DTU Library

Can the interaction between occupant behaviour and the indoor environment in residences be influenced?

Andersen, Søren

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Can the interaction between occupant behaviour and the indoor environment in residences be influenced?

Søren Andersen

Søren Andersen

PhD Thesis

Department of Civil Engineering
2016

DTU Civil Engineering, Report R_355
September, 2016

DTU Civil Engineering
Department of Civil Engineering

Can the interaction between occupant behaviour and the indoor environment in residences be influenced?

Søren Andersen
DTU BYG – PhD Dissertation
June 2016

DTU Civil Engineering
Department of Civil Engineering

1 PREFACE

This Ph.D. project is a report of 3.5 years work on the topic of occupant behaviour and indoor environment. The project was carried out at the International Center for Indoor Climate and Building Physics, at the Department of Civil Engineering at the Technical University of Denmark. The project was supervised by Professor Bjarne W. Olesen and Dr. Rune Korsholm Andersen. The work was carried out from October 2013 to June 2016. The project had its origin in my Master's thesis, which was also conducted at the center, and in which an analogue version of continuous feedback intervention was tested. In this Ph.D. project a method for indoor environmental feedback was developed. The goal was that the method should be commercially usable and I therefore hope that the findings will be used at some time in the future to help occupants obtain and maintain a healthy and comfortable indoor environment all over the world.

I am very grateful to Professor Bjarne W. Olesen, who saw the potential in the topic, opened many doors and made the project and the experiments financially possible. I should also like to express my sincere appreciation to Dr. Rune Korsholm Andersen for supervising and encouraging me when necessary, for always taking the time to help me, for the quick responses and the many conversations we have had.

I would like to thank all employees at the International Center for Indoor Climate and Energy and the Department of Building Physics for the good and inspiring work environment we shared. A special thanks to my fellow Ph.D. candidates in Office 231, I had the best time sharing the office and cookies with you.

Thanks to Dr. Max Sherman, Dr. Iain Walker, Dr. Brennan Less and the other members of the Residential Building System group at the Lawrence Berkeley National Laboratory for hosting my external stay there. It was very useful to see how things are done outside DTU.

Thanks too, to all the occupants in the housing areas Hanebred, Egevolden and Korngården where the measurements were conducted. The occupants were the backbone of the dissertation and it would not have succeeded without their cooperation.

Lastly, I would like to thank my wonderful wife and our children, to whom I dedicate this report. Thank you for your support over the last four years and for sending me off to work even on the bad days.

Enjoy the reading

Kongens Lyngby, DTU, 2016

2 SUMMARY

In the context of global climate change it has been broadly recognized that energy use in buildings must be reduced. In many cases this has been achieved by decreasing the natural infiltration rate in buildings by means of a focus on airtightness. Increasing airtightness does decrease energy use, but it also increases the impact of occupant behaviour on energy use and indoor environment.

In Denmark the indoor environment is directly linked to energy use for heating. In most buildings the indoor environment is controlled by the occupant (via thermostat setting, window opening), so any change in the occupants' control of the indoor environment will influence energy use.

Both older and more recent studies of the influence of occupant behaviour on energy use report that an increased information level and feedback on energy use can be effective in influencing occupant behaviour. The market penetration of smart meters has made it possible to measure and visualize energy use in real-time. Visualizing real-time consumption made it theoretically possible to provide feedback.

Some authors were reluctant to recommend feedback from smart meters and a national roll-out of this approach, as national savings would then depend on the truth of an unproven assumption: that all occupants will act adaptively when provided with more information. Their studies questioned the value of providing feedback to households not motivated to conserve energy and suggested that alternative approaches should be tested.

The purpose of this Ph.D. project was to investigate whether feedback on the indoor environment could be used to adaptively influence occupants' control of the indoor environment in such a way as to obtain healthy and comfortable homes and reduced energy use for heating. The project consisted of a literature study and four field studies that focused on how to affect occupants' control of the indoor environment. The four studies used measurements of the temperature, relative humidity, and CO_2 concentration in 84 rental apartments. The conclusions made in the thesis are derived from an analysis of the measurements performed in the apartments. The apartments were in three multi-storey buildings in three different municipalities of the Copenhagen area of Denmark.

The influence of how total heat cost was allocated between tenants was studied in two buildings and a significant influence on the control of indoor environment was demonstrated. The measurements indicated that heat cost allocation was a driver for occupants' behaviour. The measurements further showed the energy-saving potential of shifting from master-metering to sub-metering.

Two different feedback procedures were used to test the effect of providing indoor environmental feedback. The first method combined real-time feedback with monthly feedback letters. The second method combined real-time feedback with weekly feedback letters. The effects of the feedback procedures were investigated by using measurements, interviews and questionnaires.

Feedback on energy use gave occupants a monetary incentive and an environmental incentive to conserve energy. By using indoor environmental feedback it was possible to use health, comfort, monetary and environmental incentives to promote energy conservation.

The studies highlighted the importance of occupants being motivated to adapt their control of the indoor environment by acting on feedback. The results further indicated that occupants without a monetary incentive were not as interested in using the feedback as occupants with a monetary incentive.

The difference between the feedback procedures supported the findings of earlier studies, that feedback should be disseminated as frequently as possible. The studies demonstrated the importance of barrier-free access to real-time feedback, as even a little barrier caused the occupants to ignore the feedback. It is recommended that feedback should be disseminated by using a mobile platform, as a dedicated application, and not just through a website.

3 RESUME

I forsøget på at reducere klimaforandringerne er det bredt anerkendt at energiforbruget i bygninger skal reduceres. Dette har blandt andet betydet at den naturlige infiltrations rate er reduceret ved en øget fokus på lufttæthed. En øget lufttæthed giver automatisk et lavere energiforbrug, men betyder også at brugerne får større og større betydning for både energiforbrug og indeklima.

I Danmark er indeklimaet direkte forbundet til energi og varmeforbruget og da styring af indeklimaet i langt de fleste boliger er bestemt af beboerne, vil en ændring af beboernes styring og adfærd også have en påvirkning på energiforbruget.

Både ældre og nyere undersøgelser af brugeradfærdens påvirkning på energiforbruget, har vist hvordan øget information og feedback om energiforbruget påvirker netop dette. Med udbredelsen af smart-meters er det blevet muligt at måle og visualisere energiforbruget som det sker. På den måde er det teoretisk muligt for en forbruger at se konsekvensen af dennes handling som den finder sted. Flere undersøgelser har vist besparelser på omkring 10% som følge af feedback baseret på smart-meters. Andre undersøgelser er mere tilbageholdende og påpeger at besparelserne opstår som følge af brugernes interesse og motivation til at påtage sig en energibesparende adfærd. Disse studier stiller spørgsmålstegn ved den potentielle effekt i husholdninger der ikke påvirkes af et øget informations niveau, og anbefaler at alternative former for motivation undersøges.

Med dette Ph.d. projekt er det undersøgt om det er muligt at påvirke beboernes styring af indeklimaet i deres boliger og på den måde at opnå et sundt og komfortabelt indeklima samt et lavt energiforbrug. Projektet er opdelt i et litteratur studie og fire studier med fokus på om og hvordan menneskers styring af indeklimaet kan påvirkes. De fire studier er baseret på måling af temperaturen, luftfugtigheden og luftkvaliteten (CO_2 koncentrationen) i 84 leje lejligheder fordelt på tre bygninger i tre forskellige storkøbenhavnske kommuner.

Betydning af varmeafregningsmetoden i en boligblok blev undersøgt og viste en afgørende betydning for indeklimaet og måden dette styres. Målingerne påviste varmeafregningsmetoden som en adfærds drivende parameter. Samtidig påviste målingerne de mulige energibesparelser der kan opnås ved at afregne varmen baseret på det faktiske forbrug frem for per kvadratmeter.

To forskellige feedback procedurer blev anvendt til at undersøge effekten af indeklima baseret feedback. Den første metode kombinerede real-time feedback og månedlige nyhedsbreve. Den anden metode anvendte real-time feedback i kombination med ugentlige nyhedsbreve. Effekten af feedback metoderne blev undersøgt ved undersøgelse af målinger, interviews og spørgeskemaer. Hensigten med feedbacken var at visualisere indeklimaet for på den måde at guide beboerne til en høj indeklima kvalitet.

Forsøg med de to feedback kombinationer viste på flere punkter, at det var muligt at påvirke beboernes styring af indeklimaet og dermed deres energiforbrug. Især viste kombinationen af real-time feedback med ugentlige nyhedsbreve en betydelig påvirkning af beboernes styring af indeklimaet.

Undersøgelserne viste yderligere vigtigheden af motivation og beboernes lyst til at optimere deres styring var afgørende for effekten af feedbacken. Undersøgelserne viste en tendens af at beboere uden et penge baseret incitament ikke var lige så engagerede, som beboere med et sådanne incitament.

Undersøgelserne viste at jo oftere feedback blev modtaget jo større var effekten. En konklusion i overensstemmelse med konklusioner fra tidligere undersøgelser. Til sidst viste undersøgelserne yderligere at, ved adgangen til real-time feedback skal være så få barrierer som muligt.

4 LIST OF PAPERS

4.1 Journal Papers

4.1.1 Paper 1

Influence of heat cost allocation on occupants' control of indoor environment in 56 apartments: studied with measurements, interviews and questionnaires

Authors: Søren Andersen, Rune Korsholm Andersen and Bjarne W. Olesen
Published in: Building and Environment
Publication status: Accepted 26th February 2016
Link: http://dx.doi.org/10.1016/j.buildenv.2016.02.024

4.1.2 Paper 2

Indoor environmental effects of continuous and monthly feedback in 56 Danish apartments

Authors: Søren Andersen, Rune Korsholm Andersen and Bjarne W. Olesen
Published in: Energy Research and Social Science
Publication status: Submitted

4.1.3 Paper 3

A case study on how to influence indoor environment control using continuous and weekly feedback to the occupants

Authors: Søren Andersen, Rune Korsholm Andersen and Bjarne W. Olesen
Published in: Building and Environment
Publication status: Submitted

4.2 Conference papers

4.2.1 Paper 4

Residential Behavioural Changes through Personal Feedback on Indoor Environmental Measurements

Author: Søren Andersen[a]
Conference: 11th REHVA world congress Cima2013 – Energy efficient, smart and healthy buildings.
Publication status: Published in proceedings and presented at the conference

4.2.2 Paper 5

Indoor Environmental Patterns in Nine California Energy Retrofitted Residences

Authors: Søren Andersen, Brennan Less, Iain Walker
Conference: 6th International Building Physics Conference, IBPC201
Publication status: Published in proceedings and presented at the conference

4.3 Internal Reports

4.3.1 Internal report at Lawrence Berkeley National Laboratory

Behavioural Patterns in 10 California DER Projects

Authors: Søren Andersen, Brennan Less, Iain Walker
Institution: Lawrence Berkeley National Laboratory, Berkeley, California
December, 2014

5 INTRODUCTION

Governments everywhere have now recognized the need to reduce human impact on global climate change by issuing more restrictive regulations on energy use in the built environment [1]. In attempting to reduce energy use practitioners, developers, researchers and many others have dramatically reduced natural infiltration to the point where explicit ventilation strategies are necessary to maintain a healthy and comfortable indoor environment and reduce overheating [2–4]. In buildings where the control of the indoor environment is based on passive strategies, poor air quality and higher indoor air temperatures should trigger more frequent and longer window opening [5,6], but studies have documented air temperatures and CO_2 concentrations above the recommended values [7–9], and this indicates unexpected difference between the expected and the observed occupant strategies: occupants are supposed to open windows adaptively as part of their daily routine.

Most buildings require some kind of conditioning to maintain a high indoor environmental quality whether it be heating, cooling or ventilation. Even though a fully automatic conditioning system can maintain such an indoor environment, it has been shown that occupants prefer to have the possibility to manually control the indoor environment [10]. However, in the process of maintaining comfort, understanding how to use manual input such as thermostats correctly can constitute an obstacle [11]. When occupants act to restore comfort [12], their actions affect both their indoor environment and their energy use.

Occupant behaviour is not only an issue in new buildings. Studies of the energy use in similar buildings have shown significant differences, differences that could only have occurred because of the differences in occupant behaviour and their control of the indoor environment [13–18]. Other studies have surveyed the indoor environment in existing buildings and found an increased risk of developing asthma and allergies because the ventilation rate was too low – a ventilation rate that could have been controlled by the occupants [19].

People differ, but common for all is that we will not change our behaviour unless we are motivated to do so [20]. With the introduction of smart meters and the “internet of things”, it is possible to measure energy use as it happens and disseminate information and feedback on consumption in real-time. Studies of feedback on behaviour that affects energy use have shown that it is possible to reduce energy use through either very simple or very comprehensive feedback procedures [21–26]. Other studies have also investigated the effects of real-time feedback on energy use and their authors have argued that the positive effects expected were dependent on the assumption that people would be motivated by the increased information and that they would therefore be prepared to adapt their behaviour [27–29]. The same studies argued that because people are motivated by different aspects of the surrounding environment it is not possible to design a universally applicable solution so that a feedback intervention should be designed expressly for the user group exposed to the feedback [30,31].

In the Danish heating season the indoor environment (ventilation rate, indoor temperature) is closely linked to the energy used to maintain it, so using feedback to influence how occupants control the indoor environment would also be an opportunity to influence the energy consumption.

The overall aim of this Ph.D. project was to investigate the possibility of using indoor environmental feedback to influence occupants' control of the indoor environment. By informing occupants about the benefits of a high level of indoor environmental quality, how to obtain it, and providing the right everyday tool for monitoring the indoor environment it will be possible to obtain a healthy and comfortable indoor environment with energy use remaining as low as possible.

To achieve the overall aim of the project, the influence of occupant behaviour on energy use was studied in a literature review presented in Chapter 8 - Background. When designing a feedback procedure to influence occupant behaviour it was necessary to know what would influence behaviour, so a review on the drivers affecting occupant behaviour was conducted in Section 8.2 - Drivers affecting occupant behaviour. The survey investigated how such drivers as the outdoor weather, sociodemographic characteristics such as age, health etc. influence occupants' control of heating and window opening - the two options many occupants have to control the energy use and indoor environment. The last part of the literature review was a survey of feedback procedures. First, feedback methods such as continuous and daily feedback were surveyed. Next, detailed feedback mechanisms such as comparative feedback and tailored feedback were studied.

This Ph.D. thesis is based on the papers listed in Chapter 4, so only the essential findings and conclusions were presented, although as some results were not included in the papers they have therefore been discussed in more extensive form. The literature findings of the papers were incorporated in Chapter 8 - Background. Chapter 10 - Study 1 – Influence of heat Cost allocation presents the first study based on Paper 1. Paper 1 reported a detailed study of the influence of heat cost allocation type on the indoor environment in sub-metered and master-metered apartments. Studies 2 and 3, presented in Chapter s11 and 12 respectively, examined the influence of two different feedback procedures, based on indoor environmental measurements. In Paper 2, a combination of continuous and monthly feedback was tested in two different buildings and a total 56 apartments. In Paper 3 a combination of continuous and weekly feedback was tested in 18 apartments. The development of the weekly feedback letter was not part of Paper 3 and is therefore presented in Chapter 12. In addition to the findings of Paper 3, a study on the influence of the age of the occupants and the presence of children was conducted in Study 3 and presented in Chapter 12. In Chapter 13, Study 4 presents and elaborates on an assessment method partly used in Paper 7. The method was used to determine how occupant behaviour affected the indoor environment. The method was further used to investigate whether occupant behaviour affected the indoor environment similarly every day and whether patterns in individual daily use of energy could be established.

6 HYPOTHESIS

With a few exceptions, a households' energy use is largely determined by what is required to maintain the indoor environment. In residences the indoor environment is controlled by the occupants, which thereby indirectly control the energy used to maintain it. The literature review for this Ph.D. project found that feedback based on actual energy use did not always lead to the expected energy savings, so alternative methods should be developed and tested. The overall hypothesis of this Ph.D. project was that feedback on the indoor environment can be used to influence the occupants' control of the indoor environment and thereby their energy use for heating.

6.1 Hypothesis 1

Using indoor feedback based on the indoor environment to reduce energy use is possible because most people understand the relationship between the thermal environment and the energy required to maintain it: occupants have the necessary insight.

6.2 Hypothesis 2

A combination of feedback methods and mechanisms must be provided if they are to have the desired effect: Continuous feedback provides essential information in real-time about current conditions, while monthly and weekly feedback is also required to provide an overview of this information.

6.3 Hypothesis 3

Occupant behaviour in controlling their indoor environment constitutes their influence upon it and takes place according to a daily routine. This routine determines the building's indoor environment and can be used to diagnose when changes are required.

7 OBJECTIVES

The overall aim of this Ph.D. project was to develop and present feedback procedures based on measurements of the indoor environment. The purpose of the feedback procedures should be to help occupants obtain and maintain a healthy and comfortable indoor environment and use less energy in so doing. A subsidiary purpose was to determine and quantify the influence of the feedback procedures. To reach the overall objective three sub-objectives were therefore established:

7.1 Sub-objective 1

Determine to what extend occupant behaviour affects the indoor environment and energy use in residential buildings. Identify behavioural drivers affecting occupant behaviour and determine how these can be used to influence occupants' control of energy use and the indoor environment. Review methods for providing feedback on energy use for heating and mechanisms that can be used to influence occupant behaviour.

Sub-objective 1 was addressed in the literature study and in Study 1.

7.2 Sub-objective 2

Develop feedback procedures based on the indoor environment, enabling occupants to make informed decisions on how they should control the indoor environment. Test and document the influence of the feedback procedures through quantitative measurements and qualitative surveys. Determine whether indoor environmental feedback is capable of enabling occupants to achieve a high level of indoor environmental quality.

Sub-objective 2 was addressed in Studies 2 and 3.

7.3 Sub-objective 3

Determine if occupants' behaviour affects the indoor environment according to a daily pattern. Develop a method to assess and determine how occupants' daily routines influence the indoor environment. From the data set collected in Study 3, use this approach to determine whether the indoor environment was affected similarly every day throughout the experiment. Assess how an identification of routines can be used in feedback procedures as presented in Studies 2 and 3.

Sub-objective 3 was addressed in Study 4.

8 BACKGROUND

In this section, literature on occupant behaviour is reviewed and analysed in terms of its influence on energy use and control of the indoor environment. Behavioural drivers are reviewed to determine the parameters affecting occupants' control of heating and window opening. Feedback methods and mechanisms are reviewed with respect to how they could be used to provide feedback on the indoor environment.

8.1 Occupant behaviour's influence on energy use

In this section, papers on the effects of occupant behaviour on energy use are reviewed.

Janda named her 2011 paper: Buildings don't use energy: People do. She argued that building users play a critical but poorly understood and often overlooked role in the built environment [32]. This statement was not new, but had been proven repeatedly since the Twin Rivers program in the 1970's [13]. Socolow concluded, based on energy use in 3000 similar homes in New Jersey, US, that energy use was significantly influenced by the occupants' attitude and beliefs. Sonderegger studied 205 town houses within the Twin Rivers project and found that the lowest and highest rate of energy differed by a factor three [14]. The study showed that only 54% of the differences could be explained by the differing physical characteristics of the buildings, leaving 46% of the variance unexplained.

Raaij et al. studied 145 houses in the Dutch town of Vlaardingen, focusing on those aspects of occupants' behaviour that affected energy consumption. The paper showed an average difference of 31% between the least and highest consuming group of occupants and the paper further showed that the differences mainly occurred because of the occupants' differing perception of thermal comfort [15]. Owens et al. reviewed 31 Nordic papers surveying the energy conservation potential from 1970's to the end of 1980's. The review identified a 10-20% potential energy saving within the period and suggested that comfort was one of the main drivers for energy use and potential energy savings [16]. Maier et al. studied the energy use and indoor environment in 22 apartments, which except for their ventilation systems were identical. The study found a difference of 284% between the lowest and highest consumer. The temperature recordings in the study showed that the lowest energy use was found in the apartment with the lowest average indoor temperature [33]. Andersen described this correlation as an indication that occupants control their heating bills by altering the indoor environment [34].

Andersen studied the energy use for heating in 290 identical town houses in Denmark [17]. The study found that the highest and lowest energy consumption differed by a factor of 20. The houses were identical, leaving the paper to conclude that the differences occurred because of the occupant behaviour. Hens et al. studied the differences in energy use between low-income households in two different buildings to determine the rebound effect in 965 households. The paper found a difference of 223% between the highest and lowest consumption in Building 1 and 235% in Building 2 [35].

The above papers found differences between the highest and lowest consuming households of up to a factor 20. Although not all studies found differences of this magnitude, all studies found notable differences, differences that occurred because of the occupants' behaviour and their control of the indoor environment. Since the differences occurred as a consequence of occupant behaviour, these studies showed that considerable energy savings were achievable if the occupants adapted a more energy conserving behaviour.

Behavioural changes seldom occur spontaneously, but have to be initiated by some kind of motivation [20]. Cholewa et al. studied the effects of introducing heat cost allocation to individual apartments in a Polish multifamily building over 17 heating seasons. The study found differences of 27% between apartments with individual heat cost allocation and apartments without, in the expected direction [18]. Assuming identical physical performance of the entire building, the differences occurred because of differences in the occupant behaviour. This finding not only supports the findings of the above-mentioned studies, but also implies that occupant behaviour can be influenced by drivers at both the macro-political level and the micro level where the occupants' immediate actions are influenced.

The above papers demonstrated the influence of occupant behaviour on heating consumption. However, as some studies found the control of the energy use to be controlled by occupants' perception of the thermal environment, it seems plausible that similar findings would occur in countries where cooling is predominant.

Humphrey et al. showed how occupants' perception of the indoor environment is the basis for their control of it [12], but only one of the above studies determined how occupant behaviour affected the indoor environment. Maier et al. [33] and Andersen [34] noted that certain occupants accepted low indoor temperature in in order to reduce heating consumption, and this may have been how energy savings were achieved in the other studies. In the following section the influence of occupant behaviour on the indoor environment is reviewed.

8.2 Occupants' influence on the indoor environment

The following section reviews studies which quantitatively or qualitatively documented how occupant behaviour affected the indoor environment. Some of the studies were carried out in older buildings and some in newly renovated buildings. In this context the indoor environment was defined as the air temperature, moisture/relative humidity and air quality (in most cases as indicated by the CO_2 concentration).

The previous section demonstrated the influence of occupant behaviour on energy use. A reason for the differences is that occupants rarely have the same clothing level, activity level, metabolism, or thermal preferences and therefore experience the thermal indoor environment differently and thus will react differently. Nicol et al. [36] with reference to Humphreys et al. [12] stated that: *If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort.* Assuming that peoples' reaction differ, some will retain comfort by adapting their clothing level [37], some might adapt the thermostat set point [38], and others will react in a some other way, such as by opening or closing a window, each type of reaction will impact energy use differently.

8.2.1 Quantitative studies of the effects of occupant behaviour on the indoor environment

Despite the obvious influence of the occupant behaviour on the indoor environment it has not been possible to find a wide variety of studies quantifying the differences. The following four studies provide examples of the differences that can occur because of occupant behaviour.

Van Raaij et al. studied the home temperature and ventilation in 145 Dutch households in relation to their energy consumption [15]. The study categorised the occupants in terms of their energy use and their indoor environment, and showed how occupants' preferences for the indoor environment were reflected in their heating consumption. No specific consumption values were presented, but the paper concluded that*: comfort is the most important attitudinal component* (van Raaij &

Verhallen 1983, page 101). Maier et al. studied energy use and indoor environment in 20 identical German houses with four different ventilation strategies. Differences between the houses in both their energy consumption and their indoor environment were documented [33]. The paper showed that the average temperature in 19 of 20 apartments was within the Indoor Category I according to EN 15251-2007 [39] and could therefore be assumed to be found comfortable. However, the study also found that the lowest indoor temperatures occurred in households with the lowest energy consumption. The study surveyed the CO_2 concentration in all apartments and found the average CO_2 concentration in apartments with mechanical ventilation systems to be 33% lower than in apartments with natural ventilation (window opening) [33]. Gunay et al. studied behavioural effects on the electricity consumption in apartments with and without sub-metering. The study surveyed the thermal environment in 40 identical Canadian apartments and found the average indoor temperature to be 2°C lower in sub-metered than master-metered apartments [40]. The paper concluded that occupants with a communal incentive to reduce costs maintained a higher indoor air temperature than was found in apartments in which there was a direct and personal monetary incentive.

These three studies [15,33,40] demonstrated that control of the indoor environment was based on the occupants' perception of comfort, and how this driver could in some cases be overruled by the occupants' need to reduce their heating costs. This finding indicates that occupants have a good understanding of the indoor environment and know that a low heating bill can be obtained by maintaining low indoor temperatures. The finding further indicates that occupant behaviour can be affected by drivers that can be changed quite easily, e.g. it is easier and cheaper to install heating cost allocation to individual apartments than to increase the insulation level of a multi-storey apartment building.

The ability of occupants to maintain a healthy indoor air quality was studied by Bekö et al. [7]. The study surveyed the ventilation rate in children's' bedrooms in 500 Danish homes and found that 68% of the bedrooms had a nightly average CO_2 concentration above 1000ppm. Seen in relation to the study of Bornehag et al. who found an increased risk of allergy in houses with a low ventilation rate [19], the findings of Bekö et al. thus indicate that control of the ventilation rate might have a crucial impact on the long term health of the occupants.

8.2.2 Conflict between building installations and occupants

Brunsgaard et al. performed a post-evaluation of eight certified passive houses in Denmark. The houses were all different, but were close together in the same town. The paper evaluated the differences between the expected and the actual indoor environment, and found that one of the main reasons for the differences was the occupants' lack of knowledge on how to operate the building systems [2]. This finding that could explain why Maier et al. found that occupants preferred to open a window than to increase the mechanical ventilation rate [33]. This indicates that an insufficient introduction to the operation of the building installations had been provided.

In many households the thermal environment is controlled by window opening and the occupants' willingness to adjust the thermostats. Peffer et al. reviewed the historical development of thermostats in the United States and their usability. The study focused on programmable thermostats and found that the expected energy savings were not achieved because of misconceptions on how to optimally control the thermostats [11]. The paper did not quantify the effects of the occupants' problems with programmable thermostats, but it did state that if energy conservation is to be achieved through correct use of thermostats their operation must be intuitive.

The two papers showed how the misuse of building installations increases the differences between the design conditions and actual indoor environment and energy consumption. The studies also indicated that a sufficient introduction to the building systems and intuitive use can help to reduce the gap between the expected and the actual energy consumption. The studies further indicated that the operation of building installations must be intuitive if they are to be used adaptively.

8.3 Drivers affecting occupant behaviour

Occupant behaviour can be influenced by factors ranging from international policies [1] to the outdoor temperature at any given time [41]. The purpose of this section is to survey how energy use, indoor environment and occupant behaviour are affected by these so-called drivers. Various drivers are evaluated in terms of how they could be incorporated into a feedback situation.

8.3.1 Values, beliefs and attitude

The studies presented in this section examined the influence of values, attitudes and beliefs on our everyday life and energy consumption.

In 1979 Seligman et al. studied the factors that influenced energy consumption during a summer period in US households. The study included 125 households and showed that attitudes related to health and comfort could predict 30 - 42% of the variance in the measurements [42]. Another interesting finding of the study was that some households expressed an attitude of not believing in science and of questioning whether the 1970's energy crises were real. Such debates are highly relevant in the climate change debate in 2016, as it implies that feedback based on the necessity of energy conservation to avoid climate change are useless if the recipients will not acknowledge that global climate change is real.

Brandon et al. surveyed energy consumption over a 9 month period in 120 households in Bath, UK. The influence of different feedback techniques and environmental beliefs were analysed using regression models. The study found that pro-environmental beliefs had a significant but only marginal influence on energy consumption [43]. Vringer et al. examined consumers' attitudes to energy conservation in relation to their energy consumption, in a study that included 2.304 households. The study was unable to find a correlation between energy consumption and the value patterns of each household. The authors concluded that energy conservation policies that depend on influencing individual households to reduce their environmental impact will not be effective [44].

O'Callaghan et al. examined how environmental attitudes influenced the energy consumption for occupants in "sustainable houses" in Perth, Australia [45]. The study related energy consumption measurements to replies in response to questionnaires. Occupants in conventional dwellings were used as a control group. No statistically significant effect of pro-environmental attitudes was found. The authors concluded that the biggest influence on energy consumption was the design of the house [45]. It would have been interesting to investigate why the occupants had chosen to live in a "sustainable house" instead of a conventional house; this was not part of the study.

Sapci et al. studied the correlation between energy consumption and environmental attitudes in 612 households in the USA. They found that environmentally concerned households conserved more electricity than households expressing no environmental concerns [46], a finding indicating a positive influence of occupants' attitudes. The study further found that a non-pro environmental behaviour can be changed over time by initiatives that change attitudes. Ek et al. studied electricity use in Swedish household to determine their willingness to increase their effort to consume less energy. The results showed that environmental attitudes were an important driver for electricity saving activities [47]. In a study on energy literacy, awareness and conservation behaviour Brounen et al. found those consumers' attitudes to energy conservation did influence their use of heating and cooling installations [48].

Seligman et al. [42]. Sapci et al. [46], Ek et al. [47], and Brounen et al. [48] all found an influence of occupants' attitudes and beliefs on energy consumption, indicating that feedback interventions whose purpose is to influence occupants' attitude will be effective. Brandon et al. [43], Vringer et al. [44], and O'Callaghan [45] found some evidence against this conclusion, and predicted that attitudinal campaigns will fail. These contradictory results illustrate the complexity of this issue. However, in the light of this complexity it was considered that intervention strategies designed only to affect pro-environmental attitudes as a way of reducing energy consumption might fail. In Study

3, the feedback procedure was therefore designed to include several feedback elements of which only one was intended to influence occupants' environmental beliefs and attitudes.

Outside the built environment, Gatersleben et al. studied the relationship between sustainable values and materialism. This study found that materialism and environmental concerns were related to two different types of behaviour and that a person can exhibit both simultaneously [49]. O'Callaghan briefly reflected on this topic: by explaining how occupants were willing to adopt energy conserving behaviour, but only after their materialistic ambitions have been achieved [45]. These findings that further indicate that a successful intervention strategy must be designed to influence an occupant from several angles.

8.3.2 Heat cost allocation as motivation

Monetary incentives have in many situations proven to be a driver for people's behaviour. In this section, studies investigating the influence of the type of heating cost allocation used are evaluated, in order to quantify the effects of sub-metering and master-metering.

As earlier described, Cholewa et al. studied the influence of heat cost allocation to individual apartments in a Polish building over 17 heating seasons. After seven heating seasons the thermal insulation of the apartments was increased, and after a further six heating seasons heat cost allocation to each individual apartment was installed [18]. The study showed that individual heat cost allocation gave the occupants a monetary incentive to conserve energy and to what extent the occupants adapted their behaviour when heat cost allocation had been installed: energy consumption was reduced by 21%, after correcting for the outdoor temperature [18].

Table 1 Potential energy savings with the introduction of individual heat cost allocation, studied by Cholewa et al. [18]

	Original design	After increased insulation level	After introduction of heat cost allocator in all apartments	Last surveyed heating season
Difference in energy use [%]	26%	30%	12%	5%

Gunay et al. studied how using sub-metering or master-metering affected the thermal environment. The paper found that sub-metered apartments kept their average indoor temperature 2°C below that of master-metered apartments. The paper further showed how a monetary incentive caused occupants to maintain a lower indoor temperature and thereby reduce their energy use, in comparison with occupants without such a direct and personal monetary incentive [40]. The paper showed that occupants with a direct and personal monetary incentive controlled their indoor environment more actively than the control subjects were prepared to do. This finding indicates that feedback should preferably be provided at the level of individual rooms, so that it can be used to control the indoor environment at room level and hence the household's energy consumption.

Levinson et al. studied the influence of including utilities in the rent and why landlords tend to do so [50]. The study found that if utilities were included in the rent, occupants consumed more energy and would maintain a slightly higher indoor temperature when the apartments were unoccupied than in apartments in which utilities were not included. The paper further argues that including the utilities in the rent gives landlords a monetary incentive to upgrade the thermal efficiency of their buildings to reduce energy consumption [50], while individual heating cost allocation does not. On the other hand, Ziemele et al., after examining the criteria for implementing heat cost allocation, concluded that the variable part of an energy bill should be as large as possible to obtain the highest possible energy savings [51]. This will increase the magnitude of the potential energy savings and thereby increase the monetary reward in the form of a lower energy bill. According to the findings of Maier et al. [33] the increased monetary incentive could result in lower temperatures, perhaps even so low that the dew point of the indoor air would be reached in the joints of the building, even if windows are opened so as to maintain good indoor air quality.

Assuming that occupants will be influenced by information and feedback, occupants with individual heat cost allocation should be informed on the importance of adjuring the indoor environment to avoid conditions that might damage the building or expose the occupant to unnecessary health risks (e.g. risk of mould formation because of a low ventilation rate, low indoor temperature and high relative humidity levels). Using indoor environmental feedback in apartments with utilities included might also be beneficial, as this could provide occupants with the ability to control the indoor environment in such a way as to be comfortable and to use less energy.

These four studies showed how occupant behaviour and occupant control of the indoor environment were to a high degree influenced by individual heat cost allocation. The studies further showed that a monetary incentive leads to a higher degree of energy conservation. Guany et al. [40] and Levinson et al. [50] documented how individual heat cost allocation led to changes in the thermal environment. These studies were continued in Paper 1, which studied how the heat cost allocation type influenced occupants' control of the temperature, relative humidity and CO_2 concentration.

8.3.3 The influence of rebound and pre-bound effect

When moving into new or newly renovated houses occupants now have certain expectations, one being a low heating cost. This expectation encourages the occupant to increase the heating set point and thereby consume more energy than expected. This so-called rebound effect has been demonstrated and quantified in many studies. In this section, some of these studies are reviewed to determine the magnitude of the rebound effect. This section also introduces the "pre-bound effect". This is an effect in the opposite direction to the rebound effect, which appears when occupants know that it would be expensive to maintain a high indoor temperature and therefore reduce their consumption to less than the calculated consumption.

Hass et al. studied the rebound effect in retrofitted homes in Austria and reported a 15 to 30% effect of rebound [52]. Eydin et al. attempted to quantify the rebound effect from records of the energy use in 560.000 Dutch homes and information on their occupants [53]. The study categorised the households and found that the rebound effect was 41% for tenants and 27% for homeowners. The study further analysed the rebound effect for tenants as a function of income and found that in households in the lowest wealth quintile the rebound effect was 49%. In general the study showed that as wealth increased the rebound effect decreased, as would be expected. The wealthier occupants were presumably not cost sensitive and were likely to have maintained a high indoor temperature in their previous home [53].

Knudsen et al. investigated the occupants' satisfaction with their New Low-Energy Houses and found occupants dissatisfied with the discrepancy between their expected energy consumption and the actual energy consumption. The paper reported that occupants had problems controlling the technical equipment, which could be one of the reasons that they used more energy than expected [3].

The above findings suggest that by combining feedback on energy consumption and feedback on the indoor environment, occupants would be able to see the effect of a high indoor temperature and from this make an informed decision regarding their control of the thermal environment.

Gram-Hansen presented a comparison of the calculated and the actual energy consumption for heating in Danish dwellings depending on the energy label [54] [55]. The study showed how the actual energy consumption in houses with an energy label A, B, C (the high energy efficiency categories) and partly D was very considerably higher than what had been calculated. Meanwhile, the reverse was found in houses with the low energy efficiency ratings E, F or G. Sunikka-Blank et al. defined the latter situation as a pre-bound effect [55]. Sunikka-Blank et al. studied the pre-bound effect in 3.400 German households and reported that the effect occurred in dwellings with low thermal efficiency. The pre-bound effect was indirectly studied in Study 1 of the present project, where occupants were willing to accept a low thermal indoor environment to obtain a low heating cost.

8.3.4 The power of occupants' comfort

The above-mentioned studies demonstrated how some drivers influence human behaviour and attitudes. In this section the influence of occupants' comfort on their energy use is reviewed.

Huebner et al. studied the influence of comfort in relation to energy use and found comfort was often viewed as synonymous with thermal sensation [56]. A similar finding was reported by Frontczak et al. who found that the overall acceptability of the indoor environment can be determined by the acceptability of the thermal, visual, acoustic and air quality conditions, in that order [6]. This means that in a feedback situation, knowing that the thermal environment is a main driver for comfort indicates, for instance, that the ventilation rate cannot be increased to the detriment of thermal comfort, because as Nicol and Humphrey pointed out, people will adapt their behaviour to regain thermal comfort [12,36].

Raaij et al. reported that in the Netherlands, older energy consumers preferred a warmer thermal environment and a low level of ventilation [15] [15]. This finding was supported by Sardianou who found, based on empirical results obtained in Greek homes, that the age of the occupants and their need for heating were positively correlated [57]. Additionally, studies have shown that elderly people spend more time at home, often have bigger houses and prefer a warmer thermal environment than younger people [58]. This is an issue that policy makers have to consider, as a growing population of older people increases the absolute energy use in countries with an aging population [59–61].

8.3.5 Drivers influencing control of the indoor environment

Frontczak et al. studied which indoor environmental factors had the biggest influence on subjective comfort in Danish households. The paper found that occupants' indoor environmental comfort was influenced by the acceptability of the thermal, visual, acoustic and air quality conditions [6]. The paper also reported that occupants preferred to manually control window opening and disliked automatic control. This section reviews the factors and drivers that influence how occupants control window opening and heating.

Rijal et al. [62] and Andersen et al. [63] studied drivers influencing window opening behaviour. As expected, both studies found that the outdoor temperature was the main driver. Andersen et al. found that female occupants tended to open windows more frequently when the environment was perceived as bright as compared to dark, while male occupants did not [63]. Karjalainen reviewed studies on gender differences in thermal comfort and thermostat control and found female subjects to be more active and more sensitive even to small changes [38]. These findings support the proposition that different feedback should be provided to each gender. Andersen et. al found that the CO_2 concentration had the biggest influence on opening a window, while the outdoor temperature was the most significant influence for closing a window [64]. A literature review by Fabi et al. [41] surveyed drivers affecting window opening behaviour in dwellings and found that wind direction, rainfall, income, thermal sensation, day of week, wind speed, age and solar radiation were not drivers for window opening behaviour.

In many cases the thermal environment is controlled by the occupant interacting with a thermostat [11], which has a direct influence on the energy use. Andersen et al. found that the use of heating was strongly linked to the outdoor temperature. The paper further found that the proportion of the house that was heated was not influenced by the price of the heating [63], a tendency that could be enhanced and optimised by feedback at room level, a strategy that was tested in Study 3.

Leaman et al. reported that once office workers have adjusted a window or a thermostat because they were uncomfortable, it will not be re-adjusted when they have regained comfort, but only when they again experience discomfort [65]. This indicates that a positive effect might be obtained if a user or occupant were provided with a tool to assess the current indoor environment, so they could act in time before becoming uncomfortable. For example, if a window was opened to improve the air quality it should theoretically be closed when the indoor CO_2 concentration has approached the outdoor concentration. Subjectively assessing when this has occurred is very difficult, but a real-time feedback device would enable the occupant to precisely assess the indoor air quality and thereby avoid an unnecessarily long venting period that cools the room surfaces and thus leads to excessive use of energy to reheat them.

8.3.6 General assessment of the findings

The literature review has shown that the significance of some drivers may vary. The discrepancies between different studies illustrate the complexity of occupant behaviour and the drivers that affect it. Despite contradictory results it may be concluded that influencing and changing the environmental attitude of occupants could lead to energy savings. The studies reviewed show how comfort and especially thermal comfort is the main driver for occupant behaviour and control of the indoor environment. However, it was also demonstrated that a monetary incentive can in some cases overrule the desire for improved thermal comfort. The findings of this section support the hypothesis that providing occupant feedback on the indoor environment is a viable approach for reducing energy consumption in dwellings.

8.4 Using feedback to influence behaviour

Section 8.2.1 Values, beliefs and attitude demonstrated the importance of inducing a pro-environmental attitude to reduce consumers' energy use. Even though it was not explicitly demonstrated in these studies, it is reasonable to assume that people with a pro-environmental attitude were more motivated to reduce their energy use than people without a pro-environmental attitude. P. Wesley Schultz described how increasing knowledge and education was not enough to change behaviour, but argues that motivation is the key factor if behaviour is to be changed [20] [20].

Motivation rarely evolves spontaneously; it originates from campaigns, information, experience, emotions, social awareness etc. In this section, studies using multiple feedback methods to promote energy conserving behaviour are reviewed. The first part is a literature review of such feedback methods as continuous feedback and monthly feedback. The second part is a description of the feedback mechanism used within the feedback methods. The use of feedback is based on sociological and psychological theories outside of the scope of this dissertation that are therefore mentioned only briefly. The studies reviewed in this section had focused more on the effects of the feedback methods and less on why and how they influenced behaviour.

8.4.1 Low, medium and high dissemination frequency of feedback

In this section feedback method disseminated with low, medium or high frequency are reviewed. The review was conducted as part of Papers 2 and 3.

Continuous feedback is a method of providing real-time feedback on a measured parameter, which informs the user about the effects of their current behaviour. Smart meters have become the preferred way of providing continuous energy feedback, however, before smart meters and the "internet of things" made continuous feedback broadly accessible, continuous feedback had been tested and the effects had been documented in several studies. Paper 2 described how McClelland et al. [21] and Houweling et al. [22] used continuous feedback to reduce electricity and gas consumption by 12%. When smart meter programs were introduced they were accompanied by in-home displays visualizing real-time electricity use. The effect of in-home displays on energy use was investigated in several studies and found to reduce the average electricity consumption by 7% to 18% [23–26]

One study compared in-home displays in the price range of $20-$110 [25] with a Japanese study using an in-home display system costing $5.000 [26]. Despite the differences in cost, both studies reported reductions in energy consumption of about 10%. It should be noted that the Japanese study found heating reductions of 20-45% [26]. The Danish study *eButler,* studied the introduction of smart meters in 1400 Danish households [66]. The energy use of the 2013/14 and 2014/15 heating seasons were compared and showed that the energy use in households without smart meters increased by 2,4% while it increased by only 1% in households with smart meters (the average outdoor temperature was 0,5°C lower in the heating season 2014/15, causing a natural increase in energy use). Another finding of the *eButler* project was how the users accessed the feedback. Feedback was accessible through a website and a smartphone application. The login process was monitored and showed a clear tendency for occupants to access feedback via the smartphone application more often than via the website [66]. Regarding the use of the feedback system used in *eButler*, the study found that the first steps of using feedback to be crucial. Users who became confident with the system from the start used the system throughout the entire intervention period.

Table 2 Electricity savings initiated by in-home displays

Study	Date	Region	Number of households [-]	Average savings [%]
Ueno et al.	2005	Japan	10	12%
Darby	2006	Multiple	-	10%
Faruqi et al.	2010	North America, Japan, Australia	>1000	7%
D'Oca et al.	2015	Italy	30	18%

When used in combination with continuous feedback, daily and weekly feedback may be required to maintain the interest and novelty of continuous feedback, which otherwise may exhibit "feedback fatigue" [67][70]. Since the advent of smart meters, the number of studies using daily and weekly feedback alone has decreased. In 1976 Seligman et al. conducted a study where the percentage of the predicted energy use for air conditioning, was displayed by daily feedback in the kitchen window [68]. The study compared the daily energy use of the intervention group to a control group; both groups received information on how to reduce their electricity use through reduced use air conditioning use. Over a five week period, the feedback group reduced their daily electricity consumption by 10% compared to the control group [68].

Disseminating feedback on a monthly basis was in this PhD project defined as medium frequency. The energy bill is a simple form of feedback, informing consumers of their consumption which then might encourage them to conserve energy. Wilhite et al. tested the effect of a more informative energy bill in Oslo, Norway. The study showed that by simplifying the traditional energy bill and adding a historical comparison, energy reductions of 10% were obtained [69]. Abrahamse et al. reviewed studies investigating the effect of monthly feedback; the studies showed an effect but did not report any actual reductions [70].

The studies reviewed above showed how feedback with varying dissemination frequency influenced energy use. The studies of feedback that were performed before smart meters seemed less cost efficient than the newer studies as many of the feedback processes were not automated. However, the older studies showed how alternatives to in-home displays could be used. Based on the reviews' by Abrahamse et al. [70] and Fischer [31] it may be concluded that to achieve as much influence as possible feedback should be disseminated as frequently as possible [31,70]. These conclusions were applied in Papers 2 and 3, in which continuous feedback was combined with either monthly or weekly feedback.

The review of continuous, daily, weekly and monthly feedback was concerned only with the dissemination frequency. The following paragraphs review various feedback mechanisms that used different approaches to motivate and encourage the occupant to conserve energy.

8.4.2 Comparative feedback

A recognized feedback mechanism is comparative feedback, where the performance of a parameter is compared to historical data or to the performance of other households.

Using historical data as feedback gives the user an opportunity to follow developments in their energy use and so to be able to react if their energy consumption increases or decreases. In 1989 Wilhite et al. studied the effects of using historical comparison on the energy bill in Oslo, Norway. As described earlier, a combination of feedback mechanisms including historical comparison decreased the energy use by 10% over a three year period [69].

Social comparative feedback or social norms is when the individual is compared with a group. The American company O-Power provides their customers with a comparison of their energy use with that of their neighbours [71]. Comparative feedback is rarely used alone so determining its effect is difficult. However, Allcott studied the effects of comparative feedback in 600.000 US households and estimated that they caused a reduction of 2% in energy consumption [71]. Abrahamse et al. reviewed several studies (all combining different feedback mechanisms) and concluded that comparative feedback had led to considerable energy savings [70].

The effect of comparing individual use with social norms is highly dependent on the group with which the individual is compared. For the greatest effect, individuals should be compared with a group similar to themselves, e.g. their neighbours [72–74].The effects of social norm comparisons can be further enhanced by creating a sense of proximity. McAlaney et al. suggested that using local landmarks etc. in the feedback will help occupants to relate to the comparison and will thereby increase the effects [75]. In selecting an appropriate basis for the comparison, Burchell et al. stated that it is also important to use believable data [76]. As an example from outside the built environment, Granfield [77] studied a failed alcohol-related campaign in which 45% of the participants did not believe the data.

Using comparative feedback and social norms will often be a comparison of the individual to the average of a group. As the average then becomes the social norm, people will adapt their consumption towards the average, and although this is beneficial for those with below average performance, it does not have the intended effect for those already above average. This effect, described as the boomerang effect, can be avoided by attaching a positive message (i.e. “Great! You are above average and we hope you will stay there!”) to feedback on energy consumption and in relation to the average. Schultz et al. described the boomerang effect based on Cialdini’s findings in focus theory [74,78]. Both Schweiker et al. [79] and Geller [80] supported the use of positive messages. These aspects were discussed in detail in Paper 3.

8.4.3 Goal setting, commitment and rewards

Goal setting and commitment can be used as a feedback mechanism where an occupant defines a target for their future energy use, indoor environment or something similar and the occupant is then encouraged to reach this goal or commitment. Goal setting and commitment are often used in feedback methods as they allow the occupant to see how far they are from the goal or if they meet the expectations of the commitment [70]. Goal setting can further be described as a gamification factor, where adopting energy conserving behaviour is seen as a game and not as a necessary but negative obligation [81].

As part of the Twin Rivers program, Seligman et al. studied the effects of goal setting and the compared setting an easy goal with setting a difficult goal, with and without feedback [68]. The results showed an almost non-existent reduction in apartments with no feedback and an easy goal. Meanwhile, occupants with a difficult goal and feedback reduced their daily energy consumption by about 13%, compared to a control group [68]. Houwelingen et al. conducted a similar study combining goal setting and daily feedback, supporting the findings of Seligmann et al. by documenting larger savings by an intervention group in comparison with a control group and other feedback intervention types [22].

In a more recent study, Abrahamse et al. studied a combination of tailored information, goal setting and feedback designed to reduce direct energy use (gas, electricity and fuel consumption) and indirect energy use (energy for production, transportation etc.) [30]. The intervention group was divided into two group, one which could chose a goal and one that was assigned the goal of a 5% direct energy reduction. The results showed that both group attained their goals (in both cases there was a 5% reduction). The paper concluded that perhaps the goals had been too easy to achieve [30].

Setting a goal or committing to a certain energy saving often requires sacrifices of some kind. Schultz therefore recommended that when reaching a goal or when meeting the commitment occupants should receive some kind of reward [20]. Abrahamse et al. [70] surveyed three studies including reward programs, and found energy savings from 2% to 11% over the short term [21,82,83]. Both Abrahamse et al. [70] and Geller [80] concluded that reward programs have proven efficient, but that they were only efficient in the short-term and only when the reward is present. Geller further described how using a reward just big enough to initiate a certain behaviour will provide long term effects, while large rewards lead only to instant effects [80].

Goal setting and commitment were not used in this Ph.D. project, as it was considered that it would have required some kind of interaction between the occupants and the authors. However, using commitment to influence behaviour seems very useful when combined with real-time indoor environmental feedback. For example, if an occupant commits to open a window when CO_2 concentration is too high, the occupant will experience what it requires to maintain a high indoor air quality and from this experience may then be able to decide if he wants to use the feedback.

8.4.4 Combination of feedback methods and mechanisms

Determining the influence of a single feedback method and/or feedback mechanism was difficult as most studies had combined several, and with good reason. As described earlier by Seligman et al. the difference between using goal setting alone and goal setting in combination with feedback was a difference of conserving zero percent to occupants conserving 10% [68]. Seligman's findings have received support from the review of Abrahamse et al. [70] and from Ek et al. [47] who concluded and recommended that a feedback intervention should combine multiple feedback methods and mechanisms.

8.4.5 The importance and challenges of knowledge and information

The studies presented in this review all showed a reduction of energy consumption following interventions enabling occupants to make informed, logical and rational decisions – information and insight were the key factors for the reductions. Assuming that more information will lead automatically to reductions in energy consumption is not just common in the built environment, but also in smartphone applications tracking everything from body weight to hours of REM sleep. However, in recent years some studies have questioned the effects of information and the notion that more information must lead to energy reductions. The following paragraph will present a range of these studies and arguments that have been used to develop the hypotheses tested in the present project.

Ek et al. studied occupants' subjective willingness to adopt energy saving measures, when knowing more about potential savings. The paper concluded that more information made no difference [47]. As noted earlier, Seligman et al. studied the effects of receiving information and daily feedback compared to simply receiving information [68]. The study found that households receiving only information on how to reduce their energy use consumed 10% more than the households that also received daily feedback. This finding indicates that information alone does not necessarily reduce energy consumption.

Hargreaves et al. [67], Oltra et al. [84] and Nilsson et al. [27] studied the effects of in-home displays and demonstrated that the effects in some cases were very limited. The studies found that a lack of motivation and interest were the main barrier, which corresponds well with the emphasis that Schultz places on the importance of motivation [20]. These studies also found that for occupants to be influenced by the feedback it is essential that the feedback is easily understood and intuitive, a finding supported by Fischer [31] and Krishnamurti et al. [85].

Contributing to the policy debate, two studies by Buchanan et al. [28,29] questioned the advantages of continuous feedback and whether a major roll-out of smart meters will lead to the expected energy reductions. Both studies raised the question of user involvement and whether this can be assumed in all cases. In their 2014 paper, Buchanan et al. studied how highly motivated occupants used an in-home display that they had bought. The study found that a high degree of user involvement was necessary to reduce energy consumption [28]. The authors speculated on whether the same reductions would be achieved in households that were less motivated to engage in energy conserving behaviour [28]. In their 2015 paper, Buchanan et al. found short term reductions of 2% following the installation of in-home displays and questioned whether savings of this magnitude were sufficient for putting a smart meter in every UK household, as this would make the UK energy conservation policy dependent on each citizen's ability to reduce their energy consumption by acting on the information [29].

It should be noted that Buchanan et al. were not against the use of smart meters, but pointed out that a UK roll-out should be performed using innovative and performance-tested feedback approaches[29]. In a 2016 paper Buchanen et al. suggested that methods of increasing motivation should be tested as alternatives to providing monetary incentives [86].

8.5 Hypotheses and recommendations for feedback interventions

The above literature review concluded that feedback on energy consumption can affect occupants' energy consumption and this was a conclusion that was well-supported by several of the studies reviewed [23–26]. The conclusion was however only found to be valid under certain circumstances. For the feedback to work the occupants must be motivated to adapt their behaviour and their daily routines in order to conserve energy. If these circumstances were not met, the conclusion of the literature review would be that feedback will not work. Several studies, including the series of studies by Buchanen et al. [28,29,86], showed that when occupants were not sufficiently motivated to use the feedback or adapt their behaviour, the effect of the feedback was very limited. Energy consumption feedback relies on the assumption that occupants are motivated by either a monetary incentive or a pro-environmental attitude, and it will then lead to energy conservation. It was assumed that occupants would react based on an increased amount of information. Several studies documented that this was not always the case, indicating that motivational methods should be used in combination with energy feedback.

The literature review formed the basis for the hypotheses tested in this Ph.D. project. Instead of using feedback based on energy use and assuming that it would have the expected effect, the hypothesis was that adding feedback on the indoor environment would motivate occupants to control the indoor environment adaptively. Energy consumption is a function of the thermal environment. Using feedback to influence control of the thermal environment will therefore also influence of energy consumption and the monetary and environmental incentive are then used to increase motivation to act. The indoor environment influences the health and comfort of the occupant. Adding a health and comfort perspective to the feedback, will provide additional motivating factors that may affect the occupant at a given moment (e.g. poor air quality), but also in the long term (increased risk of developing asthma and allergies).

Using the indoor environment to promote energy conservation was considered highly relevant. Assuming that most people understand the relationship between the thermal environment and energy use, they can easily adapt their behaviour to a lower indoor temperature. For example, it is easier to reduce the indoor temperature and increase the clothing insulation level, than to find alternative light sources to a light bulb.

The reviewed studies all presented feedback procedures that with varying effects affected energy consumption. As the goal of the present project was to develop feedback methods that would enhance control of the indoor environment, a list of the principles on which feedback interventions should be based was prepared:

- Users must have an adequate introduction to the feedback system
    - Applied in Study 3
- Feedback should be provided with as high frequency as possible, preferably in real-time
    - Applied in Study 2 and Study 3
- Feedback should be tailored to each occupant/household
    - Applied in study 2 and Study 3
- When using goal setting and commitment strategies, the goals must not be too easy to obtain
    - This was not applied in any of the studies, as it would have required interaction with the users, which would be difficult to achieve in a commercial and scalable feedback process.
- The design of the feedback platform should be simple and intuitive.
    - Partly applied in Study 2 and Study 3. The continuous feedback was designed by a third part company and could not be influenced the author.
- When using social comparisons it is essential to compare the individual to an appropriate group
    - Applied in Study 3
- It should be explicit that occupants are compared to their neighbours.
    - Applied in Study 3
- To avoid the boomerang effect on users performing better than the average in a social comparison, feedback on energy use and all comparisons should be followed by a positive message.
    - Applied in Study 3
- Multiple parameters should be used to motivate and encourage occupants, e.g. by using both a monetary incentive and an environmental incentive.
    - Applied in Study 2 and Study 3

9 INTRODUCTION TO STUDIES

In the following four chapters the four studies is presented. All four studies are based on measurements of the indoor environment, represented by the operative air temperature [°C], relative humidity [%], and CO_2 concentration [ppm].

Study1 investigated and quantified how the heat cost allocation type affected the indoor environment. In the study the measurements of the operative air temperature, relative humidity and CO_2 concentration in 56 Danish apartments were analysed. The apartments were located in two building, one with sub-metered apartments and one with master-metered apartments. A summary of the study with selected highlights is presented in Chapter 10, the full study can be found in Paper 1.

Study 2 was aimed to investigate the influence of continuous and monthly feedback in the same 56 apartments as in Study 1. Continuous feedback was accessible through a web browser, while a physical monthly feedback letter was distributed by the buildings' superintendent. The letter visualized the distribution of the air temperature, relative humidity and CO_2 concentration measurement. The letter further provided general recommendations on how to maintain a high indoor environmental quality. The method and findings were summarized in Chapter 11, the full study can be found in Paper 2.

The findings of Study 2 were continued in Study 3, where the influence of a weekly feedback letter in combination with continuous feedback was investigated. The study was based on measurements of the air temperature, relative humidity and CO_2 concentration in the living room and bedroom of 18 apartments of similar layout, located in Ballerup, Denmark. The method and findings were summarized in Chapter 12, the full study can be found in Paper 3.

The weekly newsletter used in Study 3 was used to provide occupants with an overview of the indoor environment from the previous week. The weekly feedback letter was developed though four different designs, including recommendations and preferences from the occupants in Study 3. The development of the weekly feedback letter was presented as part of Study 3 in Chapter 12

In study 4, a method to assess the influence of occupants' daily routines on the indoor environment was developed e.g. how did the preparation of dinner affect the indoor environment. The method was further used to determine if the daily routines affected the indoor environment equally every day and if patterns in the influence could be established. Study 4 was presented in Chapter 13.

9.1 Sensors

All four studies were based on continuous measurements of the indoor environment in private residences. Two different commercial available products were used in the studies. The sensors were presented in the following sections. The installation cost per apartment was similar for all sensors.

Table 1 Sensor specification of the IC-Meter and Netatmo Weather Station

	Sensor type	Measuring range	Accuracy
IC Meter			
Temperature	SHT21	-40°C to 125°C	+/- 0,3°C
Relative Humidity	SHT21	0% to 100%	+/- 2.0 %RH
CO2 concentration	Non-dispensive infrared (NDIR)	400 to 2000ppm	+/- 30ppm, +/- 3%
Netatmo Weather Station			
Temperature – Indoor	Unknown	0°C to 50°C	+/- 0,3°C
Temperature – Outdoor	Unknown	-40°C to 65°C	+/- 0,3°C
Relative Humidity	Unknown	0% to 100%	+/- 3 %RH
CO2 concentration	Unknown	0 to 5000ppm	+/- 50ppm, +/- 5%
Sound [db]	Unknown	35 to 120 db	

9.1.1 IC Meter

The IC Meter was a Danish developed sensor measuring the temperature [°C], the relative humidity [%] and the CO_2 concentration [ppm] at a five minute interval [87]. The sensor used in Study 1 and Study 2 must be connected to a power plug and have WIFI connection.

Figure 1 Example of the CO_2 concentration visualization.

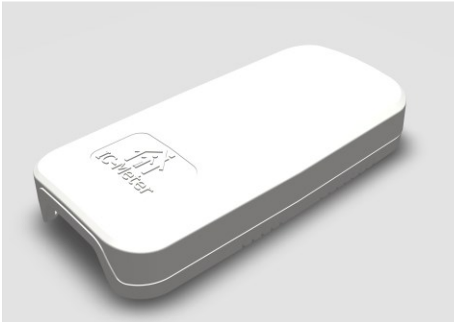


Figure 1 Rendered image of the IC-Meter unit [87]

The measurements were accessible through the company's website, using a personal user name and password. The website including the following feedback elements:

- Continuous feedback
- Daily graph visualizing the past hours of the day
- A prediction of the parameter performance based on the current development
- Monthly distribution for all measured months

The website also featured a *ventilation* feature displaying the air change rate [h^{-1} and m^3/h], minutes of cross ventilation [minutes/day], and vapor production [kg/day]. The calculation methods and definition of heavy ventilation was based on the mass balance and measurements of CO_2 concentration, indoor and outdoor relative humidity. The IC-Meter feedback was only accessible via the IC-Meter website.

9.1.2 Netatmo Weather Station

Netatmo Weather Station was a sensor developed to measure the indoor environment and outdoor weather by the French company Netatmo [88]. The Netatmo Weather Station used in Study 3 and Study 4 consisted of three units: an indoor base sensor, an indoor satellite sensor and an outdoor satellite sensor. The sensor measured the temperature [°C], relative humidity [%], CO_2 concentration [ppm], sound pressure [db] and air pressure [mBar]. The indoor satellite sensor measured the temperature [°C], relative humidity [%], and CO_2 concentration [ppm]. The outdoor satellite sensor measured the temperature [°C], and relative humidity [%]. All parameters were measured at a five minute interval. The base sensor required a power plug connection, while the satellite sensor used batteries. The base station was connected to Netatmo's server through a necessary WIFI connection; the satellite sensors transmitted their measurements to the base sensor.

The feedback visualized the real-time measurements along with a historical presentation. The content was accessible on the producer's website and their smartphone application using a personal user name and password. User name and password should only be entered the first time the user visited the website or smartphone application. The smartphone application had an extra feature, where push notifications were sent when the CO_2 concentration exceeded 1000ppm. Personal alarms/push notifications could be set and could be turned off.

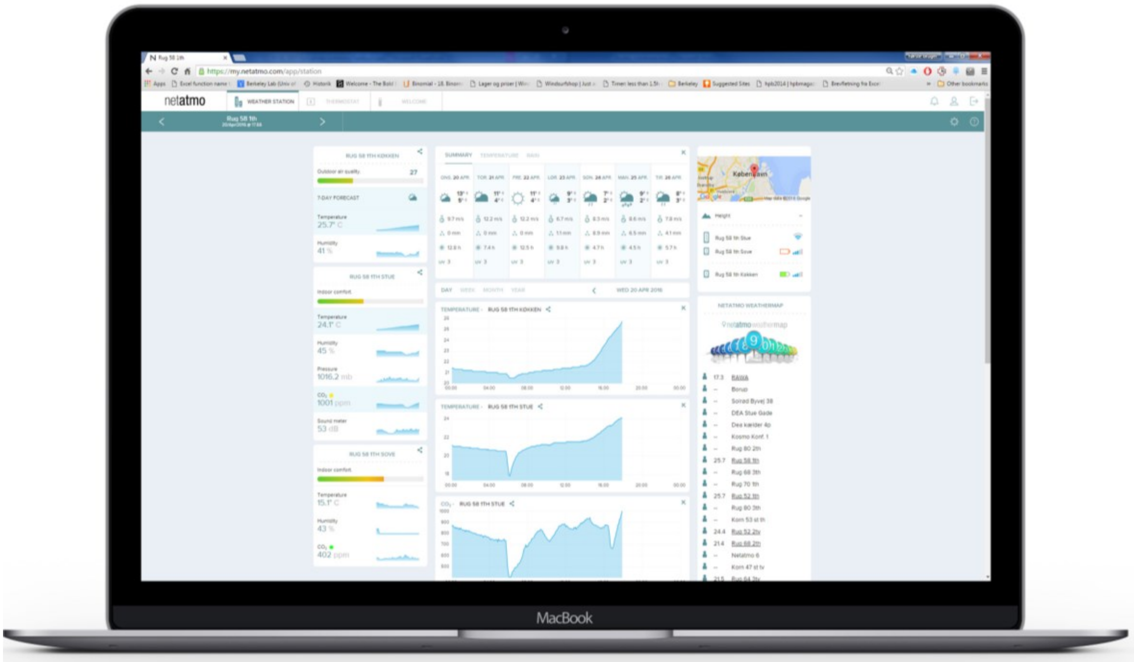


Figure 2 Example of the CO_2 concentration visualization

Figur 3 Rendered image of the Netatmo Weather Station and smartphone application (old design)

9.1.3 Measurement validation

The CO_2 sensor type in both the IC-Meter and the Netatmo Weather Station sensor were a self-calibrating type (ABC calibration [89]). The calibration was performed by assuming that the lowest measured CO_2 concentration during a certain period of time was equivalent to the outdoor concentration (approximately 400ppm). If the CO_2 concentration didn't reach the outdoor concentration for an entire week, the CO_2 sensor would have assigned 400ppm to the lowest recorded concentration. In such cases the measured concentrations would be too high, and the measured concentration would be below outdoor concentration once the actual CO_2 level returned to outdoor concentration.

The IC-Meter and the Netatmo Weather Station sensors would calibrate over time, so to account for misreading's the first six days after the installation were not used in either of the studies. The IC-Meter was used in Study 1 and Study 2, from 1st January 2013 through 29th April 2013, 0,5% of the measurements were below 380ppm. The Netatmo Weather Stations were used in Study 3 and Study 4 from 1st October 2015 through 29th February 2016, 4% of the measurements was below 380ppm.

10 STUDY 1 – INFLUENCE OF HEAT COST ALLOCATION

The aim of Study 1 was to investigate and quantify the influence of the heat cost allocation type based on indoor environmental measurements in 56 Danish apartments. Study 1 further aimed to constitute the heat cost allocation as a driver for indoor environmental behaviour.

The study was based on measurements in two buildings with different heat payment plans. The measurements were analysed to determine general differences, and differences between weekdays and weekends. Finally, the measurements were analysed for each hour of the day. Study 1 was described in Paper 1. The results and conclusions were therefore only summarized in this section.

In the literature review for Paper 1 it wasn't possible to find studies directly quantifying the influence of the occupants' behaviour on the indoor environment. Only a few studies have investigated the correlation between occupant behaviour, the cost of utilities and the payment type. Gunay et al. found an average temperature difference of 2°C between sub-metered and master-metered apartments [40]. Study 1 continued the work of Gunay et al. by quantifying the influence of two types of heat cost allocation on the temperature, relative humidity and CO_2 concentration.

10.1.1 Method

The study was conducted in 56 Danish apartments in the Copenhagen area from March through April 2013. The apartments were located in two buildings; the heat payment in Building 1 was based on master-meters whereas apartments in Building 2 were sub-metered. The difference in metering strategies, gave occupants in Building 2 a direct and individual monetary incentive to conserve energy.

The indoor environment, represented by the temperature [°C], relative humidity [%] (vapor pressure [Pa]), and CO_2 concentration [ppm] was measured with a five minute interval at a central location in each apartment.

Semi-structured interviews were conducted at the end of the intervention period, with 10 selected occupants - five from each building. The interviews were focussed on four topics: the occupants' perception of indoor environment, the occupants' heating use, the occupants' interaction with the continuous feedback device, and how the occupants would react if their energy bill was based on the indoor environmental performance. The full interview guide was presented in Appendix 2.

Questionnaires were distributed to households that received feedback and households that didn't. The questionnaires were distributed at the end of the intervention period. The questionnaire was distributed in Danish, but translated and presented in Appendix 3. The aim of the questionnaire survey was to determine how the occupants interpret the term indoor environment and how they controlled the indoor environment in their apartment. The questionnaire was distributed to occupants with and without access to real-time visualization of the indoor environment. This separation made it possible to investigate how continuous feedback and information affected the occupants' perception of indoor environment and their control of this.

To assess the influence of the heat cost allocation on the energy use, the difference of the mean indoor temperature of apartments was compared to the monthly mean outdoor temperature.

The results were not tested for statistically significance.

10.1.2 Results

Comparison of the measurements showed that the average temperature was 2.4°C higher in Building 1 than Building 2, whereas the average CO_2 concentration and vapour pressure were 161ppm and 93Pa lower, respectively.

The performance of the indoor environment was assessed in comparison to the design values of EN 15251-2007 [39]. The measurements were categorized based on the averages being above, below or within the recommendations. The distribution was presented in Table 2 and Table 3.

Table 2 Time distribution for measurements in Building 1 compared to EN 15251-2007design values.

Building 1 (Collective payment)	Recommen-dation	Below [%]	Within [%]	Above [%]	Average value	Standard deviation
Temperature	20-25 °C	0	88	12	23.5°C	1.5°C
CO_2 concentration	< 1000 ppm	-	96	4	618ppm	292 ppm
Relative humidity	30-60%	88	12	0	32%	13%

Table 3 Time distribution for measurements in Building 2 compared to EN 15251-2007design values.

Building 2 (Individual payment)	Recommen-dation	Below [%]	Within [%]	Above [%]	Average value	Standard deviation
Temperature	20-25 °C	50	50	0	21.1°C	1.6°C
CO_2 concentration	< 1000 ppm	-	82	18	778ppm	527ppm
Relative humidity	30- 60%	37	63	0	38%	10%

The measurement distribution of all apartments and the average apartment was presented in Figure 2 through Figure 4.

The interviews revealed that occupants in Building 2 focused on maintaining a low energy bill. These occupants were therefore willing to accept an indoor environmental quality below the recommendations of EN 15251-2007. Occupants in Building 1 did not have a direct individual monetary incentive to reduce their energy use and focused therefore on maintaining a high self-perceived indoor environmental quality.

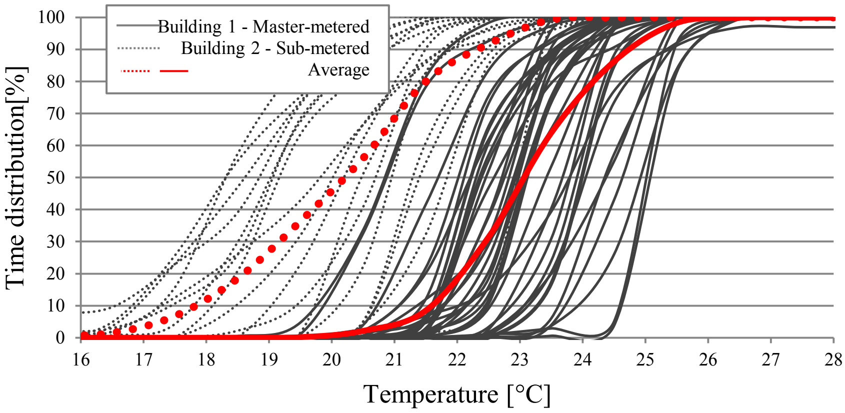


Figure 2 Average temperature summation curve of Building 1 and Building 2, and temperature summation curve of each apartment [°C].

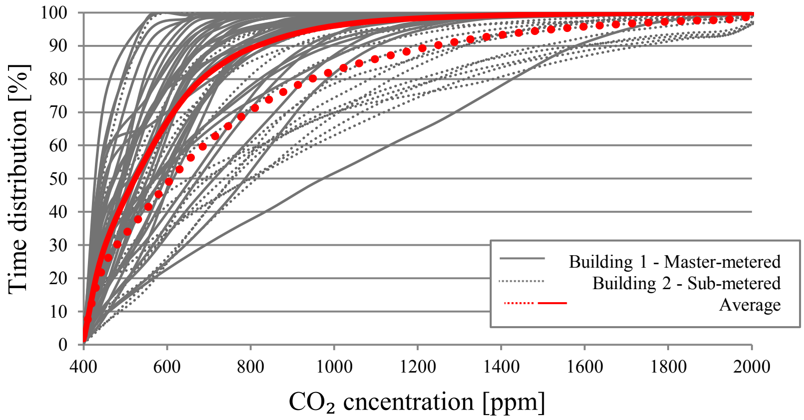


Figure 3 Average CO_2 concentration summation curve of Building 1 and Building 2, and CO_2 concentration summation curve of each apartment [ppm]

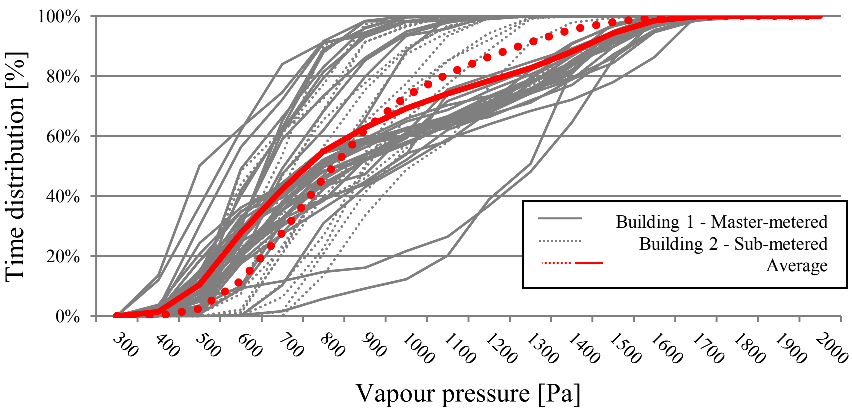


Figure 4 Average vapour pressure summation curve of Building 1 and Building 2, and vapour pressure summation curve of each apartment [Pa]

Estimating the difference in the energy use from both buildings showed that apartments in Building 1 used 2.8% more energy in March 2013 and 12.4% more energy than apartments in Building 2 in April 2013.

Table 4 Estimation of the difference in energy use between Building 1 and Building 2

Month	March 2013	April 2013
Mean monthly temperature - Building 1	23.7°C	23.7°C
Mean monthly temperature - Building 2	20.9°C	21.6°C
ΔT	2.8°C	2.1°C
Mean monthly outdoor temperature – Tout	-1.0°C	6.0°C
Difference in energy use	283%	35%

10.1.3 Discussion and conclusion

The differences in the indoor environment could have occurred due to differences in the building envelop. An evaluation of the building envelop wasn't part of the study, but the interviews found that it was possible to heat the apartments in both building to temperatures that the occupants found comfortable. The interviews found that occupants in Building 2 chose to maintain a lower indoor temperature in favour of a lower energy bill.

Indoor temperature in Building 1 was above 25°C for 12% of the measuring period and wasn't below 20°C. In Building 2, the temperature didn't exceed 25°C, but was below 20°C in 50% of the period. Cholewa et al. found that the use of heat cost allocators could result in a difference of averagely 27% [18]. Estimating the difference in the energy use between Building 1 and Building 2 presented in Table 4, it was evident that apartments in Building 1 used more energy to maintain a higher indoor temperature. The estimated energy use further showed how substantial energy savings could be reached with an introduction of heat cost allocators.

The literature review showed that the rebound effect decreased as occupants became wealthier [53]. The occupation and income of the occupants was unknown, the average income in the municipalities of the buildings was therefore used as indication of the influence of wealth. The average annual income was 278€ higher in the municipality of Building 1 than of Building 2. A difference so small, it was assessed that income didn't affect the control of the indoor environment.

The average municipality income includes incomes above and below the average. Using the municipality average income at building level, could therefore become a comparison of salaries above and below the average. The participating occupants' income, education or job situation was not documented in either the interviews or questionnaire. It was, however, of the authors' conception, that income, education and job situation was similar of the two buildings. To secure a useful socio-economic comparison of the two buildings, questions regarding the occupants' income or job situation could have been asked. However, the questionnaire was aimed to document the occupants' understanding of indoor environment and use of dwellings. To obtain as high response rate as possible, it was further aimed to limit the questionnaire to the format of two A4 pages. Questions regarding occupants' education and/or income level were deprioritized, in favour of the indoor environmental focus and the length of the questionnaire. Using the average annual municipality income as indication of the socio-economic differences at building level was therefore found acceptable.

Based on the measurements and the findings of interviews and questionnaires it was concluded that the heat cost allocation type was a driver. Paper 1 further quantified that the heat cost allocation type resulted in an average indoor temperature being 2.4°C higher in master-metered apartments, while the average CO_2 concentration and vapour pressure were 161ppm and 93 Pa lower.

In two literature reviews Fabi et al. [5,90] described how certain drivers had a bigger effect on the control of the indoor environment than others. Based on the findings of Study 1 it was concluded that the heat cost allocation provides a monetary incentive that overrules other driving forces.

11 STUDY 2 - CONTINUOUS AND MONTHLY FEEDBACK

The overall objective of this PhD project was to investigate the possibilities of using the indoor environment as a motivation and driver for the occupants' control of this. With Study 2 it was investigated how continuous and monthly feedback influenced occupants' control of the indoor environment. The study was based on measurement from 56 Danish apartments in two different buildings (the same data set as used in Study 1).

The hypothesis of the study was that using indoor environmental based feedback to reduce the energy use was possible as; most people understand the relationship between the thermal environment and their energy use. Occupants can therefore easy adapt their behaviour to a lower indoor temperature. It was further hypothesized that continuous feedback acted as an everyday guide for the occupants' control the indoor environment. The monthly feedback would meanwhile act as a reminder to use the continuous feedback.

Paper 2 surveyed how continuous and monthly feedback historical has been used to influence energy behaviour and how the indoor environment is suitable as alternative motivation to energy use based feedback. Investigating the influence of the feedback was performed by an assessment of the average of all apartments and by a linier regression model of each apartment. The occupants' self-perceived effect of the feedback was determined through semi-structured interviews and questionnaires, as described in Chapter 10. The interview guide and questionnaires were presented in Appendix 2 and Appendix 3.

Study 2 is described in Paper 2 and will therefor only present essential information and findings.

11.1 Method

The temperature [°C], relative humidity [%], and CO_2 concentration [ppm] was measured at a five minute interval. Semi-structured interviews were conducted with 10 occupants and questionnaires were distributed in the two buildings. The measurements used for this study were collected from 1st January 2013 through 30th April 2013. The questionnaire was sent to apartments that received feedback and apartments that didn't.

11.1.1 The feedback

Occupants had access to the measurements through the IC-Meter manufacturers' website [87]. The continuous feedback was only accessible through the website after a login process with a user name and password.

A monthly feedback letter was sent to the occupant the 1st March 2013 and 1st April 2013. The letter vizualized the average temperature, relative humidity, and CO_2 concentration compared to the design values of EN 15251-2007 [39]. The feedback letter further gave general recommendations on how to optimally control the indoor environment.

11.1.2 Regression analysis

To survey the influence of the outdoor temperature on the indoor temperature, linier regression models were investigated for each apartment. It was assumed, that if the influence of the outdoor temperature on the indoor temperature decreased after the feedback introduction, the feedback had affected occupants' control of the indoor environment.

The analysis was further used to assess the energy use for heating. The regression model was used to calculate the indoor air temperature based on the outdoor temperature before and after the feedback introduction. The energy use was calculated by comparing the temperature difference with and without feedback to the outdoor temperature (this analysis was not presented in Paper 2).

11.2 Results and discussion

Figure 5 through Figure 7 presented the distribution of the indoor temperature, relative humidity and CO_2 concentration of the two buildings (B1 – Building 1 and B2 – Building 2). The measurement distribution presented as a summation curve for each apartment was presented in Paper 2.

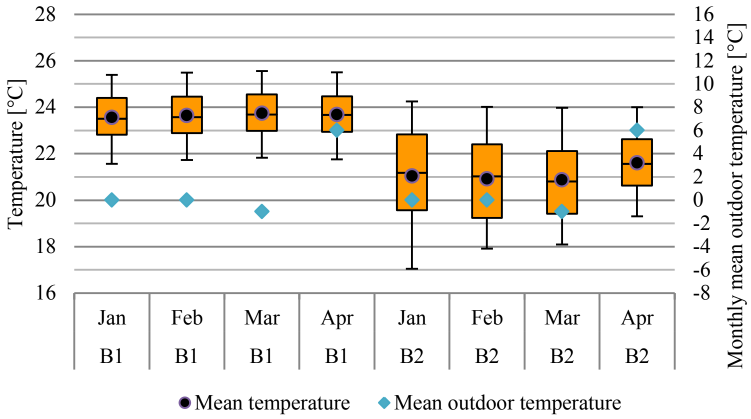


Figure 5 Monthly temperature distribution displayed with the 5th, 25th, 75th and 95th percentile and outdoor temperature (right y-axis)

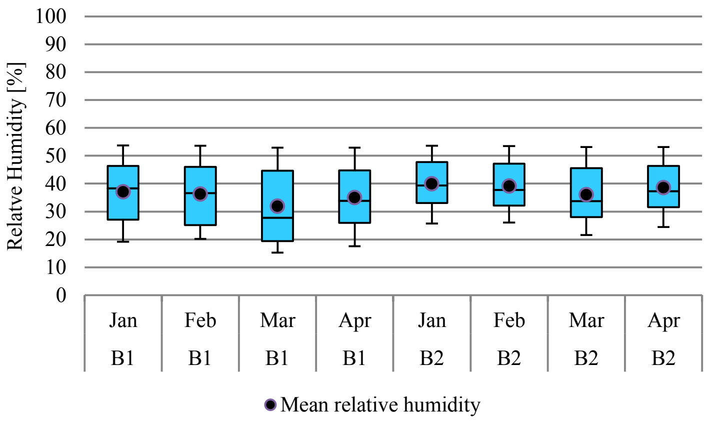


Figure 6 Monthly relative humidity distribution displayed with the 5th, 25th, 75th and 95th percentile.

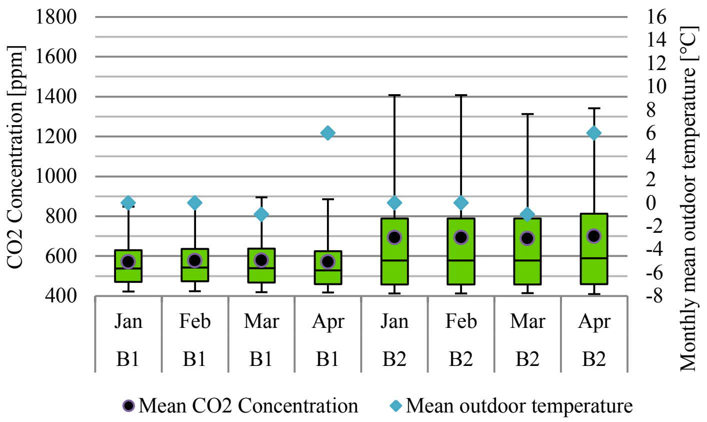


Figure 7 Monthly CO_2 concentration distribution displayed with the 5th, 25th, 75th and 95th percentile and outdoor temperature (right y-axis)

The literature review in Chapter 8 – Background found that the outdoor temperature was the main driver for the control of window opening and the heating set point. The monthly average outdoor temperature decreased 1°C from February through March. This change was assumed ignorable and changes in the indoor environmental measurements were assumed to be an effect of the feedback.

Initial assessment of the average values and distribution of the measurements indicated a minor influence of the feedback, as the temperature and relative humidity measurements were lower after the feedback introduction. Assessment of the CO_2 concentration in Paper 2 indicated the feedback hadn't had an influence in neither of the buildings, as there was no difference between before and after the feedback introduction.

11.2.1 Interviews and questionnaire findings

The semi-structured interviews showed that occupants in Building 1 in general didn't show much interest in the feedback e.g. two of four informants perceived the monthly feedback as advertisement. All six informants from Building 2 had read and understood the monthly feedback. The questionnaire was distributed to the 52 apartments that received feedback the total response rate was 42%. One of the main results from the questionnaire was on the self-perceive influence of the feedback. In Building 1, 71% believed it had an effect, while 67% in Building 2 perceived the feedback had had an influence.

11.2.2 Individual apartment assessment

In Building 1, all apartments were recommended to reduce the average air temperature. After the feedback introduction the influence of the outdoor temperature on the indoor temperature decreased in 59% of the apartments, indicating these apartments were influenced by the feedback. In Building 2, 12% of the apartments were recommended to decrease the average indoor air temperature. The results of the regression model indicated that all apartments followed this recommendation and thereby was influenced by the feedback. 65% of the apartments were recommended to maintain the average temperature as it was. However, in 45% of the apartments the indoor temperature decreased after the feedback introduction. In 24% of the apartments, occupants were recommended to increase the average indoor temperature. The regression models indicated that 75% of these followed the recommendations and thereby were influenced by the feedback. All results were found statistically significant.

From the study it cannot be concluded if the changes occurred because of the feedback, as other drivers that wasn't investigated and could have had an influence. However, 71% and 67% of the questionnaire responses in Building 1 and Building 2 perceived the feedback had had an influence.

These results make it plausible that the findings of the regression analysis occurred because of the feedback procedure.

The regression model was used to assess the energy use at apartment level. In Building 1 after the feedback introduction, the model showed that for 17 of 36 apartments the indoor temperature would decrease as the outdoor temperature decreased. In 31 of 36 apartments (86%) the model further showed, that showed that at an outdoor temperature (T_{out}) of 5°C, the indoor temperature (T_{in}) was lower after the feedback introduction. The regression model further showed that at an outdoor temperature (T_{out}) of 5°C, the indoor temperature (T_{in}) was lower after the feedback introduction than before in 31 of 36 apartments (86%). In these 31 apartments the energy use for heating was 11% lower after the feedback was introduced than before.

In Building 2 the model showed that T_{in} decreased as T_{out} decreased both before and after the feedback introduction. In 9 of 17 apartments, the model showed that at T_{out} = 5°C, T_{in} was lower after the feedback introduction. The average energy use would be 10% lower in these apartments when receiving feedback. The findings indicated that if the occupants used the feedback and were willing to adapt their behaviour substantial energy savings were reachable.

11.2.3 Influence of the heat cost allocation

Study 1 found that the heat cost allocation was a driver for the occupants’ control of the indoor environment. Paper 2 showed that occupants with a direct monetary incentive to conserve energy had a more positive attitude towards the feedback and would to a higher degree use the feedback tools. A finding that should be used in future studies.

11.3 Conclusion

From the regression models for each apartment, the interviews and questionnaire findings it was concluded that the feedback procedure had an influence on the occupants’ control of the indoor environment. From the regression analysis it was further concluded that energy savings were reachable if the occupants used the feedback.

Assessing the influence of the heat cost allocation showed that the effect of the feedback was bigger in apartments with a direct monetary incentive to conserve energy.

12 STUDY 3 – CONTINUOUS AND WEEKLY FEEDBACK

The aim of Study 3 was to test and document potential effects of a feedback procedure combining continuous and weekly feedback. The study was conducted in 18 Danish apartments using an intervention and control group to document the effect of the feedback.

The hypothesis for Study 3 was the same as in Study 2. It was hypothesis that using indoor environmental based feedback to reduce the energy use is possible as; most people understand the relationship between the thermal environment and energy use and thereby easily can adapt their behaviour to a lower indoor temperature. It was further hypothesized that continuous feedback would act as an everyday tool to guide the occupants' control of the indoor environment. Meanwhile, the monthly feedback would act as a reminder to use the continuous feedback.

The continuous feedback was provided through a website and smartphone application while the weekly feedback was a physical letter. Prior to the intervention period, the design of the weekly feedback letters were developed through an iterative process including reviews of the feedback letter from the apartments.

Study 3 was based on the findings of Paper 3. In section 12.6.3 it was investigated how the age of the occupants and the presence of children influenced the indoor environment, this investigation was not part of Paper 3.

12.1 Development of the feedback procedure

The literature review found that feedback should be disseminated with as high frequency as possible and combine multiple motivation and feedback mechanisms. At the start of Study 3 it was decided to use the Netatmo Weather Station sensors, as these could collect data at a useful interval, offer continuous feedback on all mobile platforms, and was available at a price within the budget of the project (a factor that unfortunately had a crucial impact on amount of participating apartments).

The literature review showed cases of feedback fatigue when the continuous energy feedback lost its novelty and thereby its effect. It was therefor decided to add a weekly newsletter aimed to remind the occupants of the measurements and provide them with an overview of these. The weekly newsletter was further seen as a platform for disseminating information and specific recommendations.

The fundamental idea behind the weekly feedback was to develop a newsletter acting as a reminder of the continuous feedback and thereby reduce the risk of feedback fatigue. The weekly feedback should further provide the occupants with an overview of the measurements and give useful and intuitive recommendations on how to obtain and maintain a high indoor environmental quality and low energy use.

The weekly feedback letter should further meet the following demands:

- Provide an overview of the measurements of last week
- Information, graphs, recommendations etc. must be intuitive
- The feedback must enable and exemplify to the occupants when and how the indoor environment can be improved
- The amount of text must be kept at a minimum
- The weekly feedback letter must be generic and produced by an automated process requiring no or very limited human interaction.
- The content must fit to no more than two A4 sheets

12.1.1 Initial assessment element

A general element used in all versions of the feedback letter was a rating of the measurement distribution. The European standard EN 15251-2007 provided indoor environmental design values and benchmarks for a high indoor environmental quality. The standard recommended that the benchmarks weren't exceeded for more than 5% of the time. The 5% recommendation was used to develop a rating where, the longer a parameter was outside of the recommended benchmark the worse the rating. The rating was presented in Table 5.

Table 5 Initial idea for the rating for the initial assessment element

RATING	1	2	3	4	5	6	7	8	9	10
Time outside boundary [%]	< 5	> 5	> 10	> 20	> 30	> 40	> 50	> 75	> 90	> 99
Parameter Icon										

Instead of displaying the rating as a value an icon inspired by the Facebook Like icon was used, as presented in Figure 8.

Figure 8 Left: Facebook Like icon. Right: Rating icons for an intuitive assessment

A green icon was given if the parameter was outside the EN 15251-2007 recommendation for less than 5% of the assessed period. A yellow icon was given if the parameter was outside the recommendation between 5% and 10% of the period. A red icon was given if the parameter was outside the recommendation for more than 10% of the period. The rating system was developed for the feedback letters as a general assessment element, easy to interpret and understand. The assessment was placed in the beginning of the letter, so if all assessments were green the occupant did not have to read more. If a red assessment was given, it should trigger a curiosity to read more.

12.1.2 Preliminary feedback letters

Four designs of the feedback letter with a common composition. First, a general overview provided the occupant with an assessment of the overall performance of the indoor environment. Secondly, more detailed information was presented to visualize which parameter(s) that needed extra attention and when.

In the following three sections a detailed presentation of the feedback letters was presented. The feedback letters were developed through an iterative process where four designs of the letter were developed based on the findings and recommendations of the literature review. The four first versions were presented to selected occupant in the building, these statements and assessments were used to develop the final feedback letter.

12.1.2.1 Weekly feedback letter 1

Feedback letter 1 was designed as an A5 sized postcard sent without an envelope. This format was selected as it should encourage the receiver to hang the letter on the refrigerator, a position where the occupants would see it many times during their day. The feedback letter included a general assessment of the parameters, data highlights, a rating of each parameter, and the rating of the previous week. Page two of the letter gave a written assessment, showed the daily distribution of each parameter and guidance on how to find more information.

Feedback letter was designed to only visualize the indoor environment in one room.

Figure 9 Feedback letter 1 – Front page combining five elements

The front page of the letter was divided into five elements as marked in Figure 9.

.

- Element 1, was the headline and date, intended to make the content clear. The headline and date was followed by an image of the building, giving a sense of localness.
- Element 2, was a large initial assessment icon as presented in section 12.1.1. The size of the element was chosen, so the recipient immediately could assess the performance of the indoor environment and thereby if they had to adapt their behaviour. If a green icon was given it will in theory, reduce the risk of a boomerang effect. If a yellow or red icon was given it was aimed to motivate the occupant to perform better.
- Element 3, the data highlights gave the average temperature, how many minutes and hours the air quality was outside the recommendation, and how much of the time there was an increased risk for mould formation – assessed by the amount of time the relative humidity was above 60%.
- Element 4, was a visualization of the initial assessment element as presented in Table 5. The rating of each parameter was shown on a scale from 1 to 10, 1 being the best. The ratings were followed by an explanation of the meaning of the ratings.

- Element 5, was a presentation of the general assessment and the ratings of the previous week. Element 5 were designed to enabled the occupants to make a historical comparison. A comparison indicating whether the development of the control was positive.

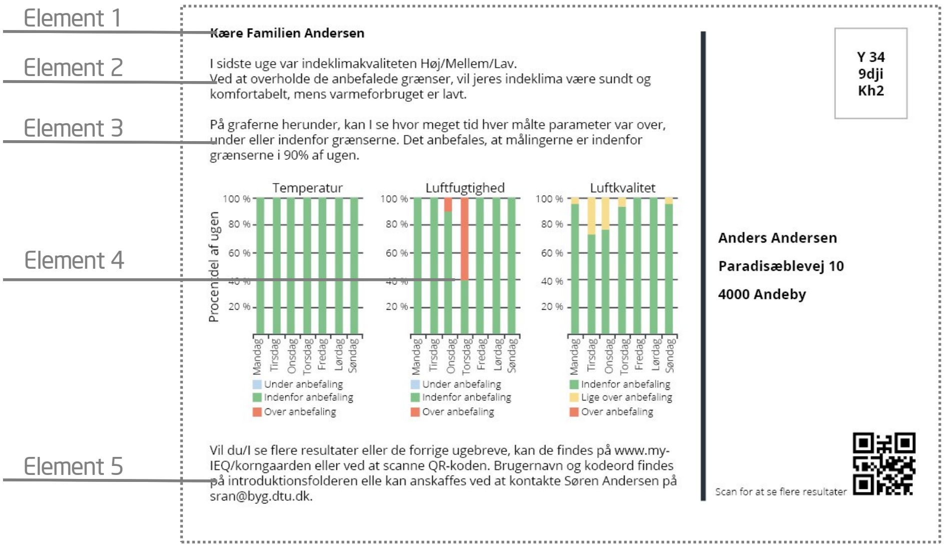


Figure 10 Feedback letter 1 – Page 2 with marking of the five elements

Page 2 of feedback letter 1 consisted of 5 elements as marked in Figure 10.

- Element 1, was a greeting of the occupant by using the name of a family member. The element was included to make the feedback letter personal.
- Element 2, was a written explanation of the indoor environmental performance. The text was aimed to explain why the recommended benchmarks should be followed.
- Element 3, introduced column plots in Element 4 and explained how these should be interpreted.
- Element 4, were three column plots visualizing the daily distribution of each parameter. The hypothesis of these plots was that occupants could recall their behaviour on a given day in the week. When combined with the assessment in the feedback letter, they could assess whether the behaviour was beneficial or not.
- Element 5, explained where the occupant could find more information and see older feedback letters. Occupants were further encouraged to contact the author if they had lost the user name and password.

Sending the feedback letter as a post card was rejected, as the information was considered as sensitive and therefore not something that a third party potential could gain access to.

12.1.2.2 Weekly feedback letter 2

Feedback letter 2 consisted of five overall elements that should enable a quick and easy overview of the measurements, but also provide detailed information on parameters exceeding the recommended benchmarks.

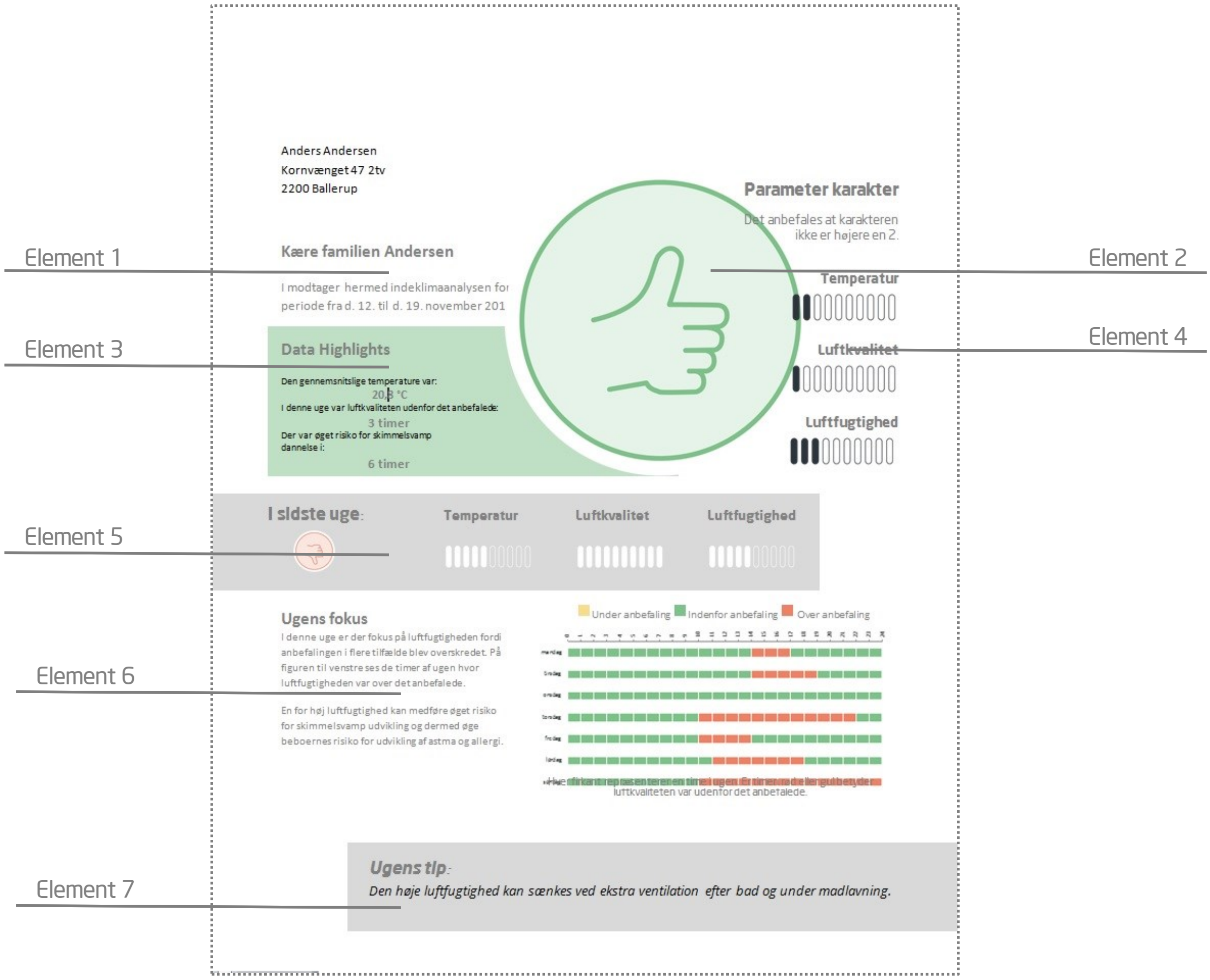


Figure 11 Feedback letter 2 and explanation of each element. Original size of letter was A4

The seven elements of feedback letter 2 were highlighted in Figure 11. The elements were described in detailed in the following:

- Element 1, by using the family name as a greeting the feedback letter was made personal. This was followed by a definition of the period the assessment was based.
- Element 2, was the general assessment of all measured parameters. The size of the element was chosen, so that it was the first thing the eye would see when the occupants browsed through the letter.
- Element 3, gave data highlights for the temperature, air quality and relative humidity. It was assumed that all occupants understood the average temperature and could relate this to their behaviour. To make sure everybody could relate to the CO_2 concentration, the highlight data showed how many hours the 'air quality' was above the recommended. The relative humidity readings was made relevant, by informing how many hours there was an increased risk of mould formation (RH >60%)
- Element 4, was the rating as presented in section 12.1.1.and used to indicate which of the parameters that wasn't optimally controlled.
- Element 5, was a visualization of the general assessment and the ratings from the previous week. This historical comparison enabled the occupant to follow the development in their control of their control.
- Element 6, was a detailed assessment of a selected parameter. Each hour of the week was assessed according to the initial assessment presented in section 12.1.1. The

detailed assessment enabled the occupant to see which hour(s) of the week that caused the poor rating. This feedback mechanism required the occupant to be able to remember they behaviour during the week. The highlighted parameter was chosen by the one with the worst rating. In case of an even score the parameters were prioritized as: temperature; air quality and relative humidity. The highlighted parameter was followed by an explanation of why this was highlighted and how to improve the measurements.

- Element 7, was a concrete recommendation given on how to improve the performance for the selected parameter in Element 6.

12.1.2.3 Weekly feedback letter 3.1 and 3.2

The third feedback letter was designed in two versions. The letter was divided into three parts, one providing a general overview, one providing a more detailed analysis of the parameter(s), and the last part making a social comparison. The feedback letters were presented in Figure 12 and Figure 13.

Figure 12 Weekly feedback letter 3.1 with element definition

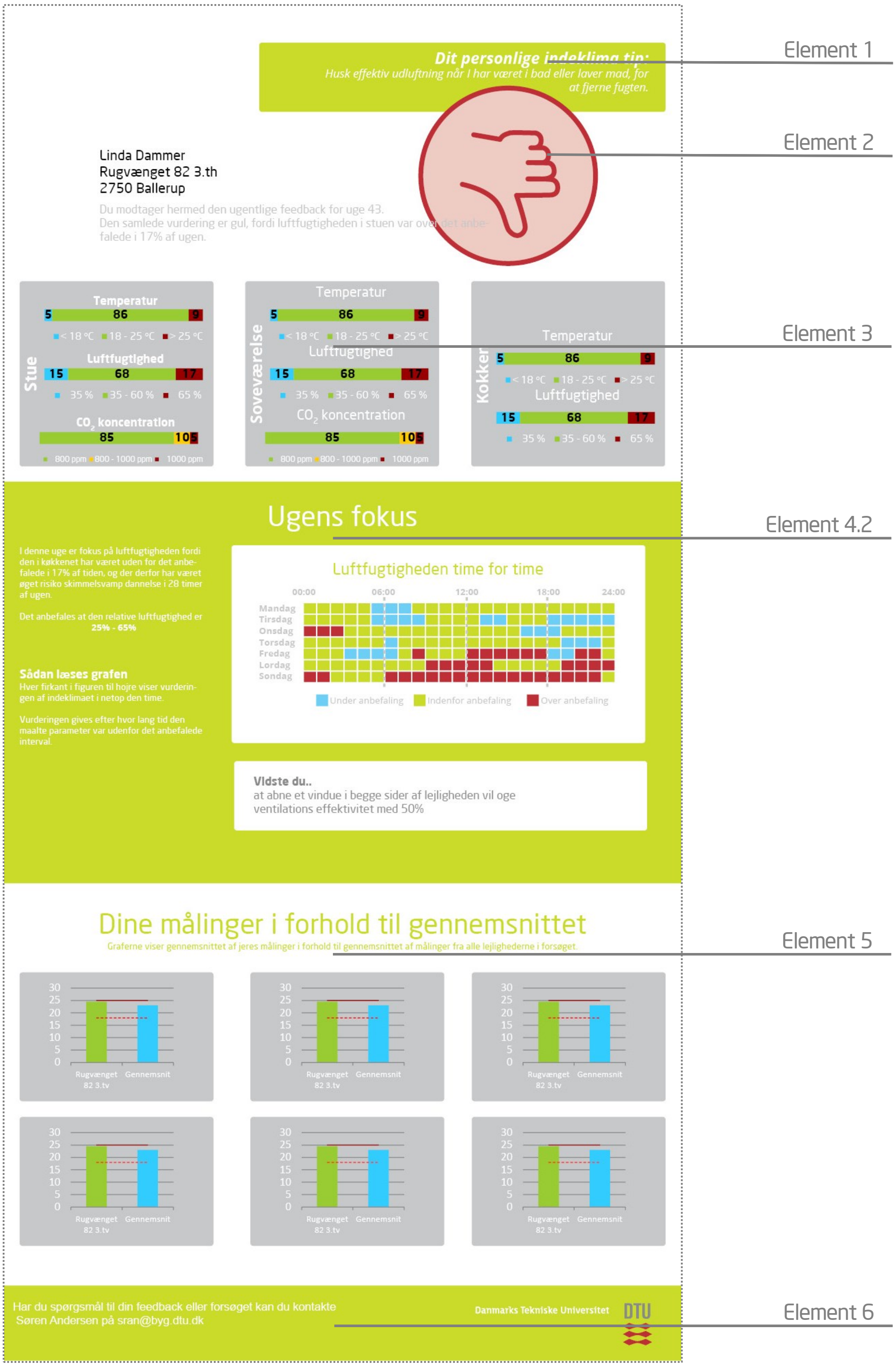


Figure 13 Weekly feedback letter 3.2 with element definition

The following sections give a detailed description of the elements in the two letters.

- Element 1, was a 'personal indoor environmental tip', a recommendation based on the measurements designed to help the occupants to an optimal control of the indoor environment.
- Element 2, was similar to the one used in feedback letter 1 and 2 and aimed to help occupants assess the measurements with a single look at the feedback letter. Optimally,

would the occupant register a green icon and know that their control was optimal and continue this, making the rest of the letter unnecessary.

- Element 3, visualized the distribution of each parameter of each room. This way the occupant could see which parameter that caused the rating and the control of which parameter that had to be changed.
- Element 4.1, showed the daily distribution of each parameter in the living room and bedroom. For this feedback to work, the occupant must remember their behaviour or control of the indoor environment on a certain day and combine this with the distribution.
- Element 4.2, was an alternative to the daily distribution. It was assumed that visualizing the daily distribution for each parameter in two rooms was too comprehensive for a moderate interested occupant. As an alternative, one parameter in one room was selected and an hour-by-hour assessment was performed. The hour-by-hour graph was accompanied by an explanation on why this was selected, the benchmark for the assessment, and a recommendation on how to improve the performance.
- Element 5, was a social comparison where the performance of a parameter in the apartments was compared to the performance of all apartments. To avoid a boomerang effect, the benchmark was shown enabling the occupant to assess if they and/or the compared group acted according to the recommended benchmarks.
- Element 6, described how the occupant could get in contact with the author in case of questions regarding the feedback or the experiment. The logo of the Technical University of Denmark was used in Element 6. The aim of the logo was to show to the occupant that the information didn't come from the housing association, but was part of the experiment.

12.2 Occupants views of the feedback letters

Interviews about the feedback letters were conducted with occupants in four apartments. Two types of interviews were conducted, with the first being a general talk on the indoor environment in the apartments, briefly touching how feedback should be (see Appendix 6 for interview guide). In the second round of interviews the feedback letters were presented and the occupants gave their opinions.

The first round of interviews showed that the occupants preferred concrete recommendations instead of using numbers. The interviews also stated that measurements should be presented as simple and intuitive graphs. 3 of 4 informants stated that they would prefer a person to guide them to the best control strategy based on the components in the apartments. One apartment stated that in the case of comparative feedback, it would be nice to know how high performing apartments acted – a sort of knowledge sharing.

In the second round of interviews the feedback letters were presented to the informants. The interviews gave the following conclusion:

- If graphs are to be used, they must be intuitive and preferable presented as pie-charts or a similar graph type.
- Give a combined assessment of each room.
- Numbers can be confusing and should instead be presented as percentage distributions in a pie-chart or similar graph type.
- Using a benchmark would make it easy to assess why the specific feedback was given.

Comparing the interview findings with the literature review findings showed coherence on several issues. Especially providing intuitive, useful and concrete information seemed (obviously) essential for a successful feedback.

12.3 Final weekly feedback letter

The final weekly feedback letter was similar to feedback letter 3.2. The letter gave a general overview, highlighted a parameter by providing an hour-by-hour assessment, and ended with a social comparison. As requested in the interviews, concrete recommendation on how to obtain a high indoor environmental quality was given along with concrete recommendation on how to improve the performance of the highlighted parameter. Additionally, the highlighted parameter was accompanied by the benchmark for that specific parameter.

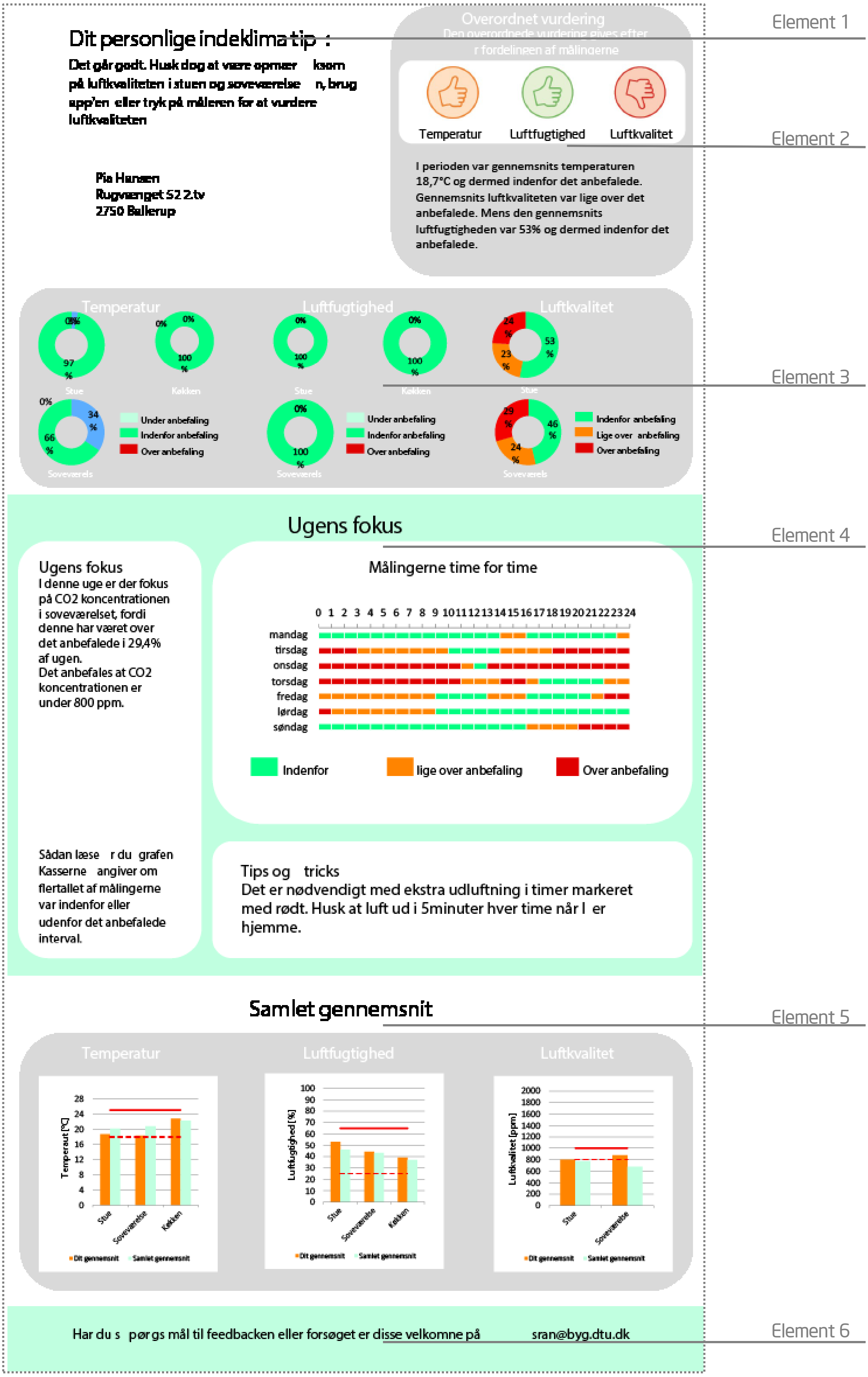


Figure 14 Final feedback letter as distributed to the occupants.

The following section gives a detailed description of the elements in the final feedback letter as visualized in Figure 14.

- Element 1, was a 'personal indoor environmental recommendation' that based on the distribution of the measurements and hour-by-hour assessment gave a concrete recommendation of how to increase the performance of the indoor environment. When possible the recommendations were followed by a positive motivational message. Concrete recommendations were requested by the occupants in section 12.2.
- Element 2, was an initial assessment of the parameters. The parameters were measured in three rooms; however, only one assessment was given per parameter. This meant that the initial assessment represented the performance of the parameter in the three rooms (living room, bedroom, and kitchen). The initial assessment was followed by a written presentation of the average value of each parameter and an assessment whether it was within the recommendation.
- Element 3, presented the distribution of each parameter in each room as a donut chart. The bar chart in feedback letter 3 was substituted with the donut charts as the occupants implied a preference for this kind of visualization.
- Element 4, was the same as element 4.2 in feedback letter 3.2, an hourly assessment of a selected parameter. The aim of the hourly assessment was to show when the occupants' control of the indoor environment beneficial could be changed. The hour-by-hour chart was accompanied by an explanation of why it was selected, how it should be interpret, and how the performance could be increased.
- Element 5, was a social comparison of each measured parameter to the average of the other apartments receiving feedback. The recommended benchmarks were visualized to avoid a boomerang effect.
- Element 6, encouraged occupant to email the author in case of questions regarding the feedback or experiment.

The final feedback letter was distributed as a physical letter. The letter was folded three ways so the occupants first would see the general assessment of the indoor environment and then the more detailed assessments.

12.4 Final feedback procedure

Invitations to participate in the experiment were sent to all 234 apartments in Korngården (four similar apartment buildings in Ballerup, Denmark); in total 18 apartments sign up to participate. The measuring sensors were installed in August and September, allowing for calibration of the sensors. A start-up package was sent to the apartments on 2nd November 2015 introducing the feedback and defining indoor environment. The start-up package also included a description of the continuous feedback and how to access this. To ease the access to the continuous feedback the occupants' user name and password was provided in the start-up package. The first feedback letters were disseminated 9th November 2015. The weekly feedback letter was distributed every Tuesday from November 2015 through February 2016 with a break between Christmas and New Year's Eve.

In every information and feedback letter occupants were encouraged to contact Søren Andersen if they had any kind of question regarding the experiment or the feedback.

12.4.1 Introduction to the feedback

The literature review described the importance of a good start of an intervention. Start-up packages were therefore sent to the intervention group, including a welcome letter, an information leaflet and bag of caramels.

The introduction letter informed the occupant that they had been selected as intervention apartment, explained how the smartphone application to access the continuous feedback could be downloaded, and provided the required user name and password. An introduction letter was sent to the control group, explaining how they should maintain their usual behaviour and not be affected by the sensors in their apartments.

The information leaflet gave an introduction to the experiment and explained the definition of indoor environment. The latter part of the leaflet described the content of the smartphone application and defined the benchmarks for a high indoor environmental quality. On the last page, ten concrete recommendations to control the indoor environment were given. The information leaflet disseminated in Danish can be found in Appendix 5.

To create a positive atmosphere around the introduction material, a bag of caramels were distributed along with the introduction letter and information leaflet.

12.4.2 Feedback dissemination

The production of the feedback letters was not fully automated and had to be manually produced. The letters were produced on Mondays and distributed to the residents' mailboxes on Tuesdays.

12.5 Method

Study 3 was conducted in 18 apartments in Ballerup, Denmark, based on measurements collected from October 2015 through February 2016. The air temperature [°C], relative humidity [%], and CO_2 concentration were measured at a five minute interval in the living room, bedroom and kitchen (the kitchen measurements were not part of the study).

The participating apartments were separated into an intervention group and a control group, with the control group used to document the influence of the feedback. The separation was performed so apartments with similar family composition and similar distribution of the indoor environment measurements were found in both groups. The age of the occupants and the family compositions were determined from Questionnaire 1.

Continuous feedback was provided to the intervention apartments via a website or a smartphone application. At the start of the intervention period, intervention apartments received a welcome letter with an introduction folder explaining how to access the continuous feedback. The weekly feedback was distributed every Tuesday throughout the intervention period as a physical letter. The letter presented average values and distribution of the measurements from the previous week, along with an intuitively understandable assessment of the distribution. The middle section of the letter was dedicated to highlight the parameter performing the worst. The performance of the parameter was presented hour by hour, to show the occupant when a change in the indoor environment would be beneficial. Finally, a comparison of the average values was presented with a comparison to the average of all intervention apartments. Two concrete recommendations on how to obtain and maintain a high indoor environmental quality was given each week. The feedback was introduced on 1st November 2015.

Semi-structured interviews were conducted with occupants from four apartments. The aim of the interviews was to survey how the occupants perceived the indoor environment in their apartments. This information was used to develop and design the content of weekly feedback letter. The information was used to assess if the feedback would affect the occupants. The interview was further aimed to survey if the occupants believed that the physical conditions of the building would limit the effects of the feedback. The full interview guide can be found in Appendix 6.

Two questionnaires were distributed to all apartments upon installation and at the end of the intervention period. The aim of the questionnaire 1 was to survey how the occupants controlled the indoor environment and their motivations for the control strategies. The occupants were further asked about age and job situation for every occupant in the household. These questions would potential be used to determine if socio-economic differences caused measurements differences between the apartments. The aim of questionnaire 2 was to survey the self-perceive influence of the feedback. Questionnaire 2 was also distributed to the control group primarily to survey if hawthorn effects had occurred. The questionnaires can be found in Appendix 7 and Appendix 8.

To assess if the energy used for heating was influenced by the feedback procedure, the temperature difference between the intervention and control apartments was compared to the average outdoor temperature in the intervention period.

12.6 Results

The first part of the result section was a presentation of the measurements as presented in Paper 3. The measurements collected in the living room and bedroom was presented in Figure 15 through Figure 20. The feedback was introduced on 1st November 2015, making the October measurements a representation of the measurements before feedback was introduced. The annotation Pre and Post refers to the period before and after the feedback was introduced.

The second part of this section investigated how the age of the occupants and the presence of children influenced the control of the indoor environment.

12.6.1 Measurements before and after feedback introduction

A general assessment of the measurements showed that the measurements responded as expected in the control apartments. The opposite development was seen in the intervention apartments.

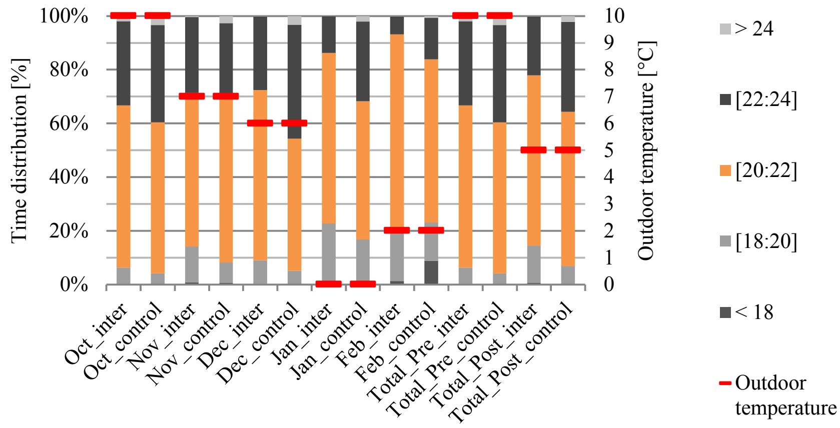


Figure 15 Living room indoor temperature [°C] measurement distribution and outdoor temperature [°C] before and after feedback was introduced and for each month

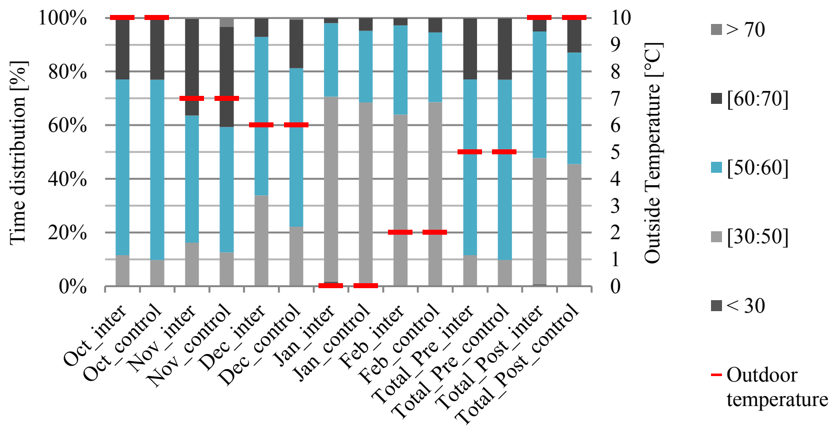


Figure 16 Living room relative humidity [%] measurement distribution and outdoor temperature [°C] before and after feedback was introduced and for each month

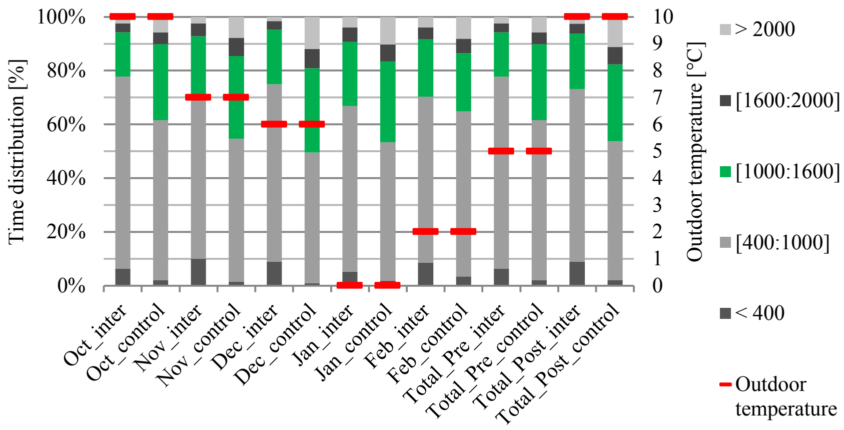


Figure 17 Living room CO_2 concentration [ppm] measurement distribution and outdoor temperature [°C] before and after feedback was introduced and for each month

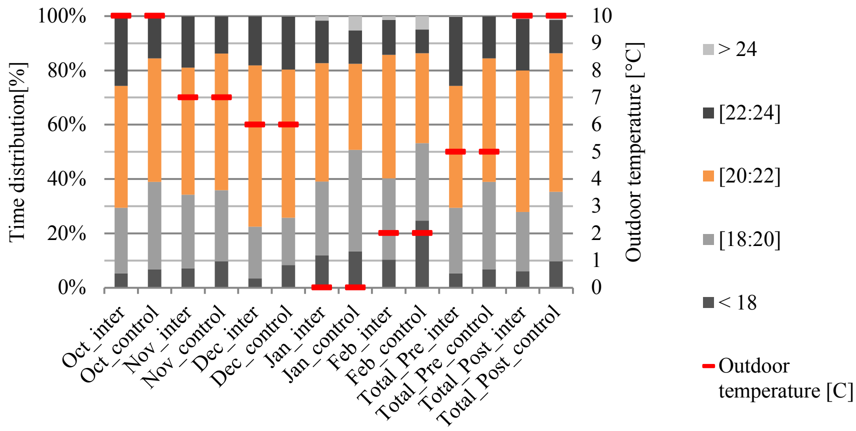


Figure 18 Bedroom indoor temperature [°C] measurement distribution and outdoor temperature [°C] before and after feedback was introduced and for each month

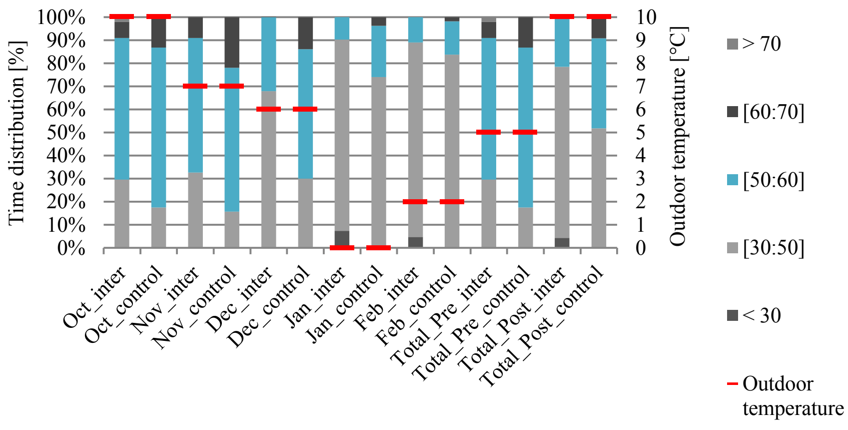


Figure 19 Bedroom relative humidity [%] measurement distribution and outdoor temperature [°C] before and after feedback was introduced and for each month

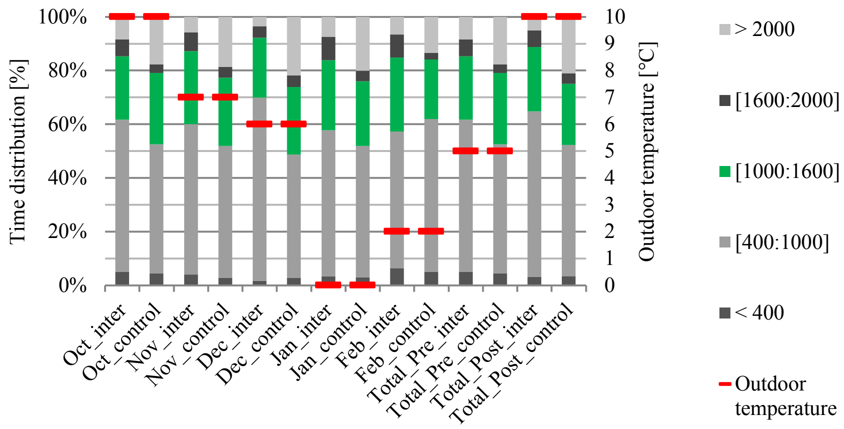


Figure 20 Bedroom CO_2 concentration [ppm] measurement distribution and outdoor temperature [°C] before and after feedback was introduced and for each month

12.6.2 Findings of questionnaire

The findings of questionnaire 1 showed that prior to the feedback introduction occupants in the intervention apartments had a higher focus on the indoor environment and their energy bill, than occupants in control apartments.

17 of 18 apartments responded to Questionnaire 2, 100% of the control apartments and 90% of the intervention apartments. Questionnaire 2 showed that 6 of 9 the intervention apartments had downloaded the smartphone application, five of these reported that there was one primary user of the feedback and that four of these primary users were females. The respondents reported that the continuous feedback was used as the primary feedback mechanism.

From questionnaire 2 in the control apartments, the questions indicated that a hawthorn effect had occurred in 50% of the cases.

12.6.3 Survey of the influence of occupants age and presence of children

In Figure 21 through Figure 26 the living room and bedroom measurements were separated according to the investigated drivers. The figures and the results were not part of Paper 3.

12.6.3.1 Presence of children

Children were present in 3 of 7 of the control apartments and in 6 of 10 of the intervention apartments.

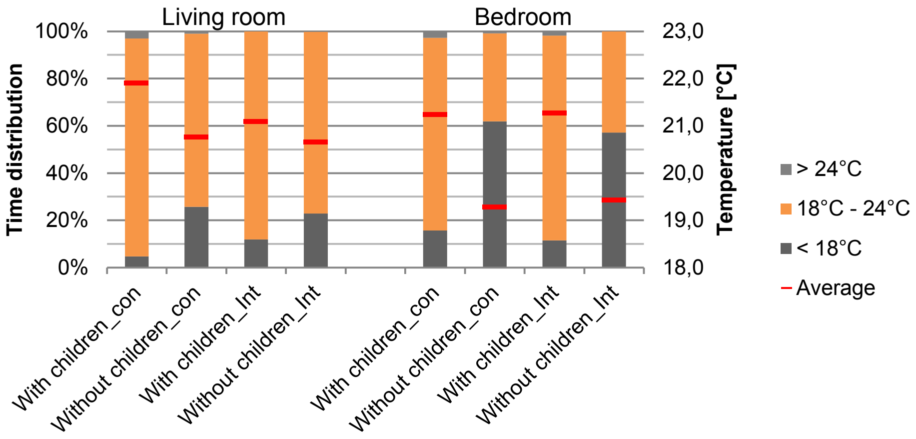


Figure 21 Temperature distribution depending on the presence of children. Right axis: average indoor temperature [°C]

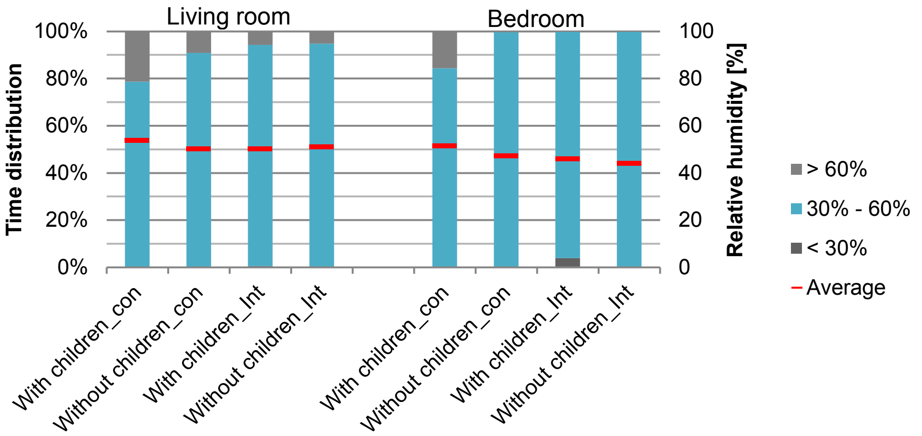


Figure 22 Relative humidity distribution depending on the presence of children. Right axis: average relative humidity [%]

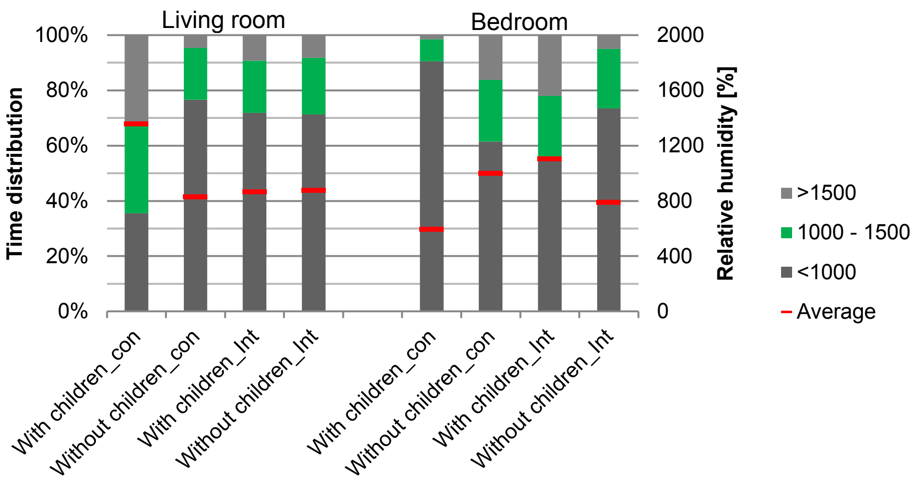


Figure 23 CO_2 concentration distribution depending on the presence of children. Right axis: average CO_2 concentration [ppm]

12.6.3.2 Age of the oldest occupant

The apartments were categorized by the age of the oldest occupant compared to the average age of the occupants. The average age of the occupants was 53. The average age of apartments above the average was 68 and 60 years for control and intervention apartments, respectively. For the below average, the average age was 40years for both control and intervention apartments.

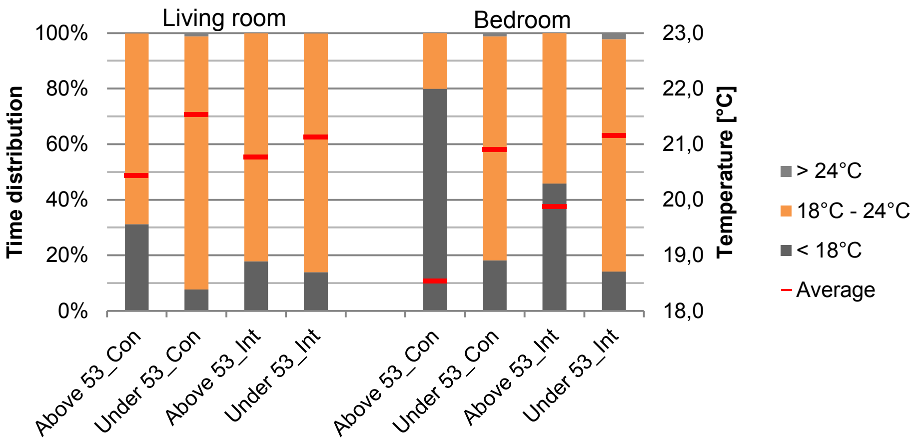


Figure 24 Temperature distribution depending on the age of the oldest occupant. Right axis: average temperature [°C]

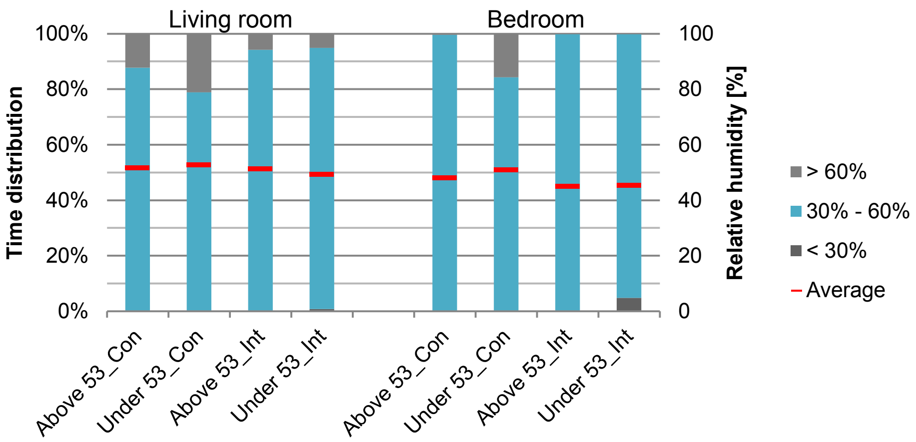


Figure 25 Relative humidity distribution depending on the age of the oldest occupant. Right axis: average relative humidity [%]

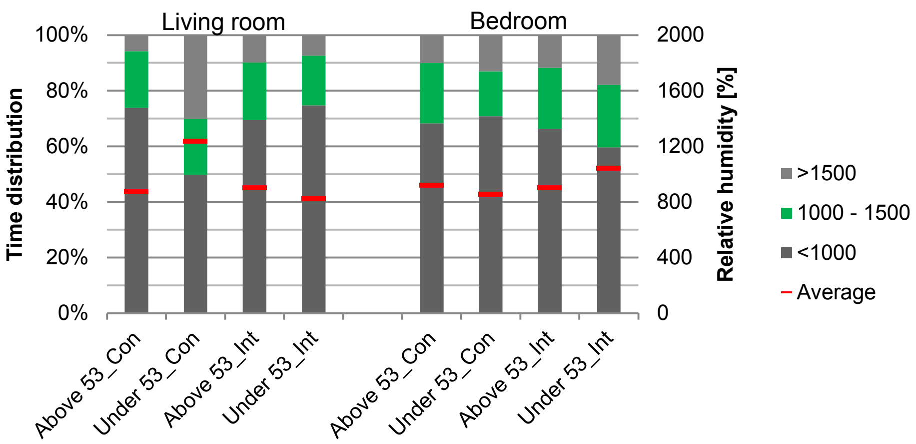


Figure 26 CO_2 concentration distribution depending on the age of the oldest occupant. Right axis: average CO_2 concentration [ppm]

12.6.4 Energy use for heating

The difference in the energy use was calculated based on the mean indoor temperature difference of the two types of apartments as a percentage of the outdoor temperature. The difference in the energy use was presented in Table 6.

Table 6 Estimation of the difference in energy use between Building 1 and Building 2

	Living room	
	Without feedback	With feedback
Control Apartments	21,7°C	21,6°C
Intervention apartments	21,5°C	21,1°C
ΔT	0,2°C	0,5°C
Mean monthly outdoor temperature	10°C	5°C
Difference in energy use	2%	10%

12.7 Discussion

The purpose of control apartments was to document the indoor environment without the occupants being influenced by feedback. From October 2015 through February 2016 the outdoor temperature decreased as shown in Figure 15. Fabi et al. [5] found that an outdoor temperature decrease would influence the occupants' control of the indoor environment, to a lower window opening frequency. In the control apartments this was reflected as a decrease of the average temperature, relative humidity and CO_2 concentration. The average indoor temperature decreased 0.1°C from the before to after the feedback introduction. 50% of the control apartment believed they had been influenced by the presence of the sensor. However, based on assessment of the measurements it was determined that a hawthorn effect was absent and the control apartment measurement therefore could be used as comparison.

The temperature measurements in the intervention apartments showed a decrease in both the average and the maximum readings. As the temperature in the control apartments was stable, the changes in the intervention apartments were assessed as a difference in the control of the indoor environment. Supporting this, the percentage of temperature above 24°C was 0% after the feedback introduction, while it maintained at the same level in the control apartments.

As the window opening frequency decreased while the outdoor temperature decreased it was expected that the CO_2 concentration increased. This was seen in the living room of both apartment types, but not to the same extent. In the control apartment the average CO_2 concentration increased 127ppm, while it increased 20ppm in the intervention apartments. The 95th percentile increased 335ppm in the control apartments, but only 27ppm in the intervention apartment. The 95th percentile of the CO_2 concentration in the bedroom showed a contrary tendency. In the control apartments it increased by 479ppm to 4997ppm. In the intervention apartments the CO_2 concentration decreased 498ppm to 2009ppm, a clear indication of differences in the control of the air quality. See Paper 3 for average values, standard deviation, 5th, 25th, 75th and 95th percentile of the measurements.

From Questionnaire 1 it was found that the occupants in the intervention apartments were more focused on maintaining a low energy use than the control apartments. The questionnaire further showed that the intervention apartments were more focused on the indoor environment than the control apartments. Additionally, the measurements before the feedback introduction showed a notably difference of the two apartment types. It could therefore be argued that the differences in the measurements didn't occur because of the feedback, but the occupants' natural interest in their indoor environment and energy use. However, as Questionnaire 2 found that more apartments of the intervention apartments had increased their interest in the indoor environment than in the control apartments, it was assumed that the feedback procedure had influenced the occupants' control of the indoor environment.

Questionnaire 2 was aimed to investigate the effect of the feedback procedure. The questionnaire found that the majority of the people who downloaded the smartphone application were females. The responses further showed that the continuous feedback was the occupant-perceived most effective feedback method, a finding supporting the finding of Abrahamse et al. regarding the dissemination frequency [70].

12.7.1 Age and children as indoor environmental drivers

A difference between families with children and families without children was found. The relative humidity and CO_2 concentration indicated lower ventilation rates in apartments with children, which could be caused by a desire to maintain a higher indoor temperature. The measurements of the intervention apartments' living room didn't show a notably difference between the segments. The bedroom temperature showed a 2.0°C and 1.8°C difference between the segments for control and intervention apartments, respectively, with higher standard deviations in apartments without children. The differences between the segments, especially in the control apartments' living room, were assessed as a clear indication of the influence of the presence of children, thereby defining it as driver for the control of the indoor environment.

Raaij et al. [15] and Santin [58] described how older occupants preferred a warmer thermal environment. The average temperature and the distribution showed opposite findings than Raaij et al. and Santin, as the temperature in general was lower with the older segment. In the control apartments' living room the temperature was 1°C higher in younger segment than in the older. The relative humidity readings were similar for the two segments, however, the CO_2 concentration, showed a higher average value and a higher variation in the younger segment. In the intervention apartments' living rooms, the results showed a small difference between the segments. In the bedrooms of the older segments in the control apartments, the temperature was 18.5°C, 2.4°C lower than in the younger segment. The relative humidity and CO_2 concentration in the bedroom indicated a higher ventilation rate with the older segment.

Using the CO_2 concentration as a representative for the air quality and occupants venting frequency, the living room results showed the older segment with and without feedback had a similar venting strategy. However, the difference between the younger segments, showed a clear difference between the segments with a better air quality in apartments receiving feedback.

12.8 Conclusion

The study presented notably differences between the intervention and control apartments, differences that because of questionnaire findings were seen as the result of the feedback procedure.

Women were the main user of the feedback and it was perceived that the continuous feedback had the biggest influence on the occupants' control.

It was further concluded that the presences of children was a driver for control of the indoor environment. Also, the age of the occupant was defined as a driver, as the control apartments showed a clear difference in all three parameters between the younger and older segment.

13 STUDY 4 – VISUALISING DAILY ROUTINES

The aim of Study 4 was to develop and test a method to visualize how occupant behaviour affects the indoor environment. The method was further aimed to determine if there was a pattern of how the indoor environment was affected. The method was used to investigate how the occupants in Study 3 affected the indoor environment.

The hypothesis tested in this study was that occupants' use their household according to a daily routine. These daily routines are reflected in the indoor environment performance and can be used to determine when changes in the occupants' control of the indoor environmental are necessary.

The procedure for the method was to separate the measurements from the surveyed period into eight categories, each category represents a three hour interval of the day. To assess the performance of the measurements in each interval, the measurements were compared to a benchmark and how often this benchmark was exceeded. A preliminary version of the analysis method was presented in conference paper: Paper 5. The preliminary version was used to assess the performance of the temperature and relative humidity in nine US households compared to the recommendations of EN 15251-2007 [39].

13.1 Method

Determination of how the occupants affect the indoor environment and whether it happens according to a pattern was done by a two-step method. Step 1 provides a general overview of how measurements in a certain time interval performed. In Step 2 the performance of each time interval for each day was calculated and assigned a rating. The rating was assigned to each time interval of the day creating so-called colour-strings. To assess if the occupants affected the indoor environment in the same way every day, the occurrence of different colour-strings were counted.

13.1.1 Definition of time interval

A fundamental element in the analysis was the time interval separation. The method was aimed to determine how occupant behaviour affects the indoor environment. Analysing the data depending on time intervals enables the method to determine how daily routines affect the performance of the measurements. For this analysis the day has been separated into eight intervals as presented in Table 7. Eight time slots were chosen, as these eight would represent a specific routine of the day. It was considered to merge the early and late night, this was however, rejected as a merge wouldn't allow for an assessment on how the CO_2 concentration developed during the night.

Table 7 Time slot separation and the event of the time slot

Time slot name	Hours	Activity level	Examples of event
Early night	00:00 – 03:00	Low	Sleeping
Late night	03:00 – 06:00	Low	Sleeping
Early morning	06:00 – 09:00	Medium	Eating breakfast
Late morning	09:00 – 12:00	Low	Leaving apartment

Early afternoon	12:00 – 15:00	Low	Empty household
Late afternoon	15:00 – 18:00	Medium	Occupants coming home
Early evening	18:00 – 21:00	High	Preparing dinner
Late evening	21:00 – 24:00	Medium	Relaxing

It was hypothesized that the occupants affected the indoor environment according to a daily routine meaning they for example prepared dinner within the same hour every day. To be able to compare how the dinner preparation etc. across the apartments affected the indoor environment an hourly separation was found too narrow, as occupants do not necessarily prepare dinner within the same hour of the day. This means that it would not be possible to compare apartments hour by hour, as the behaviour perhaps wouldn't be similar.

13.1.2 Benchmark definition and rating

To assess the performance of the indoor environment the measurements were assessed in accordance to benchmarks. Assessment of indoor environmental performance of the 18 apartments in Study 3 was conducted based on the benchmarks presented in Table 8. The benchmarks were based on the design values of the European standard EN 1521-2007 [39] in table A.3, table B.4 and table B.6. The upper temperature benchmark was lowered from 25°C to 23°C as Paper 3 found the highest measured temperatures to be below 24°C.

Table 8 Benchmarks used for determining the indoor environmental performance

	Temperature	Relative Humidity	**CO_2 concentration**
Benchmark	20-23 °C	25 – 60%	900ppm

Performance assessment of the temperature, relative humidity, CO_2 concentration was conducted based on how much time the measurements were outside the benchmark. EN 15251-2007 recommended that the design values were not exceeded for more than 5% of the time [39]. For this analysis the 5% benchmark was expanded to three levels. A rating was assigned to each time interval depending on the performance as presented in *section 12.1 - Development of the feedback procedure.* If the measurements were within the benchmark for more than 95% of the time, they received a W-rating (Within). If the parameter was outside the benchmark for 5-10% of the time it received an S-rating (Slightly outside), and if it was outside the benchmark for more than 10% it received an O-rating (Outside). Rating each time interval created a so-called colour-string, which indicated the performance for a day.

The color-string rating was used in two steps. In step 1 the calculation was performed for all measurements for each apartment from October 2015 through February 2016 and for each month. In the second step, the most and second most occurring colour-string for each apartment was calculated.

13.2 Results

In the following section the key results of Step 1 and Step 2 were presented, with the remaining results can be found in Appendix 10. The most occurring colour-strings were presented in Table 12 through Table 14 while the second most occurring colour-strings were presented in Appendix 10.

13.2.1 Step 1 calculation results

Table 9 Step 1: Temperature assessment from 17 apartments based on measurements from October 2015 through February 2016.

Time	00:00 - 03:00	03:00 - 06:00	06:00 - 09:00	09:00 - 12:00	12:00 - 15:00	15:00 - 18:00	18:00 - 21:00	21:00 - 24:00
Apartment 1	Slightly outside	Slightly outside	Slightly outside	Slightly outside	Outside	Outside	Slightly outside	Slightly outside
Apartment 2	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 3	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 4	Outside	Outside	Outside	Outside	Slightly outside	Slightly outside	Within	Slightly outside
Apartment 5	Slightly outside	Outside	Outside	Within	Within	Within	Within	Within
Apartment 6	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 7	Outside	Outside	Outside	Outside	Slightly outside	Slightly outside	Slightly outside	Within
Apartment 8	Within	Within	Within	Within	Within	Within	Slightly outside	Within
Apartment 9	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 10	Slightly outside	Outside	Outside	Within	Within	Within	Within	Within
Apartment 11	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 12	Within	Within	Slightly outside	Within	Within	Outside	Outside	Slightly outside
Apartment 13	Within	Within	Within	Slightly outside	Slightly outside	Slightly outside	Within	Within
Apartment 14	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 15	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 16	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 17	Slightly outside	Within	Slightly outside	Within	Within	Slightly outside	Slightly outside	Slightly outside
Legend		Within		Slightly outside			Outside	

Table 10 Step 1: Relative humidity assessment from 17 apartments based on measurements from October 2015 through February 2016.

	00:00 - 03:00	03:00 - 06:00	06:00 - 09:00	09:00 - 12:00	12:00 - 15:00	15:00 - 18:00	18:00 - 21:00	21:00 - 24:00
Apartment 1	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 2	Within	Within	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 3	Slightly outside	Slightly outside	Slightly outside	Slightly outside	Within	Slightly outside	Slightly outside	Slightly outside
Apartment 4	Within	Within	Within	Within	Within	Within	Within	Within
Apartment 5	Outside	Slightly outside	Slightly outside	Outside	Outside	Outside	Outside	Outside
Apartment 6	Within	Within	Within	Within	Within	Within	Within	Within
Apartment 7	Slightly outside	Slightly outside	Outside	Outside	Outside	Outside	Slightly outside	Slightly outside
Apartment 8	Within	Within	Slightly outside	Slightly outside	Slightly outside	Slightly outside	Outside	Within
Apartment 9	Within	Within	Slightly outside	Slightly outside	Slightly outside	Slightly outside	Slightly outside	Slightly outside
Apartment 10	Outside	Slightly outside	Slightly outside	Outside	Outside	Outside	Outside	Outside
Apartment 11	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 12	Within	Within	Within	Within	Within	Within	Within	Within
Apartment 13	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 14	Within	Within	Within	Slightly outside	Slightly outside	Within	Within	Within
Apartment 15	Outside	Slightly outside	Slightly outside	Outside	Outside	Outside	Outside	Outside
Apartment 16	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 17	Within	Within	Within	Within	Within	Within	Within	Within
Legend		Within		Slightly outside			Outside	

Table 11 Step 1: CO_2 concentration assessment from 17 apartments based on measurements from October 2015 through February 2016.

	00:00 - 03:00	03:00 - 06:00	06:00 - 09:00	09:00 - 12:00	12:00 - 15:00	15:00 - 18:00	18:00 - 21:00	21:00 - 24:00
Apartment 1	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 2	Outside	Outside	Slightly outside	Outside	Outside	Outside	Outside	Outside
Apartment 3	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 4	Outside	Outside	Outside	Within	Outside	Outside	Outside	Outside
Apartment 5	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 6	Outside	Slightly outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 7	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 8	Slightly outside	Within	Within	Slightly outside	Outside	Outside	Outside	Outside
Apartment 9	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 10	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 11	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 12	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 13	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 14	Outside	Slightly outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 15	Within	Within	Slightly outside	Slightly outside	Slightly outside	Outside	Outside	Slightly outside
Apartment 16	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Apartment 17	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Legend		Within		Slightly outside			Outside	

13.2.2 Step 2 calculation results

Table 12 Step 2: The most occurring temperature color string of each apartment from October 2015 through February 2016.

	00:00 - 03:00	03:00 - 06:00	06:00 - 09:00	09:00 - 12:00	12:00 - 15:00	15:00 - 18:00	18:00 - 21:00	21:00 - 24:00	Occurance [%]
Apartment 1	Red	Green	Green	Red	Red	Red	Red	Red	1%
Apartment 2	Red	Red	Red	Red	Red	Red	Red	Red	19%
Apartment 3	Green	Green	Green	Green	Green	Green	Green	Green	22%
Apartment 4	Green	Green	Green	Green	Green	Green	Green	Green	61%
Apartment 5	Green	Green	Red	Green	Green	Green	Green	Green	14%
Apartment 6	Green	Green	Green	Red	Red	Red	Red	Red	3%
Apartment 7	Green	Green	Green	Green	Green	Green	Green	Green	63%
Apartment 8	Green	Green	Green	Green	Green	Green	Green	Green	76%
Apartment 9	Green	Green	Green	Green	Green	Green	Green	Green	53%
Apartment 10	Green	Green	Red	Green	Green	Green	Green	Green	14%
Apartment 11	Red	Red	Red	Red	Red	Red	Red	Red	45%
Apartment 12	Green	Green	Green	Green	Green	Green	Green	Green	61%
Apartment 13	Red	Green	Red	Green	Green	Green	Red	Red	1%
Apartment 14	Red	Red	Red	Red	Green	Green	Green	Green	1%
Apartment 15	Red	Red	Red	Red	Red	Red	Red	Red	23%
Apartment 16	Green	Green	Green	Green	Green	Green	Green	Green	35%
Apartment 17	Green	Green	Green	Green	Green	Green	Green	Green	63%

Table 13 Step 2: The most occurring relative humidity color string of each apartment from October 2015 through February 2016.

	00:00 - 03:00	03:00 - 06:00	06:00 - 09:00	09:00 - 12:00	12:00 - 15:00	15:00 - 18:00	18:00 - 21:00	21:00 - 24:00	Occurance [%]
Apartment 1									23%
Apartment 2									19%
Apartment 3									83%
Apartment 4									95%
Apartment 5									4%
Apartment 6									89%
Apartment 7									68%
Apartment 8									76%
Apartment 9									81%
Apartment 10									4%
Apartment 11									66%
Apartment 12									88%
Apartment 13									14%
Apartment 14									57%
Apartment 15									5%
Apartment 16									5%
Apartment 17									76%

Table 14 Step 2: The most occurring CO_2 concentration color string of each apartment from October 2015 through February 2016.

	00:00 - 03:00	03:00 - 06:00	06:00 - 09:00	09:00 - 12:00	12:00 - 15:00	15:00 - 18:00	18:00 - 21:00	21:00 - 24:00	Occurance [%]
Apartment 1									84%
Apartment 2									11%
Apartment 3									18%
Apartment 4									11%
Apartment 5									5%
Apartment 6									11%
Apartment 7									34%
Apartment 8									22%
Apartment 9									1%
Apartment 10									5%
Apartment 11									17%
Apartment 12									8%
Apartment 13									9%
Apartment 14									21%
Apartment 15									51%
Apartment 16									22%
Apartment 17									12%

13.3 Discussion

13.3.1 Step 1 calculation – Preliminary assessment

The Step 1 calculation indicated how the occupants affected the indoor environment in 17 apartments. Table 9 through Table 11 visualized the differences between the apartments, indicating that the occupants did not control or affect the indoor environment in the same way. As all apartments had the same orientation, the diversity of the ratings indicates that the influence of the outdoor weather and solar radiation was not decisive.

Table 9 through Table 11 further showed how the benchmarks for all three parameter were exceeded in all apartments in at least one of the time intervals. From the method it was not possible to determine whether the measurements were below or above the benchmark; however, adapting the thermal environment to the recommended benchmarks in Table 10 would either increase the occupants' comfort or led to energy savings. The CO_2 concentration ratings in Table 11 indicated that a higher ventilation rate was recommendable in 16 of 17 apartments, as this would lead to a better indoor air quality. Assuming a low ventilation rate, the relative humidity benchmark was exceeded because of measurements above 60%. In this case, the findings of Table 10 further indicated that a higher ventilation rate was needed in 10 of 17of the apartments in order to reduce the risk of mould and fungus formation.

The diversity of the ratings in Table 9 through Table 11 indicated that the occupants did not influence the indoor environment in the same manor. The diversity further indicated how the step 1 calculation of this method can provide a preliminary view of how the occupants influenced and controlled the indoor environment.

13.3.2 Step 2 calculation – Daily routines

The second step in the calculation was aimed to determine if the indoor environment was affected according to a daily routine. In Table 12 through Table 14 the most occurring colour-string of the temperature, relative humidity and CO_2 concentration was presented along with the percentage of occurrences.

The colour-strings in Table 12 through Table 14 showed for some apartments a clear influence of the occupant behaviour on the indoor environment. For example, in Table 14 the exceeding of the benchmark during the evening, indicated how the behaviour or presence of occupants changed, leading to CO_2 concentration exceeding the benchmark.

Assessing the number of occurrences of the most and second most occurring colour-strings it was seen that it fluctuate between the apartments. A high number of occurrences where assessed as an apartment having a continuous way of influencing and controlling the indoor environment, while a low number of occurrences indicated the contrary. In 6 of 17 apartments the most occurring temperature colour-string represented over 50% of the days in the period, indicating continuality in the control of the indoor environment. For the relative humidity, in 10 of 17 apartments the most occurring colour-string represented over 50% of the days in the period. This was only valid for 2 of 17 apartments of the CO_2 concentration colour-strings. A difference indicating that the CO_2 concentration was more sensible to changes in the occupant behaviour.

In 8 of 17 apartments the most occurring colour-string indicated that the temperature was within the benchmark throughout the day. The second most occurring colour-string differed from apartment to apartment within the eight apartments, but common for these were that the occurrence of the second most occurring colour-strings ranged from 1 – 7%. These low numbers of occurrences indicated an inconsistent control of the indoor environment.

13.3.3 Applicability of the method

In Table 9 through Table 14 it was demonstrated how the method visualized differences in the indoor environment. This visualization was the aim of the method and it was assessed that the method and the result were applicable to a feedback intervention. In Study 3 one parameter was visualized by assessing the performance of every hour of the week. In Study 3 it was assumed that occupants could remember their behaviour and control of the indoor environment of a certain hour and from this see how their behaviour should not be. If occupants find the hour-by-hour assessment too detailed, using the eight time interval separation seemed as a useful alternative.

In this assessment of measurements from the 17 apartments, the benchmarks were determined based on design values recommended by EN 15251-2007 [39]. In a feedback situation for example using tailored feedback, the benchmarks can be designed to fit the purpose of the feedback i.e. if a high air quality is desired because of children with asthma the CO_2 concentration benchmark can be lowered accordingly.

13.4 Conclusion

The influence of the occupants' daily routines and their influence on the indoor environment were determined by visualizing the indoor environment performance compared to a benchmark. In the majority of the apartments, the indoor environment was not influenced according to daily routines as the influence fluctuated from day to day. 35% of the apartments showed indication of a continuous control of the thermal environment. 59% of the apartments showed indication of a continuous control of the relative humidity, while 12% showed indication of a continuous control of the CO_2 concentration.

With the presented method it was possible to visualize the influence of occupant behaviour and occupants' control on the indoor environment. The method was further assessed useful in preliminary feedback based on the indoor environment.

14 DISCUSSION

14.1 Influence of the feedback

The overall aim of this Ph.D. project was to develop and test feedback procedures that could help occupants obtain and maintain a high indoor environmental quality. Two different feedback procedures were developed and tested in Studies 2 and 3. The first procedure combined continuous feedback with monthly feedback while the second combined continuous feedback with weekly feedback. Both feedback procedures were based on indoor environmental measurements. Feedback on energy use gave occupants a monetary and environmental incentive to control the indoor environment. Using this feedback, occupants' control of the indoor environment would be affected by a monetary, environmental, health and comfort incentive. It was hypothesized that using feedback on the indoor environment would be more effective than feedback on energy use.

In Study 2 the feedback procedure was tested in 56 apartments in two buildings in the Copenhagen area of Denmark. Based on the average values obtained in all of the apartments it was not possible to quantify the influence of the feedback procedures. However, 71% (40 out of 56 apartments) questionnaire responses indicated that the occupants considered that the feedback had influenced their control of the indoor environment. A linear regression analysis was performed for each apartment to determine if the feedback had an effect. The linear regression analysis showed that the feedback had influenced occupants' control of indoor environmental parameters in 60% of the apartments. The findings of the questionnaires and regression analysis were seen as an effect of the feedback procedure. A combination of continuous and monthly feedback is therefore considered to be optimal for occupants' control of the indoor environment.

The feedback was tested in master-metered (Building 1) and sub-metered apartments (Building 2). Occupants in Building 2 had a direct incentive to conserve energy as it would lead to a lower energy bill, while occupants in Building 1 would benefit only slightly from making economies. Study 1 documented that the difference in the type of heat cost allocation did influence the occupants' focus on the energy bill and their control of the indoor environment.

The interviews found that only 1 of 4 of the sample in Building 1 had used the feedback, while all respondents in Building 2 had used the feedback. In Building 1 the occupants did not have a direct monetary incentive to conserve energy and assuming they maintained the indoor environment they preferred, the motivation for actively using the feedback came presumably from a health and environmental incentive. The interviews found that the occupants in Building 2 tried to maintain a low indoor temperature in in order to reduce their heating bill, even though they found it uncomfortably cold [91]. These findings indicate that occupants with a direct monetary incentive to conserve energy were more receptive to feedback and that a monetary incentive will enhance the effect of indoor environmental feedback.

In Study 3 a combination of continuous and weekly feedback was tested. The test was conducted in 18 Danish rental apartments (11 intervention and 7 control apartments). The average indoor temperature decreased by 0,5°C in the intervention apartments after the feedback had been introduced, while it decreased by only 0,3°C in the control apartments. The statistical significance of the temperature differences was not determined. As the measuring error of the temperature sensor was +/- 0.3°C there was a possibility that the differences occurred because of measuring errors. However, the measuring error of the CO_2 sensor was +/- 50ppm and the average CO_2

concentration was 280ppm lower in the intervention apartments than the control apartments during the intervention period. This indicates that ventilation rates were higher and implies that the temperature differences occurred because of changes in the occupants' control of the air quality (i.e. opening windows more often).

The feedback was introduced in November 2016, and the last feedback letter was distributed in February 2016. In this period the outdoor temperature decreased, which according to Fabi et al. [5] should result in a decreased window opening frequency. The window opening frequency was not surveyed, but the measurements in the control apartments showed that as the outdoor temperature dropped the average CO_2 concentration increased. In the intervention apartments the average CO_2 concentration decreased from 1047ppm to 944ppm. As there was no changes in the number of occupants, the building envelope etc. it may be assumed that the differences occurred because the feedback procedure had some influence on the occupants' control of the indoor environment. This assessment was supported by a questionnaire distributed at the end of the intervention period. 9 of 10 respondents from the intervention apartments reported that the feedback had had some influence on their control of the indoor environment. In the control apartments only 3 of 7 believed that the presence of the sensor had influenced their control of the indoor environment.

The measurements collected before the feedback was introduced showed lower average indoor temperatures and CO_2 concentrations in the intervention apartments than in the control apartments. The questionnaire distributed before the feedback was introduced, revealed that 8 of 10 respondents in the intervention apartments *agreed* or *highly agreed* that it is more important to have a high indoor environmental quality than a low energy bill, but as 3 of 7 agreed in control apartments, there was no significant difference between conditions.

14.2 Indications of energy conservation

In heated apartments the energy use is determined by the thermal environment, ventilation rate and how the occupants maintain them. The purpose of the feedback procedures tested in Studies 2 and 3 was to affect the occupants' control of the thermal environment and air quality and will therefore potentially have affected energy use. Quantifying the effects of the feedback on the energy use was unfortunately not possible in either of the studies, as neither recoding of the energy use was possible nor the occupants' energy bills were accessible. Assessing the influence was therefore performed by analysing the indoor and outdoor air temperatures.

In Study 1, the occupants in Building 2 had a direct monetary incentive to reduce their energy use, as this would result in a lower energy bill. The difference in the type of heating cost allocation resulted in a difference in the expected direction in the mean indoor temperature of 2.8°C and 2.1°C in March and April, respectively. Based on the monthly mean outdoor temperatures, this implies that Building 1 will have consumed 283% more energy in March and 35% more energy in April than the apartments in Building 2 did.

In Study 2 the influence of feedback on energy use was estimated for each apartment using a regression analysis and the outdoor temperature. From the regression analysis, the potential energy savings were estimated based on an outdoor temperature of 5°C. This calculation showed that in 75% of the apartments in both buildings the indoor temperature would be lower with feedback. In these apartments the energy used for heating would be 11% lower with feedback than without feedback (at T_{out} = 5°C).

In Study 3, the mean indoor temperature in the living rooms' of the intervention apartments was 0.5°C lower than in the control apartments during the intervention period. As the mean outdoor temperature in the intervention period was 5°C, the energy used for heating will have been 10% lower in the intervention apartments than in the control apartments. From the temperature distribution it was evident that the reduced energy use occurred mainly because of differences in the proportion of the time that the temperature was above 22°C. Paper 3 found that the temperature was above 22°C for 22% of the time in the intervention apartments while it was above 22°C for 36% of the time in the control apartments.

These findings indicate how it was possible to reduce energy use by influencing the occupants' control of the indoor air temperature. As discussed in section 14.1, they showed lower CO_2 concentration rates indicating a higher ventilation rate after the feedback were introduced. This is in agreement with the findings of Buchanen et al. who found a 2% energy reduction obtained though in-home display feedback on energy use [29], but the present project has further demonstrated that feedback on the indoor environment was capable of influencing occupants' control of the indoor environment and thus energy use.

Vellei et al. showed that continuous feedback affected occupants' control of the thermal environment in 15 dorm rooms. They found that the occupants' perceived control of the thermal environment increased with the feedback [92] and also that with an increased perception of control of the thermal environment, occupants did not perceive low temperature as uncomfortable [92]. This indicates that the feedback procedures tested in Studies 2 and 3 would be capable of influencing occupants' control of the indoor environment.

In Study 3, the energy use was 10% lower in the intervention apartments than in the control apartment. The actual energy use and the energy price were unknown. However, a national survey of how Danish households' expenses showed that on average 29% (11,067€ of 38,162€) of occupants' annual income was used for rent, heating, and electricity [93]. Assuming that all expenses used for rent, heating, and electricity was used for heating, a 10% reduction of the energy use would reduce the household energy expense by 3%.However, 29% of the annual income is not used for heating and the 3% energy expense reduction would actually be much lower. Savings in this order indicate that additional motivation besides a monetary incentive would be required to change occupant behaviour.

14.3 Participants' understanding of the feedback

It was hypothesized that the participants in the studies understood the relationship between the thermal environment and their energy use. With this understanding they would easily be able to adapt their behaviour to a lower indoor temperature.

No direct questions were asked in the interviews or questionnaires in either of the studies to confirm the hypothesis; however, some of the answers indicated that the participants understood the relationship. In Study 1 the respondents in apartments with a direct monetary incentive to conserve energy explained that they already maintained a low indoor air temperature to save money. This means that if the finding of Humphrey et al. [12] applies, occupants with a monetary incentive achieve thermal comfort by increasing their clothing insulation and by reducing the ventilation rate, as the measurements showed. In Study 3 a questionnaire was distributed before the feedback was introduced in which the occupants were asked whether they would rather increase their clothing level than increase the heating set point and if a high level of indoor environmental quality was more important to them than a low energy bill. It was assumed that a coherence of the two answers would indicate that the occupants understood the relationship between their thermal comfort and energy use. In 50% of the apartments the occupant gave the same answer or a similar answer in the two questions[1].

These findings indicate that the occupants did understand the relationship between their thermal comfort and their use of energy. They further indicate that using feedback on the thermal environment can be used to influence energy use.

[1] A similar answer was defined as an answer that differed by a factor 1 on the scale from 1 to 7

14.4 Feedback dissemination

Studies 2 and 3 gave the occupants' access to real-time visualization of the indoor environment. This was achieved in Study 2 via a website and in Study 3 via a smartphone application and website. Study 2 found that 59% of the respondents had not used the website, while Study 3 found that 67% had downloaded and used the smartphone application. Study 2 concluded that access to continuous feedback should be as barrier-free as possible, a finding that was used in Study 3. Under normal circumstances, Netatmo Weather Station users must sign up by creating a user name and password. To avoid this barrier in Study 3, the user name and password were pre-generated and sent to the participants along with detailed instructions on how to download the smartphone application.

Accessing the data through a website on a mobile platform such as a smartphone or tablet can be done; however, it was perceived that the user experience was smoother using the smartphone application than the website application. It seems likely that a higher efficiency would have been achieved if feedback had been provided by means of a smartphone/tablet application[2]. It was not possible to find studies confirming this, but using a smartphone application enables the use of "push" notifications, an option that is not possible using a web browser [94]. Web browsers can only provide "pull notifications" where the user must visit the website to receive the feedback. Using push notifications enables a simple and intuitive feedback that can be sent directly to the user at any time. The literature review concluded that this was in fact indirectly recommended by Abrahamse et al. [70] and Fischer [31].

14.5 Combining feedback methods and mechanisms

In the current project it was hypothesized that a combination of continuous feedback and weekly/monthly feedback would provide the occupants with tools for everyday use and a useful summary of the measurements. Abrahamse et al. recommended combining feedback methods and mechanisms to increase the effect of the feedback [70], advocating that the combination would be beneficial. On the other hand, Abrahamse et al. [70], Fischer [31], and Darby [25] recommended that feedback should be distributed as often as possible, which argues that the weekly and monthly feedback was unnecessary.

In Study 2, 59% of the participants stated that they had not used the continuous feedback. However, as the measurements, interviews and questionnaires indicated an influence of the feedback, it must have come mainly from the monthly feedback letter. In Study 3, the intervention apartments were asked whether the continuous feedback or the weekly feedback had the greatest effect. 50% responded that the continuous feedback had the biggest influence, 20% the weekly feedback letter and 30% did not answer.

These findings indicate that weekly or monthly feedback is necessary in case the occupants do not use the continuous feedback. In the development of the weekly feedback letter in section 12.1.2 Preliminary feedback letters the occupants stated that they would like to receive concrete recommendations on how to maintain a high level of indoor environmental quality while reducing energy use. If such recommendations could be incorporated into a smartphone application, physical feedback letters would become unnecessary as the same content can be provided within the smartphone application.

14.6 One size fits all solutions

In Studies 2 and 3 the feedback procedures used comfort, health, environment and monetary incentives for the occupants to engage in improvements in their indoor environment. However, even with four kinds of motivation the feedback procedures were "one-size-fits all solutions" that did not take account of individual occupant's user profile.

---

[2] The reflection was based on the authors own experience with the two feedback systems and therefore not a conclusive finding, but a topic to be investigated in future studies

Raaij et al. [15] and Santin [58] found that preferences for the thermal environment and window opening frequency were affected by age and family composition, findings that were supported by the findings in Study 3. Study 1 found that occupants' control of the indoor environment was influenced by the type of heat cost allocation employed. These findings indicate that occupants were motivated by different aspects of the indoor environment and the cost of maintaining it, an argument for using tailored feedback. However, even though the feedback procedures that were used were not tailored to the individual apartment or to occupant characteristics, Studies 2 and 3 documented that changes in the indoor environment nevertheless occurred. This argues that as long as a feedback procedure triggers multiple motivation aspects, a "one-size-fits-all solution" can be used to affect occupant behaviour.

14.7 Can self-calibrating sensors be used to assess IEQ

The CO_2 sensors used in the IC-Meter and the Netatmo Weather Station were self-calibrating (ABC calibration). To determine the outdoor concentration the sensor assumed the lowest measured CO_2 concentration to be equal to the nominal outdoor concentration. Such an assumption could have led to misreading's if the indoor concentration never descended to the outdoor concentration.

It could therefore be argued that self-calibrating CO_2 sensors were inappropriate for a detailed documentation of the indoor environment. The low price of self-calibrating CO_2 sensors has made indoor environmental tracking available to the general public. If the main goal of the CO_2 concentration feedback was to make people react, it is arguable that using this sensor type is acceptable, despite a potential but very small error in the accuracy of the CO_2 concentrations. In this study, the CO_2 measurements were used to evaluate the air quality and window opening and also to influence the occupants' behaviour. The indoor environment assessment may be considered acceptable as the proportion of CO_2 measurements below 380ppm was 0,5% and 4% in Studies 2 and 3, respectively. This proportion of errors was so low that it was considered acceptable that it was neglected.

14.8 Number of participants

In Study 2 one occupant from each building won an Apple Ipad worth approximately €400. In Study 3 one of the participants would receive a gift certificate worth approximately €140 to a nearby shopping mall. In both Study 2 and 3 acquire occupants to participate was difficult as it in the end was necessary to get occupants to participate, by convincing them individually by going from door to door. The reason for this unwillingness to participate is unknown, but conversations with occupants indicated that the reward versus the impact it would have on the occupants' life the possible rewards were not enough. This finding is supported by Schultz who through his findings indicated that people must be motivated to act [20].

Question 1 in Study 3 showed that 90% of the intervention apartments believed it was important to have a high level of indoor environmental quality. For future studies it could be beneficial to push the sensors to the occupants. This was occupants who are not motivated to participate will receive the feedback which will be a test that will document efficiency of the feedback procedure.

15 CONCLUSION

The overall focus for this project was to study if indoor environment feedback could be used to influence occupants' control of the indoor environment and thereby their energy use for heating. This was studied by measurements of the indoor environment, interviews with the participating occupants and questionnaire surveys. Two different feedback procedures were used to influence the occupants' control of the indoor environment. A literature review was conducted to survey how occupant behaviour influences the energy use and how feedback on energy use has been used in the literature. Four studies investigated the influence of occupant behaviour based on measurements from 3 buildings in the Copenhagen area of Denmark. From the studies the following was concluded.

- Occupants demonstrated an understanding of how thermal discomfort can be avoided without increasing the heating set point.
- Indoor environmental feedback can be used to influence occupants' control of the indoor environment.
- Indoor environmental feedback can be used to affect energy consumption for heating, by influencing the occupants' control of the heating set point.
- When using feedback as an everyday tool for assessing the indoor environment, feedback should be provided as frequently as possible if it is to be successful.
- The use of weekly or monthly feedback was not necessary, provided that the continuous feedback was sufficiently comprehensive.
- The use of the feedback was determined by its accessibility, i.e. easy access increased the use of the feedback.
    - This means that continuous feedback should be accessible via a smartphone application instead of a web browser. A smartphone application provides feedback options that were not possible on a web browser solution.
- A monetary incentive to conserve energy prevailed over other drivers and enhanced the effect of indoor environmental feedback.
- Motivation was the key factor when trying to influence occupant behaviour, i.e. if the occupants were not motivated the effect of a feedback procedure was small.
- Occupants did not change the indoor environment according to daily routines.
- Occupant behaviour was reflected in the indoor environmental measurements, so measurements of the indoor environment are a suitable basis for a feedback intervention.

16 FUTURE STUDIES

In Studies 2 and 3 the influence of indoor environmental feedback was studied in a total of 74 apartments. Not all of results were tested for statistical significance, but as the result showed an apparent influence of feedback, future studies should determine the statistical significance of the effect by conducting an extensive study on indoor environmental feedback and whether this should be accompanied by feedback on energy use.

In this Ph.D. project it was documented that feedback based on the indoor environment can be an alternative to smart meters and energy use feedback disseminated though in-home displays. However, as smart meters already are being installed they will presumably not be replaced by indoor environmental sensors. Future studies should therefor investigate how feedback on both indoor environment and energy use can be combined and utilised to influence occupant behaviour. Such studies should also investigate how the energy use in buildings without smart meters is to be calculated and implemented in feedback.

The project concluded that the use of feedback was determined by the users' motivation. Future studies should investigate how a commercial generic feedback solution can be developed to motivate all segments of a multifamily building. From Study 3 it was concluded that continuous feedback had the greatest influence on occupants, so future studies should investigate how a feedback intervention based on a smartphone application can be used to influence occupant behaviour. Such a study would require a broad representation of knowledge ranging from engineering and software developers to sociologists and user-interface designers.

17 REFERENCE LIST

[1] European Commission. Energy Efficiency and its contribution to energy security and the 2030 Framework for climate and energy policy. 2014. doi:10.1007/s13398-014-0173-7.2.

[2] Brunsgaard C, Heiselberg P, Knudstrup M -a., Larsen TS. Evaluation of the Indoor Environment of Comfort Houses: Qualitative and Quantitative Approaches. Indoor Built Environ 2011;21:432–51. doi:10.1177/1420326X11431739.

[3] Knudsen HN, Thomsen KE, Mørck O. Occupant Experiences and Satisfaction with New Low-Energy Houses n.d.;2008.

[4] Mlakar J, ??trancar J. Overheating in residential passive house: Solution strategies revealed and confirmed through data analysis and simulations. Energy Build 2011;43:1443–51. doi:10.1016/j.enbuild.2011.02.008.

[5] Fabi V, Andersen RV, Corgnati S, Olesen BW. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. Build Environ 2012;58:188–98. doi:10.1016/j.buildenv.2012.07.009.

[6] Frontczak M, Andersen RV, Wargocki P. Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing. Build Environ 2012;50:56–64. doi:10.1016/j.buildenv.2011.10.012.

[7] Bekö G, Lund T, Nors F, Toftum JJ, Clausen G, Beko G. Ventilation rates in the bedrooms of 500 Danish children. Build Environ 2010;45:2289–95. doi:10.1016/j.buildenv.2010.04.014.

[8] Psomas T, Heiselberg P, Duer K, Bjørn E. Overheating risk barriers to energy renovations of single family houses: Multicriteria analysis and assessment. Energy Build 2016;117:138–48. doi:10.1016/j.enbuild.2016.02.031.

[9] Kazanci OB, Olesen BW. Beyond nZEB: Experimental investigation of the thermal indoor environment and energy performance of a single- family house designed for plus-energy targets. ASHRAE 2014.

[10] Frontczak M, Wargocki P. Literature survey on how different factors influence human comfort in indoor environments. Build Environ 2011;46:922–37. doi:10.1016/j.buildenv.2010.10.021.

[11] Peffer T, Pritoni M, Meier A, Aragon C, Perry D. How people use thermostats in homes: A review. Build Environ 2011;46:2529–41. doi:10.1016/j.buildenv.2011.06.002.

[12] Humphreys M, Nicol F. Understanding the Adaptive Approach to Thermal Comfort. ASHRAE Trans 1998;104:991–1004.

[13] Socolow R. The Twin Rivers Program on Energy Conservation in Housinh: Highlights and Conclusions 1977.

[14] Sonderegger RC. Movers and stayers: The resident's contribution to variation across houses in energy consumption for space heating. Energy Build 1978;1:313–24. doi:10.1016/0378-7788(78)90011-7.

[15] van Raaij WF, Verhallen TMM. Patterns of residential energy behavior. J Econ Psychol 1983;4:85–106. doi:10.1016/0167-4870(83)90047-8.

[16] Owens J, Wilhite H. Household energy behavior in nordic countries-an unrealized energy saving potential 1988;13:853–9.

[17] Andersen R. The influence of occupants ' behaviour on energy consumption investigated in 290 identical dwellings and in 35 apartments 2009.

[18] Cholewa T, Siuta-Olcha A. Long term experimental evaluation of the influence of heat cost allocators on energy consumption in a multifamily building. Energy Build 2015;104:122–30. doi:10.1016/j.enbuild.2015.06.083.

[19] Bornehag CG, Sundell J, Hägerhed-Engman L, Sigsgaard T. Association between ventilation rates in 390 Swedish homes and allergic symptoms in children. Indoor Air 2005;15:275–80. doi:10.1111/j.1600-0668.2005.00372.x.

[20] Schultz PW. Conservation Means Behavior. Conserv Biol 2011;25:1080–3. doi:10.1111/j.1523-1739.2011.01766.x.

[21] McClelland L, Cook SW. Promoting Energy Conservation in Master-Metered Apartments through Group Financial Incentives 1980:20–31.
[22] van Houwelingen JH, van Raaij WF. The Effect of Goal-Setting and Daily Electronic Feedback on In-Home Energy Use. J Consum Res 1989;16:98. doi:10.1086/209197.
[23] D'Oca S, Corgnati SP, Buso T. Smart meters and energy savings in Italy: Determining the effectiveness of persuasive communication in dwellings. Energy Res Soc Sci 2014;3:131–42. doi:10.1016/j.erss.2014.07.015.
[24] Faruqui A, Sergici S, Sharif A. The impact of informational feedback on energy consumption-A survey of the experimental evidence. Energy 2010;35:1598–608. doi:10.1016/j.energy.2009.07.042.
[25] Darby S. The Effectiveness of Feedback on Energy Consumption a Review for Defra of the Literature on Metering , Billing and Direct Displays. Environ Chang Inst Univ Oxford 2006;22:1–21. doi:10.4236/ojee.2013.21002.
[26] Ueno T, Tjuji K, Inada R, Saeki O. Effectiveness of displaying energy consumption data in residential houses Analysis on how the residents respond. ECEEE Summer Study 2005:1289–99.
[27] Nilsson A, Bergstad CJ, Thuvander L, Andersson D, Andersson K, Meiling P. Effects of continuous feedback on households' electricity consumption: Potentials and barriers. Appl Energy 2014;122:17–23. doi:10.1016/j.apenergy.2014.01.060.
[28] Buchanan K, Russo R, Anderson B. Feeding back about eco-feedback: How do consumers use and respond to energy monitors? Energy Policy 2014;73:138–46. doi:10.1016/j.enpol.2014.05.008.
[29] Buchanan K, Russo R, Anderson B. The question of energy reduction: The problem(s) with feedback. Energy Policy 2015;77:89–96. doi:10.1016/j.enpol.2014.12.008.
[30] Abrahamse W, Steg L, Vlek C, Rothengatter T. The effect of tailored information, goal setting, and tailored feedback on household energy use, energy-related behaviors, and behavioral antecedents. J Environ Psychol 2007;27:265–76. doi:10.1016/j.jenvp.2007.08.002.
[31] Fischer C. Feedback on household electricity consumption: A tool for saving energy? Energy Effic 2008;1:79–104. doi:10.1007/s12053-008-9009-7.
[32] Janda K. Buildings don't use energy - People do! Planet Earth 2011;8628:12–3. doi:10.3763/asre.2009.0050.
[33] Maier T, Krzaczek M, Tejchman J. Comparison of physical performances of the ventilation systems in low-energy residential houses. Energy Build 2009;41:337–53. doi:10.1016/j.enbuild.2008.10.007.
[34] Andersen RV. Occupant Behaviour with regard to Control of the Indoor Environment 2009.
[35] Hens H, Parijs W, Deurinck M. Energy consumption for heating and rebound effects. Int Conf Build Energy Environ (COBEE 2008) 2010;42:105–10. doi:10.1016/j.enbuild.2009.07.017.
[36] Nicol F, Roaf S. Post-occupancy evaluation and field studies of thermal comfort. Build Res Inf 2005;33:338–46. doi:10.1080/09613210500161885.
[37] De Carli M, Olesen BW, Zarrella A, Zecchin R. People's clothing behaviour according to external weather and indoor environment. Build Environ 2007;42:3965–73. doi:10.1016/j.buildenv.2006.06.038.
[38] Karjalainen S. Thermal comfort and gender: a literature review. Indoor Air 2012;22:96–109. doi:10.1111/j.1600-0668.2011.00747.x.
[39] En DS. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. 2007.
[40] Burak Gunay H, O'Brien W, Beausoleil-Morrison I, Perna A. On the behavioral effects of residential electricity submetering in a heating season. Build Environ 2014;81:396–403. doi:10.1016/j.buildenv.2014.07.020.
[41] Fabi V, Andersen RV, Corgnati S, Olesen BW. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. Build Environ 2012;58:188–98. doi:10.1016/j.buildenv.2012.07.009.
[42] Seligman C, Kriss M, Darley JM, Fazio RH, Becker LJ, Pryor JB. Predicting Summer Energy Consumption from Homeowners' Attitudes'. J Appl Soc Psychol 1979;9:70–90. doi:10.1111/j.1559-1816.1979.tb00795.x.
[43] Psychology E, Faculty P, Sciences S, Ba B, Brandon G, Lewis A. Reducing Household Energy Consumption: a Qualitative and Quantitative Field Study. J Environ Psychol 1999;19:75–85. doi:10.1006/jevp.1998.0105.
[44] Vringer K, Aalbers T, Blok K. Household energy requirement and value patterns. Energy Policy 2007;35:553–66. doi:10.1016/j.enpol.2005.12.025.
[45] O'Callaghan B, Green HJ, Hyde RA, Wadley D, Upadhyay A. Exploring the influence of housing design and occupant environmental attitudes on energy and water usage. Archit Sci Rev 2012;55:176–85. doi:10.1080/00038628.2012.693813.
[46] Sapci O, Considine T. The link between environmental attitudes and energy consumption

behavior. J Behav Exp Econ 2014;52:29–34. doi:10.1016/j.socec.2014.06.001.
[47] Ek K, Söderholm P. The devil is in the details: Household electricity saving behavior and the role of information. Energy Policy 2010;38:1578–87. doi:10.1016/j.enpol.2009.11.041.
[48] Brounen D, Kok N, Quigley JM. Energy literacy, awareness, and conservation behavior of residential households. Energy Econ 2013;38:42–50. doi:10.1016/j.eneco.2013.02.008.
[49] Gatersleben B, White E, Abrahamse W, Jackson T, Uzzell D. Values and sustainable lifestyles. Archit Sci Rev 2010;53:37–50. doi:10.3763/asre.2009.0101.
[50] Levinson A, Niemann S. Energy use by apartment tenants when landlords pay for utilities. Resour Energy Econ 2004;26:51–75. doi:10.1016/S0928-7655(03)00047-2.
[51] Ziemele J, Pakere I, Blumberga D, Zogla G. Economy of Heat Cost Allocation in Apartment Buildings. Energy Procedia 2015;72:87–94. doi:10.1016/j.egypro.2015.06.013.
[52] Haas R, Auer H, Biermayr P. The impact of consumer behavior on residential energy demand for space heating. Energy Build 1998;27:195–205. doi:10.1016/S0378-7788(97)00034-0.
[53] Aydin E, Kok N, Brounen D. Energy Efficiency and Household Behavior : The Rebound Effect in the Residential Sector 2014:1–38.
[54] Gram-Hanssen K. Hverdag i det topisolerede hus. Råstof 2015:11–3.
[55] Sunikka-Blank M, Galvin R. Introducing the prebound effect: the gap between performance and actual energy consumption. Build Res Inf 2012;40:260–73. doi:10.1080/09613218.2012.690952.
[56] Huebner GM, Cooper J, Jones K. Domestic energy consumption—What role do comfort, habit, and knowledge about the heating system play? Energy Build 2013;66:626–36. doi:10.1016/j.enbuild.2013.07.043.
[57] Sardianou E. Estimating space heating determinants: An analysis of Greek households. Energy Build 2008;40:1084–93. doi:10.1016/j.enbuild.2007.10.003.
[58] Santin OG. Behavioural Patterns and User Profiles related to energy consumption for heating. Energy Build 2011;43:2662–72. doi:10.1016/j.enbuild.2011.06.024.
[59] Yamasaki E, Tominaga N. Evolution of an aging society and effect on residential energy demand. Energy Policy 1997;25:903–12. doi:10.1016/S0301-4215(97)00040-2.
[60] Tonn B, Eisenberg J. The aging US population and residential energy demand. Energy Policy 2007;35:743–5. doi:10.1016/j.enpol.2005.12.011.
[61] Hamza N, Gilroy R. The challenge to UK energy policy: An ageing population perspective on energy saving measures and consumption. Energy Policy 2011;39:782–9. doi:10.1016/j.enpol.2010.10.052.
[62] Rijal HB, Tuohy P, Humphreys MA, Nicol JF, Samuel A, Clarke J. Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. Energy Build 2007;39:823–36. doi:10.1016/j.enbuild.2007.02.003.
[63] Andersen RV, Toftum JJ, Andersen KK, Olesen BW. Survey of occupant behaviour and control of indoor environment in Danish dwellings. Energy Build 2009;41:11–6. doi:10.1016/j.enbuild.2008.07.004.
[64] Andersen RV, Olesen BW, Toftum J. Modeling window opening behaviour in Danish dwellings. Proc 12th Int Conf Indoor Air Qual Clim 2011.
[65] Leaman A, Bordass B. Productivity in buildings: the “killer” variables. Build Res Inf 1999;27:4–19.
[66] Gramstrup S, Aarup M, Svanborg K, Zakrisson A. ebutler - Final report. 2015.
[67] Hargreaves T, Nye M, Burgess J. Keeping energy visible? Exploring how householders interact with feedback from smart energy monitors in the longer term. Energy Policy 2013;52:126–34. doi:10.1016/j.enpol.2012.03.027.
[68] Seligman C, Darley JM, Becker LJ. Behavioral approaches to residential energy conservation. Energy Build 1978;1:325–37. doi:10.1016/0378-7788(78)90012-9.
[69] Wilhite H, Ling R. Measured energy savings from a more informative energy bill 1995;22:145–55.
[70] Abrahamse W, Steg L, Vlek C, Rothengatter T. A review of intervention studies aimed at household energy conservation. J Environ Psychol 2005;25:273–91. doi:10.1016/j.jenvp.2005.08.002.
[71] Allcott H. Social norms and energy conservation. J Public Econ 2011;95:1082–95. doi:10.1016/j.jpubeco.2011.03.003.
[72] Harries T, Rettie R, Studley M, Burchell K, Chambers S. Is social norms marketing effective?: A case study in domestic electricity consumption. Eur J Mark 2013;47:1458–75. doi:10.1108/EJM-10-2011-0568.
[73] Iyer M, Kempton W, Payne C. Comparison Groups as a Tool for Evaluating Energy Efficiency Programs: An Analysis of Energy Star Billing Comparison Groups. Energy 1998:179–92.
[74] Schultz PW, Nolan JM, Cialdini RB, Goldstein NJ, Griskevicius V. The constructive, destructive, and reconstructive power of social norms. Psychol Sci 2007;18:429–34. doi:10.1111/j.1467-9280.2007.01917.x.
[75] McAlaney J, Bewick BM, Bauerle J. Social Norms Guidebook. 2010.

[76] Burchell K, Rettie R, Patel K. Marketing social norms: Social Marketing and the “social norm approach.” J Consum Behav 2008;12:253–66. doi:10.1002/cb.
[77] Granfield R. Can You Believe it?: Assessing the Credibility of a Social Norms Campaign 2002:1–8.
[78] Cialdini RB, Goldstein NJ. Social influence: compliance and conformity. Annu Rev Psychol 2004;55:591–621. doi:10.1146/annurev.psych.55.090902.142015.
[79] Schweiker M, Shukuya M. Investigation on the effectiveness of various methods of information dissemination aiming at a change of occupant behaviour related to thermal comfort and exergy consumption. Energy Policy 2011;39:395–407. doi:10.1016/j.enpol.2010.10.017.
[80] Geller ES. The Challenge of Increasing Proenvironment Behavior n.d.
[81] Kuo MS, Chuang TY. How gamification motivates visits and engagement for online academic dissemination - An empirical study. Comput Human Behav 2016;55:16–27. doi:10.1016/j.chb.2015.08.025.
[82] Winett RA, Kagel JH, Battalio RC, Winkler RC. Effects of monetary rebates, feedback, and information on residential electricity conservation. J Appl Psychol 1978;63:73–80. doi:10.1037/0021-9010.63.1.73.
[83] Slavin RE, Wodarski JS, Blackburn BL. A group contingency for electricity conservation in master-metered apartments. J Appl Behav Anal 1981;14:357–63. doi:10.1901/jaba.1981.14-357.
[84] Oltra C, Boso A, Espluga J, Prades A. A qualitative study of users’ engagement with real-time feedback from in-house energy consumption displays. Energy Policy 2013;61:788–92. doi:10.1016/j.enpol.2013.06.127.
[85] Krishnamurti T, Davis AL, Wong-Parodi G, Wang J, Canfield C. Creating an in-home display: Experimental evidence and guidelines for design. Appl Energy 2013;108:448–58. doi:10.1016/j.apenergy.2013.03.048.
[86] Buchanan K, Banks N, Preston I, Russo R. The British public’s perception of the UK smart metering initiative: Threats and opportunities. Energy Policy 2016;91:87–97. doi:http://dx.doi.org/10.1016/j.enpol.2016.01.003.
[87] Wilke G. IC Meter 2015. www.ic-meter.com (accessed March 15, 2015).
[88] Netatmo Weather Station 2015:https://www.netatmo.com/product/station.
[89] SenseAir Product Specification. SenseAir S8. vol. 1. n.d.
[90] Fabi V, Andersen RV, Corgnati SP, Venezia F. Main physical environmental drivers of occupant behaviour with regard to space heating energy demand. Heal Build 2012 2012.
[91] Andersen RK. Experiences from the project Dynamic Heat Cost Allocation 2013.
[92] Vellei M, Natarajan S, Biri B, Padget J, Walker I. The effect of real-time context-aware feedback on occupants ’ heating behaviour and thermal adaptation. Energy Build 2016;123:179–91. doi:10.1016/j.enbuild.2016.03.045.
[93] Denmark S. http://www.dst.dk/da/Statistik/NytHtml?cid=20034 2016.
[94] Apple. https://developer.apple.com/library/ios/documentation/NetworkingInternet/Conceptual/RemoteNotificationsPG/Chapters/ApplePushService.html 2016.

18 APPENDIX LIST

List of appendixes:

- Appendix 1 - Paper 1
- Appendix 2 – Interview guide for semi-structured interviews used in Study 1 and Study 2
- Appendix 3 – Questionnaire used in Study 1 and Study 2
- Appendix 4 - Paper 2
- Appendix 5 - Paper 3
- Appendix 6 – Interview guide for semi-structured interviews conducted in Study 3
- Appendix 7 – Questionnaire 1 conducted as art of Study 3
- Appendix 8 – Questionnaire 2 conducted as art of Study 3.
- Appendix 9 – Final feedback letter used in Study 3 in original size
- Appendix 10 – Informational leaflet used in Study 3.
- Appendix 11 – Study 4, the second most occurring colour-string
- Appendix 12 – Paper 4
- Appendix 13 – Paper 5
- Appendix 14 – Co-Author statements for Paper 1 through Paper 3

19 APPENDIX 1

Paper 1
Influence of heat cost allocation on occupants' control of indoor environment in 56 apartments: studied with measurements, interviews and questionnaires

Authors: Søren Andersen, Rune Korsholm Andersen and Bjarne W. Olesen
Published in: Building and Environment
Publication status: Accepted 26th February 2016
Link: http://dx.doi.org/10.1016/j.buildenv.2016.02.024

Building and Environment 101 (2016) 1–8

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Influence of heat cost allocation on occupants' control of indoor environment in 56 apartments: Studied with measurements, interviews and questionnaires

Søren Andersen*, Rune Korsholm Andersen, Bjarne W. Olesen

ICIEE, Department of Civil Engineering, Technical University of Denmark, Nils Koppels Allé 402-2, 2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Article history:
Received 17 December 2015
Received in revised form
24 February 2016
Accepted 26 February 2016
Available online 3 March 2016

Keywords:
Adaptive behaviour
Window opening
Thermosat adjustment
Temperature
CO_2 concentration

ABSTRACT

People who pay their energy bills individually based on meter readings tend to spend less energy than people who pay collectively e.g. based on floor areas. It has been hypothesised that these savings are an effect of lower indoor temperatures and ventilation rates during heating seasons. The aim of this paper was to study the indoor environment in buildings with collective and individual heat cost allocation plans, to investigate how the heat cost allocation influenced occupant behaviour and how occupants controlled the indoor environment.

The effects of the heat cost allocation type were studied by comparing indoor environmental measurements between two buildings: one with collective payment and one with individual payment. The measurements were collected at 5 min intervals at a central location in each of 56 apartments in Copenhagen, Denmark over a period of two months. Questionnaires and semi-structured interviews showed a strong influence of the heat cost allocation plan on the occupants' control strategies. Occupants whose heating bills were based on floor area focused on a healthy and comfortable indoor environment. Occupants whose heating bills were based on meter readings focused on energy conservation and heat cost savings at the expense of thermal comfort and air quality.

The differences in average temperature, average CO_2 concentration and average vapour pressure were 2.8 °C, 161 ppm, and 93 Pa, respectively between apartments with collective and individual heat cost allocation.

1. Introduction

People are different; in behaviour, expression and knowledge. Seen from the built environment's perspective, this explains why energy consumption can differ by up to 300% in similar residential buildings [1].

Since the first Twin Rivers study [2], the effects of occupant behaviour and the potential energy savings have been proven in multiple studies (e.i. [3–6]). The studies showed how significant energy savings can be achieved through changes and optimisation of the occupant behaviour. However, occupants will not change behaviour if they are not motivated [7] and actions to motivate occupants and provide them with assessment tools seem necessary to reduce energy consumption.

In a review by Abrahamse et al. [8], various intervention methods aimed to reduce energy consumption were described. One of these intervention methods described the way in which the energy bill was presented. The energy bill is normally sent to occupants as a monthly, quarterly or yearly bill as a simple form of feedback. Abrahamse reported energy savings between 2.5% and 3.7% for the medium and high consuming households when comparative feedback was introduced [8]. Experiments with comparative feedback presented with the heating bill were conducted in Oslo in 1995 [3] and have been continued in several studies (i.e. [9]), showing that when occupants were made aware of their consumption in a social perspective, it decreased.

Cholewa et al. [10] compared the energy consumption for heating in 40 Polish apartments over 17 heating seasons. Half of the apartments had an individual payment plan while the other half paid collectively. The study showed a difference of 26,6% on average between the two payment plans, occurring as a result of the control of the thermal indoor environment – actual measurements of the

* Corresponding author.
E-mail address: sran@byg.dtu.dk (S. Andersen).

http://dx.doi.org/10.1016/j.buildenv.2016.02.024
0360-1323/

thermal environment were not part of the study. In the heating season 2011/2012, submetering was introduced in all apartments. In the subsequent three heating seasons the difference in the energy consumption between payment types decreased to 2.6%, indicating that when occupants became aware of their consumption it was reduced.

Whether the heating bill encourages occupants to reduce or increase their heating consumption, heating bills may have a direct influence not only on the indoor temperature but also the indoor air quality and moisture content. Both Wilhite et al. [3], Abrahamse [8], and Cholewa [10] showed reductions in energy consumption, however, the interventions' effects on the indoor environment were not investigated.

Gunay et al. [11] showed that the temperature in Canadian apartments with bulkmetering was higher than in apartments with submetering. Tenants in submetered apartments primarily kept the temperature low to keep the energy bill low, but also for environmental reasons. The paper further showed, that occupants in submetered apartments were more likely to heat different areas to different temperatures, where as bulk metered apartments rarely adjusted their thermostats [11]. In the Canadian study, the average temperature was 2 °C higher in the bulk metered apartments than in the submetered apartments during the heating season. A similar study by Levinson et al. [12] studied if including or excluding utilities in the rent would make apartments more attractive for the tenants. The study found a temperature difference of 0.6 °C−1.7 °C between apartments with utilities-included contracts and utilities not included contracts not including utilities. Both studies showed that the metering as a feedback method acted as a significant driver for the occupants' control of the indoor temperature.

In two reviews by Fabi et al. ([13,14]). the driving forces of window opening behaviour and space heating demand were surveyed. The identified drivers were grouped in five categories: Physical Environment, Contextual, Psychological, Physiological and Social [14]. Sardianou [15] has surveyed the variables affecting the heating consumption in Greek dwellings, identifying the following variables; age of respondents, number of persons in household, ownership conditions, size of dwelling, and household annual income. Andersen et al. [16] surveyed variables affecting window opening and heating behaviour in Danish dwellings. The paper concluded that heating consumption was affected by outdoor temperature, solar radiation, and ownership conditions. Frontczak et al. [17] found that 70% of their survey respondents, were *at least a bit aware of how their behaviour influenced energy use and indoor environmental quality* ([17] page 62). The identified drivers represented all five of Fabi's categories [14], constituting the complexity of identifying, modelling, and changing occupant behaviour, but also demonstrating the necessity to quantify the effects of all behavioural drivers.

The aim of this paper was to investigate and quantify the heat cost allocation as a psychological driver for occupant behaviour regarding control of the indoor environment. The effects of the heat cost allocation on the indoor environment were quantified, and explanations to of the observed differences were discussed.

This paper is based on measurements in Danish apartments, in which the thermal environment is directly linked to the energy consumption through the room by room thermostat controlled water based heating system and the window opening frequency.

2. Method

2.1. Measurements and method

Measurements of air temperature [°C], relative humidity [%] and CO_2 concentration [ppm] were taken in 56 apartments in two buildings in Copenhagen, Denmark (Building 1 and Building 2). Measurements were taken in a central hall way at 5 min intervals from 1st March 2013 to 30th April 2013, using internet-connected sensors [18]. The sensors were located approximately 1.5 m above the floor.

Building 1 was conducted in the 1970's and houses two, three and four room apartments. 39 apartments participated in the experiment. The apartments did not have individual energy meters, and heating costs were based on the individual apartment's floor area (Collective payment). Building 2 was conducted in the 1930's and houses two room apartments. 17 apartments participated in the experiment. All apartments in Building 1 paid a fixed monthly amount, which was adjusted once a year based on the actual heat consumption. The occupants in Building 2 have individual heat cost allocators and distribute heating costs based on these. (Individual payment). Both buildings were heated with water based convectors/radiators. The supply water temperature was controlled centrally based on outdoor temperature while the flow of water was controlled by thermostatic radiator valves on each radiator. In effect, the occupants controlled the temperature by adjusting the thermostats and by opening and closing windows.

The project was part of a bigger study on how indoor environmental feedback can affect occupants' control of the indoor environment. All occupants in the monitored apartments had access to the measurements of the indoor environment in their own apartment on a personal website throughout the two months.

2.2. Semi-structured interviews and questionnaire

Qualitative interviews were conducted in both buildings. The aim of the interviews was to survey the heating and ventilation strategies in each apartment. The interviews were conducted as semi-structured interviews and performed at the end of the experiment. The interviews were conducted with 10 occupants from 10 apartments (four from Building 1 and six from Building 2). The interviewees were selected by the building managers and represent a wide range of the occupants. The interviews were conducted in the occupants' apartments. A detailed description of the interview method was presented in the report by Andersen [19].

A questionnaire was sent to the occupants to survey the indoor environment regulation strategy. The questionnaire was sent to all apartments that participated in the experiment. The questionnaires were distributed at the end of the experiment period. The questionaire contained questions related to regulation strategies, understanding/perception of the term *indoor environment* and questions about the functionality of the feedback system. The latter was not included in this paper.

2.3. CO_2 sensor calibration

The CO_2 sensors in the measuring units were self-calibrating over time. Self-calibrating was done by identifying the lowest measured CO_2 concentration over the previous weeks' measurement, assuming that this was the outside concentration (400 ppm). If the CO_2 concentration didn't reach the outside concentration for an entire week, the CO_2 sensor would have assigned 400 ppm to the lowest recorded concentration and the measured concentrations would be too low. In such cases, the measured concentration would be below 400 ppm once the actual CO_2 level returned to outdoor concentration.

The sensors were installed in the beginning of March 2013 or earlier. To allow for a manufacturer recommended calibration period, the first six days were excluded in the data analysis for all measured parameters.

Table 1
Time distribution in defined intervals for measurements in heating season for Building 1.

Building 1 (collective payment)	Recommen-dation	Below [%]	Within [%]	Above [%]	Standard deviation
Temperature	20–25 °C	0	88	12	1.5 °C
CO_2 concentration	<1000 ppm	–	96	4	292 ppm
Relative humidity	30-60%	88	12	0	13%

2.4. *Infiltration rate assessment*

To assess the air change rate, the natural infiltration rate was calculated using the decay method [20]. The CO_2 concentration for each apartment was analysed to locate decay situations suitable for calculating the infiltration rate. The calculated infiltration rates were based on 40 situations from both buildings found on 5 days between 1st March and 30th April to minimize the impact of the outside weather.

3. Results

In Table 1 and Table 2, the measurements were compared with the recommended criteria in EN 15251-2007 [21] which provides design values to create a healthy and comfortable indoor environment in residential buildings.

The average temperature, CO_2 concentration, relative humidity, and vapour pressure in the two buildings differed by 2.9 °C, 157pmm, 9.8% point, and 93 Pa, respectively.

Fig. 1–Fig. 6 show the measurements distribution and the summation curve of the measurements. The summation curves were made for each apartment and as an average for Building 1 and Building 2.

The maximum CO_2 concentrations measured were 3398 ppm in Building 1 and 8934 ppm in Building 2.

3.1. *Difference between weekdays and weekends*

To survey the relationship between the control of the indoor environment and the occupancy, the difference between weekdays and weekends was visualized in Fig. 7 – Fig. 9.

3.2. *Daily differences*

The daily differences were investigated by determining the distribution of the measurement on an hourly basis. The hourly distribution for Building 1 and Building 2 was presented side by side in Fig. 10 through Fig. 12. The figures presented the hourly average value and the 5th, 25th, 75th and 95th percentile of the measurements. The minimum and maximum values were excluded as they represent one measurement at a certain time in one specific apartment.

In association with Fig. 11, the assessment of the infiltration rate based on decay of the CO_2 concentration found average infiltration rates of 4.1 h^{-1} in Building 1 and 2.7 h^{-1} in Building 2.

3.3. *Findings of semi-structured interviews*

3.3.1. *Primary indoor environment focus*

The occupants' primary focus related to the indoor environment in Building 1 was a *nice and comfortable indoor environment*. Some interviewees expressed environmental awareness as they attempted to use as little heat as possible. In Building 2, the occuants' primary focus was on obtaining a low heat consumption, in some cases to the extent that occupants accepted uncomfortable temperatures in favour of a low heating bill.

3.3.2. *Indoor environment regulation strategy*

In Building 1, the interviewees did not pursue a distinct regulation strategy and they were all aware that the heating cost were settled collectively. All occupants stated that they rarely regulated the thermostat setting and that the thermostat setting was lower in the bedroom than in the living room.

All interviewees in Building 2 exhibited energy conserving behaviour and most had a distinct strategy to regulate the thermal environment. One important observation was that 3 of 4 interviewees expressed that they were not sure how effective their strategy was in conserving energy.

3 of 4 interviewees expressed that maintaining a comfortable temperature was difficult, but acheivable when leaving the thermostat setting on 4 or 5 (out of 5) for longer periods. Questions about the usage and control of the thermostats revealed widespread misunderstandings of the functionality of thermostats, e.g. some occupants used the thermostat as an on-off valve.

3.4. *Relevant questions and answers to questionnaire*

The questionnaire response rate totalled of 42%. The response rate for each building was 35% and 60% for Building 1 and Building 2, respectively. Table 3 presented selected questions and answers.

3.5. *Sensor position*

The measurements were performed in a hallway, a central located position in the two apartment types. To determine the difference between the central location and decentral locations such as the living room, bedroom or kitchen, additional measurements were performed in five apartments. A comparison of the measurements showed that the central locations were not able to detect the peaks in the indoor environment that occurred at the decentral positions. This was further enhanced by the occupants' ability to open and close a door between the central and decentral positions. However, seen over a period of time, the differences in the average values between the central hallway and the living room were less than 15% in 5 of 5 apartments for the temperature, 2 of 5 apartments for the relative humidity, and 3 of 5 apartments for the CO_2 concentration.

Table 2
Time distribution in defined intervals for measurements in heating season for Building 2.

Building 2 (Individual payment)	Recommendation	Below [%]	Within [%]	Above [%]	Standard deviation
Temperature	20–25 °C	50	50	0	1.6 °C
CO_2 concentration	<1000 ppm	–	82	18	527 ppm
Relative humidity	30- 60%	37	63	0	10%

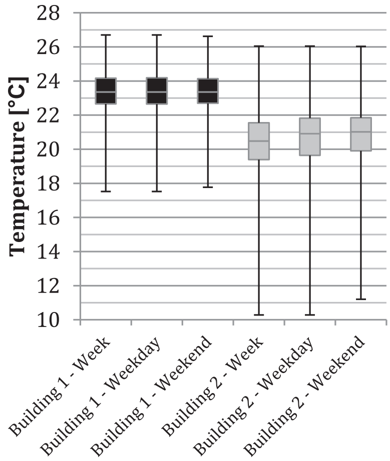


Fig. 1. Boxplot representing the median, 25th percentile, 75th percentile and min/max measurements of the temperature [°C] from March 2013 through April 2013.

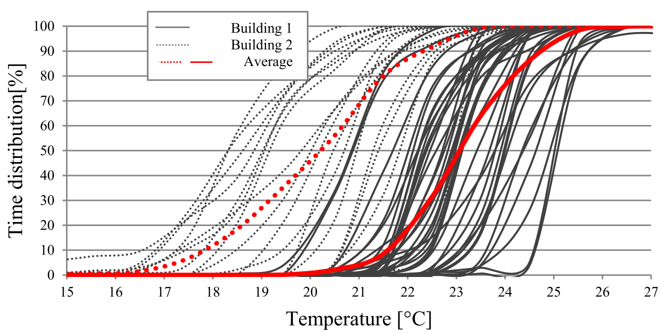


Fig. 2. Average temperature summation curve of Building 1 and Building 2, and temperature summation curve of each apartment [°C].

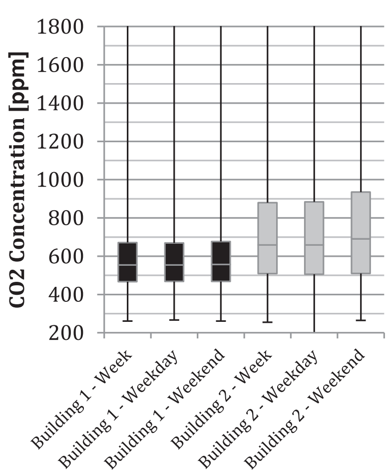


Fig. 3. Boxplot representing the median, 25th percentile, 75th percentile and min/max measurements of the CO_2 concentration [ppm] from March 2013 through April 2013.

4. Discussion

4.1. Average differences

The differences in the average temperature, humidity and CO_2 concentration between the two buildings supported the findings by Gunay et al. [11] and indicate not able impact of the heat cost allocation type.

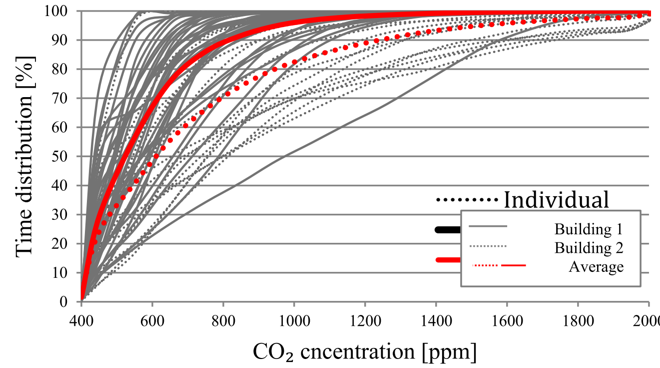


Fig. 4. Average CO_2 concentration summation curve of Building 1 and Building 2, and CO_2 concentration summation curve of each apartment [ppm].

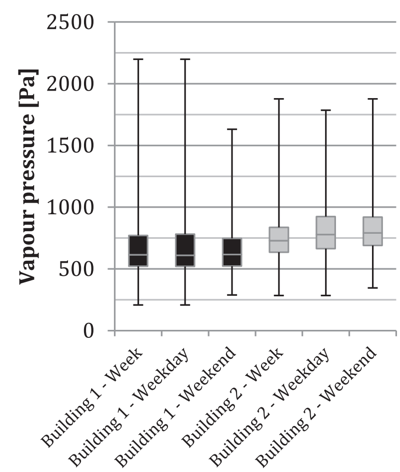


Fig. 5. Boxplot representing the median, 25th percentile, 75th percentile and min/max measurements of the vapour pressure [Pa] from March 2013 through April 2013.

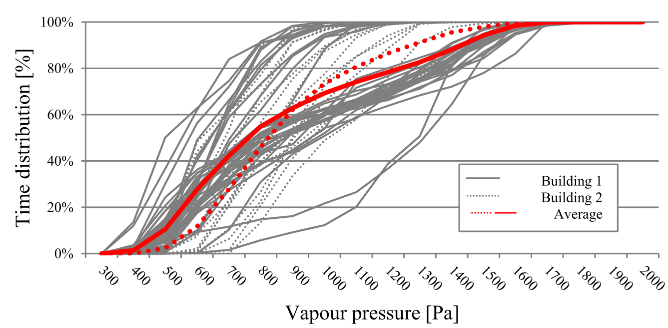


Fig. 6. Average vapour pressure summation curve of Building 1 and Building 2, and vapour pressure summation curve of each apartment [Pa].

The lowest average temperatures were found in Building 2. In order to verify that these temperatures were not a result of a poor building envelope or poorly operated systems, the maximum temperatures of Building 2 were assessed. The average of the maximum temperatures was 22.4 °C with a standard deviation of 1.2 °C. Comparing these temperatures with the recommendations of EN 15251-2007 showed that a theoretical comfortable temperature could be reached in all studied apartments in Building 2. The interviews further showed that the low temperatures were by choice, as two interviewees in Building 2 stated that high temperatures could be reached by setting the thermostats on 4 or 5

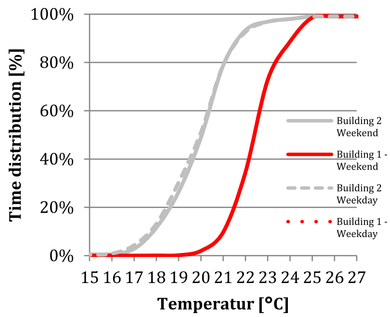


Fig. 7. Average temperature summation curve for weekdays and weekends in the heating season [°C].

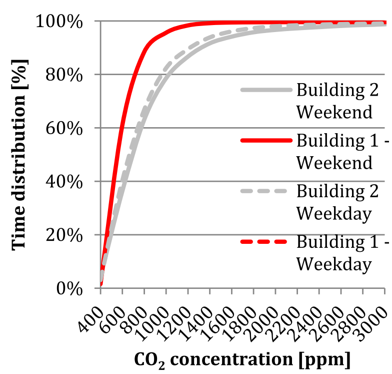


Fig. 8. Average CO_2 concentration summation curve for weekdays and weekends in the heating season [ppm].

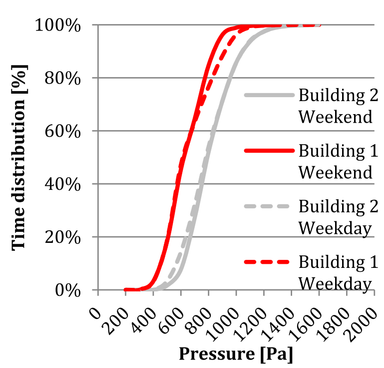


Fig. 9. Average vapour pressure summation curve for weekdays and weekends in the heating season [Pa].

(maximum position was 5) for longer periods [19].

4.2. Regulation strategies

There was a clear difference in average temperatures between the two buildings. This was also evident in the box plots and summation curves in Fig. 1 – Figure 6, differences that should be seen as differences in the regulation strategies.

The differences in the regulation strategies were further investigated by the daily variations between the maximum and minimum temperatures. The average daily variation for Building 1 and Building 2 was 1.4 °C and 0.9 °C pointing to a more stable thermal environment with collective payment (Building 2). Fig. 10 showed the hourly variation between the 95th percentile and the 5th percentile indicating a stable variation throughout the day. This was further investigated by dividing the day into eight periods: early night (00:00–03:00), late night (03:00–06:00), early morning (06:00–09:00), late morning (09:00–12:00), early afternoon (12:00–15:00), late afternoon (15:00–18:00), early evening (18:00–21:00), and late evening (21:00–24). This division was chosen as each time interval represents a typical event e.g. dinner is typically prepared and served in the early evening. The temperature variations were calculated for each apartment each day, recording the largest average temperature difference between the periods *early morning* and *early evening*: 0.06 °C for Building 1 and 0.09 °C for Building 2. A difference opposing a more stable regulation of the temperature with collective payment than with individual payment.

When asked about the regulation strategy in the interview, all occupants in Building 1 stated not to have a distinct regulation strategy, adding that they rarely regulated the thermostat setting – a strategy that could be defined as a passive strategy. The passive regulation strategy was supported by the questionnaire revealing that 9out of15 regulated the thermostat *yearly or never*. In Building 2, the regulation strategy was more active. The majority of interviewees and respondents stated to have a thermostat regulation strategy. This corresponded well with the higher standard deviation of the temperature measurements in Building 2 than in Building 1. These findings were in agreement with the findings of Gunay et al. [11].

10 of 13 respondents in Building 1 and 4 of 4 respondents in Building 2 stated to have a window opening strategy. However, 13 of 14 respondents and 7 of 9 respondents in Building 1 and Building 2 respectively, stated to open a window daily for venting purposes. This indicated that the heat cost allocation type wasn't the final driver for the window opening frequency. Andersen et al. [22] reported that the CO_2 concentration in residential buildings is a major driver for window opening. The difference in the CO_2 concentration presented in Tables 1 and 2 indicated that occupants with individual payment were willing to accept higher CO_2 concentrations and therefore postponed window opening compared to occupants in buildings with collective payments.

Fig. 11 showed a difference between the hourly average CO_2 concentrations which appeared to be notably lower in Building 1 than in Building 2. Assessment of the natural infiltration rate showed a higher infiltration rate in Building 1 than in Building 2, partially explaining the higher CO_2 concentrations in Building 2.

In most households the occupancy differs between weekdays and weekends. However, there were only small differences between weekdays and weekends in the three measured parameters (Fig. 7 through Fig. 9). This indicates that the occupancy was only loosely related to the control of the indoor environment.

4.3. Assessment of the IEQ

The recommendations used were based on EN 15251-2007 category II recommendations for residences and presented in Table 1. EN 15251-2007 recommended that the intervals should not be exceeded for longer than 5% of the measured period. Tables 1 and 2 showed that none of the parameters complied with the 5% recommendation.

The average temperature of 23.5 °C as well as a temperature distribution with temperatures exceeding the recommendations for 12% of the time showed an energy savings potential in Building 1. The frequency and duration of window openings were not monitored However, as the CO_2 concentration was within the recommendation for 96% of the time and the relative humidity was below the recommendation for 88% of the time, it could indicate long periods of venting and that an optimization of the regulation strategy would decrease the heating consumption.

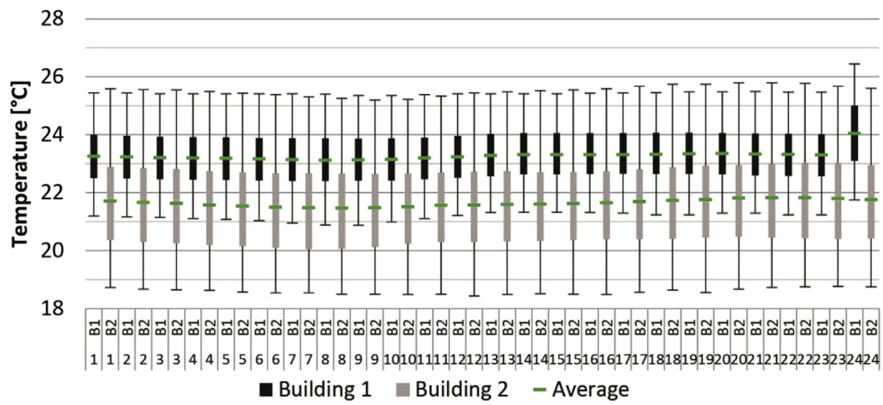


Fig. 10. Hourly temperature distribution of Building 1 (Black) and Building 2 (Grey), with the box representing the 25th and 75th percentile. Whiskers representing the 5th and 95th percentile. Green mark shows the average value. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

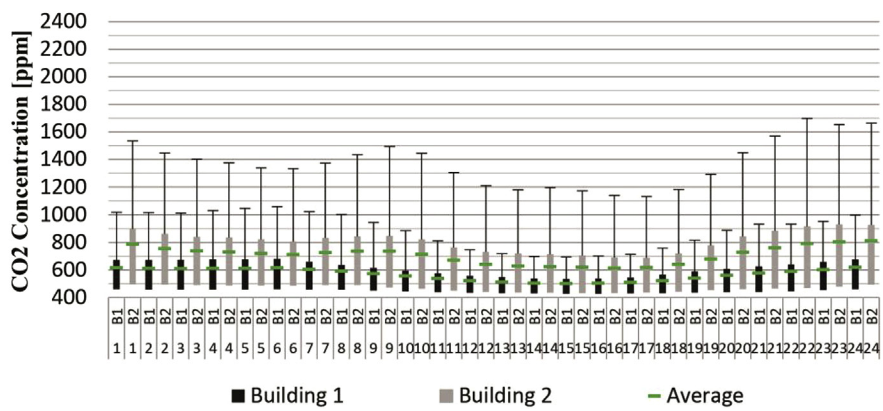


Fig. 11. Hourly CO_2 concentration distribution of Building 1 (Black) and Building 2 (Grey), with the box representing the 25th and 75th percentile. Whisker representing the 95th percentile. Green mark shows the average value. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

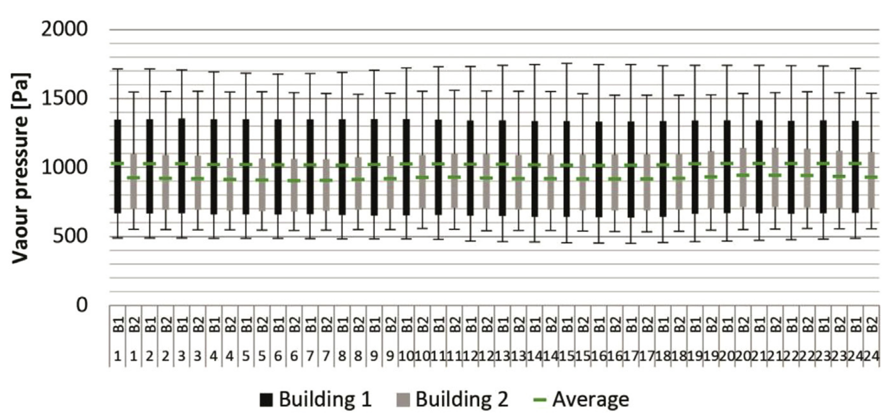


Fig. 12. Hourly vapour pressure distribution of Building 1 (Black) and Building 2 (Grey), with the box representing the 25th and 75th percentile. Whiskers representing the 5th and 95th percentile. Green mark shows the average value. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In Building 2, the temperature measurements were below the recommendation for 50% of the time, the CO_2 concentration above for 18% of the time and the relative humidity below for 37% of the time. This distribution indicated a low heating setpoint and short and insufficient venting periods. The interviews showed, that the occupants had difficulties assessing if their regulation strategies were efficient and that they had difficulties adjusting the thermostats. The interviews further showed a crucial lack of knowledge on how to operate thermostats, in line with the findings of Peffer et al. [23]. Fig. 11 showed the average, the 75th percentile and the 95th percentile CO_2 concentration to be above the recommended value, indicating unresponsiveness to poor air quality. As the occupants were already driven by low heating costs and were willing to engage in active control of the indoor environment, a comfortable indoor environment and low energy consumption seemed achievable with an higher knowledge level and the right tools to

Table 3
Selected questions and responses [n] for Building 1 and Building 2.

Question	Building 1 (collective payment)				Building 2 (Individual payment)			
1 – Do you have a defined strategy for the thermostat setting?	Yes		No		Yes		No	
	5		8		4		4	
2 – Do you have a defined strategy for venting the apartment?	Yes		No		Yes		No	
	10		3		4		4	
3 – How often is the thermostat setting changed?	Daily	Monthly	Yearly	Never	Daily	Monthly	Yearly	Never
	2	4	5	4	5	1	1	1
4 – How often is a window opened for venting?	Daily	Monthly	Yearly	Never	Daily	Monthly	Yearly	Never
	13	1	0	0	7	2	0	0

assess the indoor environment.

The relative humidity measurements were below the recommendations in EN 15251-2007 and the risk of condensation was therefore low. Fig. 12 further visualized a stable vapour pressure for both buildings with minimal variation through out the day.

4.4. Heat cost allocation as a behavioural driver

The measurements showed differences between the two buildings, differences that could have occurred because of difference in the state of the heating system, insulation level and the state of the windows etc. or because of the regulation of the indoor environment. Analyses' of building components were not performed precluding an estimation of the effects there of. However, all interviewees stated it was possible to obtain comfortable temperatures, demonstrating the heat cost allocation as a driver affecting the occupants' regulation of the indoor environment. A demographic survey was neither part of the interviews nor the questionnaires, however, the average annual income of inhabitants in the municipality of Building 1 is 278€ higher than that of inhabitants in the municipality of Building 2 [24]. A difference so small that it is acceptable to ignore.

In relation to the literature reviews by Fabi et al. [13] and [14], the results showed the drivers to be hierarchical with some drivers overruling others. This was evident in Building 2, where low heating bills were valued higher than thermal comfort. In Building 1, the desire to save money on the energy bill was not strong enough to overrule the desire for high indoor environmental quality.

4.5. Heat cost allocation in building performance simulations

Hong et al. [25] surveyed the advances in the field of occupant behaviour in building performance simulations. The study described how model inputs are typically collected specifically for the purpose of the study, making the inputs model specific [25]. This means that if the user model is used to model the occupant behaviour in another building, the user profiles of the two buildings would need to have similarities to be valid in later simulations.

The findings of this paper showed that heat cost allocation type affected the indoor environment, the interviews further showed a direct correlation between the heat cost allocation type and the occupants' attitude towards the thermal environment. Fabi et al. [14] showed that many different drivers affects the occupant behavior, in the same manor D. Yan et al. [26] described the complexity of having too many user inputs ending up with an overfitted model. This means that the heat cost allocation should not be te only user input in a user model, but could be used as a characteristic in the five user profiles describe by van Raaij et al. [27] and Guerra-Santinet al. [28].

4.6. Validity of the CO_2 sensor

When using a self-calibrating CO_2 sensor, it was necessary to reach the outside concentration at least once a week in the surveyed rooms to achieve accurate measurements. In cases where the sensor did not reach outside concentrations within a week, the reference concentration would drift upwards and the sensor would have measured concentrations lower than 400 ppm once the concentration returned to outdoor levels.

Fig. 3 indicated CO_2 concentration measurements below the outside concentration (approximately 400 ppm), which occurred due to the self-calibrating abilities of the CO_2 sensor. 0.3% of the CO_2 measurements in Building 1 and 1% of the CO_2 measurements in Building 2 where below 370 ppm. It was therefore assumed that the effects of the deviations were negligible.

5. Conclusion

The heat cost allocation in two apartment buildings had an impact on the indoor environment. Whereas the average temperature measured in apartments with collective heat cost allocation was 2.8 °C higher compared to apartments with individual heat cost allocation, the average CO_2 concentration and average vapour pressure were 161 PPM and 93 Pa lower.

The heat cost allocation type was identified as a driver for the regulation of the indoor environment. Individual payment plans triggered a more active regulation strategy compared to buildings with collective heat cost allocation. The occupants in apartments with individual heat cost allocation tended to focus on the cost of heating and accepted uncomfortable temperatures for extended periods of time. In contrast, occupants in apartments with collective heat cost payment schemes focused on creating a comfortable and healthy indoor environment with little attention to the cost of heating.

It was suggested, that the heat cost allocation type as a psychological driver, overrules the driving forces of the phycial environment, if present.

References

[1] R. Andersen, The Influence of Occupants ' Behaviour on Energy Consumption Investigated in 290 Identical Dwellings and in 35 Apartments, 2009.
[2] R. Socolow, The Twin Rivers Program on Energy Conservation in Housinh: Highlights and Conclusions, 1977.
[3] H. Wilhite, R. Ling, Buildipig and measured energy savings from a more informative energy bill, 22, 1995, pp. 145–155.
[4] O. Guerra Santin, L. Itard, Occupants' Behaviour: Determinants and Effects on Residential Heating Consumption, 2010, pp. 37–41, http://dx.doi.org/10.1080/09613211003661074.
[5] T. Maier, M. Krzaczek, J. Tejchman, Comparison of physical performances of the ventilation systems in low-energy residential houses, Energy Build. 41 (2009) 337–353, http://dx.doi.org/10.1016/j.enbuild.2008.10.007.
[6] M. Iyer, W. Kempton, C. Payne, Comparison groups on bills: automated, personalized energy information, Energy Build. 38 (2006) 988–996, http://dx.doi.org/10.1016/j.enbuild.2005.11.009.
[7] P.W. Schultz, J.M. Nolan, R.B. Cialdini, N.J. Goldstein, V. Griskevicius, The

constructive, destructive, and reconstructive power of social norms, Psychol. Sci. 18 (2007) 429–434, http://dx.doi.org/10.1111/j.1467-9280.2007.01917.x.
[8] W. Abrahamse, L. Steg, C. Vlek, T. Rothengatter, A review of intervention studies aimed at household energy conservation, J. Environ. Psychol. 25 (2005) 273–291, http://dx.doi.org/10.1016/j.jenvp.2005.08.002.
[9] S. Darby, Smart metering: what potential for householder engagement? Build. Res. Inf. 38 (2010) 442–457, http://dx.doi.org/10.1080/09613218.2010.492660.
[10] T. Cholewa, A. Siuta-Olcha, Long term experimental evaluation of the influence of heat cost allocators on energy consumption in a multifamily building, Energy Build. 104 (2015) 122–130, http://dx.doi.org/10.1016/j.enbuild.2015.06.083.
[11] H. Burak Gunay, W. O'Brien, I. Beausoleil-Morrison, A. Perna, On the behavioral effects of residential electricity submetering in a heating season, Build. Environ. 81 (2014) 396–403, http://dx.doi.org/10.1016/j.buildenv.2014.07.020.
[12] A. Levinson, S. Niemann, Energy use by apartment tenants when landlords pay for utilities, Resour. Energy Econ. 26 (2004) 51–75, http://dx.doi.org/10.1016/S0928-7655(03)00047-2.
[13] V. Fabi, R.V. Andersen, S. Corgnati, B.W. Olesen, Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models, Build. Environ. 58 (2012) 188–198, http://dx.doi.org/10.1016/j.buildenv.2012.07.009.
[14] V. Fabi, R.V. Andersen, S.P. Corgnati, F. Venezia, Main physical environmental drivers of occupant behaviour with regard to space heating energy demand, Heal Build. 2012 (2012).
[15] E. Sardianou, Estimating space heating determinants: an analysis of Greek households, Energy Build. 40 (2008) 1084–1093, http://dx.doi.org/10.1016/j.enbuild.2007.10.003.
[16] R.V. Andersen, J.J. Toftum, K.K. Andersen, B.W. Olesen, Survey of occupant behaviour and control of indoor environment in Danish dwellings, Energy Build. 41 (2009) 11–16, http://dx.doi.org/10.1016/j.enbuild.2008.07.004.
[17] M. Frontczak, R.V. Andersen, P. Wargocki, Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing, Build. Environ. 50 (2012) 56–64, http://dx.doi.org/10.1016/j.buildenv.2011.10.012.
[18] G. Wilke, IC Meter, 2015. www.ic-meter.com (accessed March 15, 2015).
[19] R.K. Andersen, Experiences from the Project Dynamic Heat Cost Allocation, 2013.
[20] S. Cui, M. Cohen, P. Stabat, D. Marchio, CO2 tracer gas concentration decay method for measuring air change rate, Build. Environ. 84 (2015) 162–169, http://dx.doi.org/10.1016/j.buildenv.2014.11.007.
[21] D.S. En, Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, 2007.
[22] R. Andersen, V. Fabi, J. Toftum, S.P. Corgnati, B.W. Olesen, Window opening behaviour modelled from measurements in Danish dwellings, Build. Environ. 69 (2013) 101–113, http://dx.doi.org/10.1016/j.buildenv.2013.07.005.
[23] T. Peffer, M. Pritoni, A. Meier, C. Aragon, D. Perry, How people use thermostats in homes: A review, Build. Environ. 46 (2011) 2529–2541, http://dx.doi.org/10.1016/j.buildenv.2011.06.002.
[24] S. Denmark, Statistic Denmark, 2016. http://www.statbank.dk/statbank5a/SelectVarVal/sav.
[25] T. Hong, S.C. Taylor-lange, S.D. Oca, D. Yan, S.P. Corgnati, Advances in research and applications of energy-related occupant behavior in buildings, Energy Build. (2015), http://dx.doi.org/10.1016/j.enbuild.2015.11.052.
[26] D. Yan, W. O'Brien, T. Hong, X. Feng, H. Burak Gunay, F. Tahmasebi, et al., Occupant behavior modeling for building performance simulation: current state and future challenges, Energy Build. 107 (2015) 264–278, http://dx.doi.org/10.1016/j.enbuild.2015.08.032.
[27] W.F. van Raaij, T.M.M. Verhallen, Patterns of residential energy behavior, J. Econ. Psychol. 4 (1983) 85–106, http://dx.doi.org/10.1016/0167-4870(83)90047-8.
[28] O.G. Santin, Behavioural Patterns and user profiles related to energy consumption for heating, Energy Build. 43 (2011) 2662–2672, http://dx.doi.org/10.1016/j.enbuild.2011.06.024.

20 APPENDIX 2

Interview guide for semi-structured interviews used in Study 1 and Study 2. The questions were translated from Danish to English.

Category 1 – Indoor environment

- How do you find the indoor environment in your apartment?
- Do you know what it takes to obtain/maintain a good indoor environment?
- Do you, do anything to control the indoor environment?

Category 2 – Heating

- How much do you pay for heating?
- Do you think that you pay more or less than other occupants in the building?
- Do you consider conserving heating – why?
- Do you, do anything to reduce your heating use?

Category 3 – ICMeter feedback

- How can you use the IC Meter feedback?
- Do you believe that you will use the feedback?
- Will the feedback make you change habits – e.g. turn the heating up and down or open windows?

Category 4 – Change of habits

- Would you reduce your heating set point if you had to pay extra for maintaining a high indoor temperature?
- What would it take (in extra cost) for you to change the heating set point?
- Would you increase the window opening, if you had to pay extra when the ventilation rate was too low?
- Would you avoid drying clothes indoor, if you had to pay extra because of high moisture measurements?

21 APPENDIX 3

Questionnaire used in Study 1 and Study 2.The questionnaire was distributed in Danish.

Question 1
On a scale from 1 to 10, to what degree do you relate the following terms with indoor environment?

- Air temperature
- Air quality
- Moisture
- Noise
- Light
- Dut
- Radon
- CO_2 emission
- Human activity
- Washing/drying of clothes
- Outdoor temperature
- Rain
- Car pollution
- Sun
- Smell
- Fungal spores
- Particles

Question 2
How often do you change the radiator thermostat value?
Options: Daily – Weekly – Annually – Not at all

Question 3
How often do you open a window to vent?
Options: Daily – Weekly – Annually – Not at all

Question 4
In which time span do you change the radiator thermostat value?
Options: Night (00 – 06)
Early morning (06 – 09)
Late morning (09 – 12)
Early afternoon (12 -15)
Late afternoon (15 – 18)
Early evening (18 – 21)
Late evening (21- 24)

Question 5
In which time span do you open a window to vent?
Options: Night (00 – 06)
Early morning (06 – 09)
Late morning (09 – 12)
Early afternoon (12 -15)
Late afternoon (15 – 18)
Early evening (18 – 21)
Late evening (21- 24)

Question 6
If a window is opened for venting, for how long is it normally open?
Options: 0 – 5 minutes
5 - 10 minutes
10 - 20 minutes
20 - 30 minutes
More than 30 minutes

Question 7
Do you have a defined strategy for the thermostat setting?
Options: yes/no

Question 8
Do you have a defined strategy for venting the apartment?
Options: yes/no

Question 9
Based on the latest week, to what degree are you satisfied with the air temperature?
Options: Very satisfied
Satisfied
Neutral
Unsatisfied
Very unsatisfied

Question 10
Based on the latest week, to what degree are you satisfied with the air quality?
Options: Very satisfied
Satisfied
Neutral
Unsatisfied
Very unsatisfied

Question 11
Can your answers be used in an unanonymised form (e.g. can the answers be compared with the energy use. No names will be published)?
Options: yes/no

The following questions were only asked to occupants who received feedback

Question 12
How often did you look at the continuous feedback at www.ic-meter.com?
Options: Daily – Weekly – Annually – Not at all

Question 13
To what degree did you find the website understandable?
Options: Very high
High
Neutral
Low
Very low
Did not use the website

Question 14
How many occupants in the apartment read the newspaper?
Options: One person
Two persons
All occupants
None

Question 15
Do you perceive that the information on how to obtain a high indoor environmental quality was sufficient?
Options: yes/no

If no, what do you think could have been better?
Options: More general explanations
More detailed explanations
Could have been more personal
Be more comprehensive
Be less general in the description
Be less detailed in the explanations
Be shorter

Question 16
Do you perceive that the feedback has had an effect on the control of the indoor environment?
Options: yes/no

Question 17
Have you, at the end of the intervention, attempted to access indoor environmental measurements on your own?
Options: yes/no

I yes, what have you done?

22 APPENDIX 4

Paper 2
Indoor environmental effects of continuous and monthly feedback intervention in 56 Danish apartments

Authors: Søren Andersen, Rune Korsholm Andersen and Bjarne W. Olesen
Published in: Building and Environment
Publication status: Submitted

Indoor environmental effects of continuous and monthly feedback intervention in 56 Danish apartments

Abstract

Energy bills, in-home displays and other information dissemination platforms are all feedback mechanism that can help users makes informed decisions regarding their energy behavior and control of the indoor environment. The aim of this paper was to use another approach and investigate if continuous and monthly feedback based on the indoor environment could be used to influence occupants' control of the indoor environment. The investigation was based on measurements performed in 56 Danish rental apartments in two buildings, by measuring the temperature, relative humidity and CO_2 concentration at a five minute interval. Semi-structured interviews were conducted with selected participants along with a questionnaire distributed to all 56 apartments. The feedback procedure was a combination of continuous feedback provided through a website and monthly feedback on paper delivered to the participants' mailbox. Assessment of the measurements showed a small difference between before and after introduction of feedback. The influence of the outdoor temperature on the indoor temperature was studied for each apartment and indicated an effect of the feedback. The interviews and questionnaires showed that 71% of the occupants believed they had changed their control of the indoor environment because of the feedback. The interviews and questionnaires further revealed the content of the feedback as useful, but the continuous feedback was infrequently used, mainly due to a complicated login process.

Keywords: Occupant behavior; Indoor Environment; Continuous feedback; Monthly feedback

1 Introduction

The Internet of Things [1] and smart meters [2] have made it possible to perform detailed measurements of both the total energy consumption, the energy use of individual appliances, and the indoor environment.

The increasing prevalence of smart meters has generated an industry of commercial displays visualizing the real time energy consumption as continuous feedback. Before smart meters were developed McClelland et al. [3] found an average electricity reduction of 12% compared to a control group, by a continuous visualization of the electricity consumption in cents per hour. Van Houwelingen et al. [4] found a 12,3% reduction of the gas consumption by combining information dissemination and continuous feedback. In more recent studies, the effects of in-home displays have been investigated. The studies conducted in Europe, North America, Japan, and Australia showed reductions in the energy consumptions from 7% to 45% [5–8].

Table 1 Electricity savings as an effect of in-home displays

Study	Date	Region	Number of households [-]	Average savings [%]
Ueno et al.	2005	Japan	10	12%
Darby	2006	Multiple	-	10%
Faruqi et al.	2010	North America, Japan, Australia	>1000	7%
D'Oca et al.	2015	Italy	30	18%

Darby [6] studied the use of multiple In-Home Display solutions. The study showed reductions in the order of 10% using IHD's in the price range of $20 - $110. An IHD solution tested in 10 Japanese households costing approximately $5.000 [6] achieved a total energy reduction of 12% with some houses reducing the heating consumption by 20 - 45% [5]. With the more expensive solution displaying much more detailed information than cheaper solution, the study demonstrated that with more information greater reductions can be expected.

In contrast to the above positive findings, Nilsson et al. [9] conducted an experiment with an IHD to visualize the real time electricity consumption in 40 households. The study didn't find any effects of the feedback, explaining this by barriers as: already low consumptions, habits, difficulties understanding the display, difficulties understanding the relationship between behavior and consumption, lack of motivation [9]. Buchanan et al. reviewed investigations of the indoor environment and found an average reduction of 2% [10]. The review questioned whether savings of this magnitude were sufficient for a government supported roll out of smart meters in all UK households. Buchanan et al. argues that macro level energy savings becomes reliant on the user to interpret the displayed feedback and being motivated by it [10].

IHD and other forms of continuous feedback is information dissemination. The studies mentioned above showed that continuous feedback can be used to influence the energy consumption. However, it should be noted that the studies used a variety of feedback mechanisms such as: direct and indirect feedback, persuasive feedback, historical comparisons, social comparisons, and many other feedback mechanism. In a literature review by Abramhamse et al. the effects of feedback mechanisms varied, demonstrating that differences between the effects of continuous feedback could be caused by the feedback mechanisms. The studies also showed that continuous feedback should be used with precaution and that the case and user profiles should be analyzed to clarify if continuous feedback is the best method to influence the occupant behavior.

Common for the studies was that for energy savings to happen the occupants must adapt their behavior, Schultz described this as energy conservation being related to sacrifices [11]. Nilsson et al. showed how occupants had troubles understanding the relationship between their behavior and the energy consumption [9], an argument indicating that alternative feedback methods were necessary if the occupants' behavior should were to be changed. With this current paper it was argued that relating behavior to energy consumption can be difficult, however, most occupants have a notion that a higher indoor temperature
is the more energy is consumed (and vice versa in the cooling season). It was assumed that by visualizing the indoor environment, occupants were given a tool to maintain a high indoor environmental quality and a tool to indirectly control the energy consumption.

1.1 Frequency of feedback

An early study by Hayes et al. [12] surveyed the effect of using historical feedback on the energy bill in 1981. The introduction of the feedback showed an energy conservation of 4,7% [12]. Wilhite et al. studied the introduction of a more informative energy bill in Oslo, Norway. A reduction of 10% of the energy consumption was achieved [13]. In a literature review, Abrahamse et al. surveyed the effects of weekly and monthly feedback dissemination and found effects of these (no actual reductions percentages were mentioned) [14]. Abrahamse et al. further concluded that the higher the frequency of the feedback the higher the positive effects [14]. A conclusion indicating that feedback with a semi-long distribution frequency as weekly and monthly feedback should not be used with other more frequent distributed feedback, if high effects are desired.

1.2 Indoor environment as motivation

Groot et al. [15] and Schultz et al. [16] described how behavioral changes will not occur if occupants aren't motivated to do so and even though the above studies showed that reductions can be obtained through a monetary reward not all occupants are motivated in this way [17].

Andersen et al. [17] studied the influence of the heating cost allocation type on the indoor environment in Danish apartments. The study found a strong association between the payment type and the occupants' control of the indoor environment. The study further found, that if the occupants' didn't have a monetary incentive to conserve energy, they focused on maintaining a high indoor environmental quality, regardless of the consequences for the energy consumption [17]. Gunay et al. conducted a similar study showing an average temperature difference of 2°C difference between sub-metered apartments and apartments paying a fixed price and therefore had no monetary incentive to maintain a low energy consumption [18]. Both studies showed how occupants without a monetary incentive didn't focus on energy conservation when controlling the indoor environment. In such cases alternative motivation methods seems therefore to be necessary, if energy conservation are to be achieved through the occupant behavior.

The aim of this study was to test a feedback procedure combining continuous and monthly feedback to motivate occupants to maintain a high indoor environmental quality, according to EN 15251-2007 [19] with the lowest possible energy consumption. The study was conducted based on measurements performed in 56 Danish apartments. In Denmark the energy consumption is directly linked to the indoor environment and changing how the indoor environment is controlled also means a possibility to influence the heating consumption.

2 Method

The measurements were collected in two buildings in the Copenhagen area of Denmark. The data set has previous been used to quantify the effects of the heat cost allocation type in the two buildings [17].

2.1 Measurements

In total the indoor environment was measured in 56 apartments, with 39 apartments in Building 1 and 17 apartments in Building 2. Building 1 was built in the 1970'ies and consisted of 2, 3 and 4 roomed apartments. Building 2 was built in the 1930'ies and consisted of two roomed apartments. Both buildings were heated by water based convectors. The supply water temperature was controlled centrally while the flow of water was controlled by thermostatic radiator valves on each radiator. In effect, the occupants controlled the temperature by adjusting the thermostats and by opening and closing windows [17].

The air temperature [°C], relative humidity [%] and CO_2 concentration [ppm] were measured every fifth minute at a central location in each apartment in the heating season of 2012/2013. This paper analyzed measurements collected from 1st of January through 31st of May.

The measurements were collected by internet connected sensors [20] recording the CO_2 concentration with an overtime self-calibrating sensor. The self-calibrating was done by locating the lowest measured CO_2 concentration in the previous weeks' measurement, assuming that this was the outside concentration (400 ppm). If the CO_2 concentration didn't reach the outside concentration for an entire week, the CO_2 sensor would have assigned 400 ppm to the lowest recorded concentration. In such cases the measured concentration below 400 ppm could appear, when the real CO_2 level returned to outdoor concentration. To account for a producer recommended calibration period, the first six days after installation were excluded in the data analysis for all measured parameters [17]. Weather data was provided by the manufacturer of the sensors [20].

2.2 Feedback

The measurements were performed as part of a project investigating possibilities of distributing heating costs between apartments based on the measured indoor environment rather than heat meters. To provide occupants with tools to assess the indoor environment each apartment had access to their measurements via individual accounts on the producer's website. To maintain the occupants' interest and enlighten those not using the internet daily, individual monthly newsletters were generated for each apartment.

2.2.1 Continuous feedback

The continuously feedback to the residents was accessible on a website. The occupants had to use a user name and password to access the data. On the website, the residents could access the following information:

- Values of the latest measurements (updated every fifth minute)
- a daily graph visualizing all three variables during the past hours of the day and predicting the result of the current occupant behavior for the rest of the day
- monthly distribution for all measured variables

The website also featured a *ventilation* function, displaying the air change rate [h^{-1} and m^3/h], minutes of cross ventilation [minutes/day], and vapor production [kg/day]. The calculation methods and definition of cross ventilation was based on the a mass balance and measurements of

CO_2 concentration and indoor and outdoor relative humidity. The continuous feedback was introduced on 1st of March 2013.

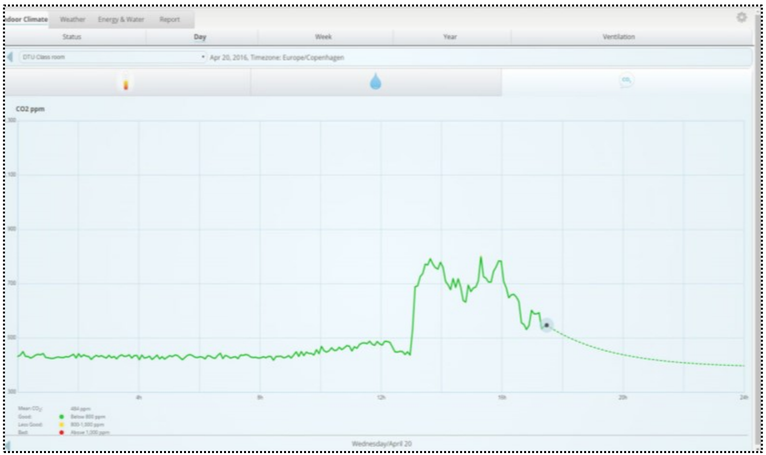


Figure 1 Example of the continuous feedback on the CO_2 concentration. Image from [20]

On the website with continuous feedback, the weather was represented by the outdoor temperature [°C], relative humidity [%], wind speed [m/s] and wind direction. The weather data was provided by nearby weather station and not at the specific location.

2.2.2 Monthly feedback

An individual monthly newsletter was distributed to each apartment by the building managers of the respective buildings. The first newsletter was distributed primo March 2013 including measurements from February 2013 and consisted of the four sections as described in Table 2. The overall aim of the feedback letter was to provide the occupants with an intuitive and comprehensible assessment of the indoor environment.

Temperature (indoor in °C)	22.5°C	- Less good indoor environment
Moisture (relative humidity)	26 %	- Good indoor environment
Fresh air (CO_2 concentration)	534 ppm	- Good indoor environment

Figure 2 Assessment of measurements as visualized in the monthly feedback letter. Originally disseminated in Danish, but translated for this paper.

Table 2 Description of the four sections the monthly feedback letter

Section of letter	Description
Introduction	Informed the occupants on; the content of the newsletter, the period of which the measurements were performed, how to access the continuous measurements.
Assessment of measurements	The monthly average value of the temperature, relative humidity and CO_2 measurements. The values were followed by a smiley icon in green, yellow or red depending on whether the average value was within the recommendations, slightly outside the recommendations or outside of the recommendations (see Figure 2).
Explanation and motivation	A table showing the benchmarks for the smiley icons used to assess the indoor environment.

General recommendations for a good indoor environmental quality	The same four recommendations were given in each newsletter (translated from Danish): • Vent for 10 minutes each time • Maintain the CO_2 concentration under 800 ppm • Maintain a temperature of 19-22°C • Maintain a moisture content of 30 – 55%

2.3 Semi structured interviews and questionnaire

Qualitative interviews and quantitative questionnaires were conducted in both buildings, aimed to survey the heating and ventilation strategies in each apartment. The interviews were conducted as semi-structured interviews and performed at the end of the study. The interviews were conducted with 10 occupants from 10 apartments. Four were conducted in Building 1 (one male and three female) and six were conducted in Building 2 (one male and 5 female). The informants were selected by the building managers and were chosen to represent a wide range of the occupants. The interviews were conducted in the informants' apartments. A detailed description of the interview method was presented in the report by Andersen [21].

A questionnaire was distributed to 112 apartments in both buildings to apartments receiving feedback and apartments that didn't. The questionnaires were distributed at the end of the experiment period. The questionnaire contained questions related to control strategies, understanding/perception of the indoor environment and questions on the functionality of the feedback system.

2.4 Infiltration rate assessment

Andersen et al. [21] analyzed the air change rate by the natural infiltration rate using the decay method [22]. The average infiltration rate of Building 1 was 4,1h^{-1} and 2,7h^{-1} in Building 2 [21].

2.5 Regression analysis

Fabi et al. found the outdoor weather as a significant driver for the control of the window opening and heating set point [25,26], and as the outdoor temperature changed from the reference period to the intervention apartment this would have influenced control of the indoor environment.

To investigate the influence of the feedback while correcting for differences in the outdoor temperature differences a linear regression analysis was performed for each apartment in both buildings. The investigation was performed at apartment level to determine if the individual household used the feedback. To assess the impact of the feedback, the influence of feedback was compared to the recommendation given by the monthly feedback to either increase, maintain or decrease the average indoor temperature. The regression models were based on Equation 1 and were made to determine the outdoor temperature's influence on the indoor temperature

$$\boldsymbol{T_{in} = a_1 \cdot T_{out} + a_2 \cdot Period + a_3 \cdot T_{out} \cdot Period + b} \quad (1)$$

Where:

T_{in} is the measured indoor temperature [°C]

T_{out} is the measured outdoor temperature at nearby weather station [°C]

Period is a binary variable determining if the period was with or without feedback

3 Results

3.1 Total assessment

Figure 3 through Figure 7 showed the measurement distribution for the period before feedback was introduced (annotated as Pre) and the period after feedback was introduced (annotated as Post).

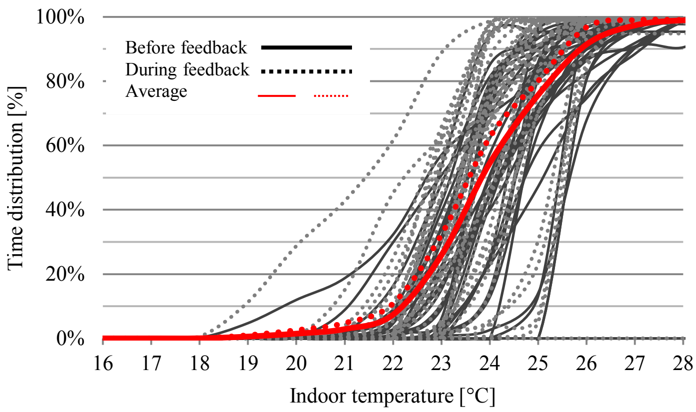


Figure 3. Temperature [°C] distribution before and after feedback introduction in Building 1

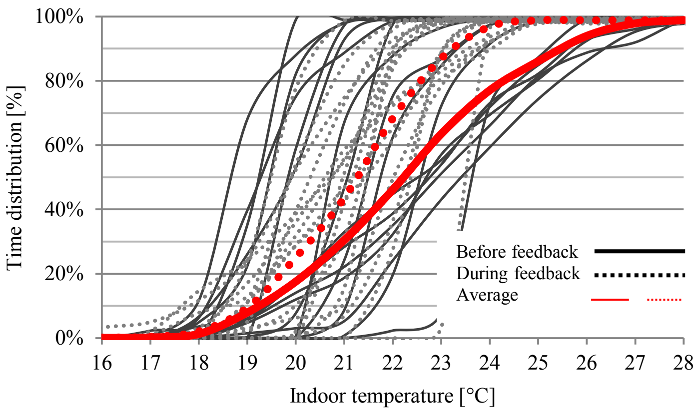


Figure 4. Temperature [°C] distribution before and after feedback introduction in Building 2

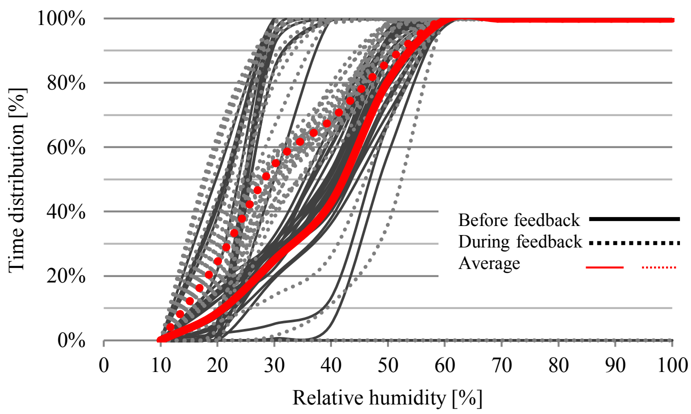


Figure 5. Relative humidity [%] distribution before and after feedback introduction in Building 1

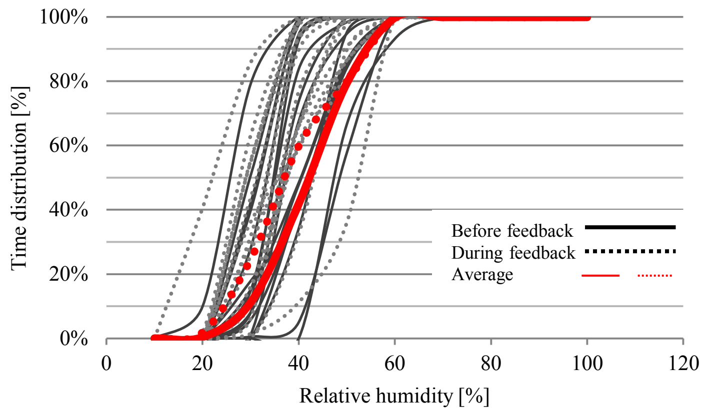


Figure 6 Relative humidity [%]distribution before and after feedback introduction in Building 2

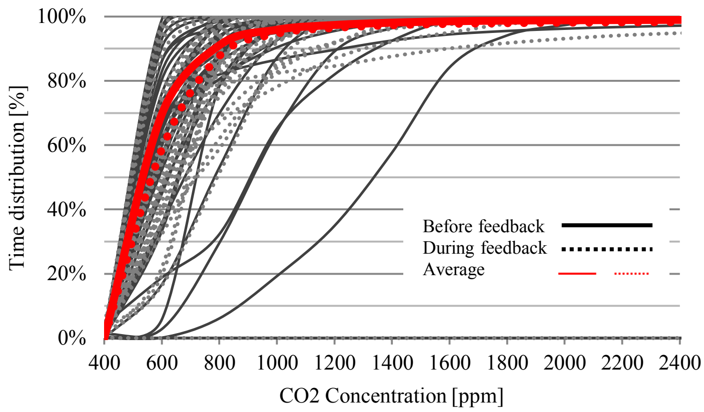


Figure 7 CO_2 concentration [ppm] distribution before and after feedback introduction in Building 1

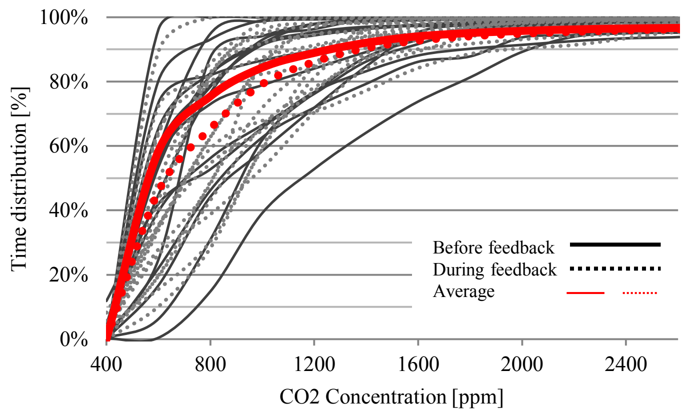


Figure 8 CO_2 concentration [ppm] distribution before and after feedback introduction in Building 2

3.2 Monthly distribution

A monthly distribution of the measurement was performed for both buildings presented in Figure 9 through Figure 11.

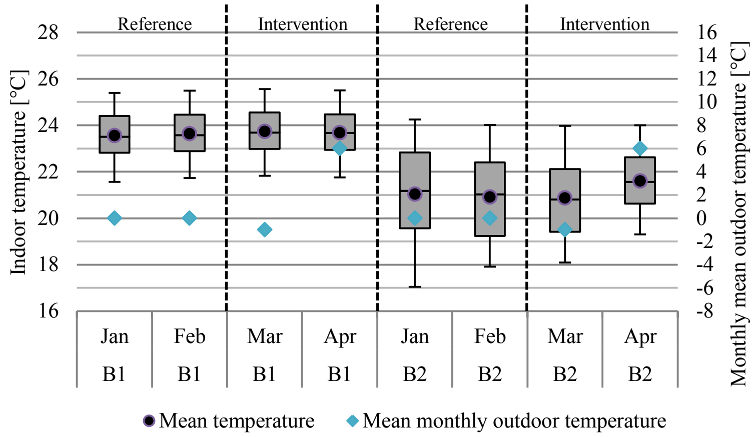


Figure 9 Monthly distribution of the indoor temperature [°C] displayed with the 5th, 25th, 75th and 95th percentile and outdoor temperature [°C]

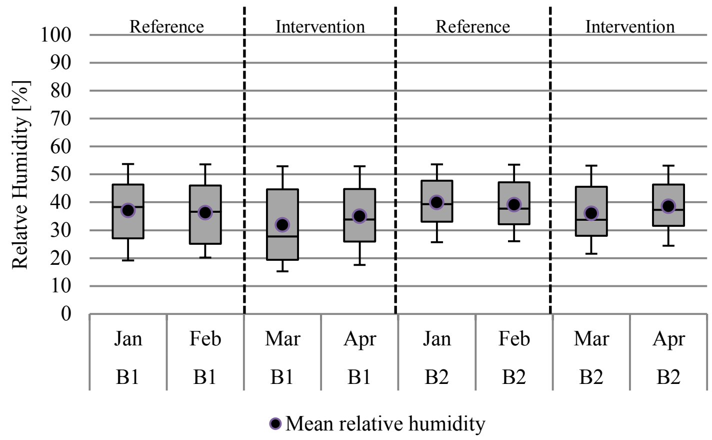


Figure 10 Monthly distribution of the relative humidity [%] displayed with the 5th, 25th, 75th and 95th percentile.

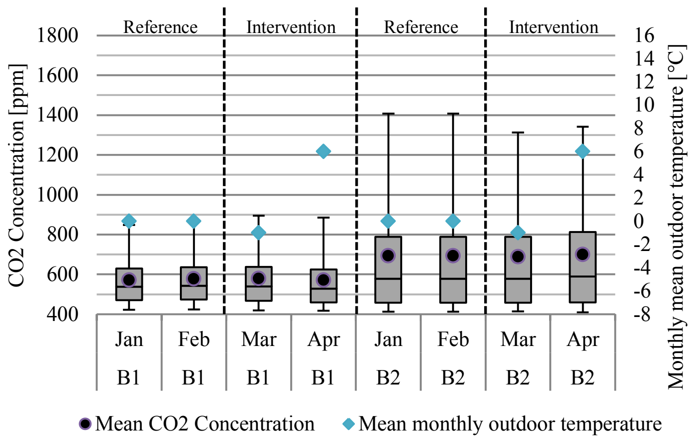


Figure 11 Monthly distribution of the CO_2 concentration [ppm] displayed with the 5th, 25th, 75th and 95th percentile and outdoor temperature [°C]

3.3 Individual distribution

In Building 1, all apartments were recommended to decrease the indoor temperature as this was above the recommendation of having an average temperature of 22°C. In the regression models, the intercept was reduced after the feedback introduction in 59% of the apartments. This indicted that the indoor temperature has been compared to before the feedback was introduced. The average R^2 value for all apartments in Building 1 was 0.17 (median 0.15 and standard deviation 0.10). In

41% of the apartments the regression models showed that the outdoor temperature had an increasing effect on the indoor temperature profile, resulting in higher temperatures after the feedback was introduced.

In Building 2, 65% of the apartments were recommended to maintain the indoor temperature as it was in February, 24% were recommended to increase and 12% were recommended to decrease the indoor temperature. For apartments recommended to decrease the average indoor temperature, the regression model showed a lower impact of the outdoor temperature after the feedback was introduced. In 47% of the apartments in Building 2, the influence of the outdoor temperature was reduced after the introduction of the feedback. The average R^2 value was 0.44 (median: 0.41, standard deviation: 0.16).

All results were found to be significant ($p<0.05$).

3.4 Key finding of semi' structured interviews

The interviews focused on how the informants controlled the indoor environment, their perception of this and their perception of the feedback.

3.4.1 Difference in indoor environmental control attitude

Andersen et al. [17] found that the occupants' strategies for controlling the indoor environment in Building 1 was focused on maintaining a *nice and comfortable indoor environment.* Some informants expressed an environmental awareness as they attempted to use as little heat as possible. In Building 2 the primary focus of the occupants were on a low the heat consumption, in some cases to the extend where the occupants accepted uncomfortable temperatures in favor of a low heating bill [17].

3.4.2 Feedback perception

In Building 1, one of the informants had used and understood the smiley icon on the monthly feedback letter; the remaining informants had read the letter but were uncertain of the meaning of the content. Two informants expressed no interest in the letters or measurements as it was perceived as advertisement. All informants in Building 2 had read and understood the monthly feedback letters.

The interviews showed that most informants were affected by the color of the smiley, even though they were uncertain of the meaning. The smiley icon and the color of this were seen as a school mark, the informants preferred to receive green marks as it meant they were acting correct. The general recommendations for a good indoor environmental quality were perceived as too general. The section should have provided specific recommendation on how to receive green smiley icons. Knowledge sharing amongst the residents took place in both buildings where residents discussed their results and ways to get green smiley icons.

All informants had access to real time measurements through a website, but only one informant from Building 1 and four from Building 2 had logged in at least once. Three informants had had a positive experience and used the website more frequently after the first visit. Two informants found the login process too complicated to use the website again.

3.5 Key findings of questionnaire survey

The response rates of the questionnaires were; Total: 42%, Building 1 with/without feedback: 35 / 17%, Building 2 with/without feedback: 60 / 44%.

To determine the usage of the continuous feedback website occupants were asked about the usefulness and the comprehensibility of the website.

Table 3 User experience with the continuous feedback website

Answer obtions:	Very high	High	Neutral	Low	Very low	Didn't use the website
To what degree did you find the website understandable						
Total	0%	24%	18%	0%	0%	59%
Building 1	0%	10%	30%	0%	0%	60%
Building 2	0%	43%	0%	0%	0%	57%
To what degree did you find the website useful						
Total	0%	25%	13%	0%	0%	63%
Building 1	0%	11%	22%	0%	0%	67%
Building 2	0%	43%	0%	0%	0%	57%

The occupants were asked if they found the General recommendations for a good indoor environmental quality adequate. In total 58% responded *Yes* and 42% responded *No.*

To evaluate the combined feedback process, occupants were asked if the feedback affected their control of the indoor environment. In total 71% of the respondents believed the feedback had affected the control strategy, while 29% didn't. In Building 1, 75% of the respondents believed the feedback had had an effect, while 67% in Building 2 were of the same perception. When asked, if the occupants had attempted to get feedback on the indoor environment after the study ended; 29% of the respondents answered *Yes* and 71% answered *No*.

4 Discussion

The overall aim of this study was to investigate the possibility of using continuous and monthly feedback as methods to influence occupants' control of the indoor environment and thereby the energy consumption.

Fabi et al. [25,26] demonstrated how the outdoor temperature was a driver for both the window opening frequency and the heating control. From March to April the average outdoor temperature increased from -1°C to 6°C, from the monthly boxplots in Figure 9 through Figure 11 it was evident that this didn't affect the control of the indoor environment. As 7°C increment of the average outdoor temperature didn't affect the measurements, the decrease of the outdoor temperature from February to March of 1°C should not have affected the measurements either. Therefore, if the feedback had influenced the control of the occupant behavior it would show as differences in the pre and post measurements. Figure 3 through Figure 6 showed lower measurements after the feedback introduction, assessed as an indication of the influence of the feedback. The CO_2 concentration summation curves and boxplots showed neglect able differences between pre and post feedback for both buildings, indicating that the feedback didn't affect the window opening frequency in the apartments.

4.1 Feedback at apartment level

From February to March the average outdoor temperature decreased 1°C. It was further assumed that all other drivers (number of occupants, building envelope etc.) remained the same before and after the feedback introduction. Therefore, if the regression analysis showed that the influence of the outdoor temperature decreased after the feedback introduction, the decrease was assumed to be an effect of the feedback.

Based on the average indoor temperature before the feedback introduction, all apartments in Building 1 were recommended to reduce the average temperature. The regression analysis showed that in 59% of the apartments, the influence of the outdoor temperature decreased after the introduction of the feedback – indicating an effect of the feedback in these apartments. In Building 2, 12% of the apartments were recommended to decrease the average indoor temperature. The regression analysis showed that the coefficient decreased indicating that the recommendation was followed, as the influence of the outdoor temperature on the indoor temperature decreased. 65% of the apartments were recommended to maintain their current control of the indoor temperature as it was. From the regression analysis it was found that the indoor temperature decreased in 45% of these apartments after the feedback introduction. 24% of the apartments were recommended to increase the indoor temperature; this recommendation was followed in 75% of the apartments.

As the control of the indoor environment not only is influenced by the outdoor temperature, but multiple other drivers, it cannot be concluded that the reduced influence of the outdoor temperature occurred because of the feedback procedure. However, as the interview informants in Building 2 stated to have been affected by the smiley icons despite not fully understanding them and that 75% of the questionnaires respondents in Building 1 and 66% in Building 2 stated that the feedback had an impact on the control of the indoor environment, it seems plausible that the difference in the measurements were induced by the introduction of the feedback.

4.2 Influence of heat cost allocation

Andersen et al. [22] investigated the indoor environmental differences in the apartments from March 2013 through April 2013. The investigation showed how occupants' goals for the indoor environment were influenced by the different heat cost allocation schemes in the two buildings. The occupants in Building 1 (which had a collective billing system where the heating bill for the entire building was distributed to the apartments based on the floor area) controlled the indoor environment with a focus of achieving a comfortable and healthy indoor environment. In Building 2 (which had individual billing based on heat cost allocators in each apartment), the occupants were more active in the control of the indoor environment with the aim of obtaining a low heating bill. The differences in the aims for the indoor environment could have affected the occupants' willingness to follow the recommendations of the feedback.

Andersen et al. [22] showed that as occupants in Building 1 didn't have a direct monetary incentive to conserve energy, they focused on maintaining a self-perceived comfortable indoor environment. Assuming that occupants of Building 1 perceived their indoor environment as good, there was neither a monetary incentive nor a comfort based incentive to follow the recommendations of either the continuous or monthly feedback. The occupants' control of the indoor environment in Building 2 was primarily driven by the occupants' aim of a low energy bill. Visualization of the indoor environment and recommendations on how to obtain an optimal energy bill would therefore theoretically be a useful tool for the occupants' control of the indoor environment. This was backed by the tendencies found by the interviews that the occupants had used the feedback and understood the content of the feedback.

These findings demonstrate that the feedback procedure should be fitted and designed to the users in order to obtain substantial effects. A finding in coherence with Buchanan et al. who argued that "a one-size fits all" solution doesn't necessarily work as people don't react to feedback in the same manor [10].

4.3 General assessment of the feedback procedure

50% of the informants in the interviews had used the website more than once and 59% of the questionnaire respondents' stated not to have used the continuous feedback at all. A finding indicating that the observed effect of the feedback was mainly an effect of the monthly feedback.

The continuous feedback was only accessible through a website using a user name and a password; two informants found this login process too complicated to use the continuous feedback. These two findings indicated both that the main influence mechanism were the monthly feedback.

All informants had access to real time measurements through a website, but only one from Building 1 and four from Building 2 had logged in at least once. Three informants had had a positive experience and used the website more frequently after the first visit. When asked about the degree of usefulness of the website 25% of the respondents found the degree high. However, as two informants found the login process too complicated to use the website again it was concluded that even though the content of the continuous feedback was useful, the process for the occupants to access it must be effortless.

5 Conclusion and recommendations

Based on the individual apartment assessments, the qualitative interviews and questionnaires, it was concluded that the feedback had influenced the control of the indoor environment. 60% of the apartments followed the recommendations of the monthly feedback. The interviews found that 50% of the informants and 71% of the questionnaire respondents stated that the feedback had had an effect on their control of the indoor environment. There was a small difference in the temperature and relative humidity. All apartments were not influenced by the feedback or followed the recommendations of the feedback.

The measurements showed a tendency of a higher influence in Building 2. This indicated that occupants controlling the indoor environment with a monetary incentive, to a higher degree welcomed assessment tools as the tested feedback.

Despite an influence of the feedback was demonstrated, the study didn't demonstrate a consistent effect of the feedback procedure. However, the procedure did influence the majority of the apartments indicating the positive effects of using indoor environmental feedback.

Semi-structured interviews and questionnaires showed that the content of the feedback was useful, but that the login process of accessing the continuous feedback was a barrier for the occupants' daily use of it. A login to access continuous feedback should be avoided.

6 Acknowledgement

The study was partly funded by the Danish Ministry of City, Living and Urban Areas in 2012.

7 Reference

[1] Lin CS, Lee IT. Internet of Things. Int J Commun Syst 2010;23:553–68. doi:10.1002/dac.

[2] Darby S. Smart metering: what potential for householder engagement? Build Res Inf 2010;38:442–57. doi:10.1080/09613218.2010.492660.

[3] Mc Clelland and Stuart W. Cook L. Energy Conservation Effects of Continuous In-Home Feedback in All-Electric Homes. J Environ Syst 1979;9:1–1. doi:10.2190/L8BU-ECLK-PEC5-KKTW.

[4] van Houwelingen JH, van Raaij WF. The Effect of Goal-Setting and Daily Electronic Feedback on In-Home Energy Use. J Consum Res 1989;16:98. doi:10.1086/209197.

[5] Ueno T, Tjuji K, Inada R, Saeki O. Effectiveness of displaying energy consumption data in residential houses Analysis on how the residents respond. ECEEE Summer Study 2005:1289–99.

[6] Darby S. The Effectiveness of Feedback on Energy Consumption a Review for Defra of the Literature on Metering , Billing and Direct Displays. Environ Chang Inst Univ Oxford 2006;22:1–21. doi:10.4236/ojee.2013.21002.

[7] Faruqui A, Sergici S, Sharif A. The impact of informational feedback on energy consumption-A survey of the experimental evidence. Energy 2010;35:1598–608. doi:10.1016/j.energy.2009.07.042.

[8] D'Oca S, Corgnati SP, Buso T. Smart meters and energy savings in Italy: Determining the effectiveness of persuasive communication in dwellings. Energy Res Soc Sci 2014;3:131–42. doi:10.1016/j.erss.2014.07.015.

[9] Nilsson A, Bergstad CJ, Thuvander L, Andersson D, Andersson K, Meiling P. Effects of continuous feedback on households' electricity consumption: Potentials and barriers. Appl Energy 2014;122:17–23. doi:10.1016/j.apenergy.2014.01.060.

[10] Buchanan K, Russo R, Anderson B. The question of energy reduction: The problem(s) with feedback. Energy Policy 2015;77:89–96. doi:10.1016/j.enpol.2014.12.008.

[11] Schultz PW. Conservation Means Behavior. Conserv Biol 2011;25:1080–3.

doi:10.1111/j.1523-1739.2011.01766.x.

[12] Hayes SC, Cone JD. Reduction of residential consumption of electricity through simple monthly feedback. J Appl Behav Anal 1981;14:81–8. doi:10.1901/jaba.1981.14-81.

[13] Wilhite H, Ling R. Measured energy savings from a more informative energy bill 1995;22:145–55.

[14] Abrahamse W, Steg L, Vlek C, Rothengatter T. The effect of tailored information, goal setting, and tailored feedback on household energy use, energy-related behaviors, and behavioral antecedents. J Environ Psychol 2007;27:265–76. doi:10.1016/j.jenvp.2007.08.002.

[15] Groot E De, Spiekman M, Opstelten I. 361 : Dutch Research into User Behaviour in Relation to Energy Use of Residences. PLEA 2008-25th Conf Passiv Low Energy Archit 2008:1–7.

[16] Schultz PW, Nolan JM, Cialdini RB, Goldstein NJ, Griskevicius V. The constructive, destructive, and reconstructive power of social norms. Psychol Sci 2007;18:429–34. doi:10.1111/j.1467-9280.2007.01917.x.

[17] Andersen S, Andersen RK, Olesen BW. Influence of heat cost allocation on occupants' control of indoor environment in 56 apartments: studied with measurements, interviews and questionaires. Build Environ 2016. doi:10.1016/j.buildenv.2016.02.024.

[18] Burak Gunay H, O'Brien W, Beausoleil-Morrison I, Perna A. On the behavioral effects of residential electricity submetering in a heating season. Build Environ 2014;81:396–403. doi:10.1016/j.buildenv.2014.07.020.

[19] En DS. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. 2007.

[20] Wilke G. IC Meter 2015. www.ic-meter.com (accessed March 15, 2015).

[21] Andersen RK. Experiences from the project Dynamic Heat Cost Allocation 2013.

[22] Cui S, Cohen M, Stabat P, Marchio D. CO2 tracer gas concentration decay method for measuring air change rate. Build Environ 2015;84:162–9. doi:10.1016/j.buildenv.2014.11.007.

[23] Fabi V, Andersen RV, Corgnati S, Olesen BW. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. Build Environ 2012;58:188–98. doi:10.1016/j.buildenv.2012.07.009.

[24] Fabi V, Andersen RV, Corgnati SP. Main physical environmental variables driving occupant behaviour with regard to natural ventilation n.d.

[25] Fabi V, Andersen RV, Corgnati S, Olesen BW. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. Build Environ 2012;58:188–98. doi:10.1016/j.buildenv.2012.07.009.

[26] Fabi V, Andersen RV, Corgnati SP, Venezia F. Main physical environmental drivers of occupant behaviour with regard to space heating energy demand. Heal Build 2012 2012.

23 APPENDIX 5

Paper 3
How to influence indoor environment regulation with continuous and weekly feedback: a case study of 18 Danish apartments

Authors: Søren Andersen, Rune Korsholm Andersen and Bjarne W. Olesen
Published in: Building and Environment
Publication status: Submitted

Case study on how to influence indoor environment control using continuous and weekly feedback to the occupants

Søren Andersen*[1], Rune Korsholm Andersen[1], and Bjarne W. Olesen[1]

[1]ICIEE, Department of Civil Engineering, Technical University of Denmark, Nils Koppels Allé 402-2, 2800 Kgs. Lyngby, Denmark

*Corresponding email: sran@byg.dtu.dk

Abstract

Using feedback to motivate and guide occupants to conserve energy has been tested and used at many occasions. Some studies documented an effect of the feedback while were more reluctant. In Danish households the energy use for heating is mainly influenced by the indoor temperature and the air change rate. The aim of this paper was to investigate if it was possible to use indoor environmental based feedback to influence occupants' control of the indoor environment and its impact on the energy use.

The paper presents measurements of the air temperature, relative humidity and CO_2 concentration performed in 18 Danish rental apartments. An intervention group received continuous feedback through a smartphone application and weekly feedback as a physical letter. The continuous feedback visualized the indoor environment in real time along with a historical comparison. The weekly feedback letter provided an overview of the measurements, gave detailed recommendation on how to improve the performance of one parameter, and finally made a social comparison to their neighbors. The recommendations were given with basis in the indoor environment and the energy use. This way, the energy use would not dramatically increase because of a change in the indoor environment. A control group who did not receive feedback, was used to define how the indoor environment was control without the influence of feedback

Based on differences in measurements and questionnaire responses, it was concluded that the occupants' control of the indoor environment was influenced by the feedback procedure. Occupants perceived the continuous feedback as the factor that had the main influence on the control of indoor environment.

Keywords: Occupant behavior, indoor environment, real time feedback, weekly feedback

1 Introduction

International policies have agreed that reductions in use of fossil fuels are necessary to address climate changes and a possible lack of fossil fuel in the future, with energy reductions in all sectors from energy production to residential energy use. When decisions to reduce energy consumption are agreed at macro level, some of the reductions must be accomplished at micro level by occupants renovating their house or changing their energy behavior.

In the UK a smart meter program was rolled out at great scale [1] to provide citizens with a tool to monitor the electricity use and to motivate an energy conserving behavior. Smart meters are used in many countries and are often accompanied by an in-home display providing feedback to the occupants [2,3].

Multiple studies have shown positive effects of in-home-displays and other feedback procedures [3–6], but some studies questions the use of smart meters as primary mechanism to promote energy conservation ([7–9]). Raaij et al. [10] studied sociodemographic variables and the thermal environment of 145 Dutch households and found that different occupants with similar sociodemographic values have the same goal for the thermal environment and/or heating bill [10]. Both Gunay et al. [11] and Andersen et al. [12] demonstrated how sub-metering of energy consumption influenced occupants' control of the indoor environment and thereby the total energy consumption. These findings all show that occupants are different and indicate that different approached should be used if their energy consumption is be influenced by feedback. Guerreiro et al. studied the sociological and psychological aspects of the use of smart meters through a quantitative survey in 515 households. Supporting the finding of Raaij [10], Santin [13], Gunay [11] and Andersen [12], the paper found indications of the use of feedback from smart meters were influenced by factors as subjective norms, perceived usefulness of the smart meter, risk perception and procedural justice [14].

Nilsson et al. studied the effect of in-home-displays in 72 households and found no significant effects on the electricity consumption [15]. The paper described that the two most important barriers for a positive effect was the households' understanding of the display and the occupants' lack of interest. Tamar et al. supported the finding of occupants' understanding of the feedback as a barrier for a high effect. The paper presented guidelines for in-home displays based on customers' preferences [16]. Burchanan et al. found short term energy savings of 2% and questioned if this justifies installation in all homes, when the responsibility for the effect of smart meters is placed on occupants [8].

1.1 Tailored feedback

Tailored feedback is feedback specifically designed for individual households and will not necessarily be useful to the other households. Abrahamse et at. found that tailored information, goal setting and tailored feedback, meant that the intervention apartments reached a goal of a 5% energy reduction [17]. Fisher surveyed how consumers preferred electricity consumption feedback and found feedback should be given on the actual energy consumption, involve appliance-specific breakdowns and be presented in an understandable and appealing way [18] – a type of feedback which by the present paper was defined as tailored feedback.

1.2 Use of comparative feedback

Abrahamse et al. defined comparative feedback as: *Feedback about individual performance relative to performance of others* ([19] page 271). Comparative feedback is a mechanism used to provoke a competitive urge and desire to perform well in the recipient of the feedback. Comparative feedback is a wide term and covers techniques as historical data comparison, and comparison to both bigger and smaller focus groups, and to some extent goal setting.

Allcott [20] studied effect of a utility related company providing its customer with comparison of their energy consumption to the average of the neighbors. Allcott compared the effects of this low cost non-price intervention to the effects of increased cost of energy. He found that the effects of the comparative feedback were equivalent to the effects of a 11 to 20% price increase on the short term and 5% on the long term [20]. Both Abrahamse et al. [17] and Burchell et al. [21] stressed the importance of using a relevant and representative focus group, a group similar to the group the intervention is aimed to influence. Burchell et al. further stated the importance of highlighting to the intervention group that the comparison is based on a similar focus group e.g. by writing: *Your energy consumption was above the average in your neighborhood* [21].

When using social norm comparison some participants will perform better than the average and therefore perhaps increase their consumption. To prevent this so-called Boomerang effect, precautions must be taken. Schultz et al. [22] studied the challenged and found, based on the findings in focus theory by Cialdini et al. [23], that if the normative information was followed by an positive message, a boomerang effect could be avoided [22]. Schultz et al. conducted an experiment to test the effect of this message type on the energy consumption in residences. The paper found that high-consuming households receiving only comparative feedback reduced their consumption of 1.22kwh/day, while high-consuming households receiving comparative feedback and an descriptive message reduced their consumption with 1.72kWh/day [22]. A similar finding was made by Schweiker et al., who found that actions followed by satisfaction were more likely to happen again [24]. Geller supported the use of positive messages by stating that when a positive attitude is linked to a certain behavior, it is more likely to become the norm [25].

1.3 Dissemination frequency and fatigue

Abrahamse et al. reviewed the effects of several feedback techniques, the effects of these and concluded that a higher feedback dissemination frequency resulted in a higher effect [22]. A conclusion indicating, that a higher effect can be obtained with smart meters and in-home-displays than with a monthly or quarterly energy bill.

Cholewa et al. [27] studied the effect of sub-metering on the long term in a Polish apartment block for 17 heating seasons. The results showed that the sub-metering acted as a driver for energy conservation compared to a control group. The paper further proved that the energy conservation was persistent throughout the 17 heating seasons.

When using information dissemination regardless of the type, there is an opportunity that feedback fatigue occurs reducing the effect of the feedback. Missing long term effects could be a result of feedback fatigue, where the feedback loses its novelty value and becomes irrelevant and uninteresting to the recipients of the feedback. Hargreaves et al. studied how occupants in 12 UK households interacted with the feedback from their smart meters. The study was conducted as qualitative interviews and found that householders' knowledge about their electricity consumption increased because of the smart meters. On the long term, the use of the feedback was reduced [28].

The effect of smart-meters and in-home displays rely on the assumption that occupants can interpret the electricity feedback. From this feedback occupants must determine energy use of high consuming devices. As described by Buchanan et al. [8], the effect further relies on the occupants being motivated to make the analysis and put in the effort to obtain the energy reductions. In the 2016 paper, Buchanan et al. suggested that alternative methods should be tested before smart meters were installed in every U.K. household [9].

With this study an alternative method to indirectly affect the energy use was investigated. In Danish households, the heating consumption is mainly influenced by the occupants' control of the heating set point and ventilation rate and thereby the indoor environment. When using energy based feedback, occupants' are given a monetary and environmental incentive to conserve energy. The aim of this study was to investigate if indoor environmental feedback could be used to influence occupants' control of the indoor environment and thereby their energy use. By using indoor environmental based feedback, the occupants' comfort and health (represented by air quality) can be used as additional motivation to the monetary and environmental incentives. The study investigated how a combination of continuous feedback and weekly newsletters could enhance the occupants' knowledge of the indoor environment and thereby help them make informed decision when controlling the heating set point or window opening.

2 Method

The study was conducted in four similar apartment blocks in Ballerup, Denmark. The buildings were built in 1958, in 1985 the windows were replaced and in 1995 the roof was renovated. Each building had four floors with apartments containing a living room, two bedrooms, a bathroom, a kitchen and a central hall way. The apartments were heated by water based convertors and naturally vented; there was no exhaust ventilation from kitchen or bathroom, and there was no window in the bathroom. The electricity was metered for each apartments and the heating was metered for each all four building blocks and sub-metered with heat cost allocators for each apartment.

The experiment was conducted in the winter period from October 2015 to February 2016. Feedback was provided to the intervention groups from November 2015 to February 2016. To assess and validate differences during the feedback period, the participating apartments were separated into intervention apartments and control apartments. Intervention apartments received information on how a good indoor environment was defined, how to achieve a high indoor environmental quality, and continuous and weekly feedback from November 2015 to February 2016. Occupants in the control group received information on the aim of the study, but no other information before the measuring period ended in February 2016. Occupants in the control apartments were instructed not to actively change their behavior and routines despite the indoor environment was monitored; they were further informed that the detailed measurements were not seen by others than the authors of this paper. These two precautions were made to reduce a possible Hawthorn effects.

In total 18 apartments participated in the experiment of which 11 were placed in the intervention group and 7 in the control group. To perform this separation the participants were divided into one of the five categories in Table 1. Within each category the measurements of October 2015 were compared in order to have apartments performing similarly in both the intervention and control group.

Table 1 Distribution of apartments in the intervention and control group

Apartment category	Intervention group	Control group	Total
Single male	1	0	1
Single female	2	1	3
Family with young children	6	3	9
Younger couple	0	1	1
Old couple	2	2	4
Total	11	7	18

To engage occupants to participate in the study one apartment could win a gift certificate of 1000 DKK (roughly 140€) to a local store, the only obligation to win was to participate as either intervention or control group.

2.1 Data collection

Collecting the measurements was performed in each apartment by Netatmo Weather Station sensors in the living room, bedroom and kitchen. The living room sensor and bedroom sensor measured the temperature [°C], relative humidity [%], CO_2 concentration [ppm], air pressure [mBar], and sound pressure [db] at a five minute interval. The sensors were placed at a similar position approximately 1.5meters above the floor. The sensors were placed at locations with good air distribution, visible to the occupants and not affected by heat from convertors or direct sun. The living room sensor was equipped with a LED light that would light up in red for a short time (roughly 5 sec) if the CO_2 concentration exceeded 1000 ppm. The kitchen sensor measured the temperature [°C], relative humidity [%]. The accuracy of the temperature, relative humidity, and CO_2 concentration was: +/- 0,3°C, +/- 3.0 %, and +/- 50ppm, +/- 5%

The CO_2 sensors in the measuring units were self-calibrating sensors, meaning that the lowest measured CO_2 concentration in the previous running week is assumed as the outdoor concentration. For accurate readings, it is required that outdoor concentration is reached at least once a week, as the CO_2 concentration readings would be higher than the actual CO_2 concentration. Occupants were asked to reach outdoor concentration at least once a week to secure accurate readings, as recommended by the producer. To avoid misreading of the CO_2 concentration the first week of measurements was excluded for all apartments. It was assumed that outdoor concentration was reached within the first six hours after installation.

Questionnaires were distributed to all apartments in October 2015 and after the experiment ended in February 2016. The questionnaires were aimed to evaluate the feedback procedure and whether the feedback was used and if its content was usable.

2.2 Feedback procedure

On 1st November 2015 occupants' in the intervention group received a welcome letter; an information folder and a bag of candy in order to create a positive atmosphere around the welcome letter. The feedback consisted of continuous feedback provided through a website and/or smartphone application visualizing the real time measurements, and a weekly newsletter including indirect feedback on the measurements from the previous week.

The information folder gave a short introduction to the experiment, but focused on explaining the content of the smartphone application. The introduction folder explained how the temperature, relative humidity and air quality (represented by the CO_2 concentration) influence occupants comfort and energy consumption of the building. Recommendations on how to interpret and react to the real time measurements visualized by the continuous and weekly feedback were given in accordance with the design values of EN 15251-2007 [29].

Table 2 Recommended benchmarks for a high indoor environmental quality in the experiment

Parameter	Recommendation
Air Temperature [°C]	20 – 25
Relative Humidity [%]	25 – 65
CO_2 concentration [ppm]	< 1000

The last page of the information folder was a list of ten recommendations on how to maintain a high indoor environmental quality. The recommendations were concrete and something that easily could be implemented in the daily routines. The ten recommendations were presented in Appendix 1.

2.3 Continuous feedback

The continuous feedback was accessible through a website and smartphone application, occupants' was encouraged to use the smartphone application. The introduction folder guided the occupants on how to download the application for their smartphones, a login and password had been pre-generated to ease the installation process. Occupants' were further encouraged to contact the authors in case of questions regarding the installation process.

The continuous feedback in the smartphone application was divided into three section; measurements in living room and bedroom, measurements in kitchen, and 5 days weather forecast.

The living room and bedroom section showed the real time measurement of the temperature [°C], relative humidity [%], CO_2 concentration [ppm], and sound pressure [db]. The section further included an indication of the air quality (based on the CO_2 concentration), the indication changed from green over yellow to red when the indoor air quality decreased. The kitchen section showed the indoor temperature [°C], relative humidity [%], pressure [mBar], and dew point [°C]. The latter two was not used or explained in the study and was an unavoidable item in the commercial available smartphone application. If the smartphone was tilted historical data was accessible. A button in the smartphone application would highlight the meaning of each item in application.

The smartphone application had a push notification feature where the user received push notifications when a parameter exceeded the benchmark defined in Table 2. In this study push notifications on the CO_2 concentration was used, the occupants were able to disable the feature.

2.4 Weekly feedback

The weekly feedback was provided to the apartments as a physical letter every Tuesday after 1st of November 2015 to 29th February 2016. The weekly feedback was aimed to visualize the indoor environment in three detail levels: General, detailed and social. The weekly feedback was further aimed to provide concrete and useable recommendation specific to the apartments.

The first general level provided a rating of each measured parameter; temperature, relative humidity and air quality. The rating was performed according to the recommendations in Table 2 and the 5% recommendation of EN 15251-2007 [29], where it was recommended that the measurements didn't exceed the benchmarks for more the 5% of the time. If the parameter was within the recommendation for the entire week a green icon was shown on the letter, if it was outside for less than 5% of the week a yellow icon was given and if the parameter was outside of the recommendation for more than 5% a red icon was given. The second part of the first level was a visualization of the distribution of the measurements using doughnut charts for each parameter of each room.

The second level was a detailed visualization of one of the measured parameters in one room. For the highlighted parameter a chart showing an assessment of each hour of the week was generated, the assessment was performed in accordance with the icons in the first level. The hour-by-hour chart was followed by an explanation of why this parameter was selected and a concrete recommendation on how to improve the performance of this parameter.

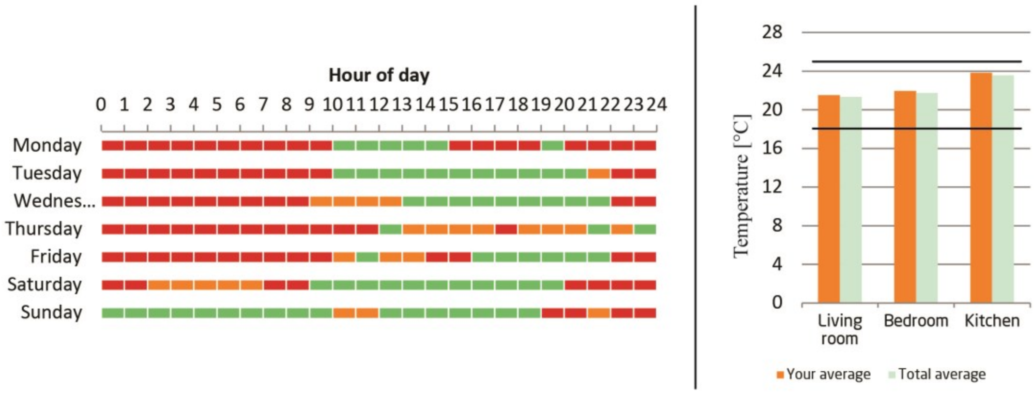


Figure 1 Left: example of hour-by-hour chart. Right: Example social comparison column chart

The third level was a social comparison where the average values of the temperature, relative humidity and CO_2 concentration were visualized in a column chart with the average of all intervention apartments. For occupants to compare with the recommendations the benchmarks of Table 2 was included in the charts.

3 Results

To investigate the overall performance of the apartments the temperature [°C], relative humidity [%] and CO_2 concentration [ppm] was visualized in Figure 2 to Figure 7 as the percentage time spend in the given interval in the living room and bedroom. The average value, standard deviation, 5^{th}, 25^{th},75^{th} and 95^{th} percentile for each parameter were presented in Table 3 and Table 4for the living room and bedroom, respectively. The 5^{th} and 95^{th} percentile was used as representation of the minimum and maximum readings, as the actual minimum and maximum reading would represent one measurement from one apartment not necessarily being representative for all apartments.

The aim of the study was to test a combination of continuous and weekly feedback in order to influence the occupants' control of the indoor environment and thereby energy consumption. A general assessment of the measurements in Figure 2 through Figure 7 showed a difference between the living room and the bedroom, determining the potential effects of the feedback was therefore performed at room level.

Table 3 Average, standard deviation and percentiles of measurements in the living room

	Intervention type	Parameter	Average	Standard deviation	5th percentile	25th percentile	75th percentile	95th percentile
Before feedback	Control	Temperature [°C]	21,7	1,2	20,1	20,9	22,5	23,7
	Intervention	Temperature [°C]	21,5	1,1	19,8	20,8	22,2	23,5
	Control	Relative humidity [%]	56	5	48	52	59	65
	Intervention	Relative humidity [%]	56	5	47	53	59	63
	Control	CO2 concentration [ppm]	996	533	437	680	1163	2072
	Intervention	CO2 concentration [ppm]	823	411	387	551	961	1674
After feedback	Control	Temperature [°C]	21,6	1,2	19,8	20,7	22,4	23,5
	Intervention	Temperature [°C]	21,1	1,1	19	20,4	21,9	22,7
	Control	Relative humidity [%]	51	7	39	45	56	63
	Intervention	Relative humidity [%]	49	7	37	45	55	60
	Control	CO2 concentration [ppm]	1123	665	459	735	1316	2407
	Intervention	CO2 concentration [ppm]	843	435	343	534	1022	1701

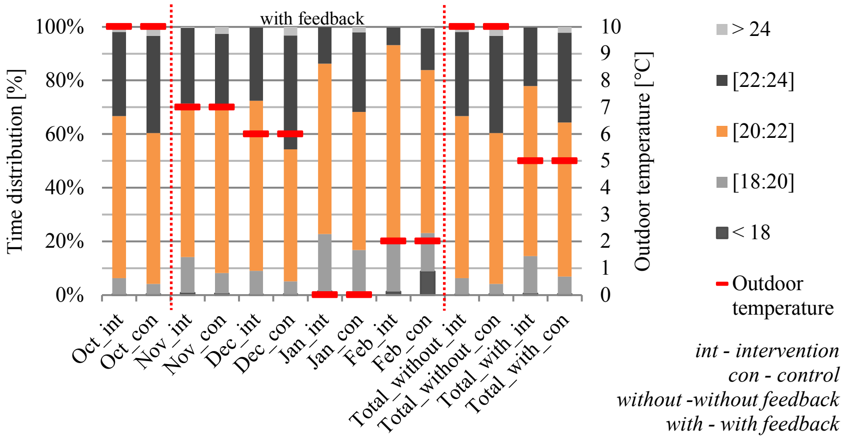


Figure 2 Living room indoor temperature [°C] measurement distribution and outdoor temperature [°C] before and after feedback was introduced and for each month

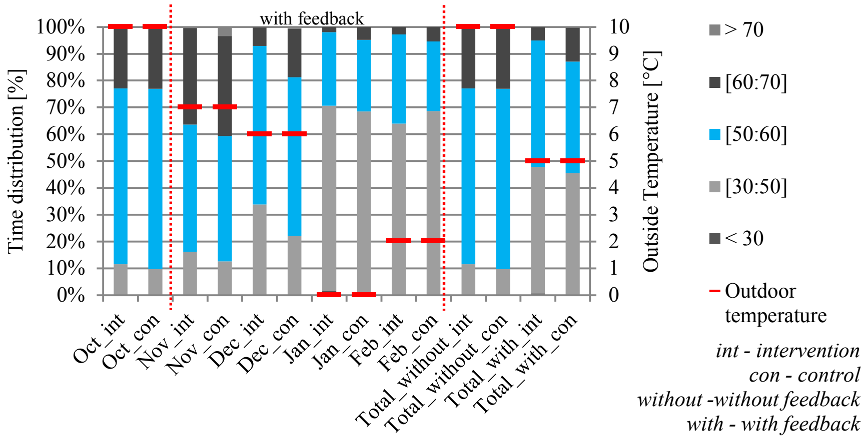


Figure 3 Living room relative humidity [%] measurement distribution and outdoor temperature [°C] before and after feedback was introduced and for each month

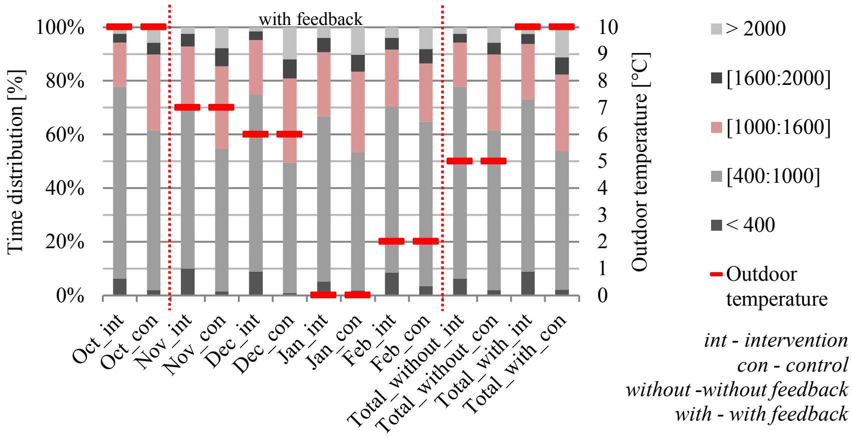


Figure 4 Living room CO_2 concentration [ppm] measurement distribution and outdoor temperature [°C] before and after feedback was introduced and for each month

Table 4 Average, standard deviation and percentiles of measurements in the bedroom

	Intervention type	Parameter	Average	Standard deviation	5th percentile	25th percentile	75th percentile	95th percentile
Before feedback	Control	Temperature [°C]	20,3	1,6	17,7	19,3	21,6	22,5
	Intervention	Temperature [°C]	20,7	1,7	17,8	19,7	22	23,5
	Control	Relative humidity [%]	54	5	47	51	57	62
	Intervention	Relative humidity [%]	52	6	44	49	55	65
	Control	CO2 concentration [ppm]	1374	1206	403	574	1422	4518
	Intervention	CO2 concentration [ppm]	1047	803	399	505	1302	2505
After feedback	Control	Temperature [°C]	20,2	1,6	16,5	19,6	21,4	23,1
	Intervention	Temperature [°C]	20,7	1,6	17,8	19,8	21,8	23,1
	Control	Relative humidity [%]	49	8	37	44	54	63
	Intervention	Relative humidity [%]	44	7	30	40	49	53
	Control	CO2 concentration [ppm]	1520	1354	417	635	1596	4997
	Intervention	CO2 concentration [ppm]	944	543	414	536	1197	2009

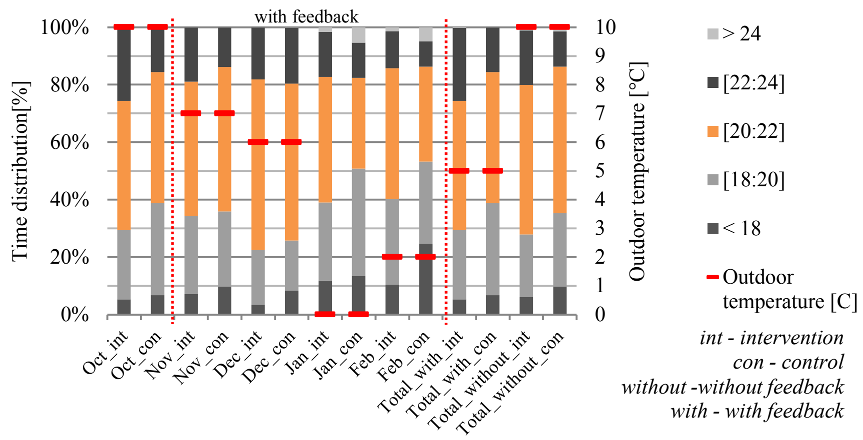


Figure 5 Bedroom indoor temperature [°C] measurement distribution and outdoor temperature [°C] before and after feedback was introduced and for each month

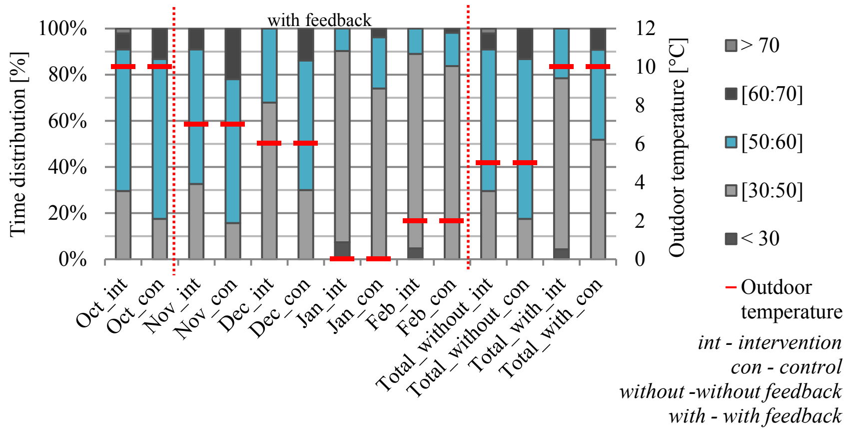


Figure 6 Bedroom relative humidity [%] measurement distribution and outdoor temperature [°C] before and after feedback was introduced and for each month

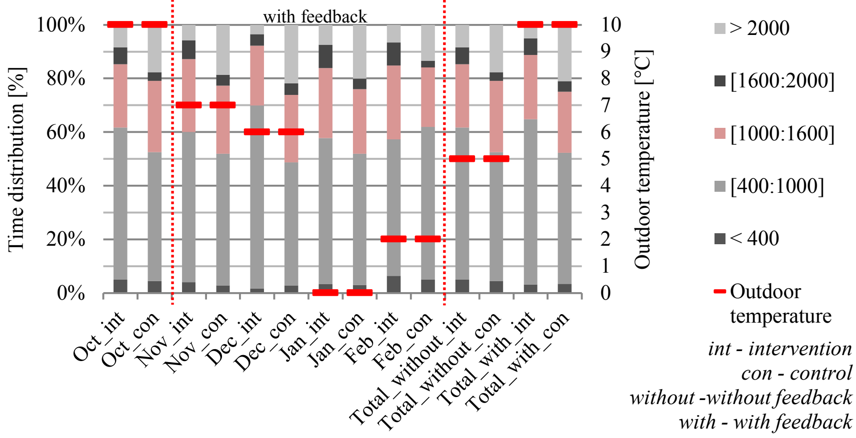


Figure 7 Bedroom CO_2 concentration [ppm] measurement distribution and outdoor temperature [°C] before and after feedback was introduced and for each month

3.1 Weekly feedback fatigue survey

To survey the effects of the weekly feedback letter and if feedback fatigue occurred over the week, the measurement distribution were analyzed for each day of the week for each month. The distribution was visualized with boxplots showing the 5th, 25th, 75th and 95th percentile of the measurements. The 5th and 95th percentile were used as representative for the minimum and maximum measurements as the actual minimum and maximum reading only would represent one reading in one apartment.

The analysis was performed for both the living room and bedroom in the intervention apartments, but only the living room results were included.

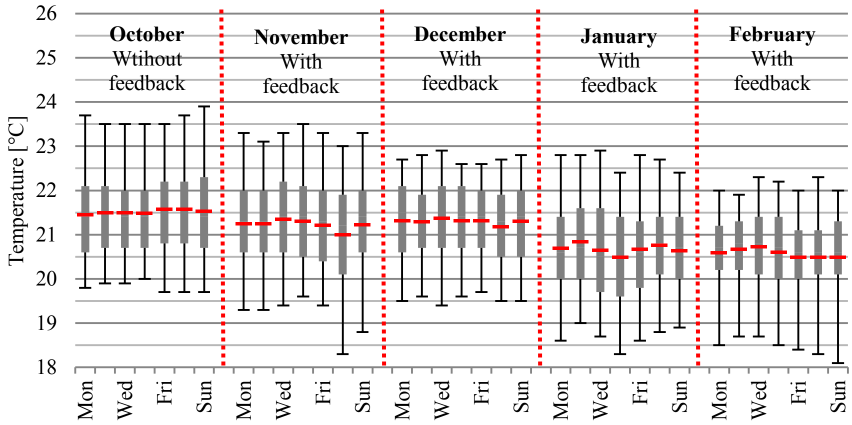


Figure 8 Daily distribution of living room temperature [°C] measurements without and with feedback for the intervention. Average values marked with horizontal line

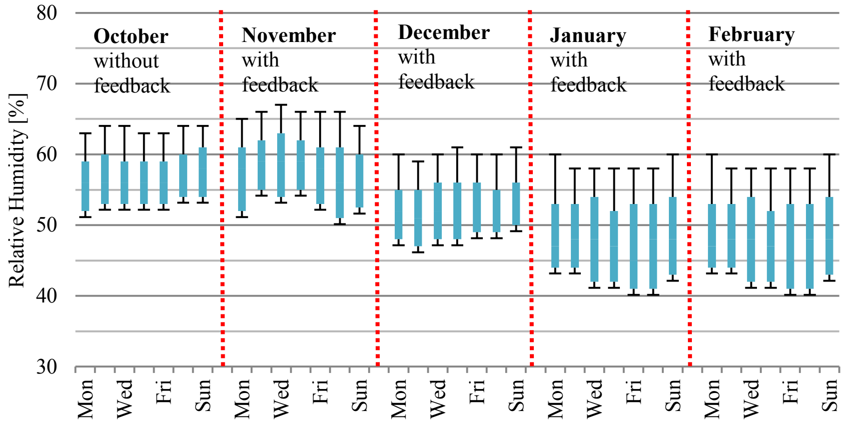


Figure 9 Daily distribution of living room relative humidity [%]measurements without and with feedback for the intervention and control apartments. Average values marked with horizontal line

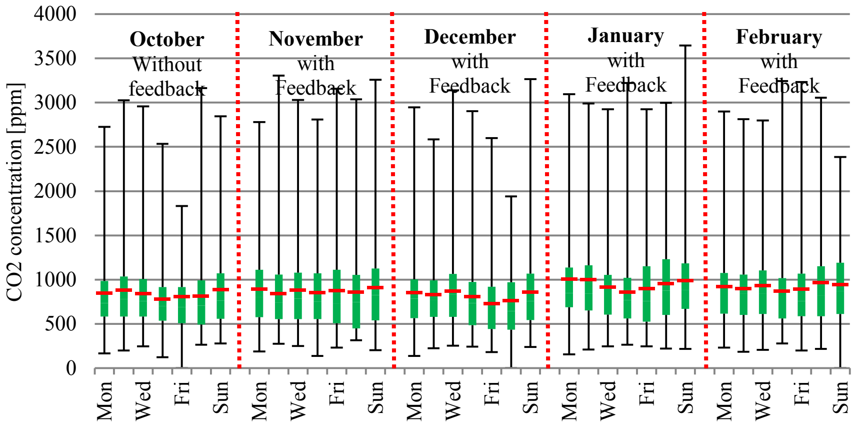


Figure 10 Daily distribution of living room CO_2 concentration [ppm] measurements without and with feedback for the intervention and control apartments. Average values marked with horizontal line

3.2 Findings of questionnaire 1

The questionnaire was answered by the occupants while the measuring units were being installed before the feedback introduction, a total of 18 questionnaires were filled out. Questionnaire 1 was aimed to survey how occupants controlled the indoor environment and the goals and values for this.

Table 5 Highlighted questions and answers questionnaire 1 in the intervention apartments

To what degree do you agree with:	Highly disagree	Disagree	Partly disagree	Neutral	Partly agree	Agree	Highly agree
It is important to have a low heating bill	0%	0%	10%	0%	0%	30%	60%
It is important to have a high air quality	0%	0%	0%	10%	0%	10%	80%
rather have a high indoor environmental quality than a low energy consumption	0%	0%	0%	20%	0%	20%	60%

Table 6 Highlighted questions and answers questionnaire 1 in the control apartments

To what degree do you agree with:	Highly disagree	Disagree	Partly disagree	Neutral	Partly agree	Agree	Highly agree
It is important to have a low heating bill	0%	0%	25%	0%	13%	25%	38%
It is important to have a high air quality	0%	0%	0%	25%	25%	25%	25%
rather have a high indoor environmental quality than a low energy consumption	13%	0%	0%	25%	25%	0%	38%

3.3 Findings of questionnaire 2

The response rate of questionnaire 2 was totally 95% with 91% for intervention apartments and 100% for control apartments. In Table 7 Selected questions and answers from Questionnaire 2 in the intervention apartments Table 7 and Table 8 highlighted questions and answers were presented. Occupants were asked to answer the questions based on their behaviour during the feedback period.

Table 7 Selected questions and answers from Questionnaire 2 in the intervention apartments

To what degree do you agree with:	Highly disagree	Disagree	Partly disagree	Neutral	Partly agree	Agree	Highly agree
We have changed the control of the indoor environment in the living room	0%	11%	0%	0%	56%	22%	11%
We have changed the control of the indoor environment in the bedroom	0%	11%	0%	11%	44%	22%	11%
We have become more aware of our indoor environment	0%	0%	0%	0%	33%	44%	22%
We have become more aware of our energy consumption	0%	22%	11%	11%	22%	11%	22%

To investigate the occurrence of hawthorn effect [30], the control apartments were asked if they believed that the presence of the measuring unit had had an effect on their control of the heating or venting. 50% believed it had had an effect, while 50% disagreed.

Table 8 Selected questions and answers from Questionnaire 2 in the control apartments

To what degree do you agree with:	Highly disagree	Disagree	Partly disagree	Neutral	Partly agree	Agree	Highly agree
We have changed the control of the indoor environment in the living room	43%	0%	14%	0%	14%	29%	0%
We have changed the control of the indoor environment in the bedroom	29%	29%	14%	0%	9%	29%	0%
We have become more aware of our indoor environment	14%	0%	0%	0%	43%	29%	0%
We have become more aware of our energy consumption	29%	0%	0%	0%	29%	43%	0%

To survey the use of the continuous and weekly feedback, occupants were asked for their perception of their use of the smartphone application and the weekly newsletter. For the smartphone application; 67% of the intervention apartments downloaded it and received the continuous feedback, 80% of these reported that there was one primary user and that 80% of these were women. When asked how often the continuous feedback was used, 33% used it several time a day, 33% used it once a day, 17% a few times a week, and 17% hadn't used it. When asked if the participants found the continuous feedback useful, 100% agreed. Regarding the weekly newsletter, 100% of the responses both understood the content and understood why they received the assessments they did.

As a final question, the occupants were asked whether the smartphone application or the weekly newsletter had the biggest effect (or if it was equal). 50% perceived the biggest effect from the smartphone application, 20% from the newsletter and 30% didn't answer.

4 Discussion

4.1 Indoor environment in control apartments

The purpose with the measurements in the control apartments was to document the indoor environment in apartments which did not receive feedback. The living room measurements indicated that the occupants did not change their control of the indoor environment before and after the feedback introduction. From October 2015 to February 2016 the outdoor temperature decreased. This was reflected in the relative humidity and CO_2 concentration measurements. The slight decrease in relative humidity could be a natural effect of lower moisture content in the outdoor air with decreasing outdoor temperature. The CO_2 concentration increased, which could be explained by Fabi et al. who found that windows were opened less frequently, when the outdoor temperature decreased [31]. The stable measurements indicated that occupants' control of the indoor environment in the living room wasn't influenced by the feedback. The results presented in Table 4 showed a similar tendency in the bedroom as in the living room, as the measurements seemed to only be influence by the weather. The measurements presented in Table 3 and Table 4 indicated that the occupant behaviour in the control apartments was not affected by the feedback.

In Questionnaire 2, 50% of the occupants stated they had been affected by the presence of the sensor. The measurements in each control apartment were close to constant, indicating that a hawthorn effect did not affect the measurements. The measurements from the control apartments were therefore considered suitable as a documentation of how the measurements would have been in the intervention apartments if the intervention apartments had not received feedback.

4.2 Feedback influence in the living room

The average temperature in the living room decreased 0.4°C after the feedback introduction. The 95th percentile of the temperature measurements (used as representative for the maximum) decreased 0.8°C after the introduction of feedback. The monthly distribution showed that before the feedback introduction 2% of the living room measurements were above 24°C. After the feedback introduction the indoor temperature was below 24°C 100% of the time. This could have been an effect of the decreasing outdoor temperature, but as 2-3% of the temperature measurements in the control apartments were above 24°C each month after the feedback introduction, it is more likely that the decrease in maximum temperatures was an effect of the feedback procedure. The percentage of time in the 22-24°C intervals (Figure 2) decreased from 31% in October to 7% in February. This could be an effect of the decreasing outdoor temperature, but since the same tendency was not observed in the control apartments, the development was interpreted as a difference in the heating behaviour between the two apartment groups induced by the feedback.

Occupants tend to open windows less when the outdoor temperature decreases [31–35]. As a consequence, it was expected that the monthly CO_2 concentration increased with decreasing outdoor temperature. Comparing the *Total columns* and the *Monthly columns* of the control (con) and intervention(int) apartments in Figure 4, the CO_2 concentration increased for both apartment types but not to the same extent (this was true, on a monthly basis and in total). The notable higher CO_2 concentrations in the control apartments indicated differences in the window opening behaviour induced by the feedback intervention.

The difference between the control and intervention apartments could be because of an influence of the feedback procedure. However, Questionnaire 1 surveyed to which degree the occupants tried to obtain a low energy bill; 90% of the intervention apartments *agreed* or *highly agreed* that this was a goal for them while 53% of the control apartments *agreed* or *highly agreed*. 80% of the intervention apartments stated that they would *Rather have a high indoor environmental quality than a low energy bill* (agree or highly agree). This was only true for 38% of the control apartments. These findings indicated that in general, the occupants in the intervention apartments were more motivated to maintain a low energy use and a high indoor environmental quality than the occupants in the control apartments. Questionnaire 2 found that 89% of the intervention apartments had become more aware of their indoor environment after the feedback introduction. The differences between intervention and control apartments were therefore most likely a result of the feedback procedure and because of different goals for the energy bill as documented in Questionnaire 1.

4.1 Feedback influence in the bedroom

Since the control apartment temperature and CO_2 measurements developed as expected with the decreasing outdoor temperature and the findings of Fabi et al. [31,36], the indoor environment in the bedrooms of the control apartments was most likely not influenced by the feedback procedure.

The average temperature in the bedrooms of the intervention apartments did not change during the intervention period. The relative humidity decreased 8 percentage points as the CO_2 concentration decreased 103ppm. These small changes indicated a stable indoor environment before and after the feedback introduction and thereby that the feedback did not affect the indoor environment in the bedrooms' of the intervention apartments.

The monthly relative humidity measurements of the intervention apartments decreased during the intervention period. This development was a natural consequence of a decreasing outdoor temperature. Before the feedback introduction, 9% of the relative humidity measurements were above 60%. After the feedback introduction, none of the readings were above 60%. In the control apartments 13% of the readings were above before and 9% were above after the feedback introduction, a result indicating differences in the control of the indoor environment after the feedback introduction.

The average, the standard deviation, and the 95th percentile of the CO_2 concentration in the intervention apartments' bedroom decreased after the feedback introduction. In the control apartments the same factors increased, which was expected as a lower window opening frequency because of the decreasing outdoor temperature. The opposing developments in the intervention and control apartments demonstrated a clear difference in the control of the indoor environment.

The differences between the control and intervention apartments in both the relative humidity and CO_2 concentration demonstrated a difference in the control of the indoor environment. Although the there were differences between the two groups before the feedback introduction Questionnaire 2 indicated that the differences were a result of the feedback intervention: 77% of the intervention apartments and 38% of the control apartments stated that they *partly agreed, agreed or highly agreed* to be more focused on the indoor environment in the bedroom after the feedback introduction.

4.2 Feedback fatigue survey

By assuming that the differences between the control apartments and the intervention apartments occurred because of the feedback and by assuming the magnitude of the measurement differences as the effect of the feedback, it was possible to assess if feedback fatigue occurred in the feedback period.

The feedback fatigue assessment was performed by the amount of time the measurements were above the recommended benchmark for each parameter. The assessment of the monthly distribution in Figure 2 to Figure 7 showed differences in the same order between the control and intervention apartments in November and December for all parameters. In January the difference between the control and intervention apartments decreased, while there were no differences in February for all parameters in both apartment types. The outdoor temperature decreased from December to February, but as the outdoor temperature in January and February was alike the indoor environmental measurements would have been alike if the effects of the feedback had been persistent. The smaller differences in February, compared to January were therefore seen as a form of feedback fatigue.

The weekly newsletter was disseminated every Tuesday in the intervention period. To survey if feedback fatigue occurred during the week a daily distribution of the measurements were studied in Figure 8 to Figure 10. Fatigue during the week didn't happen in any of the months, which corresponds well with occupants perceiving the continuous feedback as the predominantly feedback mechanism.

4.3 Over all evaluation of the feedback method

Before the feedback was introduced the average living room temperature was 0.2°C higher in the control apartments. While the average CO_2 concentration was 173ppm higher in the control apartments than intervention apartments, the average relative humidity was the same. Questionnaire 1 found that occupants in the intervention apartments were more focused on a low energy use and high indoor environment quality. A finding that could explain the differences before the feedback was introduced and indicates a low effect of the feedback. However, Questionnaire 2 found an increased focus on the indoor environment in the intervention apartments after feedback introduction, indicating that the feedback had influenced the control of the indoor environment in the intervention apartments.

Schultz et al. [22] described how a boomerang effect could occur as the intervention apartments already performed better than the control group before the feedback introduction. The measurements and the responses in Questionnaire 2 did however confirm that a boomerang effect was not present. Questionnaire 2 also found that the occupants were primarily influenced by the continuous feedback, minimizing the effect of the social comparison. The social comparison in the newsletter compared the occupant to the intervention group. The occupant would thereby be compared to occupants performing in similar ways, which should reduce the risk of a boomerang effect [22].

The questionnaire responses in Table 7 and Table 8 showed a tendency of a self-perceived change in the occupants' energy and indoor environmental behaviour. For example 66% of the intervention apartments *agreed* or *highly agreed* to have become more aware of the indoor environment, while this was only evident for 29% of the control apartments. The differences in the answers supported the findings of the measurements, that the feedback had had an effect in the intervention apartments.

5 Conclusion

Based on the demonstrated differences between the intervention apartments and the control apartments in both measurements and questionnaire responses it was concluded that the feedback procedure had an influence on the control of the indoor environment.

Based on comparisons of measurements in intervention and control apartments before and during the feedback period, it was concluded that the feedback intervention resulted in the following:

- A 0.3 °C lower average temperature in the intervention apartments
- Shorter periods of time with temperatures above 24°C (2 % in the control group and 0% in the intervention group)
- Shorter periods with high relative humidity (None of the measurements were above 60% RH in the intervention group. 9% of measurements above 60% RH in control group compared to)
- An average CO_2 concentration 280ppm lower in the intervention apartments
- A 706ppm lower maximum CO_2 concentration in the intervention apartments
- An increased focus on the general indoor environment in the intervention apartments

It was not possible to determine the individual effects of the continuous and weekly feedback, but the questionnaire responses of the occupants' in the intervention apartments indicate that the continuous feedback was the primary influence.

6 Appendix

6.1 Appendix 1

Ten recommendations were given on the last page of the introduction leaflet. The recommendations were published by The Council For A Healthy Indoor Environment..

1. Vent multiple times every day (5 to 10 minutes each time) – and when there is a need.
2. Adjust and maintain the ventilation systems.
3. Do not dry clothes indoor.
4. Make sure to vent thoroughly after a shower.
5. Maintain a stable and suitable temperature in all rooms.
6. Repair water damaged immediately.
7. Use a few health certified cleaning products.
8. Do not smoke indoor.
9. Have an easy to clean furniture design. Clean frequently.
10. Do a thorough cleaning once a year.

7 Reference

[1] Darby S. Smart metering: what potential for householder engagement? Build Res Inf 2010;38:442–57. doi:10.1080/09613218.2010.492660.

[2] Pekka A, Saco LD, Orchard N, Vorisek T, Rochas C, Morch AZ, et al. Definition of Smart Metering and Applications and Identification of Benefits. Security 2008:1–42.

[3] Faruqui A, Sergici S, Sharif A. The impact of informational feedback on energy consumption-A survey of the experimental evidence. Energy 2010;35:1598–608. doi:10.1016/j.energy.2009.07.042.

[4] Ueno T, Tjuji K, Inada R, Saeki O. Effectiveness of displaying energy consumption data in residential houses Analysis on how the residents respond. ECEEE Summer Study 2005:1289–99.
[5] D'Oca S, Corgnati SP, Buso T. Smart meters and energy savings in Italy: Determining the effectiveness of persuasive communication in dwellings. Energy Res Soc Sci 2014;3:131–42. doi:10.1016/j.erss.2014.07.015.
[6] van Houwelingen JH, van Raaij WF. The Effect of Goal-Setting and Daily Electronic Feedback on In-Home Energy Use. J Consum Res 1989;16:98. doi:10.1086/209197.
[7] Buchanan K, Russo R, Anderson B. Feeding back about eco-feedback: How do consumers use and respond to energy monitors? Energy Policy 2014;73:138–46. doi:10.1016/j.enpol.2014.05.008.
[8] Buchanan K, Russo R, Anderson B. The question of energy reduction: The problem(s) with feedback. Energy Policy 2015;77:89–96. doi:10.1016/j.enpol.2014.12.008.
[9] Buchanan K, Banks N, Preston I, Russo R. The British public's perception of the UK smart metering initiative: Threats and opportunities. Energy Policy 2016;91:87–97. doi:http://dx.doi.org/10.1016/j.enpol.2016.01.003.
[10] van Raaij WF, Verhallen TMM. Patterns of residential energy behavior. J Econ Psychol 1983;4:85–106. doi:10.1016/0167-4870(83)90047-8.
[11] Burak Gunay H, O'Brien W, Beausoleil-Morrison I, Perna A. On the behavioral effects of residential electricity submetering in a heating season. Build Environ 2014;81:396–403. doi:10.1016/j.buildenv.2014.07.020.
[12] Andersen S, Andersen RK, Olesen BW. Influence of heat cost allocation on occupants' control of indoor environment in 56 apartments: studied with measurements, interviews and questionaires. Build Environ 2016;101:1–8. doi:10.1016/j.buildenv.2016.02.024.
[13] Santin OG. Behavioural Patterns and User Profiles related to energy consumption for heating. Energy Build 2011;43:2662–72. doi:10.1016/j.enbuild.2011.06.024.
[14] Guerreiro S, Batel S, Lima ML, Moreira S. Making energy visible: sociopsychological aspects associated with the use of smart meters. Energy Effic 2015;8:1149–67. doi:10.1007/s12053-015-9344-4.
[15] Nilsson A, Bergstad CJ, Thuvander L, Andersson D, Andersson K, Meiling P. Effects of continuous feedback on households' electricity consumption: Potentials and barriers. Appl Energy 2014;122:17–23. doi:10.1016/j.apenergy.2014.01.060.
[16] Krishnamurti T, Davis AL, Wong-Parodi G, Wang J, Canfield C. Creating an in-home display: Experimental evidence and guidelines for design. Appl Energy 2013;108:448–58. doi:10.1016/j.apenergy.2013.03.048.
[17] Abrahamse W, Steg L, Vlek C, Rothengatter T. The effect of tailored information, goal setting, and tailored feedback on household energy use, energy-related behaviors, and behavioral antecedents. J Environ Psychol 2007;27:265–76. doi:10.1016/j.jenvp.2007.08.002.
[18] Fischer C. Influencing Electricity Consumption via Consumer Feedback. A Review of Experience. ECEEE 2007 Summer Study 2007 2007:4–9. doi:10.4236/ojee.2013.21002.
[19] Abrahamse W, Steg L, Vlek C, Rothengatter T. A review of intervention studies aimed at household energy conservation. J Environ Psychol 2005;25:273–91. doi:10.1016/j.jenvp.2005.08.002.
[20] Allcott H. Social norms and energy conservation. J Public Econ 2011;95:1082–95. doi:10.1016/j.jpubeco.2011.03.003.
[21] Burchell K, Rettie R, Patel K. Marketing social norms: Social Marketing and the "social norm approach." J Consum Behav 2008;12:253–66. doi:10.1002/cb.
[22] Schultz PW, Nolan JM, Cialdini RB, Goldstein NJ, Griskevicius V. The constructive, destructive, and reconstructive power of social norms. Psychol Sci 2007;18:429–34. doi:10.1111/j.1467-9280.2007.01917.x.
[23] Cialdini RB, Goldstein NJ. Social influence: compliance and conformity. Annu Rev Psychol 2004;55:591–621. doi:10.1146/annurev.psych.55.090902.142015.
[24] Schweiker M, Shukuya M. Investigation on the effectiveness of various methods of information dissemination aiming at a change of occupant behaviour related to thermal comfort and exergy consumption. Energy Policy 2011;39:395–407. doi:10.1016/j.enpol.2010.10.017.
[25] Geller ES. The Challenge of Increasing Proenvironment Behavior n.d.
[26] Abrahamse W, Steg L, Vlek C, Rothengatter T. A review of intervention studies aimed at household energy conservation. J Environ Psychol 2005;25:273–91.

doi:10.1016/j.jenvp.2005.08.002.
[27] Cholewa T, Siuta-Olcha A. Long term experimental evaluation of the influence of heat cost allocators on energy consumption in a multifamily building. Energy Build 2015;104:122–30. doi:10.1016/j.enbuild.2015.06.083.
[28] Hargreaves T, Nye M, Burgess J. Keeping energy visible? Exploring how householders interact with feedback from smart energy monitors in the longer term. Energy Policy 2013;52:126–34. doi:10.1016/j.enpol.2012.03.027.
[29] Dansk Standard. DS/EN 15251:2007: Input-parametre til indeklimaet ved design og bestemmelse af bygningers energimæssige ydeevne vedrørende indendørs luftkvalitet, termisk miljø, belysning og akustik. 2007:54.
[30] Seligman C, Darley JM, Becker LJ. Behavioral approaches to residential energy conservation. Energy Build 1978;1:325–37. doi:10.1016/0378-7788(78)90012-9.
[31] Fabi V, Andersen RV, Corgnati S, Olesen BW. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. Build Environ 2012;58:188–98. doi:10.1016/j.buildenv.2012.07.009.
[32] Andersen R, Fabi V, Toftum J, Corgnati SP, Olesen BW. Window opening behaviour modelled from measurements in Danish dwellings. Build Environ 2013;69:101–13. doi:10.1016/j.buildenv.2013.07.005.
[33] Calì D, Andersen RK, Müller D, Olesen B. Analysis of occupants' behavior related to the use of windows in German households. Build Environ 2016;103:54–69. doi:10.1016/j.buildenv.2016.03.024.
[34] Haldi F, Robinson D. Interactions with window openings by office occupants. Build Environ 2009;44:2378–95. doi:10.1016/j.buildenv.2009.03.025.
[35] Rijal HB, Tuohy P, Nicol F, Humphreys M a., Samuel a., Clarke J. Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings. J Build Perform Simul 2008;1:17–30. doi:10.1080/19401490701868448.
[36] Fabi V, Andersen RV, Corgnati SP, Venezia F. Main physical environmental drivers of occupant behaviour with regard to space heating energy demand. Heal Build 2012 2012.

24 APPENDIX 6

Interview guide for semi-structured interviews conducted in Study 3. The interviews were conducted in Danish the interview guide was translated from Danish to English in this report.

- Have you received indoor environmental feedback before this experiment?
- In what way to you believe that you can read and understand information regarding your indoor environment?
- Do you miss information on how to obtain/maintain a good indoor environment?
- When is the apartments most likely occupied – and by how many?
- Do any of the occupants have any health issues related to the indoor environment?
- How do you perceive the air temperature in the apartment?
- How do you perceive the air quality in the apartment?
    - Do have a hunch if the indoor environment is good or poor?
    - Do you experience discomfort because of the indoor environment – health related or physical present in the apartment?
    - If the air quality is perceived as poor. Do you do anything to avoid the poor air quality? E.g. do you have a defined venting strategy? Do you vent while cooking, when drying clothes indoor or after a shower?
- Do you find it difficult to obtain a comfortable indoor environment (temperature/air quality)?
    - If yes, do you think it is related to the physical condition of the building?
        - How do you find the state of the radiator thermostat values?
        - How do you find the state of the window opening possibilities?
        - Is it possible to cross ventilate?
        - Does outside noise keep you from venting?
        - Do you perceive the physical conditions of the building as an obstacle for maintaining a good indoor environment?
- Do you perceive that your indoor environment is affected by the indoor environment in the neighboring apartments?

25 APPENDIX 7

The questionnaire was answered during installation of the data collecting equipment.

Question 1
On a scale from 1(highly disagree) to 7 (high agree), do you agree with the following?

1.1 We have a defined strategy for controlling the indoor environment in our apartment?
1.2 We have a defined strategy for controlling the radiator thermostat valves?
1.3 Having a low heating cost is important
1.4 I'll rather increase my clothing level than increase the heating set point.
1.5 It's easy to obtain a comfortable temperature in the apartment
1.6 It is possible to reach temperatures above what I find comfortable
1.7 We have a defined venting strategy(e.g. create cross ventilation)
1.8 Venting happens according to a defined pattern
1.9 The venting method is effective (e.g. the air feels fresh after 5 minutes)
1.10 It's important to have a high indoor air quality
1.11 A window is often kept open for venting throughout the entire day
1.12 Rather have a high indoor environmental quality than a low energy use

Question 2
How often do you change the radiator thermostat value?
Options: Daily – Weekly – Annually – Not at all

Question 3
How often do you open a window to vent?
Options: Daily – Weekly – Annually – Not at all

Question 4
In which time span do you change the radiator thermostat value?
Options: Night (00 – 06)
Early morning (06 – 09)
Late morning (09 – 12)
Early afternoon (12 -15)
Late afternoon (15 – 18)
Early evening (18 – 21)
Late evening (21- 24)

Question 5
In which time span do you vent?
Options: Night (00 – 06)
Early morning (06 – 09)
Late morning (09 – 12)
Early afternoon (12 -15)
Late afternoon (15 – 18)
Early evening (18 – 21)
Late evening (21- 24)

Question 6
In which time span do you cook?

Early morning (06 – 09)
Late morning (09 – 12)
Early afternoon (12 -15)
Late afternoon (15 – 18)
Early evening (18 – 21)
Late evening (21- 24)

Question 7
In which time span is the apartment occupied?
Options: Night (00 – 06)
Early morning (06 – 09)
Late morning (09 – 12)
Early afternoon (12 -15)
Late afternoon (15 – 18)
Early evening (18 – 21)
Late evening (21- 24)

Question 8
When a window is opened for venting, for how long is it normally open?
Options: 0 – 5 minutes
5 - 10 minutes
10 - 20 minutes
20 - 30 minutes
More than 30 minutes

Question 9
Do you find the indoor environment in the apartment good?
Options: yes/no

Question 10
Without looking in your old bills, do you know how much you pay for heating?
Options: yes/no

26 APPENDIX 8

The second questionnaire was distributed in two versions. The first version was distributed to the control group, while the second version was distributed to the intervention group. Both questionnaires were distributed in Danish.

Questionnaire distributed to the control group

The occupants were asked to answer the questions based on the time during the experiment period.

Question 1
On a scale from 1(highly disagree) to 7 (high agree), do you agree with the following?
1.13 We have changed the control of the indoor environment in the living room
1.14 We have changed the control of the indoor environment in the bedroom
1.15 We have changed the venting strategy in the entire apartment
1.16 We have been more active in the window opening in the living room
1.17 We have been more active in the window opening in the bedroom
1.18 We are more aware of the indoor environment
1.19 We are more aware of our heating use

Question 2
Do you believe that the presence of measuring equipment have made you more aware of your control of the heating and venting?
Options: yes/no

Questionnaire distributed to the intervention group

The occupants were asked to answer the questions based on the time during the experiment period.

Question 1
On a scale from 1(highly disagree) to 7 (high agree), do you agree with the following?
1.1 We have changed the control of the indoor environment in the living room
1.2 We have changed the control of the indoor environment in the bedroom
1.3 We have changed the venting strategy in the entire apartment
1.4 We have been more active in the window opening in the living room
1.5 We have been more active in the window opening in the bedroom
1.6 We are more aware of the indoor environment
1.7 We are more aware of our heating use

Question 2
Did you download the Netatmo smartphone app?
Options: yes/no

Question 3
How often did you use the app?
Options: Multiple times a day
Once a day
A couple of times a week
A couple of times a month
Have not used the app

Question 4
When during the experiment did you use the app?
Options: Throughout the entire period
Mostly in the beginning
Mostly after receiving the weekly newsletter

Questions 5
The app was easy to use and understand
Options: yes/no

Question 6
The content of the app was useful
Options: yes/no

Question 7
If there is more than one occupant, was there a primary user of the app
Options: yes/no

If yes, who was the primary user?
Options: A female
A male
Child(ren)

Question 8
I understood the content of the weekly newsletters
Options: yes/no

Question 9
I understood why I received the given feedback
Option: yes/no

Question 10
What had the biggest influence on your control of the indoor environment?
Options: Smartphone app
Weekly newsletters

27 APPENDIX 9

Final Weekly feedback letter used in Study 3 in original size

28 APPENDIX 10

Informational leaflet used in Study 3.

Figure 27
Page 1 – Front page

Figure 28
Page 2 – A general introduction to the study, the aim of the study and how access the continuous feedback

Introduktion

I forbindelse med renoveringen af Korngården gennemføres i efteråret 2015 et forsøg hvor beboerne hjælpes til at opretholde et sundt og komfortabelt indeklima uden at energiforbruget løber løbsk.

Baggrunden for forsøget findes i de mange tiltag og produkter der udvikles til at synliggøre energiforbruget i hjemmet og som skal hjælpe beboerne med at spare på varmen. Med dette forsøg ønsker vi at undersøge om det er muligt at hjælpe beboerne til at opretholde et indeklima hvor der er balance mellem temperaturen, en høj luftkvaliteten, en lav risiko for skimmelsvamp dannelse og til sidst et lavt energiforbrug.

I forsøget gøres dette ved at synliggøre indeklimaet og give råd og vejledning til hvordan et godt indeklima bedst mulig opnås i netop jeres lejlighed.

I forsøget kan du følge indeklimaet på to måder. I det daglige kan du følge indeklimaet via Netatmo app'en på din smartphone eller computer. I starten af hver uge vil du yderligere modtage et nyhedsbrev, der fortæller om hvordan indeklimaet har været i den forgangne uge og hvordan du kan gøre det bedre i næste uge - hvis der altså er behov for det.

Figure 29
Page 3 - Explanation of the content of the leaflet, the feedback and important dates i.e. when the first feedback letter is given and when the intervention will end.

I denne folder kan du læse om hvordan forsøget er planlagt til at forløbe, hvad der skal ske, hvad indeklima er, hvorfor det er så vigtigt og lidt om hvordan du bruger visualiseringen af feedbacken.

Har du spørgsmål om indeklimaforsøget, målerne eller om indeklimaet så er du velkommen til at kontakte Søren Andersen på sran@byg.dtu.dk

Vi vil fra DTU gerne takke for din deltagelse i forsøget.

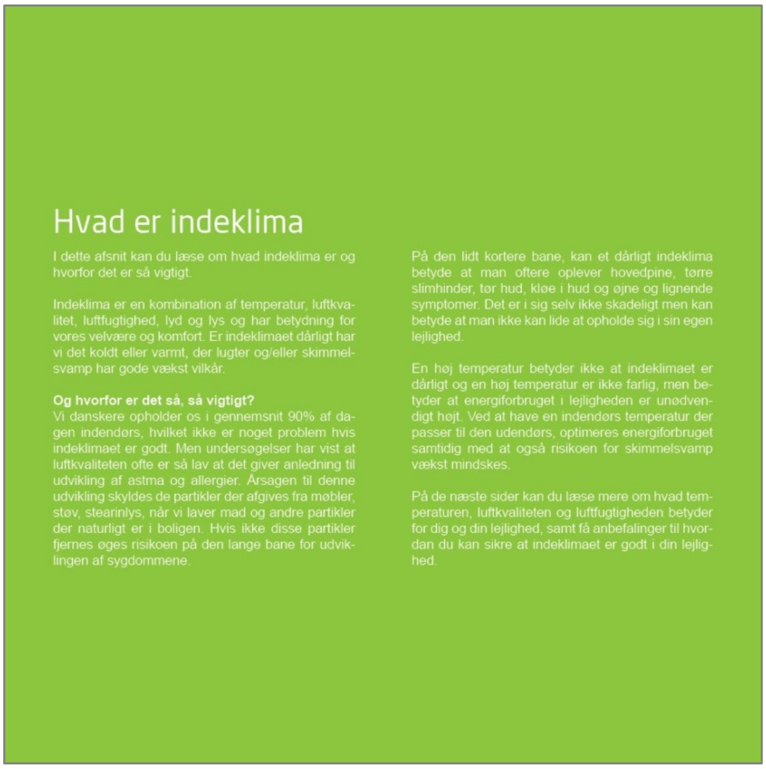
Vigtige datoer

2. november 2015
Den aktive del af forsøget startes, hvor der gives adgang til feedback på app.

9. november 2015
Denne dag vil modtages det første feedback brev.

28. februar 2016
Forsøget afsluttes officielt og målerne indsamles. Hvis muligt vil vi gerne lade målerne stå for at indsamle yderligere data – men mere om det senere.

Foråret 2016
Som en del af Søren Andersens ph.d. præsentation offentliggøres målingerne og resultaterne i anonymiseret form af videnskabelige artikler.



Hvad er indeklima

I dette afsnit kan du læse om hvad indeklima er og hvorfor det er så vigtigt.

Indeklima er en kombination af temperatur, luftkvalitet, luftfugtighed, lyd og lys og har betydning for vores velvære og komfort. Er indeklimaet dårligt har vi det koldt eller varmt, der lugter og/eller skimmelsvamp har gode vækst vilkår.

Og hvorfor er det så, så vigtigt?
Vi danskere opholder os i gennemsnit 90% af dagen indendørs, hvilket ikke er noget problem hvis indeklimaet er godt. Men undersøgelser har vist at luftkvaliteten ofte er så lav at det giver anledning til udvikling af astma og allergier. Årsagen til denne udvikling skyldes de partikler der afgives fra møbler, støv, stearinlys, når vi laver mad og andre partikler der naturligt er i boligen. Hvis ikke disse partikler fjernes øges risikoen på den lange bane for udviklingen af sygdommene.

På den lidt kortere bane, kan et dårligt indeklima betyde at man oftere oplever hovedpine, tørre slimhinder, tør hud, kløe i hud og øjne og lignende symptomer. Det er i sig selv ikke skadeligt men kan betyde at man ikke kan lide at opholde sig i sin egen lejlighed.

En høj temperatur betyder ikke at indeklimaet er dårligt og en høj temperatur er ikke farlig, men betyder at energiforbruget i lejligheden er unødvendigt højt. Ved at have en indendørs temperatur der passer til den udendørs, optimeres energiforbruget samtidig med at også risikoen for skimmelsvamp vækst mindskes.

På de næste sider kan du læse mere om hvad temperaturen, luftkvaliteten og luftfugtigheden betyder for dig og din lejlighed, samt få anbefalinger til hvordan du kan sikre at indeklimaet er godt i din lejlighed.

Figure 30
Page 4 - Definition of the term indoor environment and why it is important

Feedback

I forsøget vil du modtage 2 typer af feedback. Den første type er en app hvor du kan følge indeklimaet time til time og hvordan det er lige nu. Med app'en får du et værktøj der kan fortælle om radiatorerne varmer for meget og skal skrues lidt ned, eller om der er behov for ekstra ventilation for at få en bedre luftkvalitet eller sænke luftfugtigheden.

Den anden type feedback er et ugentlig nyhedsbrev. Nyhedsbrevet sendes engang om ugen er desginet og viser hvordan indeklimaet var i den forgangne uge. I ugebrevet fremhæves en af de målte parametre, fordi denne har været udenfor det anbefalede for ofte og der gives et råd til hvordan du nemmere kan kontrollerede den parameter.

Download Netatmo app'en ved at søge på Netatmo i App Store eller GooglePlay.

Du kan også se målingerne på www.netatmo.dk

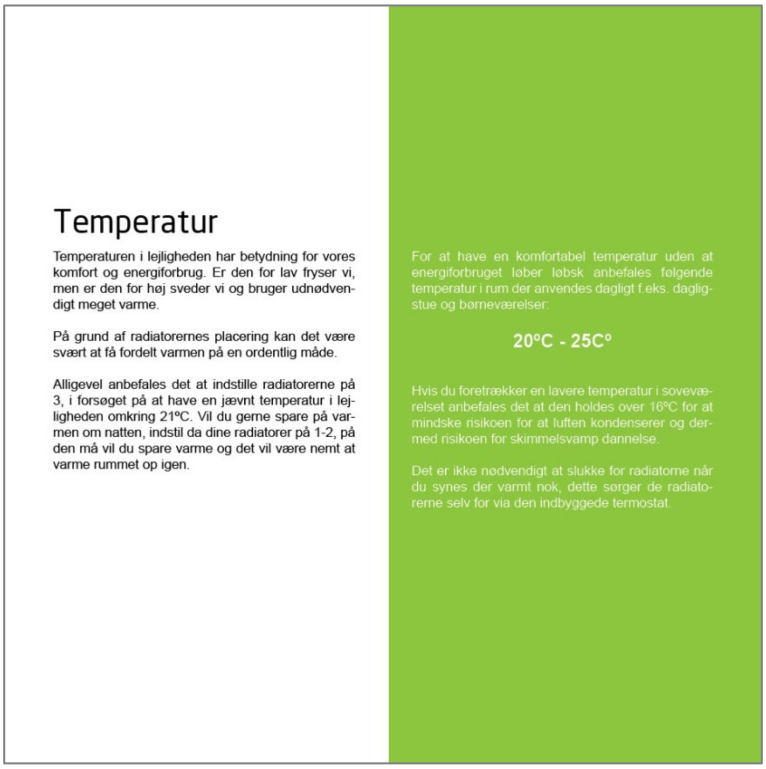
Der er oprettet brugernavn og kodeord til dig, du finder det i velkomstbrevet.

Er brevet blevet væk, kan Søren Andersen kontaktes på 31537145 (gerne sms) han vil da sende et nyt login til dig.

Download Netatmo app til både Android og Iphone

Figure 31
Page 5 – General introduction to the continuous feedback and how to download the smartphone application

Figure 32
Page 6 - Introduction to the temperature, how to assess it and recommended benchmark.



Temperatur

Temperaturen i lejligheden har betydning for vores komfort og energiforbrug. Er den for lav fryser vi, men er den for høj sveder vi og bruger unødvendigt meget varme.

På grund af radiatorernes placering kan det være svært at få fordelt varmen på en ordentlig måde.

Alligevel anbefales det at indstille radiatorerne på 3, i forsøget på at have en jævnt temperatur i lejligheden omkring 21ºC. Vil du gerne spare på varmen om natten, indstil da dine radiatorer på 1-2, på den må vil du spare varme og det vil være nemt at varme rummet op igen.

For at have en komfortabel temperatur uden at energiforbruget løber løbsk anbefales følgende temperatur i rum der anvendes dagligt f.eks. dagligstue og børneværelser:

20ºC - 25Cº

Hvis du foretrækker en lavere temperatur i soveværelset anbefales det at den holdes over 16ºC for at mindske risikoen for at luften kondenserer og dermed risikoen for skimmelsvamp dannelse.

Det er ikke nødvendigt at slukke for radiatorne når du synes der varmt nok, dette sørger de radiatorerne selv for via den indbyggede termostat.

Figure 33
Page 7 – Highlighting the temperature feedback in the smartphone application (a newer user interface has been released since this)

Luftkvalitet

Luftkvalitet vurderes ud fra CO_2 koncentrationen. CO_2 er ikke farligt, men når der er meget CO_2 i luften så er der også mange skadelige stoffer i luften, f.eks. formaldehyd og svampesporer.

De skadelige partikler kommer naturligt ind i lejlighederne, men heldigvis er det nemt at fjerne igen med effektiv udluftning.

Det kan være svært at vurdere luftkvaliteten i et rum, især hvis man sidder i det. Derfor anbefales det at man bruger Netatmo appen og de notifikationer der gives.

Er CO_2 koncentrationen høj (over 1000 ppm) anbefales det at man åbner et vinduer til den igen er omkring 400 ppm. Udekoncentrationen er ca. 400ppm.

Luftkvaliteten vurderes ud fra CO_2 indeholdet i rummet. CO_2 er ikke skadeligt i de koncentrationer der findes i boligen, men når CO_2 koncentrationen er høj, så er antallet af skadelige partikler også højt.

CO_2 måles i enheden parts per million (ppm) og det anbefales at koncentrationen er:

under 1000 ppm

CO_2 koncentrationen stiger i takt med antallet af mennesker i rummet og deres aktivitet. Derfor er der ekstra behov for ventilation når der er mange mennesker i lejligheden og hvis luften føles tung.

Figure 34
Page 8 - Introduction to the indoor air quality, how to assess it and recommended benchmark. It was explicitly explained how CO_2 represents the air quality

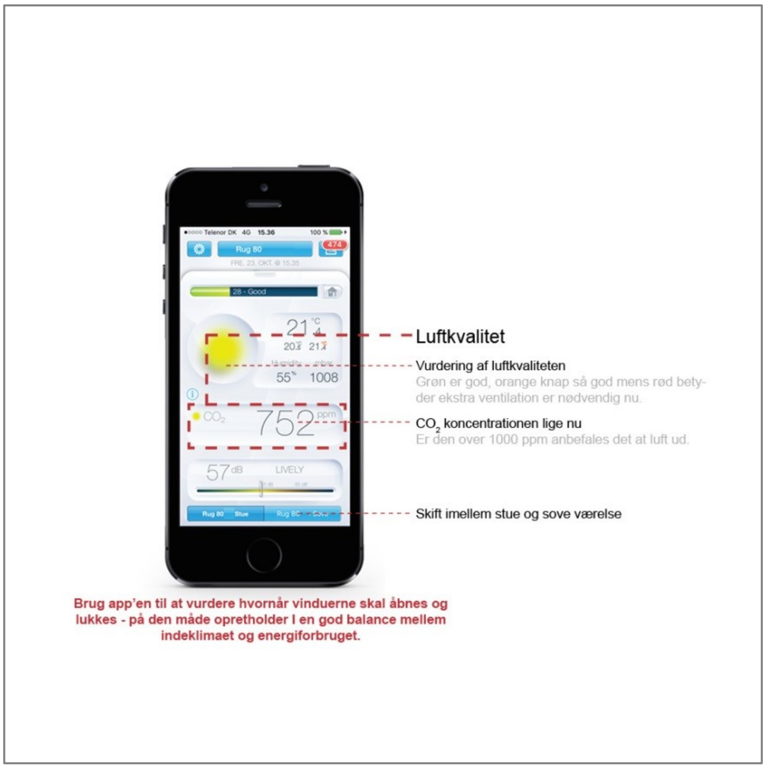
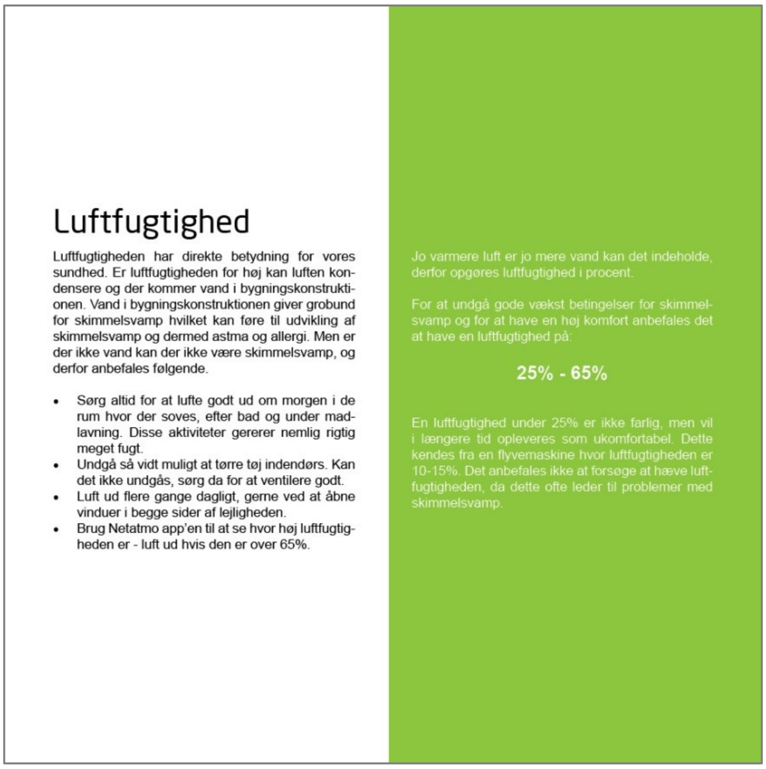


Figure 35
Page 9 – Highlighted the section in the continuous feedback visualizing the indoor air quality represented by the CO_2 concentration.

Figure 36
Page 10 – Introduction to the relative humidity, how it can affect occupants, recommendations to avoid moisture problems and definition of benchmark



Luftfugtighed

Luftfugtigheden har direkte betydning for vores sundhed. Er luftfugtigheden for høj kan luften kondensere og der kommer vand i bygningskonstruktionen. Vand i bygningskonstruktionen giver grobund for skimmelsvamp hvilket kan føre til udvikling af skimmelsvamp og dermed astma og allergi. Men er der ikke vand kan der ikke være skimmelsvamp, og derfor anbefales følgende.

- Sørg altid for at lufte godt ud om morgen i de rum hvor der soves, efter bad og under madlavning. Disse aktiviteter gererer nemlig rigtig meget fugt.
- Undgå så vidt muligt at tørre tøj indendørs. Kan det ikke undgås, sørg da for at ventilere godt.
- Luft ud flere gange dagligt, gerne ved at åbne vinduer i begge sider af lejligheden.
- Brug Netatmo app'en til at se hvor høj luftfugtigheden er - luft ud hvis den er over 65%.

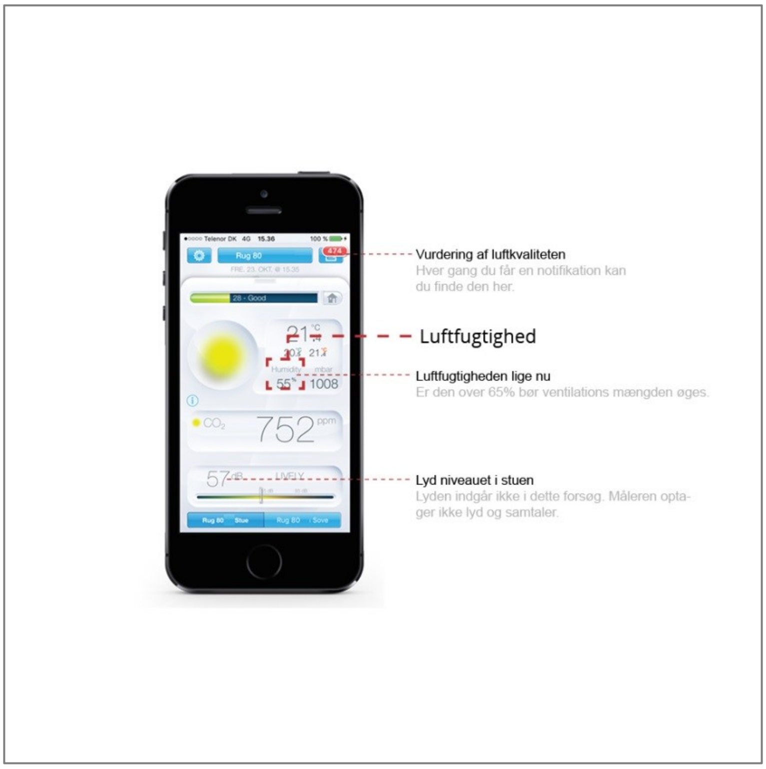
Jo varmere luft er jo mere vand kan det indeholde, derfor opgøres luftfugtighed i procent.

For at undgå gode vækst betingelser for skimmelsvamp og for at have en høj komfort anbefales det at have en luftfugtighed på:

25% - 65%

En luftfugtighed under 25% er ikke farlig, men vil i længere tid opleveres som ukomfortabel. Dette kendes fra en flyvemaskine hvor luftfugtigheden er 10-15%. Det anbefales ikke at forsøge at hæve luftfugtigheden, da dette ofte leder til problemer med skimmelsvamp.

Figure 37
Page 11 - Highlighted the section in the continuous feedback visualizing the relative humidity and the sound level



10 Gode Indeklima Råd

1. Luft ud flere gange dagligt (5 – 10 min. pr. gang) - og når der er særlige behov.
2. Indreguler ventilationen og vedligehold ventilationssystemerne.
3. Tør ikke dit tøj i boligen.
4. Luft grundigt ud efter badet.
5. Hav en jævn og passende temperatur i alle rum.
6. Få udbedret vandskader omgående.
7. Anvend få og sundhedsmærkede rengøringsmidler.
8. Ryg IKKE indendørs.
9. Indret rengøringsvenligt, gør jævnligt rent.
10. Gør hovedrent en gang om året

De gode råd er udgivet af RÅDET FOR ET SUNDT INDEKLIMA

Figure 38
Page 12 – Last page with 10 concrete recommendations on how to maintain a high indoor environmental quality

29 APPENDIX 11

The second most occurring colour-strings calculated in Step 2 as presented in Study 4

Table 15 Step 2: The second most occurring temperature colour string of each apartment from October 2015 through February 2016.

	00:00 - 03:00	03:00 - 06:00	06:00 - 09:00	09:00 - 12:00	12:00 - 15:00	15:00 - 18:00	18:00 - 21:00	21:00 - 24:00	Occurrence [%]
Apartment 1									1%
Apartment 2									0%
Apartment 3									6%
Apartment 4									5%
Apartment 5									4%
Apartment 6									3%
Apartment 7									1%
Apartment 8									3%
Apartment 9									7%
Apartment 10									4%
Apartment 11									28%
Apartment 12									3%
Apartment 13									1%
Apartment 14									1%
Apartment 15									3%
Apartment 16									3%
Apartment 17									4%
Legend		Within		Slightly outside			Outside		

Table 16 Step 2: The second most occurring relative humidity colour string of each apartment from October 2015 through February 2016.

	00:00 - 03:00	03:00 - 06:00	06:00 - 09:00	09:00 - 12:00	12:00 - 15:00	15:00 - 18:00	18:00 - 21:00	21:00 - 24:00	Occurrence [%]
Apartment 1									2%
Apartment 2									0%
Apartment 3									1%
Apartment 4									1%
Apartment 5									1%
Apartment 6									1%
Apartment 7									2%
Apartment 8									2%
Apartment 9									1%
Apartment 10									1%
Apartment 11									1%
Apartment 12									1%
Apartment 13									3%
Apartment 14									1%
Apartment 15									1%
Apartment 16									1%
Apartment 17									4%
Legend	Within		Slightly outside			Outside			

29.1.1 Table 17 Step 2: The second most occurring CO_2 concentration colour string of each apartment from October 2015 through February 2016.

	00:00 - 03:00	03:00 - 06:00	06:00 - 09:00	09:00 - 12:00	12:00 - 15:00	15:00 - 18:00	18:00 - 21:00	21:00 - 24:00	Occurrence [%]
Apartment 1	Outside	Outside	Outside	Outside	Within	Outside	Outside	Outside	5%
Apartment 2	Within	Within	Within	Within	Within	Within	Outside	Outside	1%
Apartment 3	Within	Within	Outside	Within	Within	Outside	Outside	Outside	1%
Apartment 4	Within	Within	Within	Within	Within	Outside	Within	Within	5%
Apartment 5	Within	Within	Within	Within	Within	Within	Within	Within	2%
Apartment 6	Within	Within	Within	Outside	Outside	Within	Outside	Outside	1%
Apartment 7	Outside	Outside	Outside	Outside	Within	Within	Outside	Outside	3%
Apartment 8	Within	Within	Within	Within	Within	Outside	Outside	Outside	18%
Apartment 9	Within	Within	Outside	Outside	Outside	Within	Within	Within	1%
Apartment 10	Within	Within	Within	Within	Within	Within	Within	Within	2%
Apartment 11	Within	Within	Within	Within	Within	Outside	Outside	Outside	8%
Apartment 12	Outside	Outside	Within	Within	Within	Outside	Outside	Within	2%
Apartment 13	Outside	Outside	Outside	Outside	Within	Within	Outside	Outside	5%
Apartment 14	Within	Within	Within	Within	Within	Within	Within	Outside	1%
Apartment 15	Within	Within	Within	Within	Within	Within	Outside	Outside	2%
Apartment 16	Within	Within	Within	Within	Within	Outside	Outside	Outside	3%
Apartment 17	Within	Within	Within	Within	Within	Outside	Outside	Outside	8%
Legend	Within		Slightly outside			Outside			

30 APPENDIX 12

Paper 4

Residential Behavioural Changes through Personal Feedback on Indoor Environmental Measurements

Author: Søren Andersen[a]

Conference: 11th REHVA world congress Cima2013 – Energy efficient, smart and healthy buildings.

Publication status: Published in proceedings and presented at the conference

Resident Behavioural Changes through Personal Feedback on Indoor Environment Measurements

Søren Andersen[#1]
[#]*International Center for Indoor Environment and Energy, Technical University of Denmark*
Nils Koppels Allé, Building 402, DK-2800 KGs. Lyngby, Denmark
[1]sran@byg.dtu.dk

Abstract
The scope of the paper was to investigate opportunities to influence occupant behaviour in seven Danish apartments in order to obtain improved indoor environment and reduced energy consumption. The aim was to investigate intervention methods with continuous feedback and monthly feedback sessions. Recordings of the indoor temperature, relative humidity, CO_2 concentration, window opening frequency and radiator thermostat settings were conducted. One group of participants were only exposed to continuous feedback on CO_2 concentration, temperature and relative humidity, while another group was exposed to both continuous feedback and monthly feedback meeting. At the monthly feedback meetings the occupants were introduced to the recordings and guidance on which changes in the occupant behaviour could improve the indoor environment were given. The recordings were visualised to the occupants as charts showing the time distribution of each parameter (temperature, relative humidity and air quality) within the indoor environment categories of EN 15251, 2007. No clearly defined changes in the user behaviour were observed, but recording of tendencies imply a certain effect of the interventions. The tendencies revealed that both continuous and monthly feedback must be used to obtain an effect. The investigation revealed that intervention methods influenced the user behaviour of the occupants, but the occupants must be motivated to follow the interventions.

Keywords - ***Occupant behaviour; Indoor environment; control intervention; energy consumption***

1. Introduction

In the EU 40 % of the total energy consumption is consumed in buildings, and as reaction to this the EU countries has tighten the allowable CO_2 emission in all new building regulations with high demands to the total energy consumption. As a consequence, demands for increased airtightness have been included in building codes of many EU member states. A positive effect of a high airtightness is low energy consumption. However, on the negative side the indoor environment and the energy consumption is to a greater extent depended on the occupant behaviour, and are thereby more vulnerable towards mistakes and misunderstandings on how to obtain a good indoor environment and low energy consumption.

Studies have shown that indoor air quality in many Danish dwellings does not meet the recommendations for a good indoor air quality [4]. Studies have furthermore shown that a low indoor air quality can led to an increased risk of developing asthma and allergies [5]. Both studies indicate that improvements of the indoor environment in dwellings are necessary. It has been proven that differences in energy consumptions of similar houses can be up to 300 %, and often is caused by the difference in the resident behaviour [2].

With a mechanical ventilation system it ought to be easy to secure a good indoor environment disregarding the effects of occupant behaviour. However, not all new dwellings are equipped with a mechanical ventilation system. Other methods providing the option for a good indoor air quality and low energy consumption is therefore essential as relying on the occupants alone have been proven not to be sufficient.

Studies have shown that occupant behaviour interventions do have an effect on the energy consumption and are achievable [1]. The aim of this paper was to investigate the effect of an intervention method developed to improve the indoor environment and reduce the energy consumption in seven Danish apartments.

2. Method

The intervention method provided the occupants with two types of feedback: continuous feedback and monthly feedback. The continuous feedback visualized the temperature [°C], relative humidity [%] and CO_2 concentration [ppm] in the room in which it was placed. The monthly feedback was given as personal oral presentation and discussion at a personal session in the participants' individual apartments. Recordings of the temperature, relative humidity, CO_2 concentration, window openings and radiator thermostat set point were performed. The monthly feedback was based on the recordings of the previous month.

The apparatus providing continuous feedback was mounted on an acrylic glass plate with additional information on how to achieve a high quality on the indoor environment.

The measurements were conducted in 7 apartments placed in an apartment complex consisting of 7 buildings. The buildings were erected in 1968 and only windows have been renovated since. The apartments were located at different floors. One occupant from the involved apartments was a board member of the residents' association. The board members had all aggraded to participate; however, this did not include all occupants of the involved apartments.

The recordings were separated in 3 phases. The first phase was from December 16th 2011 through January 9th 2012. The measuring equipment was installed to record the temperature, relative humidity and CO_2 concentration in the living room and bedroom in each apartment. Questionnaire 1 was distributed in the first phase. The second phase from January 10th 2012 through February 2nd 2012 was launched with a meeting where information on the importance of the indoor environment and how to obtain a good indoor environment was distributed in writing; additional information was given as an oral presentation. Personal feedback sessions were performed in the third phase, February 3th 2012 through March 6th 2012.

Questionnaires were distributed prior to and after the recordings and surveyed the perceived indoor environmental quality and revealed if any occupants suffered from symptoms that could imply illnesses caused by the indoor environment. The questionnaire further surveyed the occupants' knowledge on general indoor environment related terms. The second questionnaire would additional surveyed the occupants' experience with the intervention method.

The measurements were conducted in all apartments. The recorded parameters are presented in Table 1. Time of window opening and window closing was recorded when the action happed in living room, bedroom, kitchen and terrace door (opens from living room). In some apartments the radiator thermostat setting was recorded in the kitchen instead of the bedroom, as the radiator was not used in the bedroom.

The apparatus providing the continuous feedback displayed the present indoor temperature, relative humidity and CO_2 concentration at the given position. Additional, 3 LED lights indicated the level of measured CO_2 concentration with the following levels; Green - Normal (< 800 ppm), Yellow - High (1200 ppm), Red – Very high (> 1200 ppm). An alarm was given at CO_2 concentrations above 1600 ppm, the alarm was given every 10 seconds with concentrations above 1600 ppm (the alarm could be muted if desired). The apparatus was mounted on an acrylic glass plate (length X high: 500 mm x 150 mm). Information on the acrylic glass plate is presented in Table 2.

The continuous feedback apparatus' were distributed at a joint meeting with all participants. The aim of the apparatus and how the occupants should react on the feedback was explained at the meeting.

All participants were given a poster with general information on the indoor environment and how to act on the displayed values on the apparatus. The occupants were encouraged to place the poster on a visible place in the apartment.

Table 1, Description of measured and recorded indoor environment parameters

Recorded parameter	Properties
CO_2 concentration	Recording range: 0 … 5000 ppm
Temperature	Temperature [°C]
Relative humidity	Relative humidity [%]
Window opening	AC-current was given when regulation of the window was made. Only opening or closing of the window could be done, not degree of opening.
Thermostat setting	Thermostat gave a certain current at a certain thermostat setting, which was recorded.

Monthly feedback was given as private session held in the occupants apartments. The feedback was conducted as a talk between the occupant and the author. The measurements were displayed and explained, and guidance on what had been done right and wrong was given. It was only one occupant from each apartment who participated in the feedback sessions. The occupants were given a short report with the graphs showing the recordings and recommendations at the end of the session.

The recordings were analysed by separating the measured value into the indoor climate category I through IV according to EN 15251, 2007 [7]. The recordings were hereafter assessed and compared with each other to create a general assessment of the indoor environment of the apartments. Based on the general analysis detailed analysis were performed, when assessed to be rewarding. The detailed analysis should reveal tendencies in the user behaviour.

3. Results

Analysing the results did not reveal any general changes in the occupant behaviour, but tendencies have been registered.

3.1. Temperature

Assessing the temperature recordings of the living room imply that the preferred heating set point is between 18 °C and 21 °C corresponding to Indoor category II and III according to EN 15251, 2007 [7].

Table 2, Information and guidance displayed alongside measurements of indoor CO2 concentration, relative humidity and temperature.

Heading	Given information
Air quality	- The CO_2 concentration is an indicator of how well the air quality is. Green: CO_2 concentration is good Yellow: CO_2 concentration is high. Vent for 5 – 10 minutes Red: CO_2 concentration is very high: Vent until the yellow light appears or for 10 - minutes.
Moisture	- At a relative air humidity of 75 % the risk of mould and fungus formation is high. - Avoid drying of newly washed clothes and always vent after a shower.
Temperature	- The indoor temperature should be adjusted corresponding to the outdoor temperature. - If the indoor temperature is below 20 °C, you should increase the heating in order to avoid the risk of mould formation. - If the indoor temperature is above 23 °C you should reduce the heating in order to reduce the heating bill. Adjust the clothing level corresponding to the outdoor temperature
Comfort	- Adjust the indoor climate to a level you find comfortable. - Do not expose yourself to large temperature fluctuation, draughts or other indoor climate relations you find uncomfortable.

In two apartments the heating set point was above 21 °C. This heating set point affected the indoor air quality because an interior temperature above 21 °C was not possible if the indoor air quality should be as the recommendations stated. In one apartment the insulation level of the floor determined the temperature and thermal sensation. The apartment was situated above the basement, which had led to a low surface temperature of the apartment's floor. In the apartment the low surface temperature was compensated by increased heating consumption, but the surface temperature of the floor was still perceived as cold by the occupants.

All occupants stated that heating in the bedroom was not in use. Recordings of the bedroom temperature supports the statements as the measurements primarily were below 18 °C. The recordings further show that the temperature not will exceed 20 °C when the room is occupied.

3.2. Air quality

The majority of the CO2 concentration recordings were below 1000 ppm. Assessment of the presence of occupants indicates that even though the apartments were occupied, the infiltration rate was still high enough to maintain a CO_2 concentration below 1000 ppm. High peak values were reached when a room have been occupied for a longer time period. High peak values were especially seen in apartment 5, 6 and 7.

In apartment 6 recordings as displayed in Figure 1 were made. The recordings suggest that the ventilation was increased corresponding to where the CO_2 concentration and temperature drops.

In apartment 1 through 6 the bedroom door was kept closed during the night, which in all cases resulted in CO_2 concentrations above 1200 ppm almost every night. In some cases CO_2 concentrations above the limit of the measurement equipment of 5000 ppm were reached. In apartment 7 the bedroom door was kept open during the night and even though concentrations above 1200 ppm were recorded, the concentration did not reach the same level as in apartments, which kept the bedroom closed at night.

None of the occupants reported in the questionnaire that information on chemical pollutants have had any direct effect on the motivation to follow the given recommendation.

3.3. Humidity

The relative humidity did not exceed 75 % in any of the investigated rooms. Recordings of the relative humidity below 35 % primarily occurred on days with low outdoor temperatures.

In one apartment the relative humidity was recorded in an additional room (not bedroom or living room), where newly washed clothes were set to dry. In this room, the relative humidity exceeded 75 %.

3.4. Heating set point

Assessing the thermostat regulation imply that the thermostats were used as an on/off function and not a thermostat. Further, when used the thermostat was at a maximum performance. Regulation of the thermostat was performed when a change in the occupancy of the room happened.

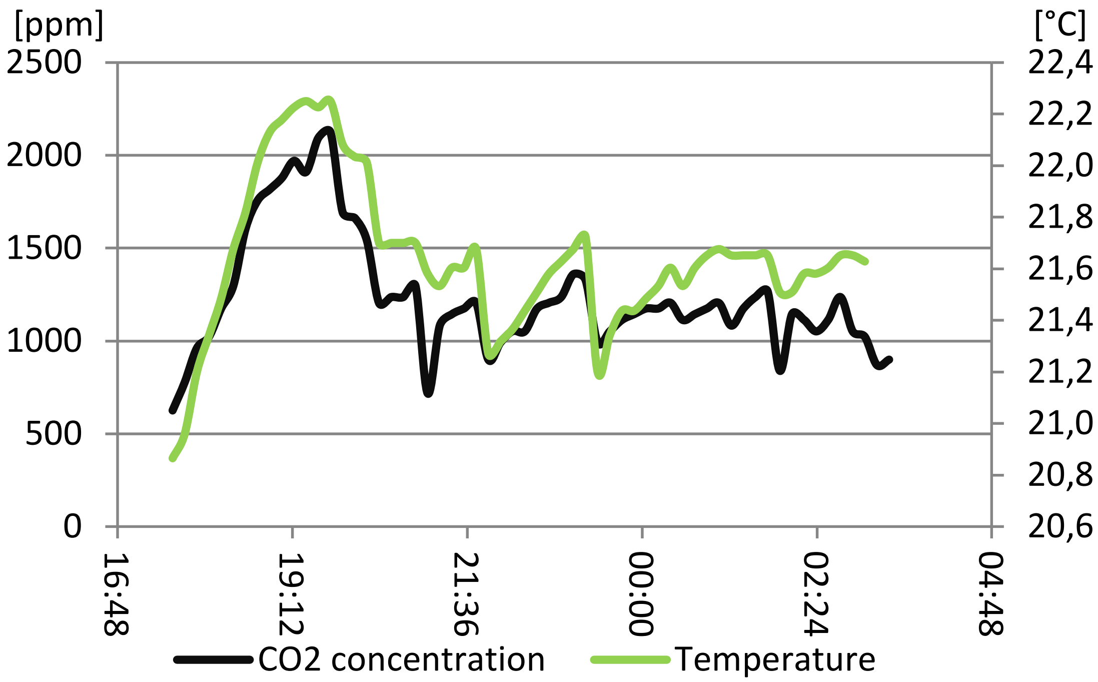


Figure 1, CO_2 [ppm] and temperature [°C] recordings from the living room in apartment 6 on the evening of the 11th February 2011 in phase 3

4. Discussion

The aim of this paper was to investigate the performance of two intervention methods, continuous feedback and monthly feedback. The development of the intervention methods had been inspired by a review of intervention methods performed by Abrahamsen [1]. The reviewed intervention methods investigated the efficiency of intervention methods aimed at reducing energy consumption in primarily North American dwellings. The primarily aim of the investigated intervention method of this paper has been to improve the indoor environment according to the standards of EN 15251, 2007. The review by Abrahamsen [1] revealed higher efficiencies of the intervention methods than what was achieved in this paper. The difference could be caused by the difference of the occupants' estimation of how important a good indoor environment is.

Changes in the occupant behaviour in the two apartments who only received continuous feedback were not observed. The reason for the missing improvements is believed to be two different causes. In one apartment one occupant gave a comment on the LED indicators, which could imply that the meaning of the visualizer had been misunderstood. In the second apartment one occupant stated that if window opening should be more frequently (or happen at all) it would reduce the indoor temperature, which was preferred above 21 °C, and this was not desirable for the occupant. This implies that the importance of a good indoor air quality either was not understood or neglected. The statement further implies that an unnecessary increase of the energy consumption was not a subject of concern.

In the apartments, which received continuous feedback and monthly feedback direct change in the user behaviour regarding habits detected in phase 1 could not be surveyed. However, tendencies in apartment 6 imply an effect of the feedback. Detailed analysis, as displayed in Figure 1, of recordings from the living room reveals sudden drops in the CO_2 concentration. It has not been possible to determine if it was an effect of the visualisation of the air quality or just enhanced occupant awareness regarding the air quality, but in either way is it a result of user influence and not due to natural infiltration and is therefore considered as a result of the intervention.

Figure 1 show a delay in the temperature drop during ventilation as a result of the thermal mass of the building. Figure 1 further show that the temperature not will drop significantly as long as the venting periods not are longer as recommended.

Two apartments only received continuous feedback; here no registration of changes in the occupant behaviour was documented. In the tree apartments which received both continuous feedback and monthly feedback the following changes and tendencies were registered. In the second questionnaire the occupant in apartment 1 stated that the awareness of chemical pollutants was increase. Changes in the occupant behaviour were, however, not attempted. In apartment 6 long venting periods were stopped as a direct result of the feedback meeting, and venting due to high CO_2 concentration were recorded. These tendencies suggest that changes in the occupant behaviour cannot be achieved with only continuous feedback. Changes can potentially be achieved using both continuous feedback and monthly feedback.

It was assumed that the information given at the information meeting would have been sufficient to motivate the occupants to follow the recommendations. Additional it was assumed that the given recommendations were easy to read and understand and therefore would be read and used. However, based on the results of the intervention it is assessed that the motivation generated from the information meeting was not sufficient to change the attitude of the majority of occupants.

Even though only limited improvements of the indoor environment caused by user behaviour changes were achieved, it does not seem acceptable to assume that effect of the intervention methods not are achieved, because only seven apartments (here of 2 control apartments) participated. In the same statement it could be argued that control apartments are not necessary with the small number of participants. Further, it was expected that all occupants of the apartments would have participated, but it turned out only to be the board members who participated. In apartment 6 the only resident was the board member. Apartment 6 was also the only apartment with the greatest success rate regarding changes in the user behaviour. Comparing the recordings from apartment 6 with all other apartments suggest that the more occupants that participate and follow the recommendations and guidelines, and thereby attempt to change the user behaviour, the more likely is the changes to happen.

The CO_2 concentration was for a majority of the recorded time below 1000 ppm. Comparing the window opening frequency revealed that the low CO_2 concentration might be a result of a high infiltration flow and not a ventilation pattern determined by the occupants. This assessment was further supported by the indoor air temperature, which quickly dropped when the thermostat setting was off. Even though the infiltration rate was high, peak values above the recommended still was recorded, and intervention in the user behaviour to improve the indoor environment still was necessary.

In the questionnaire the occupants were asked to assess the quality of the indoor environment, here 5 assessed it to be *Good,* while 2 replied either *Neutral* or *Bad*. Comparing the answers with the limited user behaviour changes would raise the question if intervention should be done in apartments were the occupants are satisfied with the indoor environment? However, recordings of the indoor environment revealed very high CO_2 concentration and thereby implied that improvements of the indoor environment were not only achievable, but also necessary. Assessment of the recordings suggests that a better motivation for the occupants is necessary if improvements of the indoor environment are necessary and if it should be obtained through changes in the occupant behaviour.

At the information meeting the issue of drying newly washed clothes indoor was raised. The occupants were encouraged to dry the clothes somewhere else, or to increase the ventilation if it could not be avoided. In apartment 5 newly washed clothes were set to dry in an additional room, here recordings of the relative humidity above 75 % were registered. The recommendation about avoiding it or increasing ventilation had been neglected. The reason for neglecting the recommendation may have been a combination of missing drying opportunities and that the occupants didn't find it necessary to follow the recommendations. Neglecting recommendations that contradict the occupants' persuasions have been registered by Andersen [3] and are believed to be the reason for not following the recommendations.

5. Conclusion

Continuous feedback in combination with monthly feedback was most effective in achieving changes in the occupant behaviour.

The cost of achieving the recommended indoor environment was assessed to be too high for the occupants to accept.

Achieving a high efficiency of the intervention method can only be done if all occupants of the dwelling participate and if the occupants are well motivated to obtain the indoor environment.

6. References

[1] Abrahamse, W., Steg, L., Vlek, C. and Rothengatter, T., 2005. A review of intervention studies aimed at household energy conservation. *Journal of Environmental Psychology,* **25**(3), pp. 273-291.

[2] Andersen, R.V. 2009, Occupant Behaviour with regard to Control of the Indoor Environment.

[3] Andersen, R.V., Toftum, J., Andersen, K.K. And Olesen, B.W., 2009. Survey of occupant behaviour and control of indoor environment in Danish dwellings. *Energy and Buildings,* **41**(1), pp. 11-16.

[4] Beko, G., Lund, T., Nors, F., Toftum, J. And Clausen, G., 2010. Ventilation rates in the bedrooms of 500 Danish children. *Building and Environment,* **45**(10), pp. 2289-2295.

[5] Bornehag, C., Sundell, J., Hagerhed-Engman, L. And Sigsgaard, T., 2005. Association between ventilation rates in 390 Swedish homes and allergic symptoms in children. *Indoor air,* **15**(4), pp. 275-280.

[6] Callesen, M., Beko, G., Weschler, C., Sigsgaard, T., Jensen, T., Clausen, G., Toftum, J., Norberg, L. And Hoest, A., 2012. Associations between multiple indoor environmental factors and clinically confirmed allergic disease in early childhood. *Allergy,* **67**, pp. 630-630.

[7] European Standard (2007). EN 15215, 2007 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, 1. edition.

31 APPENDIX 13

Paper 5
Indoor Environmental Patterns in Nine California Energy Retrofitted Residences

Authors: Søren Andersen, Brennan Less, Iain Walker
Conference: 6th International Building Physics Conference, IBPC201
Publication status: Published in proceedings and presented at the conference

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2015) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

6th International Building Physics Conference, IBPC 2015

Indoor Environmental Patterns In Nine California Energy Retrofitted Residences

Søren Andersen[a]*, Brennan Less[b], Iain Walker[b]

*[a]Technical Univercity of Denmark, Nils Kopels Alle 402, Kgs. Lyngby 2800, Denmark
Lawrence Berkeley National Laboratory, 1 Cyclotron Road,Berkeley, 94720, United States of America

Abstract

As part of a study of energy retrofits in nine California buildings indoor measurements of temperature and relative humidity were made between 2010 and 2012. The aim of this paper was to compare the temperature and relative humidity measurements in relation to recommendations for a healthy, comfortable and low energy consuming indoor environment. Energy conserving behavior during the heating season was detected in all buildings. The paper further aimed to find patterns in the measurement to determine if an energy retrofit affects the occupants' behavior and indoor environmental regulation strategies. No general pattern could be defined.

Keywords: Occupant behavior; Indoor environmentall patterns

1. Introduction

Studies have showed that changing peoples' behavior and routines requires an intervention, as people not will change unless they are motivated to do so [1]. An intervention can be anything from an information pamphlet in the mail box, a comparison to the neighbors on the energy bill, replacement of an inefficient pump or a comprehensive energy retrofit. Studies have showed how small interventions can affect the energy consumption, but have not shown how they affect the indoor environment ([2], [3]). Andersen et al. showed a clear difference in average temperature and CO_2 concentration profiles between two buildings with two different heat cost allocation payment methods [4].

This paper studied nine California buildings that all had gone through a comprehensive energy retrofit. The nine buildings were all different in floor planning, sustainability strategies, occupancy, orientation, insulation level, age of occupants, etc. For all the buildings the owners had a vision of a low energy consuming home. The buildings were not built to comply with any certification meaning no goals for the indoor environment were set.

The aim of this paper was to survey the indoor environmental conditions (temperature and relative humidity) in comparison to the recommended design values of ASHREA Standard 55-2010 *Thermal Environmental Conditions for Human Occupancy* [5] and European Standard EN 15251(2007) [6] in order to investigate if the indoor environment was deprioritized in the attempt to reduce the total energy consumption as much as possible. The paper further aimed to investigate the effects of a comprehensive energy retrofit on the indoor environment.

Mapping occupants' behavior have been done with interviews and questionnaires ([7], [8]), by long term detailed measurements or a combination ([9], [10]). These experiments can be both costly and complex if the occupant disturbance is to be kept at a minimum, which is desired to secure that the experiment and occupants don't start on the wrong foot and become a source of irritation for the occupant and thereby increase the risk that the occupants may disrupt the experiment [11]. The cost of conducting measurement driven behavior experiments often lead to low quantity of measured data and thereby reduce the opportunity to statistically demonstrate any behavior changes. In this paper, a procedure aimed to analyze continuous measurements for performance and patterns from a low quantity of measured data was presented. The analysis procedure provides the user with an easy, fast and intuitive method of visualizing patterns in measured indoor air conditions.

2. Method

The measurements were performed from 2010 through 2012 with varying length in each residence. The temperature and relative humidity were measured every 5th minutes in two positions, primarily the living room and a bedroom. The measuring positions were placed on both 1st and 2nd floor, when present. The nine surveyed buildings were all located in the San Francisco region in northern California, USA. Due to the differences in the landscape of the region, the buildings were found in different microclimate zones and the outdoor weather was therefore not comparable for the nine locations. Common for the buildings were the owners' visions of building a low energy-consuming house. The nine buildings were not built to comply with any specific certification; however, most were designed with the Passive House or similar certifications in mind. For further details on the buildings and the measurements collection see [8].

2.1. Benchmarks for comparison

The thermal environment of the nine buildings were conditioned by either a water based system or ventilation system, both controlled by the occupant. Determining the performance of the thermal environment was therefore done utilizing design values of ASHRAE Standard 55-2015 Figure 5.3: *Acceptable operative temperatures ranges for naturally conditioned spaces*. Andersen et al. [12] defined the outdoor weather as the primary driver for closing an open window, indicating that the benchmark should be defined by the adaptive method. However, outdoor weather profiles were not accessible for all locations and a static interval has therefore been used instead. To allow for a dynamic regulation of the thermal environment the temperature benchmark has been defined as 20-26°C.

The relative humidity benchmark was defined as 25-60% based on recommendations of EN 15251 (2007) Table B.6. Using recommendations of the European Standard was assessed as acceptable, as the relative humidity benchmarks were set to assess the comfort level (due to a low relative humidity) or the risk of mold development (due to a high relative humidity).

2.2. Analysis method and pattern location

To analyze the measurements for patterns, a procedure based on benchmarks was developed. The basic of the procedure was to define a time period and an acceptable range for each measured parameter, and then calculate how much time the parameter was within and outside of the acceptable range. If the measurements primarily were within the acceptable range the period received the Within (W) rating, if the measurements primarily were below the Below (B) ranking is assigned, and if the measurements primarily were above the ranking was Above (A). Acute periods of high/low temperatures or high relative humidity levels could be just as crucial for the energy consumption or health of the buildings. To take this into account, a 5% limit was introduced. The 5% limit means that if the measurements were below or above the recommended interval for more than 5% of the period the B or A ranking were assigned to the period – if the measurements were both below and above 5%, the highest would be chosen.

To locate patterns in surveyed buildings the analysis procedure has been used for each measuring positions. For these buildings the procedure was used to find patterns for each day. Each day was divided into seven periods: night (00:00-06:00), early morning (06:00-09:00), late morning (09:00-12:00), early afternoon (12:00-15:00), late afternoon (15:00-18:00), early evening (18:00-21:00), and late evening (21:00-23). The separation was chosen as each period represents a significant event, e.g. the occupants will get out of bed in the early morning, while dinner most likely will be prepared in the early evening.

The procedure was performed on a yearly basis and for the heating and cooling season. The output of the analysis was daily code (e.g. WWAWAWB) referred to as a Color String.

3. Results and discussion

The annual average indoor temperature was 20.9°C with standard deviation 2,3°C, while the annual average relative humidity value was 54.2% for all measurements with a standard deviation of 8.9 percentage points. The average values for both the temperature and the relative humidity were within the recommended range, but in the lower and upper end, respectively. The standard deviation of both parameters showed that for temperature, measurements were found both above and below the recommendations. For the relative humidity the standard deviation showed that measurements significantly exceeded the recommended range.

The average temperature in the lower part of the range could be an indication of a low energy consuming behavior. This was supported by the lower average temperature for the heating season of 20.2°C (standard deviation of 2.2°C), showing that the heating set points indirectly were affected by the outdoor temperature. The average temperature for the cooling season was 19.7°C (standard deviation of 2.0°C). Only one of the surveyed buildings used active cooling indicating that the average temperature below the recommended range was a result of low outdoor temperatures and that the temperatures were floating with the outdoor temperature. The difference between the seasons could be seen as an expression of the occupants' ability to adapt to lower outdoor temperature in the heating season, but choosing a higher level of comfort during the cooling season.

3.1. Daily profiles

Daily profiles based on the average values of each hour of the day were made for the year, heating season and cooling season (see Figure 1 and Figure 2). The figures included the standard deviation as indication of general tendencies in the profiles, assuming a low standard deviation indicates that the average value were representative for all the measuring positions, while a high standard deviation show a wide spread of the measurements and thereby no a general tendency.

Figure 1 showed the three average temperature profiles included standard deviation profiles. All three profiles showed a pattern with a low point in the morning and a high peak in the late afternoon/early evening (15:00 – 21:00). The temperature profiles decreased from approximately 21:00 to 6:00-8:00 in the morning, a tendency that could indicate a heating point night setback, a dynamic thermostat regulation, or that the temperature were floating with the outdoor temperature – all three indicating an energy conserving behaviour. The standard deviation of the temperature profiles were between 1.8°C and 2.4°C for all three profiles, revealing that the hourly average values were found in both the upper and lower part of the recommended interval. Figure 1 showed a difference between the heating and cooling season, with a daily average profile of the cooling season notably higher than the heating season profile. The measured variations between time of day and between seasons were seen as a proof of an energy conserving behaviour.

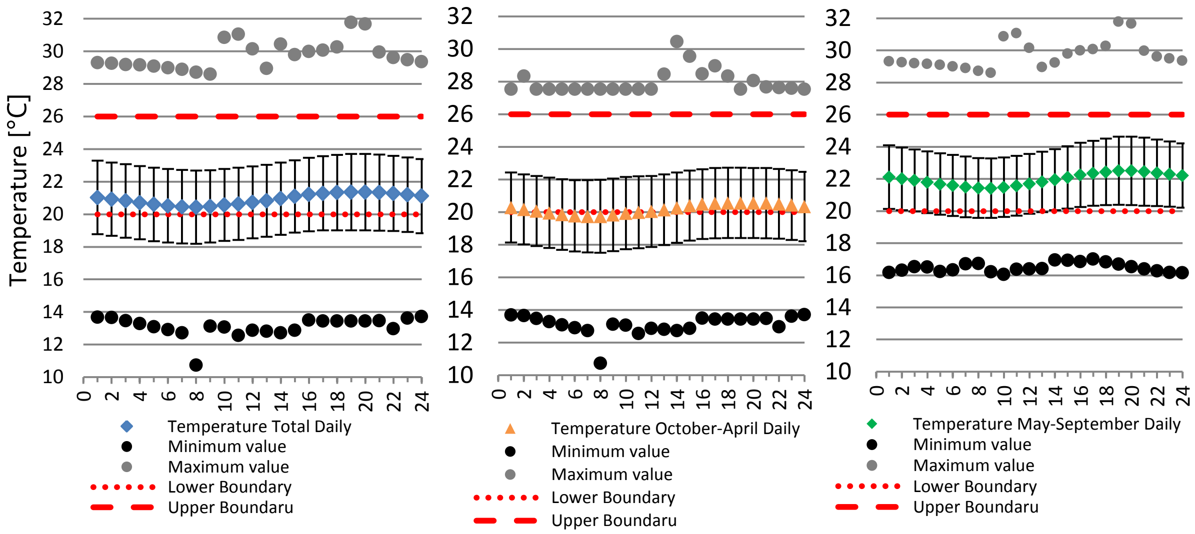


Figure 1 Daily average temperature profiles for a) year, b) heating season and c) cooling season, including standard deviation and the recommended boundaries. X-axis represents the hour of the day.

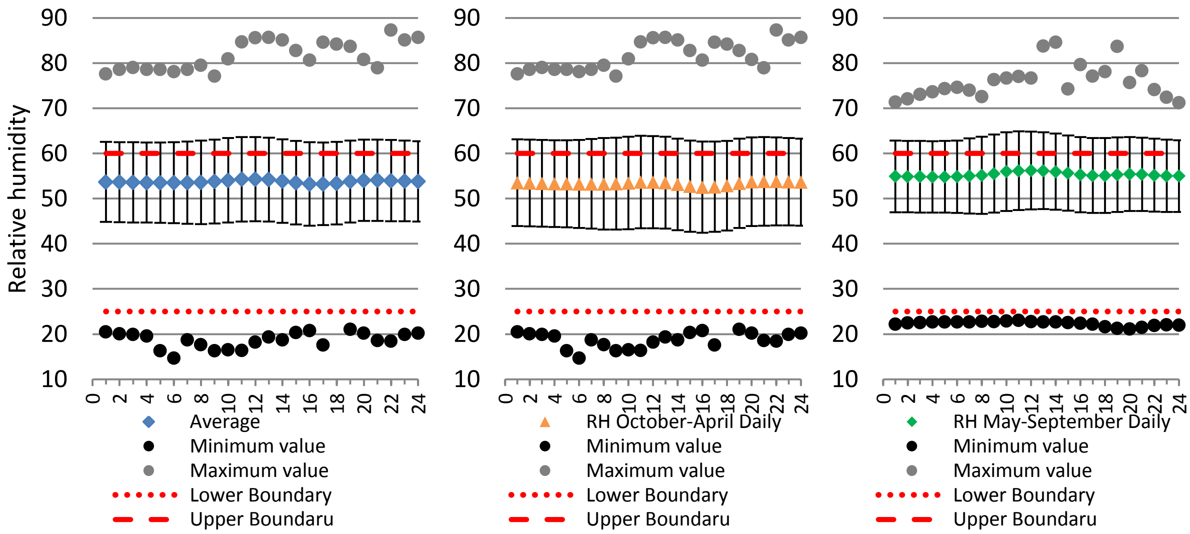


Figure 2 Daily average relative humidity profiles for a) year, b) heating season and c) cooling season, including standard deviation and the recommended boundaries. X-axis represents the hour of the day.

Figure 2 showed the daily relative humidity average and standard deviation profiles for the year, heating season and cooling season. The profiles showed a peak between 12:00 and 15:00, with a decrease in the afternoon. The profiles further showed an increase between 18:00 and 21:00 similar to the peaks in the temperature profiles. The profiles fluctuated between 52% and 57% relative humidity and thereby just within the recommended range. The standard deviation profiles showed a bigger variation from approximately 7:00 to 23:00 than during the night. These variations were assessed as an indication of a non-uniform control of the relative humidity and therefor an indirect energy conserving behaviour as energy for excessive ventilation, air conditioning, dehumidification etc. was not necessary.

General patterns of the daily profiles were not defined for neither the temperature profiles nor relative humidity profiles as the standard deviations of both were assessed as too high for a definition. However, the assumed non-uniform temperature and relative humidity control indicated an energy conserving behaviour.

3.2. Color String analysis

The most and second most occurring color string for the temperature and relative humidity were determined for each measuring position in the nine houses (18 positions in total). The most and second most occurring color strings were presented in Table 1 for the year, heating season and cooling season for the temperature and the relative humidity. Table 1 showed that the temperatures in 67% of the measuring positions were below the recommend levels for the entire day. Whether the occupants perceived the temperature as uncomfortable or whether it was an intentional regulation strategy was unknown. However, Andersen [13] revealed through interviews; that if Danish occupants were motivated to conserve energy by a monetary reward, occupants will accept an uncomfortable indoor environment (uncomfortable defined by EN 15251:2007). As similar reward situations were present in the nine buildings, the results could indicate that the regulation strategies in the buildings were be intentional, in an attempt to conserve energy for heating. For the year, heating season and cooling season the most occurring relative humidity color string showed that the measurements were within the recommendations. However, the analysis showed that on a yearly basis the second most occurring color string (33% of the measuring positions) the relative humidity exceeded the recommended range throughout the entire day.

Gunay et al. [9] stated that occupants in sub-metered apartments controlled the indoor environment separately room by room. Detailed assessments of each measuring position in this study showed similar color strings for the positions within each house, contradicting the findings of [9]. The lack of differences between measuring positions were most like due to size of the used benchmark intervals, and ruling out dynamic regulations based on the color string analysis should not be done.

Table 1 the most and 2nd most occurring color strings of the temperature and relative humidity based on the year, heating season and cooling season (B – below recommendation, W – within recommendation, E- Exceeding recommendation).

	Most Occurring Percentage of occurrences %	Night	Early morning	Late morning	Early afternoon	Late afternoon	Early evening	Late evening	**2nd most Occurring** Percentage of occurrences %	Night	Early morning	Late morning	Early afternoon	Late afternoon	Early evening	Late evening
Temperature																
Yearly	56	B	B	B	B	B	B	B	44	W	W	W	W	W	W	W
Heating Season	67	B	B	B	B	B	B	B	50	W	W	W	W	W	W	W
Cooling Season	50	W	W	W	W	W	W	W	28	W	W	W	W	W	W	W
Relative Humidity																
Yearly	72	W	W	W	W	W	W	W	33	A	A	A	A	A	A	A
Heating Season	72	W	W	W	W	W	W	W	33	A	A	A	A	A	A	A
Cooling Season	56	W	W	W	W	W	W	W	22	A	A	A	A	A	A	A

3.3. Delimitation of the color string analysis procedure

In the color string procedure, each day was separated into seven parts each designed to represent a daily routine. A more detailed separation by separating into hours of the day was considered. However, a preliminary test of the detailed separation gave the same most occurring color string as found in Table 1, but with a 2nd most occurring color string that only would represent a very low percentage 1% of the color strings. The results only show the most common occurring color string and not those that may arise from alternate behaviors. A less detailed separation level was considered by combining the early and late morning to morning. That separation model was rejected, as it possibly would combine routines such as breakfast and lunch, and thereby rules out the opportunity to investigate the effects that other behaviors such as cooking or going to bed had on the indoor environment.

In section *3.1 Daily profiles* and in Figure 1 variation throughout the day was seen and it was concluded that a dynamic or no regulation, in case of a floating strategy, of the temperature and relative humidity was used in the buildings. Neither the results presented in Table 1 nor the detailed assessment was able to highlight the variations.

To determine if the occupants' regulation of the indoor environment were energy conserving within the recommended interval a more detailed separation would have been necessary, additionally a more detailed rating procedure would have been more informative. However, as with the definition of the time periods, the preliminary tests showed that a more detailed interval mesh only would show the most occurring color string. The color string analysis procedure proved useful for the preliminary assessment of the indoor environment and would therefore be recommended for use in the early stages measurement assessments.

4. Conclusion

The continuous measurements were on average within the recommended intervals and signs of energy conserving behavior were detected in the heating season. A low average indoor temperature were detected during cooling season, indicating none energy conserving behavior and indoor environmental regulation.

The measurements were surveyed for indoor environmental patterns. A daily profile illustrated that the temperature followed the expected occupant activities. Due to a high standard deviation of the measurements general patterns for neither the temperature nor relative humidity were not defined.

An analysis method for surveying patterns in continuous measurements were presented and tested on the measurements. The method calculated the distribution compared to an interval and proved applicable for providing a general overview of continuous measurements, but couldn't give a detailed picture within the intervals, which would have been useful determining if conserving behavior were conducted.

References

[1] Schultz P.W: Conservation means behavior. Conservation Biology; 2011. P. 1080-1083
[2] Wilhite H, Ling R. Measured energy savings from amore informative energy bill. Energy and Buildings 22; 1995. P. 145-155
[3] Abrahamsen W, Steg S, Vlek C, Rothengatter T. The effect of tailoring information, goal setting, and tailored feedback on household energy use, energy-related behaviors, and behavioral antecedents. Jorunal of Environmental Psychology; 2007. P. 265-276
[4] Andersen R, Andersen S, Olesen BW. Effect of individual and collective heat cost allocation on indoor environment in Danish apartments. Presented at Symposium on Occupant Behavior; Newcastle 2014.
[5] ASHRAE Standard 55-2010, "Thermal Environmental Conditions for Human Occupancy". Atlanta, USA. 2010.
[6] En 15251 (2007), "Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics". Brussels: European Committee for Standardization.
[7] Gram-Hanssen K. Residential heat comfort practices: Understanding users. Building Research and Information; 2010. P. 175-186
[8] Hauge B. Anthropological investigation and analysis of the significance of fresh air from the outside and into French Homes. Report for Velux A/S; 2010.
[9] Gunay H B, O'Brien W, Beausoleil-Morrison I, Perna A. On the behavioral effects of residential electricity submetering in a heating season. Build Environ. 21; 2012. P. 432-451
[10] Less B, Fisher J, Walker I. Deep Energy Retrofit - Eleven California Case Studies. Report of Enrivonmental Energy Technologies Division, Lawrence Berkeley National Laboratorium; 2012.
[11] Jacobsen K V. Change of Occupant behavior in danish apartments basd on building renovation and personal feedback. Master thesis report from Technical University of Denmark; 2014.
[12] Andersen R, Fabi V, Toftum J, Corganati S P, Olesen B W. Window opening behaviour modelled from measurements in Danish dwellings. *Build. Environ.* 69; 2013. pp. 101–113
[13] Andersen R K. Erfarringer fra projekt Dynamisk varmeregnskab. Report for the Danish Ministry of Housing, Urban and Rural Affairs; 2013

32 APPENDIX 14

Co-author statements for Paper 1through Paper 3

Technical University of Denmark

Joint author statement

If a thesis contains articles (i.e. published journal and conference articles, unpublished manuscripts, chapters etc.) made in collaboration with other researchers, a joint-author statement verifying the PhD student's contribution to each article should be made by all authors. However, if an article has more than three authors the statement may be signed by a representative sample, cf. article 12, section 4 and 5 of the Ministerial Order No. 1039 27 August 2013 about the PhD degree. We refer to the Vancouver protocol's definition of authorship.

A representative sample of authors is comprised of

- Corresponding author and/or principal/first author (defined by the PhD student), and if there are more authors:
- 1-2 authors (preferably international/non-supervisor authors)

Titel of the article	Influence of heat cost allocation on occupants' control of indoor environment in 56 apartments: studied with measurements, interviews and questionnaires
Author(s)	Søren Andersen, Rune Korsholm Andersen, Bjarne W. Olesen
Journal/conference * if applicable	Building and Environment
Name of PhD student	Søren Andersen
Date of Birth	07. November 1985

Description of the PhD student's contribution to the abovementioned article

Søren Andersen wrote the paper as part of his Phd dissertation and was thereby the main contributor to the paper.

Søren Andersen has in collaboration with Rune Korsholm Andersen conducted the data analysis.

Søren Andersen handled the submission process and incorporated comments and needed correctiosn from the peer reviewers.

Signature of the PhD student [signature] Date 02/05/2016

Signatures of co-authors

As a co-author I state that the description given above to the best of my knowledge corresponds to the process and I have no further comments.

Date (DD/MM/YY)	Name	Signature
05/05/16	Rune Korsholm Andersen	[signature]
	Bjarne W. Olesen	[signature]

Technical University of Denmark

Joint author statement

If a thesis contains articles (i.e. published journal and conference articles, unpublished manuscripts, chapters etc.) made in collaboration with other researchers, a joint-author statement verifying the PhD student's contribution to each article should be made by all authors. However, if an article has more than three authors the statement may be signed by a representative sample, cf. article 12, section 4 and 5 of the Ministerial Order No. 1039 27 August 2013 about the PhD degree. We refer to the Vancouver protocol's definition of authorship.

A representative sample of authors is comprised of

- Corresponding author and/or principal/first author (defined by the PhD student), and if there are more authors:
- 1-2 authors (preferably international/non-supervisor authors)

Titel of the article	Indoor environmental effects of continuous and monthly feedback intervention in 56 Danish apartments
Author(s)	Søren Andersen, Rune Korsholm Andersen, Bjarne W. Olesen
Journal/conference * if applicable	Building and Environment
Name of PhD student	Søren Andersen
Date of Birth	07. November 1985

Description of the PhD student's contribution to the abovementioned article

The aim of the paper was discussed by the authors. Søren Andersen wrote the paper as part of his PhD project and was the main contributor to the paper.

Data general analysis was performed by Søren Andersen. The used Regression analysis was performed in corporation with Rune Korsholm Andersen.

Søren Andersen handled the submission process and incorporated comments and needed corrections from peer reviewers.

Signature
of the PhD student [signature] Date 02/05/2016

Signatures of co-authors

As a co-author I state that the description given above to the best of my knowledge corresponds to the process and I have no further comments.

Date (DD/MM/YY)	Name	Signature
05/05/16	Rune Korsholm Andersen	[signature]
	Bjarne W. Olesen	[signature]

Joint author statements shall be delivered to the *PhD administration* along with the PhD thesis

Technical University of Denmark

Joint author statement

If a thesis contains articles (i.e. published journal and conference articles, unpublished manuscripts, chapters etc.) made in collaboration with other researchers, a joint-author statement verifying the PhD student's contribution to each article should be made by all authors. However, if an article has more than three authors the statement may be signed by a representative sample, cf. article 12, section 4 and 5 of the Ministerial Order No. 1039 27 August 2013 about the PhD degree. We refer to the Vancouver protocol's definition of authorship.

A representative sample of authors is comprised of

- Corresponding author and/or principal/first author (defined by the PhD student), <u>and if there are more authors:</u>
- 1-2 authors (preferably international/non-supervisor authors)

Titel of the article	How to influence indoor environment control using continuous and weekly feedback: a case study of 18 Danish apartments
Author(s)	Søren Andersen, Rune Korsholm Andersen, Bjarne W. Olesen
Journal/conference * if applicable	
Name of PhD student	Søren Andersen
Date of Birth	07. November 1985

Description of the PhD student's contribution to the abovementioned article

Søren Andersen analyzed the data and have written the paper with essential inputs and comments from the co-authors.

Søren Andersen has conducted the submission process and incorporated comments from peer reviewers.

Signature
of the PhD student

Date 02/05/2016

Signatures of co-authors

As a co-author I state that the description given above to the best of my knowledge corresponds to the process and I have no further comments.

Date (DD/MM/YY)	Name	Signature
05/05/16	Rune Korsholm Andersen	
	Bjarne W. Olesen	

Joint author statements shall be delivered to the *PhD administration* along with the PhD thesis

This project investigated if indoor environment feedback can be used to influence occupants' control of the indoor environment and thereby influence their energy use.The investigation was performed in four studies analysing measurements of the indoor environment. The studies documented that the occupants' motivation to adapt their behaviour is the key element. Two feedback procedures were tested, with findings showing how the occupants' behaviour mainly was affected by continuous feedback.The project concluded that indoor environmental feedback can be used to influence occupant behaviour.

DTU Civil Engineering
Technical University of Denmark

Brovej, Bygning 118
2800 Kongens Lyngby
Tlf. 45251700

www.byg.dtu.dk/english

ISBN 9788778774484
ISSN 1601-2917