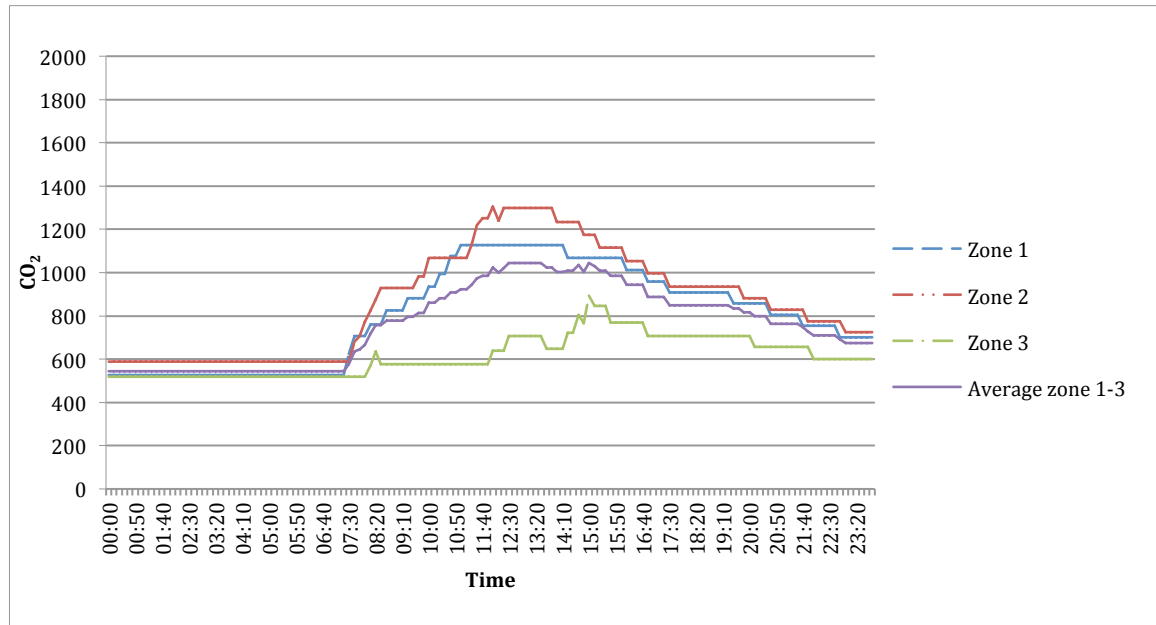


Figure 15 CO₂ concentration on the ground floor during October 21 2013

The room on the 1st floor was not occupied during 21th of October. However, the CO₂ concentration was still slightly higher during the occupant period as shown in Figure 16.

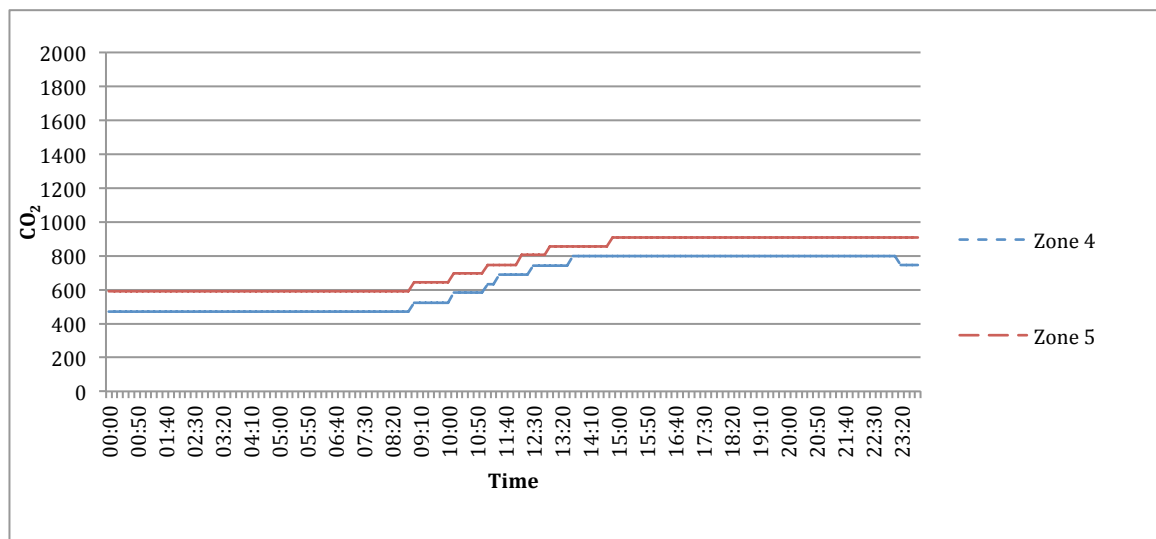


Figure 16 CO₂ concentration on 1st floor on the 21 October 2013

The reason for that could be that the chimney 2 supports both floors and the polluted air from the ground floor escapes not only through the chimney 2 but also entered the 1st floor. We noticed a similar case during one visit to the building, where the 1st floor was unoccupied and the internal windows were closed. By opening internal windows the CO₂ levels dropped, indicating that the air flow was directed back to the chimney.

The air change per hour is calculated only during October 21, as the data is incomplete for other days. The 1st floor was not occupied during that day.

The number of occupants in the building was counted on the ground floor.

During the 1-hour period (11-12PM) there were 2 children and 8 adults in the zone 1-3, on the ground floor. It was calculated that the occupants produce 175 CO₂ emissions in an hour.

To be able to keep the CO₂ levels below 1000ppm, the air change should be a 1.1 ach. The measured average CO₂ concentration for 1-3 zones was 1304 ppm, which is considered moderate. Knowing the actual concentration, I estimated that actual air change is 0.74 ach.

4.2.2.2 External conditions during experiment 2

The average external temperature on the 21th of October between 10-12 am was 13.5°C with the wind speed of 1.5 m/s from the south-west direction. The internal temperature was on average 21.5°C during the occupied hours.

The average infiltration n was calculated to be 0.0013 ach and estimated based on the weather conditions between 17.00 to 24.00 on the 21 of October.

4.2.2.3 Measurements of the concentration of CO₂ from windows and chimneys

In this section we present the results of measuring the concentration of CO₂, and temperature recorded by the additional meters described in section 3.3

The meters installed in the windows and chimneys showed (Figure 17) that the concentration of CO₂ in the chimneys was higher than in the rooms, which indicated that the chimneys were working as extractors. Furthermore, the experiment showed that the windows, which were located closes to the chimney were working constantly as air supply windows, such as in windows 2.1 and 2.2 in zone 2 on the ground floor and 4.3 in zone 4 on the 1st floor, as shown in Figure 17 and 18.

The CO₂ concentration at the bottom of the windows on the ground floor hardly varied and was lower than in the top of the window, which indicated that the incoming air did not mixed with the incoming air.

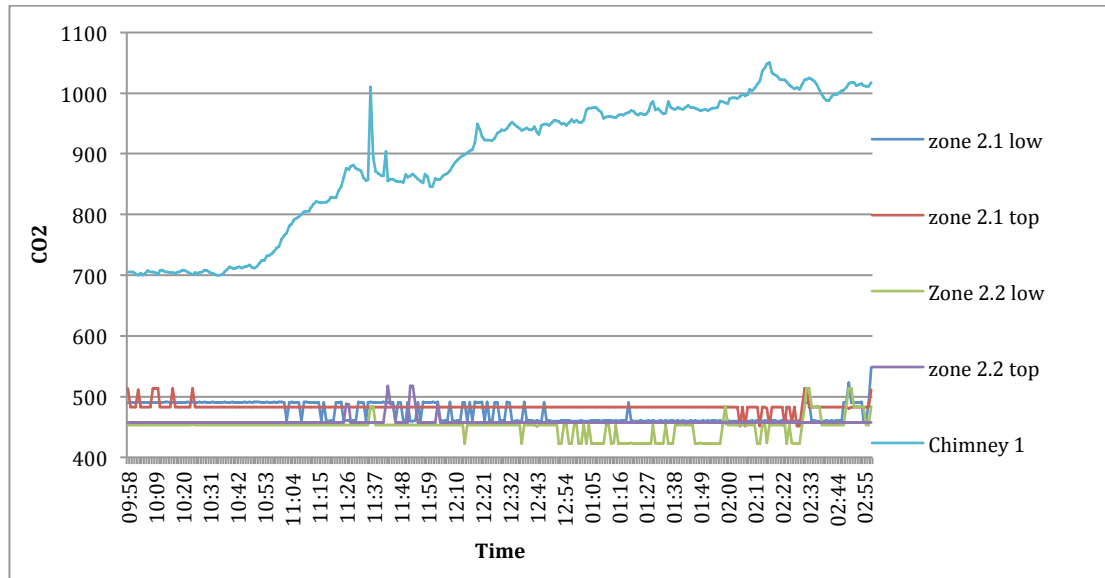


Figure 17 The levels of CO₂ concentration in windows in Zone 2 and in the Chimney 2, which is the closest to the windows openings.

Other windows, which had a longer distance to the chimneys, such as window 1.1 in Zone 1 on the ground floor, window 4.2 in Zone 4 and window 5.1 in Zone 5, (Figure 18), worked as both supply and extract.

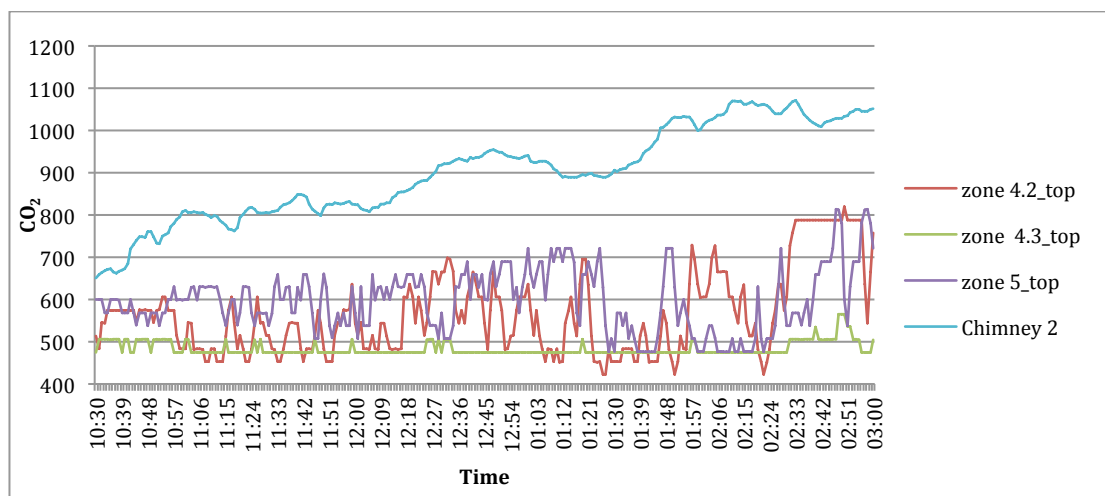


Figure 18 The levels of CO₂ concentration in windows in Zone 4 on the 1st floor and in the Chimney 2, which is the closest to the windows openings.

4.2.2.4 Measurements of temperature in windows

The incoming temperature through the ventilation windows was stable and varied from 13 -16°C at the top of the window and was at least 2-3°C warmer at the bottom of the windows (Figure 19). As the temperature difference was so small between the top and the bottom of the window it was not clear whether the incoming air mixed with the air in the gap.

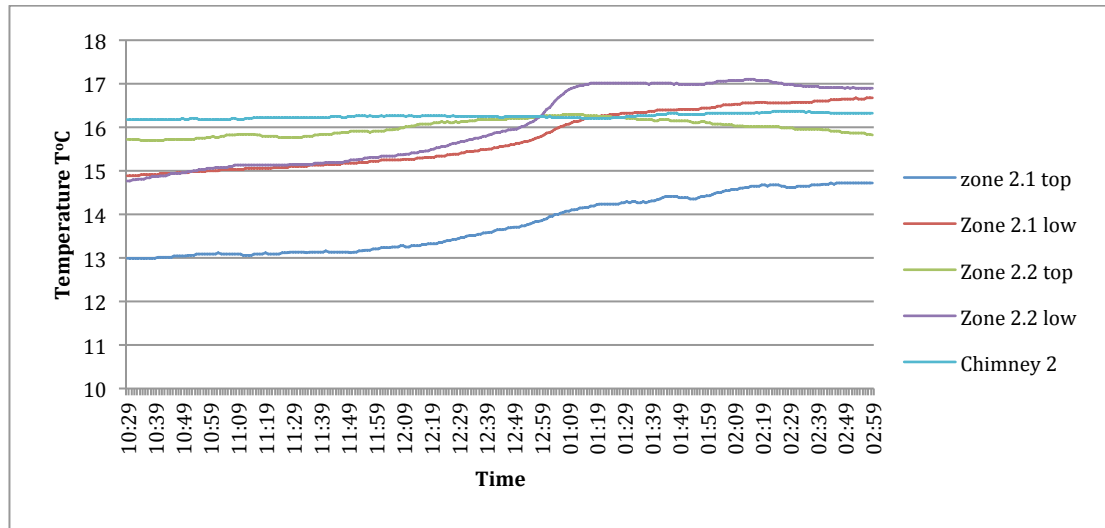


Figure 19 The temperatures in the top and the bottom of the windows in Zone 2, which were working as inlets.

The temperature in the rooms was between 21-23°C during the occupied hours, therefore the incoming air at 13-16°C could possibly create a feeling of draft for the occupants. From the experiment we were not able to determine the temperature of the incoming air.

4.2.2.5 Summary of the results of experiment 2

The results are summarised in Figure 20 for the 21st of October between 11-12am. During this period the occupants on the ground floor were usually in zone 3 on the ground floor preparing and eating lunch.

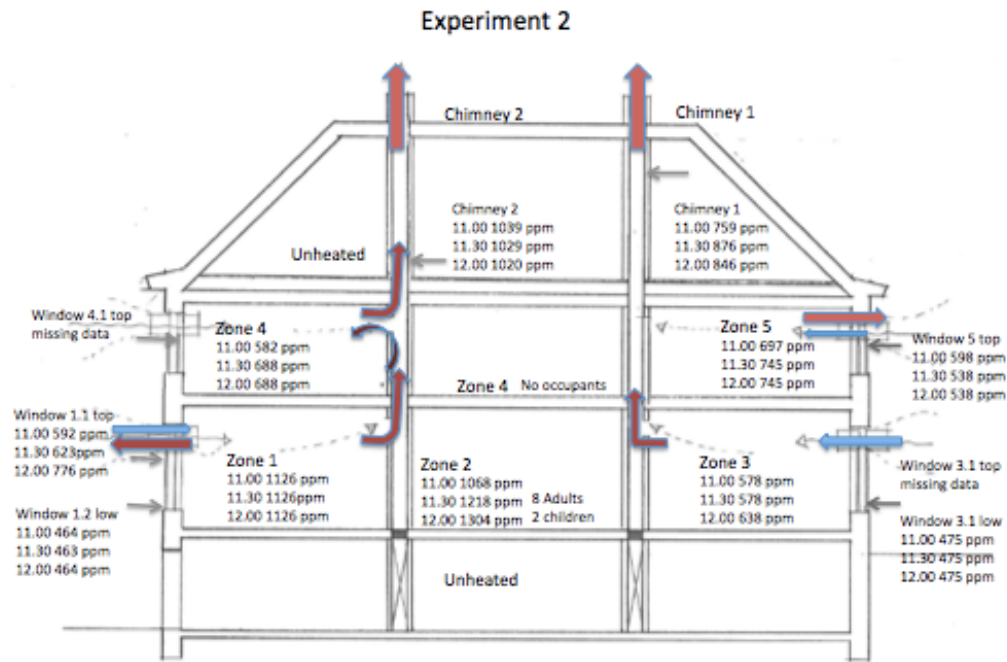


Figure 20 Summary of the experiment 2

Summary of the results of experiment 2

- (i) Experiment 2 recorded CO₂ levels in the rooms at 10 minute time intervals. It provided more detail about the air quality in the room than in experiment 1. The recorded CO₂ levels in the room were moderate or high during the short periods of the time (10min) on the ground floor and bad on the first floor.
- (ii) Knowing the occupancy in the room, it was possible to estimate the air change in the rooms, which was lower than required. The air quality was moderate during the analysed day, 21st of October, but was worse during other days, e.g. Friday the 18th of October or Tuesday the 22nd of October, but the data to analyse these was partially missing.
- (iii) We used a simplified assumption that the room has well mixed air and the air exchange was only to the outside. However, our measurements showed that the air in 1-3 zones was not well mixed as the CO₂ concentration differed by 100 - 600ppm from room to room. We also noticed that the polluted air from the ground floor was moving through the chimney to unoccupied zone 4 and 5, showing that the air in the building was also mixing with the air between the zones and not only with outside.
- (iv) As the external windows were constantly open, the airflow was sufficient to create a flow through the windows located close to the

chimneys, such as 2.1 and 2.2 (south façade) on the ground floor and 4.2. (south façade) on the 1st floor which worked as air supplies, and chimneys 1 and 2 which worked as air extractors. The windows on the east facades 1.1 and west 5.1 worked as both supply and extractor. Although the data was not complete, it was possible to estimate how the air moved in the room and confirm the air was incoming from the windows and was extracted from the chimneys as predicted.

- (v) In experiment 2 the “ventilation windows” worked as simple windows, where the fresh air passed through the external frame and directly through the secondary frame to the room, as the incoming temperature of the air was close to the external temperature (the preheating affect was less then 2-3°C.
- (vi) Due to missing data from the key measurements on other days, we were only able to investigate one single day, which is not sufficient to confirm our model.

4.3 Ventilation window strategy - Experiment 3

Experiment 3 was conducted to investigate the performance of the “ventilation window” when the windows are function as ventilation windows.

Experiment 3 was carried out during a 7-day period in November from the 1st to 8th in 2013 to investigate the ventilation window strategy.

4.3.1 Set up of ventilation strategy for Experiment 3

During the period of the experiment 3, the natural ventilation was automatically controlled by the Windows Masters program. All external ventilation windows were closed most of the time except for a 3 min period each hour. The internal windows were constantly open 30cm (100%) during occupancy and were manually regulated by occupants if it was too cold. During Experiment 3, the windows worked as “ventilation windows” except for the 3 min period of each hour, where the windows worked as normal windows. The idea was that the leaky external frames should provide the required ventilation supplemented by 3 min of normal ventilation. During no occupancy all internal and external windows were closed.

The CO₂ meters were installed in all 9 ventilation windows and both chimneys for the same purposes as in experiment 2, which was to investigate how the air is moving through the building.

4.3.2 Results of Experiment 3

The highest CO₂ levels were recorded on the 4th of November 2013 in Zone 5 on the 1st floor and in Zone 4 on the 1st floor on the 7th of November 2013. During the 4th of November, Windows Masters forgot to set the automatic control of windows. Therefore, the fully functional system was only available from the 5th of November as shown in Figure 21.

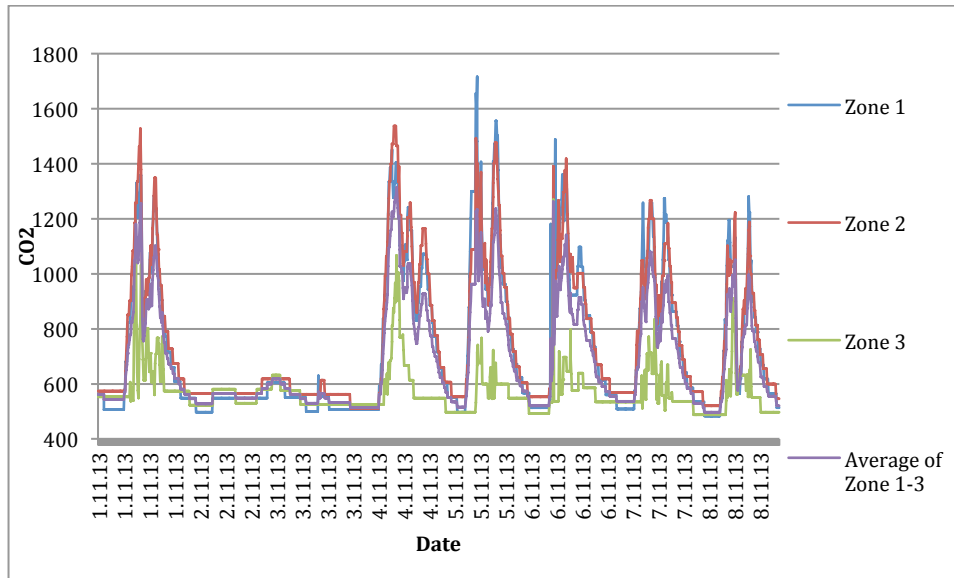


Figure 21 CO₂ concentrations in the rooms during Experiment 3

We investigated in detail the day of 7th of November 2013 between 11 and 12pm, because we had most complete data from the day.

4.3.2.1 External conditions during experiment 3

The average external temperature between 7-17 on the 7th of November was 9.8°C and the wind velocity varied between 1-4 with an average wind velocity of 2.4m/s with the direction of south west. The average internal temperature during the occupied hours was 22°C in Zone 1 and 2 and 24°C in Zone 3 on the ground floor and 21°C in Zone 4 and 20°C in Zone 5.

The infiltration n during no occupancy was calculated to be 0.003 ach and estimated based on the weather conditions between 17.00 to 24.00 on the 7th of November 2013. The external temperature during that period was, on average 8.3 °C and the wind velocity varied between 1.5-3 with an average wind velocity of 2.2m/s with the direction of south west.

4.3.2.2 Analysis of the concentration of CO₂ in the occupied rooms

During the occupancy on the 7th of November 2013, in hours before midday the number of occupants was stable on the ground floor with 7 adult females and 10 children between age 0.6-2.8 years. It was calculated that the occupants produce 154.7 CO₂ emissions in an hour.

To be able to keep the CO₂ levels below 1000ppm, the air change needed to be a 0.98 ach. The measured average CO₂ concentration for 1-3 zones was 1079 ppm, which is considered good, however in Zone 1 and Zone 2 the CO₂ concentration was 1258 and 1266 respectively, as shown in Figure 22. The average low CO₂ concentration is due to the low concentration in Zone 3. Knowing the actual concentration, I estimated that actual air change for the average of zone 1-3 to be 0.87 ach.

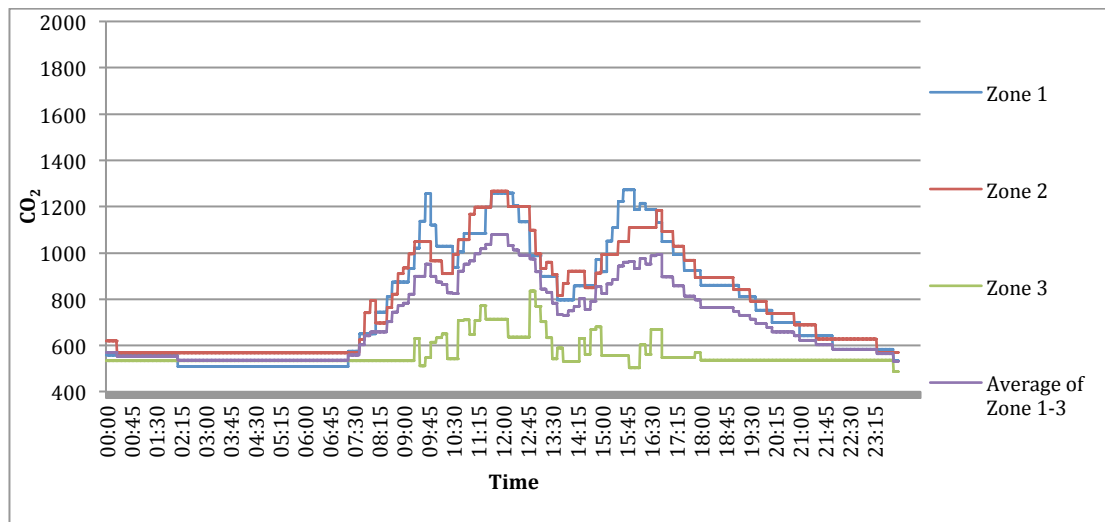


Figure 22 CO₂ concentration on the ground floor in zone 1-3 during occupancy on the 7th of November 2013

In the room on the 1st floor, CO₂ concentration was higher, reaching 1934ppm during a 10 min period in Zone 4 and varying between 1200 and 1700ppm during the occupancy, as shown in Figure 23. The high CO₂ concentration also appears in Zone 6, which is the separate office with one occupant. We did not investigated Zone 6 because the occupant was feeling a draught from the window and had the window closed most of the time.

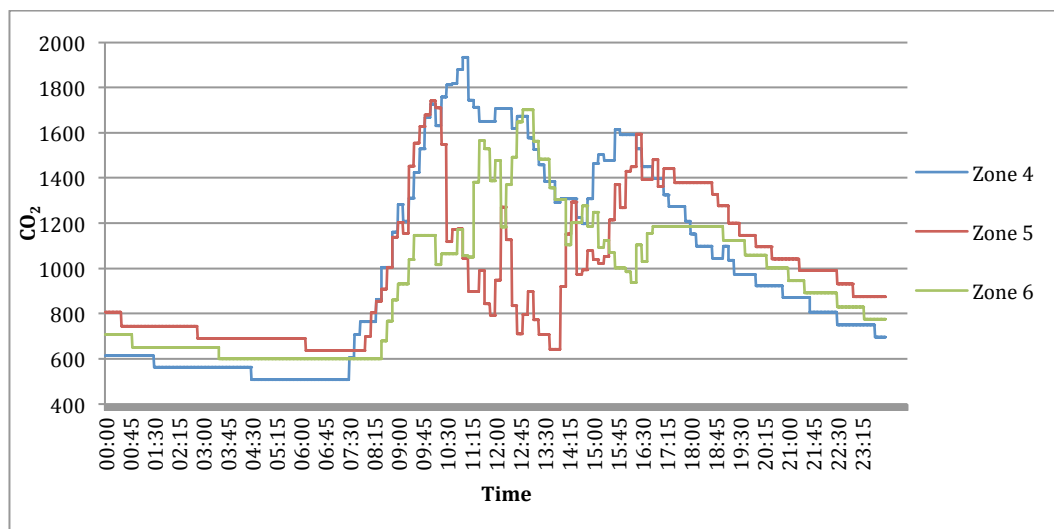


Figure 23 CO₂ concentrations on the 1st floor during November 7th 2013.

During a 1-hour period before midday, the number of occupants was also stable on the 1st floor with 4 adult females and 11 children between age 0.6-2.8 years. It was calculated that the occupants produce 89.6 CO₂ emissions in an hour. The volume of the zone 4 is 143m³.

To be able to keep the CO₂ levels below 1000ppm, the air change needs to be 1.04 ach. The measured CO₂ concentration for zone 4 was 1934 ppm, which is considered bad. The actual concentration was estimated to be 0.4ach.

4.3.2.3 Measurements of the concentration of CO₂ from windows and chimneys

The meters installed in the windows and chimneys showed that the concentration of CO₂ in the chimneys was higher than in the rooms on the ground floor, as shown in the Figure 24. It indicated, that even though the air flow in the chimneys were fluctuating, the chimney 2 was still working as an extractor most of the time, and the windows 2.1 and 2.2 in Zone 2 were working as air supply. During a 3 min period each hour, when the external windows opened, the CO₂ levels dropped in the windows on the south façade as well as in the chimney 2. It is not clear whether the opening of the external windows increased the air exchange in the rooms by increasing the air velocity, or it disturbed the airflow and reversed the airflow in the chimney 2.

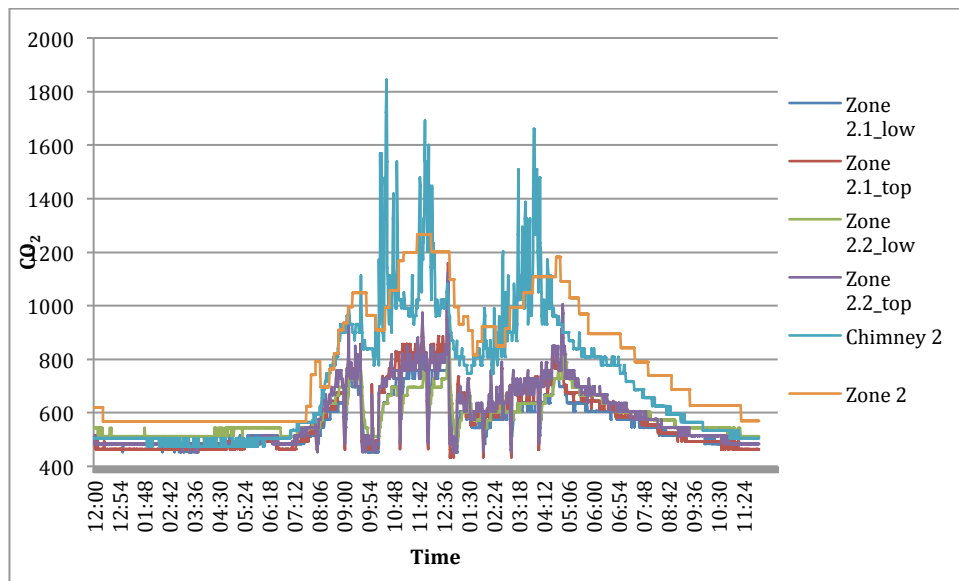


Figure 24 CO₂ concentration in the zone 2(south façade) on the 7th of November.

The CO₂ concentration at the bottom of the windows in Zone 2 had the lowest variations and was only slightly lower (100ppm) than at the top of the window, which indicated that the incoming air probably did mixed with the air in the gap of the window.

As the wind direction was from the south-west, the window on the east facing façade 1.1 on the ground floor worked both as an extractor and supply, as shown in Figure 24. The window 4.1 on the 1st floor worked mostly as an extractor, as the CO₂ concentration was highest, as shown in Figure 25.

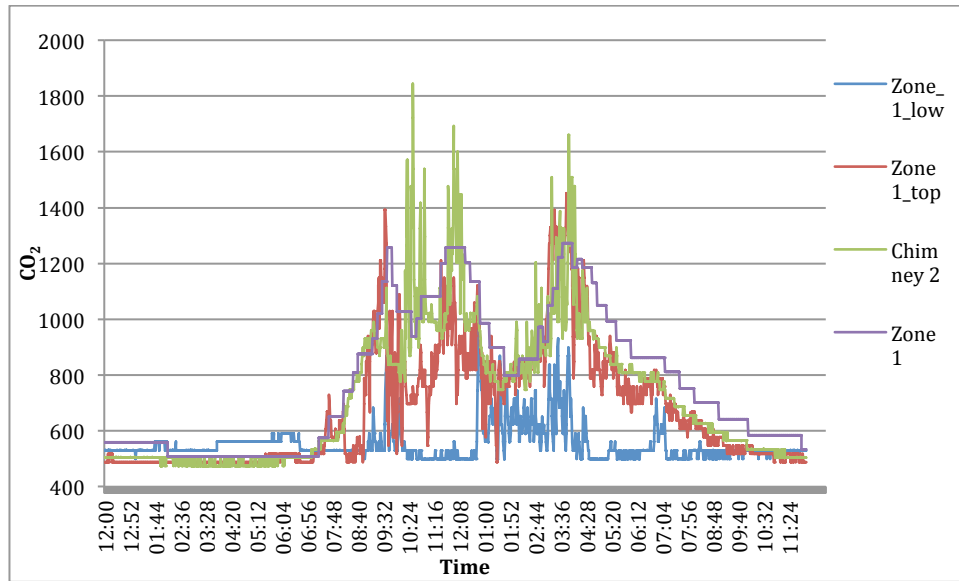


Figure 25 CO₂ concentration in Zone 1 (east facing façade) on the 7th of November 2013.

The window 3.1 on the west facing façade on the ground floor worked as an air supply with the lowest CO₂ concentration recorded in Zone 3 (Figure 26). Chimney 1 is located in the same room and worked mostly as an extractor. Zone 3 had the best air quality in the building, which was possible influenced by the wind direction as the wind direction was south west.

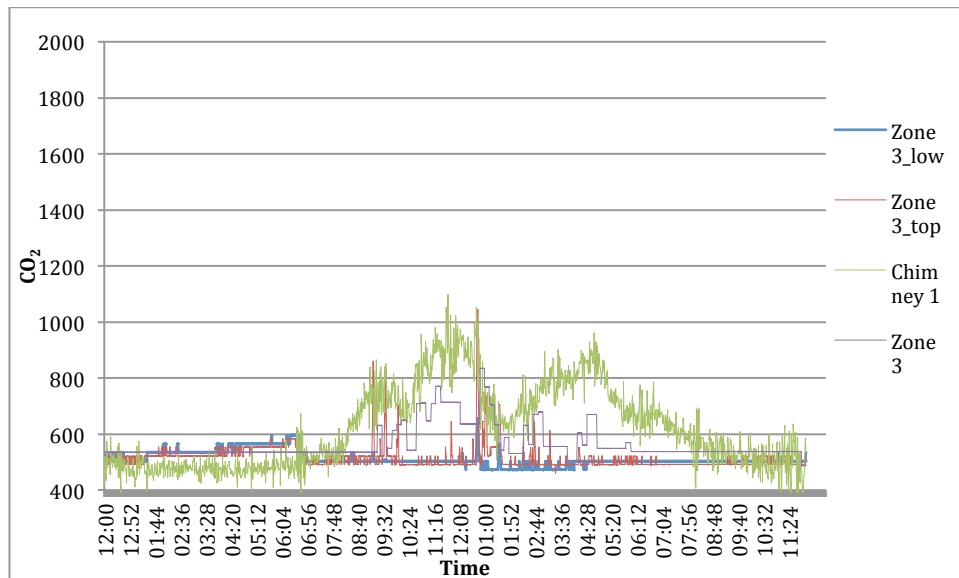


Figure 26 CO₂ concentration in Zone 3 on the ground floor during the 7th of November 2013

As chimney 2 was working as the air extractor for both floors, the high CO₂ concentration in chimney 2 could also be caused by the average higher CO₂ concentration on the 1st floor, as shown in Figure 27.

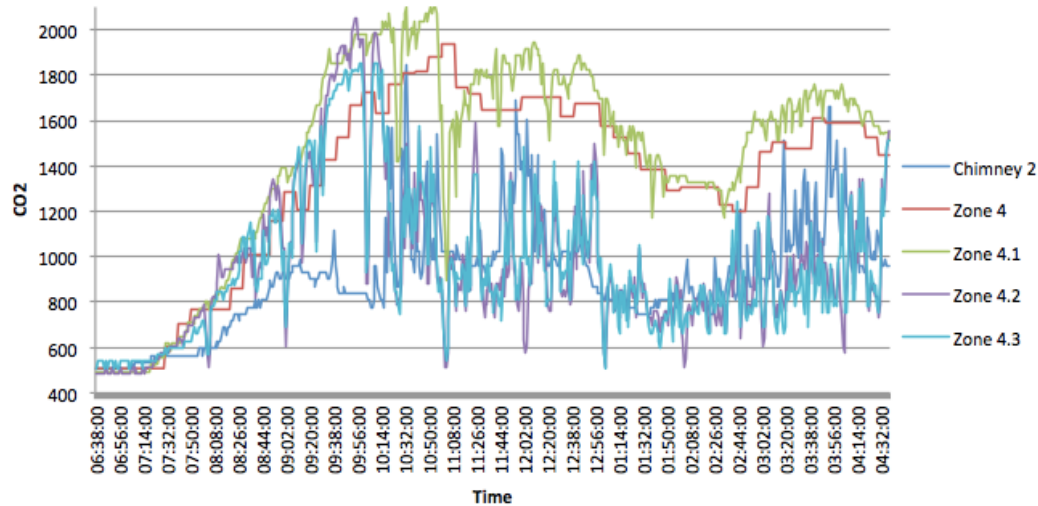


Figure 27 CO₂ concentration in the zone 4 (south façade) on the 1st floor during 7th of November 2013.

The CO₂ concentration in chimney 2 was lower than the average room concentration on the 1st floor, as shown on the Figure 27. The highest CO₂ concentration was recorded at the top of window 4.1 on the east facing façade, which worked as an air extractor and was influenced by the south-west wind. The CO₂ concentration at south facing windows 4.2 and 4.3 and chimney 2 was slightly lower, with high fluctuation, indicating that the air was moving both ways.

The relatively lower CO₂ concentration, with high fluctuation was also recorded in window 5.1 in Zone 5 on the 1st floor (Figure 28). Note that Zone 5 has no direct connection to chimney and is connected to chimney 2 through an opening between zone 4 and 5. Therefore window 5.1 works both as a supply and extractor.

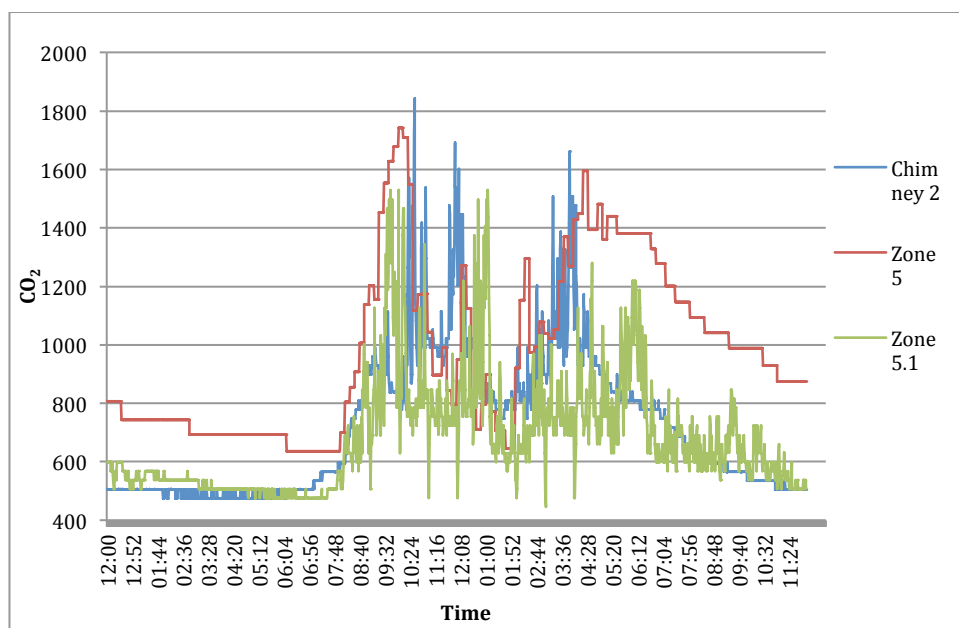


Figure 28 CO₂ concentration in Zone 5 on the 1st floor during the 7th of November 2013

4.3.2.4 Measurements of temperature in windows

The incoming temperature through the ventilation windows was stable for the top part of the windows and varied from 14 -16°C, as shown in Figure 29. The temperature at the bottom of the windows was at least 3-5°C cooler during the unoccupied hours and increased during the day, reaching the temperature of the incoming air in the top of the window. The drop in the temperature at the top of the windows apparently occurred due to opening of the external doors by the occupants. The smaller drops in the temperature occur every hour due to the automatic opening of the windows controlled by Windows Masters.

The temperature difference between the top and the bottom of the windows was changing during the occupied hours, indicating that there was probably some kind of mixing of the air in the gap of the window. Note, that the temperature in the lower part of the window was cooler than in the top, which indicated that the air was coming in through the leakage in the external frame, as predicted, and was different from experiment 2 where the temperature in the top was cooler.

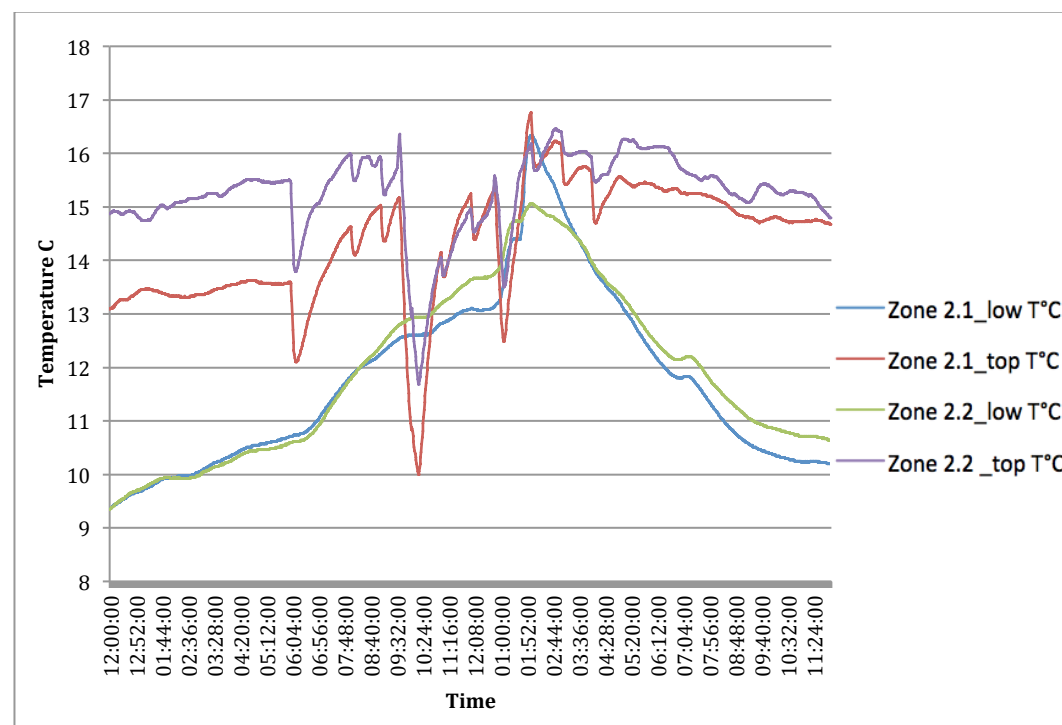


Figure 29 Temperature in the gaps in windows 2.1 and 2.2 in Zone 2 on the 7th of November 2013

4.3.2.5 Summary of the results of experiment 3

The results are summarised in Figure 30 during the 7st of November 2013 between 11-12am. During this period, the occupants on the ground floor were in zone 3 on the ground floor and in Zone 4 at the 1st floor preparing and eating lunch.

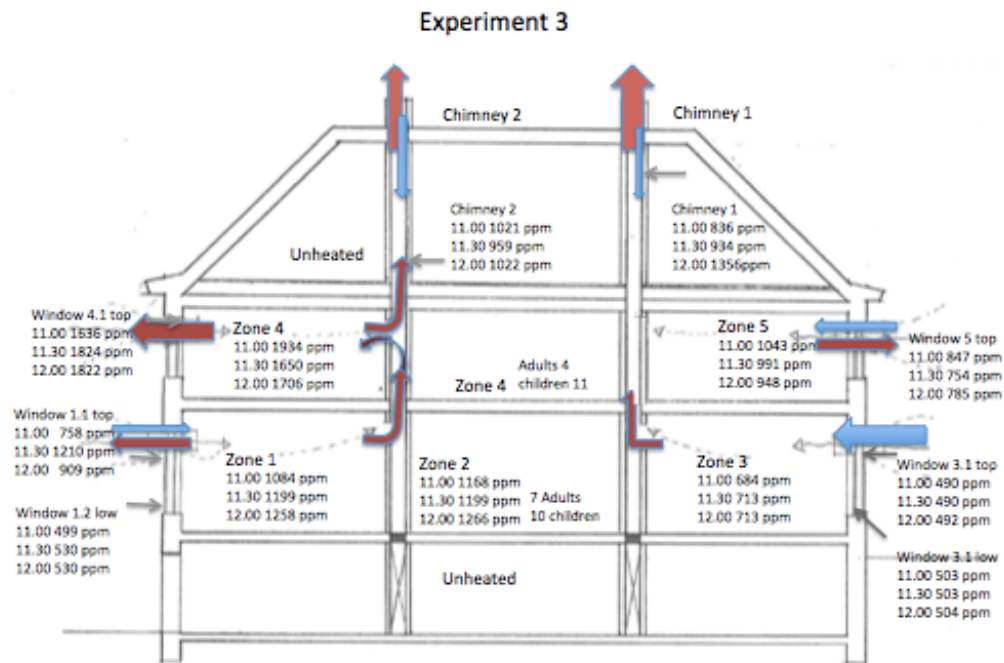


Figure 30 Summary of Experiment 3

Summary of the results:

- (i) Experiment 3 recorded CO₂ levels in the rooms at 10 min time intervals and showed more detailed air quality in the rooms than in experiment 1.
- (ii) In experiment 3 the “ventilation windows” worked as predicted, where the fresh air passed through the external frame, was preheated and mixed with the escaping air from the room (the preheating affect was around 5°C)
- (iii) Even with closed external windows and a low wind velocity, the wind had an influence on the pressure difference inside the house and dominated the airflow through the building from the west Zone 3 on the ground floor and Zone 5 on the 1st floor to the east window 1.1 in Zone 1 on the ground floor and window 4.1 in Zone 4 on the 1st floor.
- (iv) Chimneys 1 and 2 had similar CO₂ concentrations as in Experiment 2. The windows located close to the chimneys, such as 2.1 and 2.2 (south façade) on the ground floor and 4.3. (south façade) on the 1st floor, worked as air supplies and chimneys 1 and 2 worked as air extractors. However, the airflow fluctuated and indicated that there was not sufficient airflow through the system.

- (v) There were more fluctuations recorded in supply windows and chimneys and the opening of a window or door was more visible on the CO₂ concentration recordings or the temperature in the windows.
- (vi) The CO₂ levels were moderate on the ground floor but too high on the 1st floor during the occupancy, which indicated that the system could not provide sufficient airflow to the 1st floor. Knowing the occupancy in the room, it was possible to estimate the air change in the rooms, which was lower than required.
- (vii) The external windows were closed most of the time, except for 3 min periods every hour, and therefore did not provide sufficient airflow through system especially for the 1st floor. The reason for this could be that the external frames were tighter than predicted, and the external temperature was higher than estimated in the dynamic simulation model, which predicted that the windows should additionally open when the external temperature was above 5°C.
- (viii) As in experiment 1 and 2, we used a simplified assumption that the room has well mixed air and the air exchange was only to the outside. However, our measurements showed that the air in 1-3 zones was not well mixed as the CO₂ concentration differed by up to 600ppm from zone 1 and 3.

Due to many uncontrolled parameters, such as (i) always changing number of occupants and their exact position, (ii) the air movements between the rooms, as well as (iii) opening and closing the doors not only to the rooms but also to outside etc., created a great challenge in estimating, measuring and calculating the actual air flows in the windows or even in the chimneys. The air change calculation could only provide the rough estimate of the air change in the room,

5 Discussion

The purpose of the study was: (i) to investigate whether our solution provides sufficient fresh air to the occupants of the building without creating drafts for the occupants, (ii) whether air supply is provided through the “ventilation window” and extracted through the chimneys, as assumed, and (iii) how the system works in a real building during usage.

We investigated three strategies:

- (i) where fresh air was provided by **pulse ventilation**, Experiment 1;
- (ii) where fresh air was provided by **stream ventilation**, Experiment 2;
- (iii) where fresh air was provided by **ventilation window**, Experiment 3.

5.1 Does the system provide sufficient fresh air

Neither of the three window opening strategies **could 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 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 may 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 the system should provide a minimum of 1.04 ach, however the system provided only 0.4 ach

5.2 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 did the 9 windows with the automatic control from Windows Masters work as “ventilation windows”. During Experiment 3 the air supply was additionally added by the “pulse ventilation” in a similar way as in the experiment 1.

During experiment 2, a stable flow in the chimneys and the windows close to the chimneys was observed. However, as the internal and external window were open in the same side, the window worked as a simple opened window and not as a “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 system worked as predicted and the CO₂ concentration was lower in the windows close to the chimney, which we interpreted as an indication that the windows worked as an air supply, even 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.

5.3 Options for improvement

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 were slightly open during the occupied hours, the flow in the chimney and in the windows close to the chimneys is stable. However no preheating effect was then observed. To achieve the preheating effect and to provide the required airflow the system should be improved:

- (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 31 is automatically controlled by Windows Masters) and the internal window should be closed on the top window. The internal window on the opposite side (4) as show in Figure 31 should be open. In the bottom of the frame the air passage must be established between (1) and (3) as well as the air passage between (4) and (3) as shown on the Figure 33. The fresh air is then expected to come in through the open external window (2) and be 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). It is hoped that the chimney will then have a stable flow and the windows close to the chimney will work as the air supply. By having opening external windows wider on the 1st floor than on the ground floor (4:1) the pressure difference might be equalised.
- (ii) To connect zone 5 to chimney 1, as zone 5 has to low air circulation.

The assumption that the external wind can be ignored using ventilation window system was incorrect. The wind influence was mostly visible during experiment 3 where the system was configured to work as predicted.

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

This investigation of a natural ventilation system in a natural environment reveals how difficult it is to estimate, measure and calculate the air flow in the building, where the zones are connected and people are moving constantly between the spaces. During the project we used simplified estimates to calculate the measured CO₂ levels in the building. The system could be better modelled using a dynamic calculation model and more detailed readings of the airflow in the building and more detailed registration of the movements of the occupants.

12 Article in periodical journal FM Blad

Hvordan skal Facilities Management reagere på klimaforandringernes påvirkning af bygninger

Rimante A. Cox June 2012

HVORDAN SKAL FACILITIES MANAGEMENT REAGERE PÅ KLIMAFORANDRINGERNES PÅVIRKNING AF BYGNINGER?

AF RIMANTE A. COX,
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På trods af adskillige internationale forsøg på at forhindre klimaforandringer ved at reducere drivhusgasudledning, er det nu klart, at et vist niveau af den globale opvarmning er uundgåelig. Derfor ligger der en betydelig forskningsopgave i at undersøge, hvordan forskellige lande kan tilpasse sig til disse klimaforandringer. For eksempel har der været udført en del studier af konsekvenserne for vores helbred og velvære samt af effekten af klimaændringer på landbrugsproduktion og økosystemer. I dette projekt behandler vi effekten af klimaforandringer på bygninger og kommer med et bud på hvordan FM skal reagere på det.

Man kunne tro, at en forventet generel stigning af den globale temperatur på mellem 2 og 4 grader ikke i alvorlig grad vil påvirke vores bygninger. Men fremtidens klimamodeller forudsiger også en stigning i ekstreme vejrphenomener såsom hedeølger, langvarig tørke, og intens nedbør, som ofte forårsager oversvømmelser, såvel som storme og orkaner. Disse ekstreme vejrforhold, som er konsekvenser af disse temperaturstigninger, kan forårsage betydelige skader på bygninger og infrastruktur. Et eksempel på det har vi allerede oplevet under den ekstreme nedbør i juli 2011 i Københavns område, hvor veje og boligområder blev oversvømmet.

For at forstå, hvordan bygninger bliver påvirket af klimaforandringer, er der behov for at udvikle lokale klimamodeller, som kan forudsige temperatursvingninger (ikke blot gennemsnitlige årlige eller månedlige temperaturer, men daglige eller på timebasis), sandsynligheden for ekstreme nedbørsmængder og deres intensitet, hvordan vindintensiteten vil stige i fremtiden, og hvordan det vil påvirke oversvømmelser i lokaler områder. Det Danske Meteorologiske Institut (DMI) råder over avancerede klimamodeller til at forudsige ekstreme vejrforhold i Danmark som del af det Europæiske Ensembles¹ projekt.

I samarbejde med DMI, vil vi i projektet benytte disse forudsigelser til at forstå, blandt andet hvordan bygningers interne og eksterne konstruktioner bliver påvirket af øget termiske eksponeringer og øget nedbør.

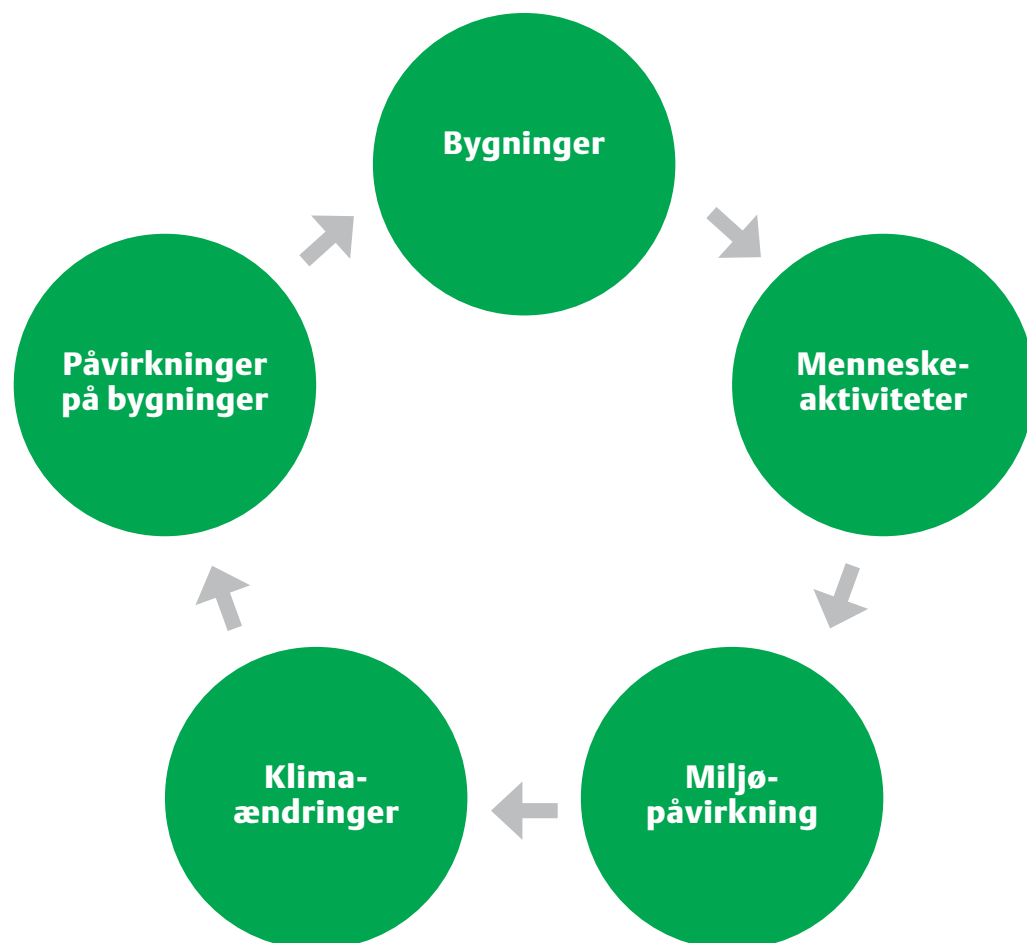
Forholdet mellem klimaforandringerne og bygninger er illustreret i figur 1. Bygninger beskytter men-

nesker fra det omgivende miljø, fra vejr og skiftende klima. Bygninger er også et produkt af menneskelige aktiviteter: den måde vi vælger at designe, drive og vedligeholde vores bygninger har en indvirkning på det omgivende miljø. For eksempel, stammer den største del af energiforbruget i bygninger fra fossile brændsler, som forårsager klimaforandringer, og klimaforandringer påvirker vores bygninger. Derfor stilles her et spørgsmål: skal vi tilpasse vores bygninger til klimaforandringerne, eller skal vi også reducere bygningernes påvirkning på klimaforandringerne?

I dette projekt skelner vi mellem tilpasnings- og afhjælpningsstrategier. Tilpasningsstrategier behandler symptomer af klimaforandringer, såsom forøget temperatur, og afhjælpningsstrategier herimod beskæftiger sig også med den underliggende årsag. For eksempel, når den gennemsnitlige temperatur stiger, vil man i henhold til tilpasningsstrategien tilføje ekstra kapacitet til kølingssystem. I så fald vil bygninger bruge mere energi til køling. Den øgede efterspørgsel efter energi, hvis det leveres af fossile brændsler, forværrer den globale opvarmningssituation, idet den gennemsnitlige temperatur vil stige yderligere. Dette vil igen føre til yderligere stigninger i energiforbruget til afkøling af bygninger. Hermed er den onde cirkel skabt, hvor den umiddelbare løsning efterfølgende gør problemet værre. For at undgå denne uholdbare situation, er det vigtigt ikke kun at behandle de øjeblikkelige symptomer, men også de grundlæggende årsager til klimaforandringerne. I den forbindelse er en afhjælpningsstrategi en strategi, der ikke kun omhandler et umiddelbart problem, men også overvejer, hvordan forskellige løsningsforslag kan påvirke det fremtidige miljø. Således kan en afhjælpningsstrategi for køling af bygninger anbefale at installere passiv køling, eller sikre, at energiforbruget til klimaanlæg er leveret af bæredygtige, CO2 neutral kilder.

Et andet eksempel på forskellen mellem tilpasnings- og afhjælpningsstrategier kan illustreres med forskellige løsningsforslag i forbindelse med oversvømmelsesproblemer. Ved at behandle vægge med vandfaste materialer eller at etablere en omfangsdræn kan man løse det øjeblikkelige problem med oversvømmelsen. Med disse

¹ Ensembles er et integreret forskningsprojekt, der har opstillet sandsynlige klima-prognoser for Europa ved hjælp af de nyeste klimamodeller og analyseværktøjer.



Figur 1 Forholdet mellem bygninger og klimaforandring

løsninger vil muligvis lede vand til de omkringliggende bygninger eller aflaste det lokale afløbssystemer. Ifølge afhjælpningsstrategien ville disse konsekvenser overvejes og regnvandsafstrømningen ville måske reduceres ved for eksempel at anvende et grønt tag, eller indsamling af regnvand til anvendelse på stedet, eller forøgelse af nedsivning af grunden.

Afhjælpning af klimaforandringernes miljøpåvirkninger er en vigtig faktor også i relation til drift og vedligeholdelse af bygninger som er en del af Facilities Management (FM), da disse yder et væsentligt bidrag til virksomhedens miljøpåvirkning. Der er et stort potentiale i at reducere miljøbelastningen gennem FM, selv om dette ikke er blevet anerkendt som en vigtig aktivitet for bæredygtige FM af virksomheder (Junnla SHA, 2006) (Lindholm AL, 2011). Mens facilities management kun tæller en lille brøkdel af en virksomheds budget, kan det have en væsentlig indflydelse på virksomhedens miljøpåvirkning. For eksempel, i henhold til (Junnla S., 2004) (Lindholm AL, 2011), udgør Facilities Management udgifter 4-6 % af en virksomheds omkostninger, men bidrager med 53-82% til den samlede miljøbelastning, selv når der tages højde for forskellige typer virksomheder, deres størrelser, placeringer og budgetter. Således vil anvendelsen af bæredygtig Facilities Management

(FM) være en mulighed for at reducere en virksomheds samlede miljøbelastning samt understøtte virksomhedens bæredygtige image.

I dag, kan afhjælpningsstrategier undertiden være dyrere end tilpasningsstrategier. Men vi forventer, at dette kan ændre sig i den nærmeste fremtid, når forskellige regeringer rundt omkring i verden introducere nye bygningsreglementer og eventuelle afgifter på udledning af drivhus gas.

For at undersøge, hvordan afhjælpningsstrategier kan anvendes i praksis, har vi indledt et samarbejde med Gentofte Kommune, hvor vi anvender afhjælpningsstrategier ved renovering af historiske bygninger i Gentofte kommune, tre detaljerede casestudier bliver gennemført.

Nogle af de forskningsspørgsmål, vi vil overveje at inkludere, er:

- Hvordan vil øget termisk eksponering og nedbør skade historiske bygninger?
- Vil indre konstruktioner blive beskadiget ved øget intern relativ luftfugtighed?
- Kan beplantning afhjælpe virkningerne af klimaforandringerne i det bebyggede områder?
- Hvordan kan avancerede naturlig ventilation anvendes i de historiske bygninger?

BÆREDYGTIGT FM

Vi forventer, at denne forskning blandt andet vil bidrage med: (i) metoder til at analysere og forudsige klimaforandringernes påvirkninger på levetid og vedligeholdelse af bygninger i Danmark, (ii) en analyse af metoder til drift og vedligeholdelse af bygninger ved at anvende afhjælpningsstrategier i forhold til klimaforandringerne, (iii) værktøj (eller metoder) til at understøtte

en prioritering af hvilke afhjælpningsstrategier, der er mest kosteffektivt for levetiden af de bygninger, (iv) levering af grundlæggende ny viden, der kan bidrage til udformning af nye bygningsreglementer i Danmark, der vil gøre nye bygninger mindre følsomme og mere fleksibel over for klimaforandringer.

Samarbejdspartner

Ph.d projekt: Klimaforandringerne og deres påvirkning på bygningers vedligeholdelse og drift udføres af Rimante A. Cox. Projektet er et samarbejde mellem Institut for Byggeri og Anlæg, DTU Byg, Center for Facility Management, Realdania Forskningscenter og Gentofte Ejendomme, og giver en unik mulighed for at arbejde på tværs af forskellige forskningsfag som bygningsfysik, facilities management som samt et tæt samarbejde med industrien. Da projektet er baseret på klimatologi, er DTU Klimacenter og Danmarks Metrologisk Institut også en del af samarbejdet. Formålet med projektet er at undersøge problemet på at reducere klimaforandringernes påvirkninger på bygninger ved hjælp af tre casestudier baseret på de historiske bygninger i Gentofte.

Rimante A. Cox

er ph.d.-studerende på Danmarks Tekniske Universitet. Hendes ph.d.-afhandling omhandler klimaforandringer og deres påvirkning på bygningers levetid og vedligehold. Hun har tidligere arbejdet som konsulent inden for bæredygtighed for Southfacing Services Ltd, UK, og var rådgiver inden for bæredygtigt design, vedvarende energi og bæredygtigheds-vurdering som f.eks. certificering af bygningsbæredygtighed. Hun er akkrediteret BREEAM konsulent for kontorer i UK og BREEAM international, og er energirådgiver. Hun har en M.Sc. i Miljømæssige design og projektering fra UCL University College London, UK og en B.Sc. som diplomingeniør fra IHK, (Ingeniørhøjskole i København) i Danmark. Inden hendes videregående uddannelse arbejdede hun i 5 år som projektleder og bygherrerådgiver hos COWI i Danmark.

PER ANKER JENSEN

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To adapt to climate change, it is necessary to have readily available future weather files and to economically quantify the threats to buildings. Adaptation methods should be both resilient and sustainable. This thesis first considers how to quantify climate change threats with limited data for future weather. 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.

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