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Improving Occupants' Satisfaction with Mechanical Ventilation using Technical and Non-Technical Solutions

Slutrapport til højnelse af tilfredsheden med mekanisk ventilation i renoverede etageboliger

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BUILD REPORT

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Improving Occupants' Satisfaction with Mechanical Ventilation using Technical and Non-Technical Solutions

Slutrapport til Højnelse af tilfredsheden med mekanisk ventilation i renoverede etageboliger

Alireza Afshari, Niss Skov Nielsen, Samira Rahnama, Ivan T. Nikolaisson, Alessandro Maccarini & Marco Marigo

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Contents

Summary

This project focuses on evaluating occupants' and building management staff's experiences with mechanical ventilation in renovated residential buildings in Denmark. It proposes technical and non-technical solutions to increase satisfaction levels among occupants and staff. The project is divided into two phases: Phase 1 studies the impact of new mechanical ventilation systems on occupant satisfaction with indoor climate, ventilation system, annoyance, and functionality. Phase 2 investigates the impacts of faults in a CAV AHU system on thermal and electrical energy use, thermal comfort, and indoor air quality. The study develops fault models, defines KPIs, and evaluates how faults can affect energy use and indoor climate conditions. The conclusions of each phase are as follows:

Phase 1: Tenants experience more noise, draughts, and dry conditions after the renovation and installation of a new decentralized ventilation system, which may be the reason why fewer people are satisfied with the ventilation system. Conversely, there are also fewer people who are dissatisfied with the new ventilation system than with the old central ventilation system. The perceived indoor air quality has not improved after the renovation, which may be due to increased experience of dry air in winter and drafts and noise from the ventilation system. An important conclusion, however, is that there is a correlation between satisfaction with the decentralized ventilation system and satisfaction with the indoor climate. Furthermore, satisfaction with the decentralized ventilation system is closely linked to having received written instructions for use in connection with the installation and to the fact that the residents have dared to adjust the system and feel that they can adjust it as they wish. In order for the residents to be satisfied with the system, is it required that they are introduced to the system and that they gain confidence and experience in using the system.

Phase 2: Fault impact detection
The presence of faults in a typical Danish ventilation system can lead to increased energy use. Poor bypass damper operation is the main cause of thermal energy increase, followed by poor insulation of ducts and sensor faults. Fans' efficiency degradation may lead to increased electric energy use. The results obtained can be useful for producers and manufacturers of these systems, as they give awareness of the impact that poor design and operations can have on systems' energy use.

Resumé (in Danish)

Dette projekt fokuserer på at evaluere beboeres og bygningspersonalets oplevelser med mekanisk ventilation i renoverede boliger i Danmark. Dette omfatter tekniske og ikke-tekniske løsninger til at øge tilfredshedsniveauet blandt beboere og personale. Projektet er opdelt i to faser: Fase 1 undersøger virkningen af nye mekaniske ventilationsanlæg på beboernes tilfredshed med indeklima, ventilationssystem, gener og funktionalitet. Fase 2 undersøger virkningen af fejl i et CAV AHU-system på termisk og elektrisk energiforbrug, termisk komfort og indendørs luftkvalitet. Studiet udvikler modellering for fejlindstillinger der definerer KPI'er og evaluerer hvordan fejl kan påvirke energiforbrug og indendørs klimaforhold.

Konklusionerne for hver fase er som følger:

Fase 1: Beboere oplever mere støj, træk og tørre forhold efter renoveringen og isætning af et nyt decentralt ventilationssystem, hvilket kan være årsagen til at færre er tilfredse med ventilationssystemet. Omvendt er der også færre der er utilfredse med det nye ventilationssystem end med det gamle centrale ventilationssystem. Den opfattede indendørs luftkvalitet er ikke forbedret efter renoveringen, hvilket kan skyldes øget oplevelse af tør luft om vinteren og træk og støj fra ventilationssystemet. En vigtig konklusion er dog at der er sammenhæng mellem tilfredshed med det decentrale ventilationssystem og tilfredshed med indeklimaet. Endvidere at tilfredshed med det decentrale ventilationssystem er tæt forbundet med at have modtaget en skriftlig brugsanvisning i forbindelse med installationen og med at beboerne har turde kaste sig ud i at justere systemet og føler at de kan justere det som de ønsker. For at beboerne skal blive tilfredse med systemet kræves der også at de introduceres til systemet og at de opnår en sikkerhed og erfaring med brug af systemet.

Fase 2: Tilstedeværelsen af fejl i et typisk dansk ventilationssystem kan føre til øget energiforbrug. Dårlig drift af bypass-spjæld er den primære årsag til øget termisk energiforbrug, efterfulgt af dårlig isolering af

kanaler og sensorfejl. Forringelse af ventilatorers effektivitet kan føre til øget elektrisk energiforbrug. Resultaterne kan være nyttige for producenter og fabrikanter af disse systemer, da de giver bevidsthed om den påvirkning, dårligt design og drift kan have på systemernes energiforbrug

Introduction

Buildings account for roughly 40 % of the energy use globally [1]. This fact, combined with the goal of the Danish government of becoming CO_2 neutral by 2050, leads to the development of significantly higher energy-efficient buildings in Denmark [2]. To provide a satisfactory indoor climate in newly constructed and renovated energy-efficient buildings, one solution is to use balanced mechanical ventilation. Over the last few decades, the focus on ensuring a satisfactory indoor climate has increased as it is estimated that people spend around 90% of their time indoors [3]. In a recent study, dissatisfactions related to mechanical ventilation systems in renovated residential buildings have been documented among occupants and building management staff [4]. Dissatisfied and irritated occupants are likely to take measures that potentially increase the running costs and energy use of the ventilation system [5]. These measures can have a negative impact on the indoor climate of the building without the realization of the occupants [6]. Some studies suggest that the gap between final energy use and simulated energy use is due to the lack of proper design of ventilation strategies, where occupant behaviors and preferences are not taken into account. [7], [8].

Improving the satisfaction of occupants and building management staff with mechanical ventilation in future and current renovated residential buildings, without compromising the indoor climate and energy use, can be a challenging task. Many studies have shown that occupant behavior plays an important role in the final energy use of a ventilation system and indoor climate [4]– [7]. Ventilation technologies that can be flexible to occupant behavior, such as demand-controlled ventilation (DCV), have shown promising results in terms of reduced energy use and improved indoor climate. DCV systems use a ventilation strategy that can be governed by a chosen pollutant concentration level. [10]. One of the main pollutants of concern in residential buildings, that has a negative impact on indoor air quality, is relative humidity [11]. DCV using humidity sensors has been developed, both for balanced mechanical ventilation and exhaust ventilation systems. A study conducted on 31 new apartment building equipped with exhaust DCV based on humidity control, show energy savings in fan drive ranging between 35-50%, without compromising indoor climate [12]. A study conducted by Afshari and Bergsøe documented 20-30% airflow reductions for a relative humidity setpoint of 45% in a Danish apartment with exhaust DCV [13]. In the study, it is noted that constant air volume (CAV) ventilation, can lead to overventilation and thereby higher energy use. The relative humidity-based balanced DCV strategy also shows a reduction in airflow rates. [14] It should be noted that the reduction of energy use, which can be achieved with the use of DCV, does not necessarily correlate with improved IAQ[15]. Some studies suggest that DCV systems that are only regulated by one parameter, often risk the accumulation of others [16], [17]. CO_2 concentrations are often used as a ventilation rate indicator, where no other pollution source is dominant, such as relative humidity in bathrooms [18]. It has been shown that a balanced DCV with CO_2 control reduces energy demand and reduces contaminant concentration [19]. A novel temperature based DCV system was developed and tested in laboratory conditions [20]. The advantage of this system is the possibility of regulating the air temperature in individual rooms with heat valves and a relatively low time constant of the system when compared to conventional heating techniques. While the DCV has the potential in reducing the energy demand and maintaining a satisfactory indoor climate, the occupants' interaction with the technology will be the determining factor of its performance. A study suggests the use post evaluation methodology, to understand how occupants interact with new technologies in order to improve energy performance and the occupants' well-being [21]. The present project aims to evaluate whether the occupants and building management staff satisfaction with indoor climate can be improved with new technologies in DCV.

This project also aims to identify potential barriers to successfully implementing mechanical ventilation systems in major and minor renovated residential buildings. In this project, a major renovation is considered a renovation process where the building's envelope receives significant energy-efficient upgrades and is equipped with a balanced mechanical ventilation system. Minor renovation is considered as a renovation with relatively minor changes, without changing the existing ventilation system. In recent years, dissatisfaction with balanced mechanical ventilation systems has been reported by the occupants and building management staff in major renovated apartment buildings in Denmark. Dissatisfaction related to; noise, dryness, smell, and lack of personal control have been documented. These dissatisfactions are unexpected since the purpose with balanced mechanical ventilation is to improve the quality of indoor climate, which in some cases fails to achieve the purpose it was meant for. To determine the cause of these dissatisfactions, a quantitative survey was carried out. The target group of the survey was the occupants, of 30 renovated apartment buildings. A separate qualitative survey was conducted by building management staff, maintenance staff, and by project managers to occupants in the 30 buildings. Based on the survey results, the cause of this dissatisfaction was identified, and solutions were proposed. The solutions were of technical and non-technical nature.

Aim

The project aims to evaluate occupants' and building management staff's experiences and satisfaction with mechanical ventilation system and indoor climate in renovated residential buildings in Denmark and to propose technical and non-technical solutions with the purpose of increasing the satisfaction level among occupants and building management staff.

Methodology

The project is divided into two phases, where different methodologies and methods are used in each phase to accomplish the research goals.

Phase 1 (Perception of mechanical ventilation system)

The intention with this study is to analyze the impact that new mechanical ventilation systems have in residential buildings, on occupant satisfaction with the indoor climate, and their general satisfaction with the ventilation system.

A questionnaire regarding satisfaction with the indoor climate, and satisfaction with the ventilation system, annoyance in the indoor climate and evaluation of the functionality of the decentral ventilation system, has also been used in this part.

Materials:
An extensive amount of data was collected regarding the building (geometry, location, type of ventilation) and occupants' perception of the mechanical ventilation system. The occupants' perceptions of indoor climate performance in the residential building were documented through a survey. A separate survey was developed for building-related personnel such as building management and maintenance workers.

Questionnaires were delivered through local building managers to occupants from around 20 renovated residential buildings. Landsbyggefonden selected the buildings from various housing organizations as a basis for the study to make this study as representative for their apartments as possible.

The questionnaire was sent out to 1443 occupants. The response rate was 8% equivalent with 116 occupants fulfilled the questionnaire. From these 98 answers have been used in the analysis between new and continuate tenants - as 18 respondents did not answer for how long they have lived in their apartment. All 116 were used in the remaining analysis.

The 98 occupants were divided into the following categories:

1: occupants, who have lived in the apartment since before the renovation, and who have the original ventilations system (continuate tenants with central ventilation) n=24.

2: occupants, who have lived in the apartment since before the renovation, and who have had a new decentralized ventilation system installed which they can regulate themselves (continuate tenants with decentral ventilation) n=17.

3. occupants who have moved into the apartment after the renovation has taken place, and who have the original ventilation system (new tenants with central ventilation) n=22.

4. occupants who have moved into the apartment after the renovation has taken place, and who have had a new decentralized ventilation system installed which they can regulate themselves (new tenants with decentralized ventilation) n=35.

Methods:
The included results in this report are primarily descriptive proportion calculations between the groups 1-4, supplied with statistic calculations dependent on data. Persons' regression analysis, Chi-square tests and Logistic regressions are included to support the tendencies. $P<=0.05$ is used as level of significance in the analysis.

Phase 2 (Fault impact detection)

Phase 2 aims to investigate the impacts due to the presence of faults in a CAV AHU installed in a typical Danish residential apartment on thermal and electrical energy use, thermal comfort, and indoor air quality. The building and the system models were created in Modelica, A list of fault models was built, and the impact of each one, with different intensities, was studied through annual simulations. In the first step, a free-fault model representing a typical Danish residential building was developed (Section 2.1). Consequently, specific faults for AHU systems were defined according to a literature review and added to the free-fault model, outlining the "with-fault model" (Section 2.3, Appendix 2). In the subsequent step, KPIs were defined (Section 2.4, Appendix 2) as the difference between free-fault and with-fault simulation results on relevant parameters. Finally, the KPIs were evaluated, showing how faults can affect energy use and indoor climate conditions.

Results

Phase 1 (Perception of mechanical ventilation system)

As shown in the distribution between the four groups of occupants 47% of occupants have the central mechanical ventilation systems after the renovation, while 53% have received a decentral ventilation system in connection with the renovation.

In addition, the group of continuate tenants who experienced the renovation was 40%, and those who moved into one of the buildings after the renovation was 60% (new tenants).

The results further show: that occupants overall evaluate the indoor climate as more uniform as less are satisfied and less are unsatisfied with the indoor climate and indoor air after renovation and upset of the new decentral ventilations system. The results further show, that the occupants experience more dry air during summer and winter since the decentral ventilation system is installed. Some of them have even felt headache and dryness in their eyes from this increasing dryness in the indoor climate. Others experience more noise and draft after installation of the decentral ventilation system.

There is a high correlation between satisfaction with indoor climate and satisfaction with the ventilation system. Satisfaction with the ventilation system is related to receiving written information about the system's functionality and the occupants' experience of having control over the ventilation system.

Results of the functionality questions among continuate tenants show, that: fewer are satisfied with the ventilation system's ability to remove humidity from kitchens and from bathrooms after installation of the decentral ventilation system. The same tendency is seen regarding satisfaction with the system's ability to avoid high and low temperatures. Finally renovation of the apartment in connection with installation of the decentral ventilation system is related to a 5fold reduction in the presence of mold in the apartments.

The following descriptive results were presented in the Danvak Theme meeting (DanvakTemamøde), See Appendix 1:

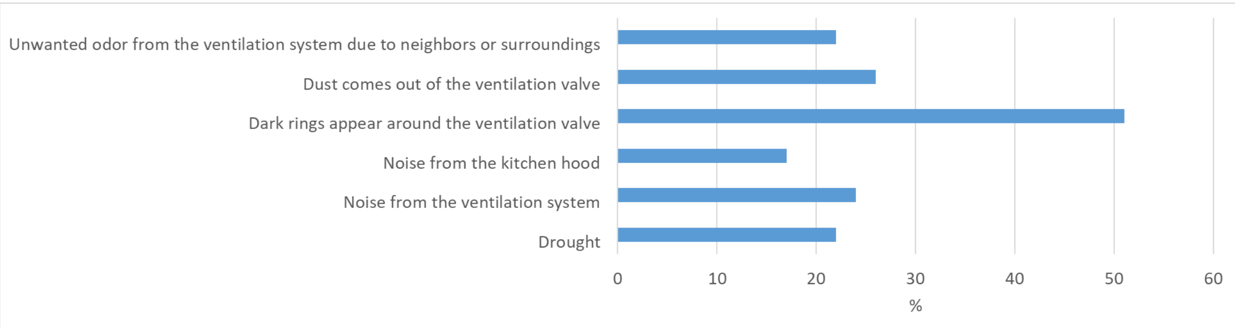

Figure 1 Answers to the question "Please mark if you experience or have noticed the following".

The occupants were questioned regarding the presence of unwanted odor from the ventilation system (due to neighbors or surroundings), dust coming out of the ventilation valve, dark rings appearing around the ventilation valve, noise from the kitchen hood, noise from the ventilation system, and draught. Figure 1 depicts the residents' response with odor 22%, dust 26%, dark rings 51%, noise from the kitchen 17%, noise from ventilation systems 24% and draught 22%.

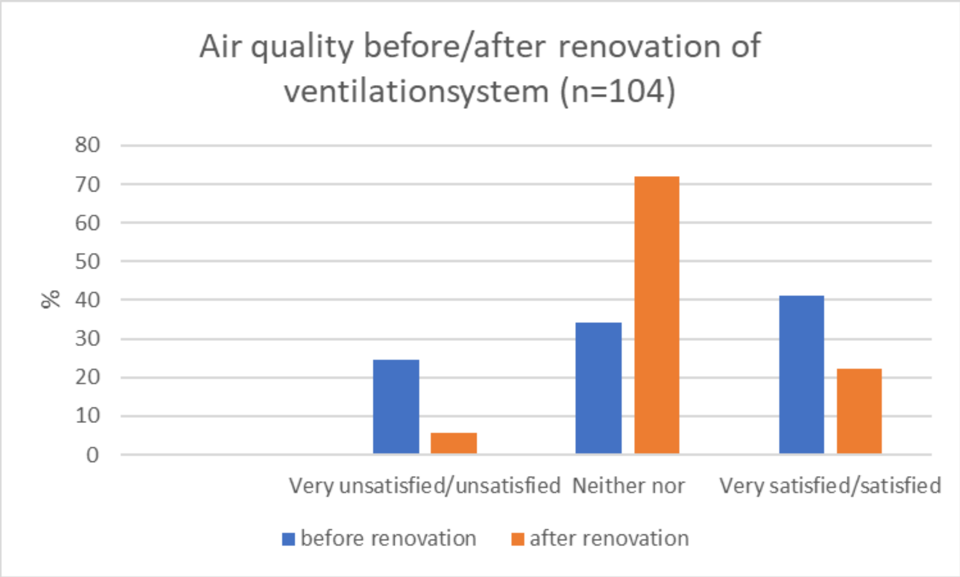

Figure 2a Answers to the question “How satisfied/dissatisfied were you with the air quality in the indoor air quality BEFORE/AFTER the installation of the new ventilation system?”

Figure 2 Answers to the question “How satisfied/dissatisfied were you with the air quality in the apartment indoor climate BEFORE/AFTER the installation of the new ventilation system?” The results before the renovation shows that a proportion of 24,4% among the whole population were unsatisfied/very unsatisfied with the indoor air quality before the renovation; 34,1% were neither unsatisfied or satisfied with the air quality (Neither nor), and finally a proportion of 41,5% were satisfied/very satisfied with the air quality before the renovation of the ventilation system. The result after the renovation shows, that 5,8% are unsatisfied/very unsatisfied with the air quality after the renovation. Most of the population: 72,1% evaluate the quality as neither satisfactory or unsatisfactory after the renovation. Finally, a proportion of 22,1% evaluate the air quality as being satisfactory/very satisfactory after the renovation. The differences are analyzed by use of Pearsons Chi-Square test. The result is p: 0,001 which means that the difference between the evaluation of the indoor air quality before and after the renovation is significant.

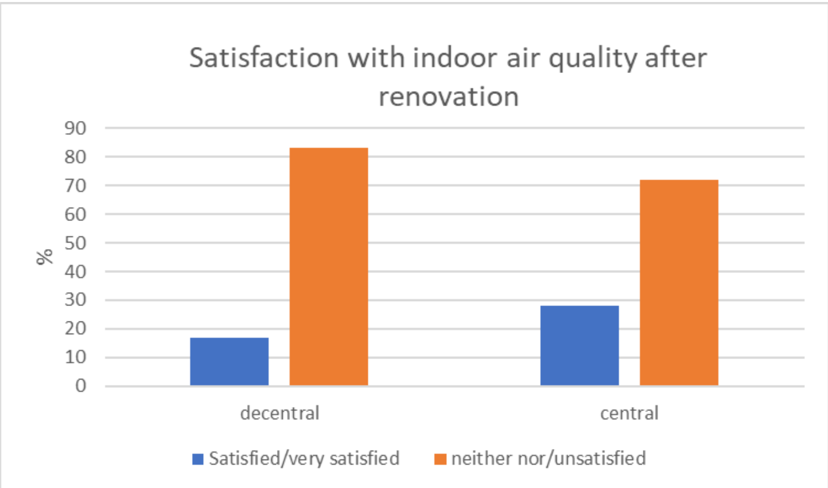

Figure 2b Satisfaction with the indoor air quality after renovation among occupants with decentral and with central ventilations systems.

The results in Figure 2 b show that 83% and 72% were unsatisfied or very unsatisfied with the indoor air quality among occupants with decentral and with central ventilation systems respectively. Likewise, were 17% among occupants with decentral and 28% among occupants with central ventilation systems are satisfied or very satisfied with the air quality after the renovation. This difference was tested by use of Pearsons Ci-Square test that showed: p=0,134 which show that the difference between the two groups is not significant (n=104).

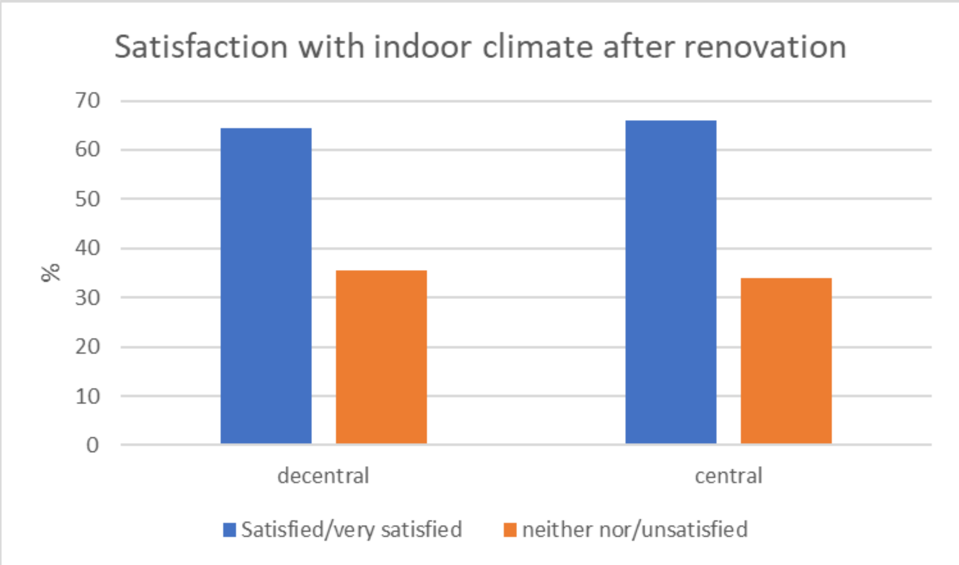

Figure 2c Satisfaction with the indoor climate after the renovation among occupants with the central and the decentral ventilation system.

The occupants with the central and the new decentral ventilation systems were asked about their satisfaction with the indoor climate (n=104).

In Figure 2c is it shown that 64.4% and 66% among the groups with the decentral and the central ventilation system respectively is very satisfied or satisfied after the renovation. Further, that 35.6% and 34% respectively are unsatisfied or evaluate the indoor climate as neither nor in the two groups. Tested by Pearsons Chi-Square, the p value =0.885 which show non-significant difference between the two groups of occupants regarding their satisfaction with the indoor climate.

How come that there are no significant overall differences in the indoor air quality and in the indoor climate after installation of the new decentral ventilation system compared to the old central system?

The occupants were questioned related to the perceived dry air during winters in the apartment before and after the installation of the new ventilation system. Figure 3 shows that 60,5% of residents never perceived dry air before the renovation and 30,8 % after the renovation. The percentage of residents who perceived dry air often/ very often before and after the renovation was 7,9% and 18%, respectively. Whereas the percentage of residents who perceived dry air “occasionally” before and after the renovations was 7,9% and 23,1%, respectively.

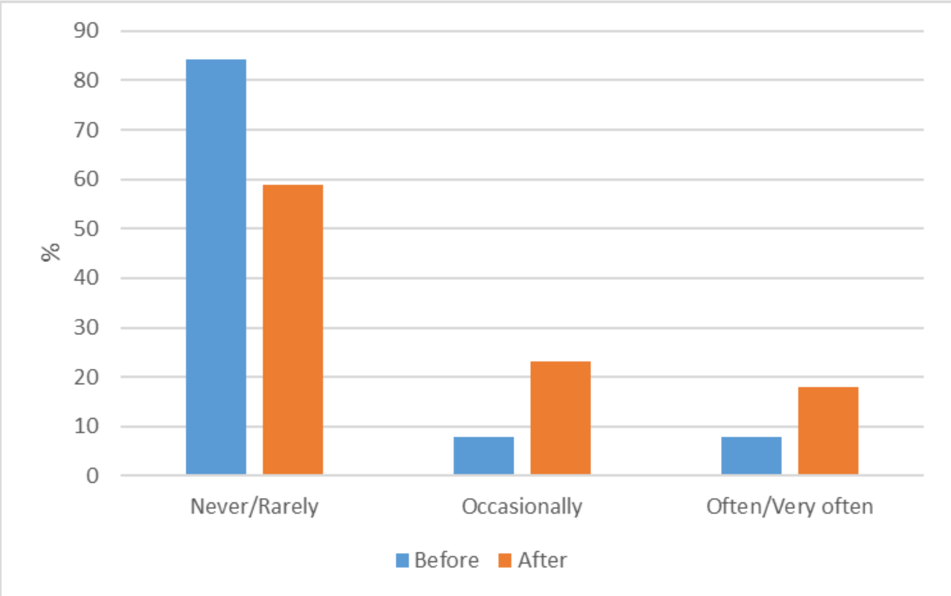

Figure 3 Answers to the question among occupants with the decentral system “Did you experience too dry air in the apartment (dry nose, eyes and/or throat) in the winter BEFORE/AFTER the installation of the new ventilation system?”

The results show that more occupants experience dry air occasionally (from: 8% to 22%) and often (from: 8% to: 18%) after installation of the decentral ventilation system.

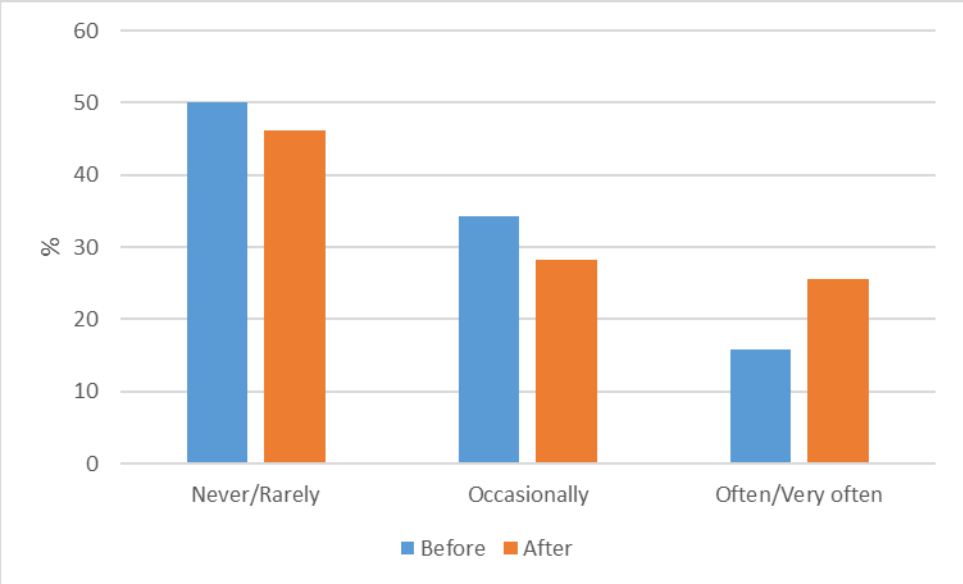

Figure 4 Answers to the question “Did you experience draughts in your apartment BEFORE/AFTER the installation of the new ventilation system?”

The occupants with the decentral system were further questioned related to the perceived draught in the apartment before and after the installation of the new ventilation system. Figure 4 shows that 42,1% of residents never perceived draught before the renovation and 28,2 % after the renovation. The percentage of residents who perceived draught often/ very often before and after the renovation was 7,9% and 7,9%, respectively. The percentage of residents who perceived draught “occasionally” before and after the renovations was 7,9% and 17,9%, respectively.

Table 1 Significance between being Very unsatisfied/unsatisfied with the indoor climate and with the ventilation system on the one hand and significant annoyances from the indoor climate on the other hand (noise and draft)

	Indoor climate	**Decentral ventilation system**
Drought	0.043*	0.000***
Noise from the ventilation system	0.011*	0.003***

Table 1 shows results from Logistic regression tests are shown regarding indoor annoyances among occupants which are very unsatisfied/unsatisfied with the indoor air climate and with the ventilation system. The results shows that draft and noise from the ventilation system are significant annoyances related with unsatisfaction with indoor air climate and with the ventilation system.

Are there benefits from the decentral ventilation system?

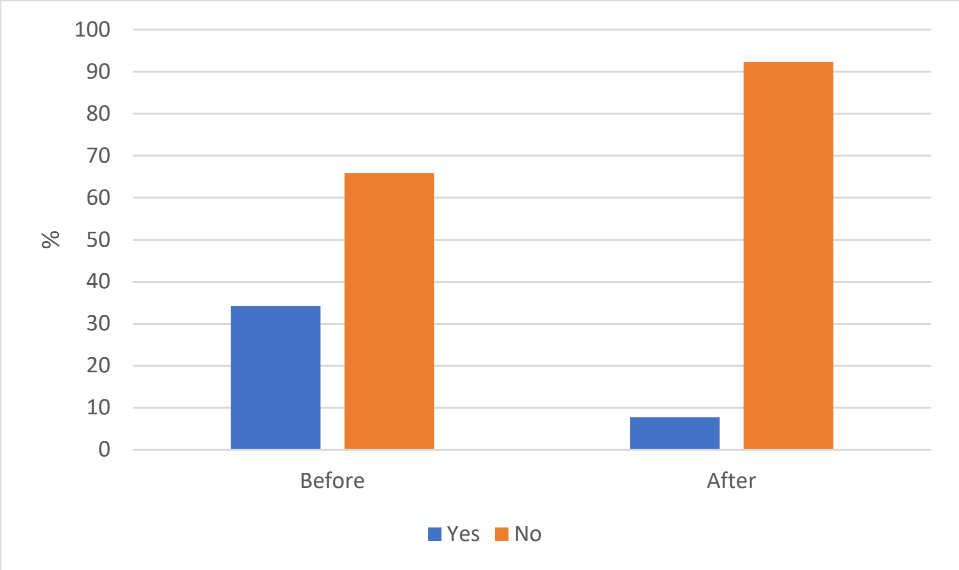

Figure 5 Answers to the question “Was there mold in your home BEFORE/AFTER the new ventilation system was installed?”

The occupants were asked questions related to the presence of mold in the residence apartment before and after the installation of the new ventilation system. Figure 5 shows that 7,7% of residents reported the presence of mold after the installation of the new ventilation system, while 34,2% reported mold before the installation of ventilation systems. In all a 5 fold reduction in presence of mold after installation of the decentral ventilation system compared to before the renovation.

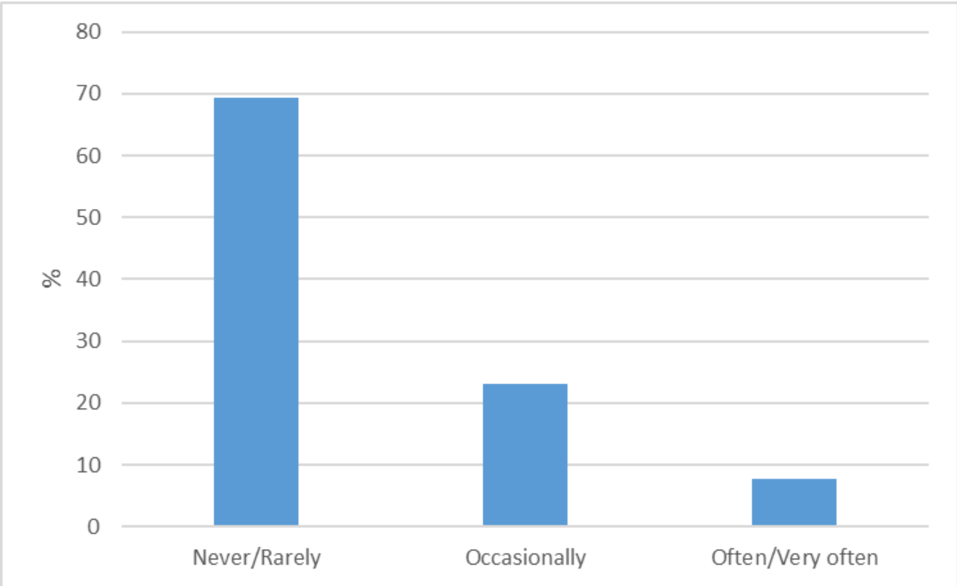

Figure 6 Answers to the question “How often do you adjust ventilation-related settings on your ventilation panel AFTER the installation of the new decentral ventilation system?”

The occupants were questioned related to the ability to make adjustment of ventilation-related settings on the ventilation panel AFTER the installation of the new decentral ventilation system. The results showed that

69,3% “never/rarely” had ability to make adjustment of ventilation-related settings on the ventilation panel, 23,1% answered “occasionally”, and 7,7% answered often/very often.

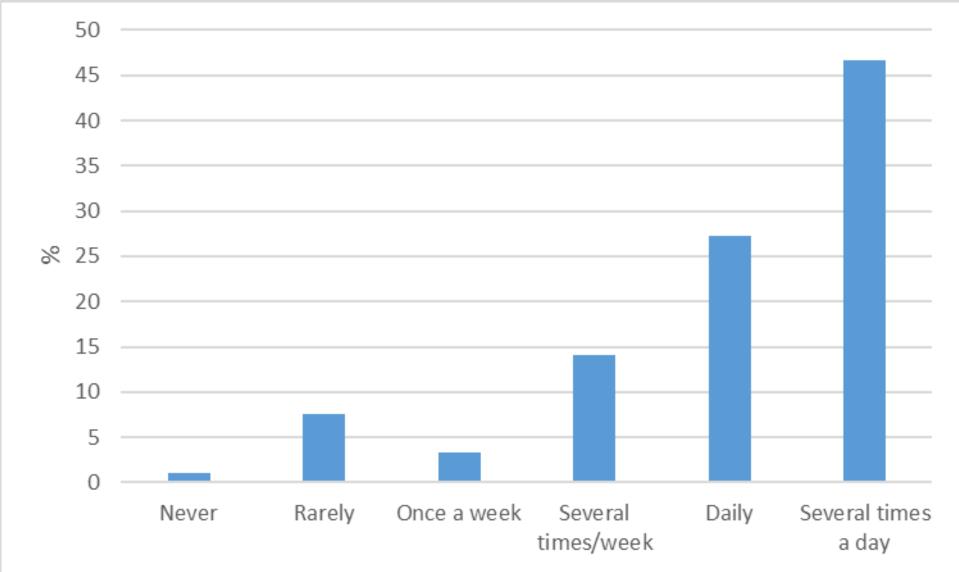

Figure 7a Answers to the question “How often do you open windows?”

Asked question:

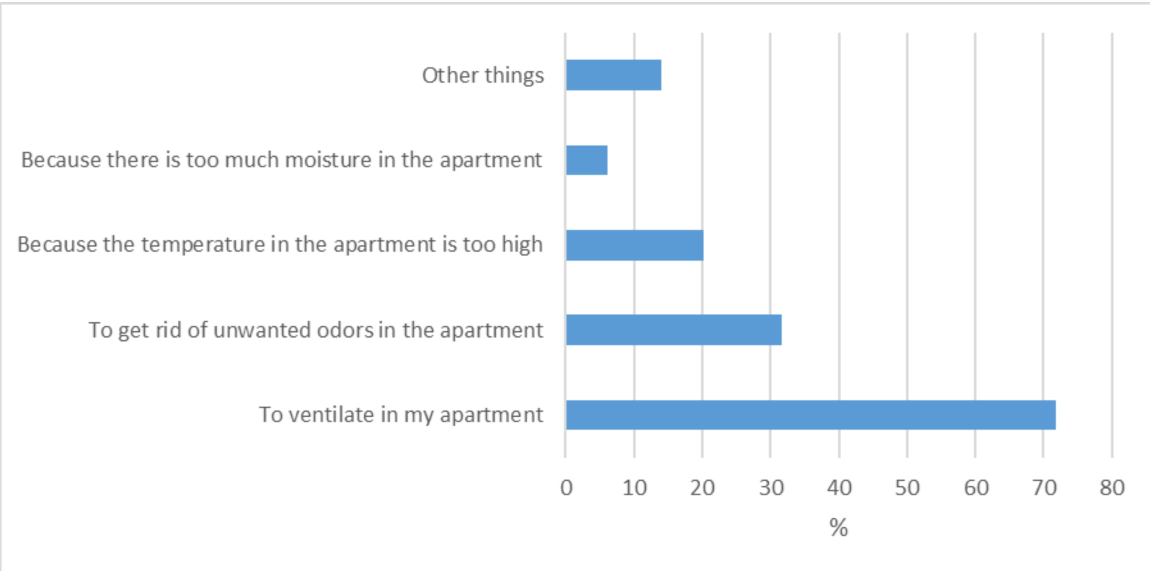

Figure 7b Answers to the question “Why do you open windows?”

The occupants were questioned related to the window opening before installation of the ventilation systems. Figure 7a shows that 8,6% of the residents answered Never/Rarely, 3,3% do once a week, 14,1% open several times per week, 27,2% do daily and 46,7% open windows several times a day.

It was also asked why the residents open the windows 7b: the majority 72% answered for the sake of ventilation in their residential building, 32% answered ‘to get rid of unwanted odors in the apartment’, 20% and 7% gave the reason of high air temperatures and high moisture in the apartment respectively, while 13% answered ‘other things’.

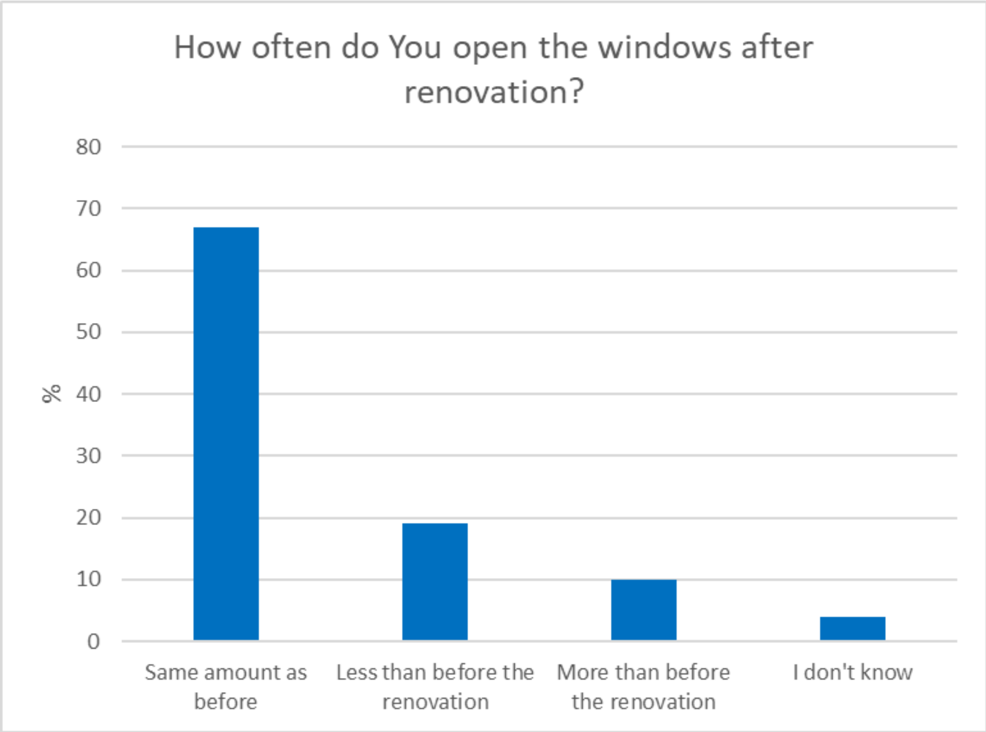

Figure 7c The occupants change in window opening behavior after the renovation.

The results show that 2/3 (67%) of the occupants have not changed this behavior since the renovation. 19% open their windows less often, while 10% conversely open their windows more frequently than before the renovation. Finally, 4% do not know if they have changed this behavior.

How is the satisfaction with the decentral ventilation system?

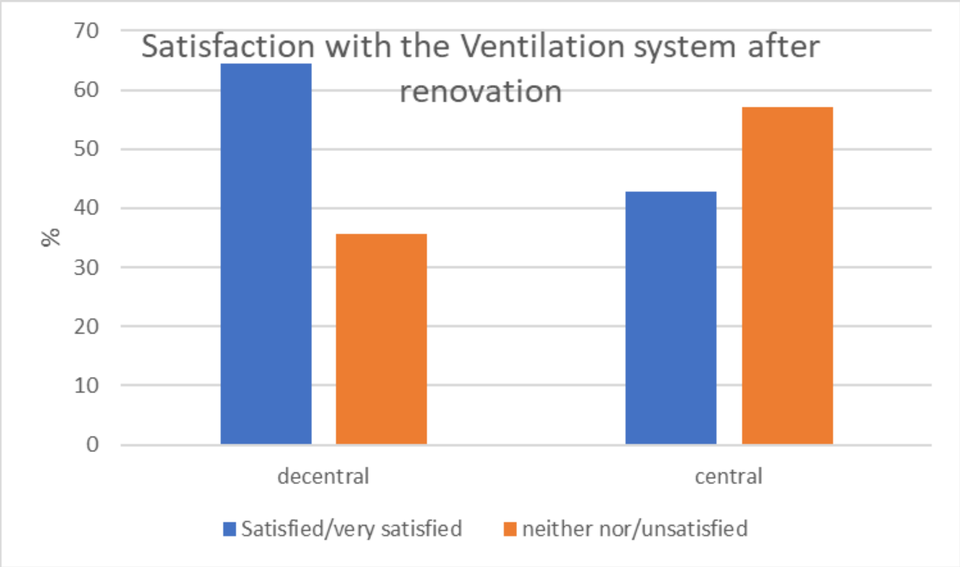

Figure 8a Satisfaction with the ventilation system after renovation among the groups of occupants with the central and the decentral ventilation system.

The occupants were asked about their satisfaction with the ventilation system after the renovation of the ventilation system. Results in Figure 8 show, that 64,4% and 42,9% are satisfied or very satisfied with the decentral and the central ventilation system respectively. The proportions which are unsatisfied/neither nor is 35,6% and 57,1% among occupants with decentral and central ventilation systems respectively. This difference is tested by Pearsons Chi-Square test showing that p=0.043 which is significant at 0.05 level.

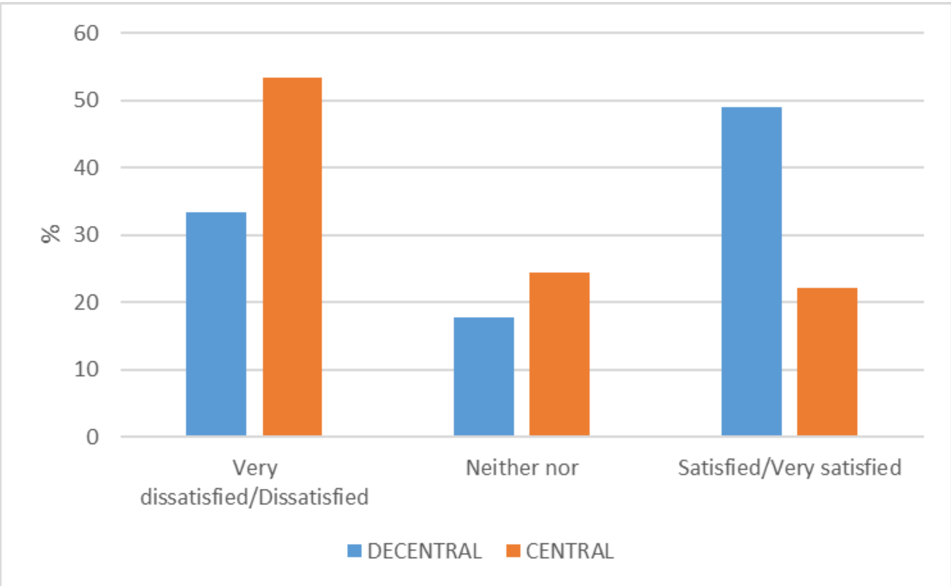

Figure 8b Answers to the question "How satisfied are you with the amount of control you currently have over the central/decentral ventilation system?"

The occupants were asked regarding satisfaction with the amount of control over the central/decentral ventilation system after the installation of new ventilation systems. Figure 8 shows that 33,3% and 53.4% responded Very dissatisfied/Dissatisfied with decentral ventilation systems and central ventilation systems respectively. 17.8% responded with ‘Neither nor’ for decentral and 24,4% for central, whereas 48,9% and 22.2% were found Satisfied/very satisfied with decentral and central ventilation system, respectively.

This difference between decentral and central was tested by Mann Whitney U-test. The results show that p=0.028 which is significant at 0.05 level.

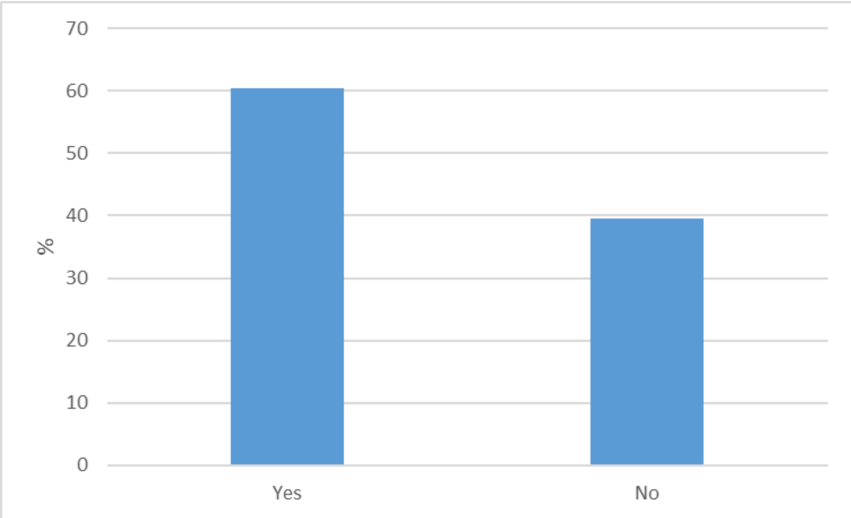

Figure 9a Answers to the question “Can you turn your decentral ventilation system on and off?”

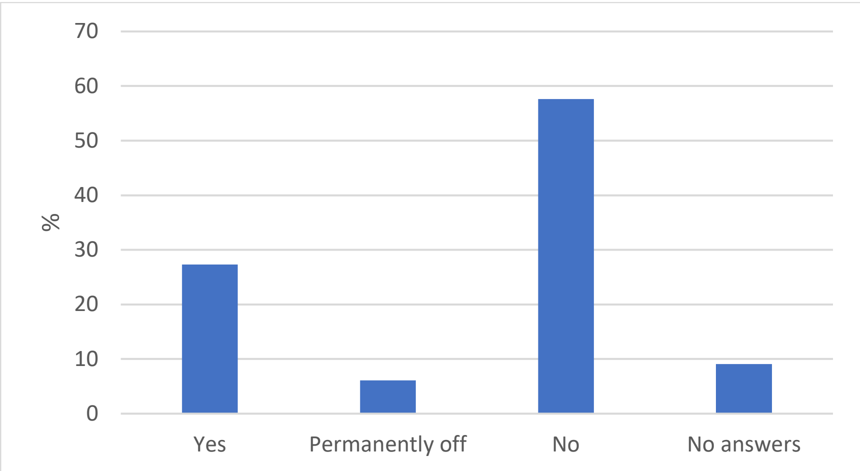

Figure 9b Answers to the question “Do you turn your ventilation system on and off? (Decentral ventilation system”.

The occupants with decentral system were asked questions related to the ability to turn on/off their decentral ventilation systems. Figure 9a shows that 60,4% responded “yes” and 39,6% responded “No”. The occupants were further asked if they either turn on or turn off their decentral ventilation system. Results in the figure 9b shows that 27,3% responded “Yes”, 57,6% “No”, 6,1% answered “permanently off” and 9,1% did not respond to the question.

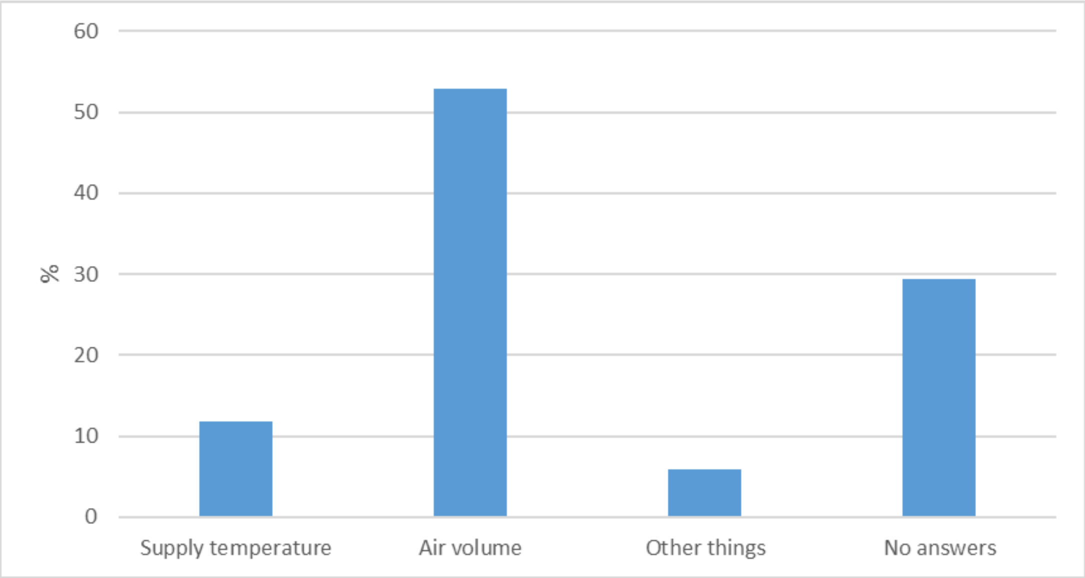

Figure 10 Answers to the question “What settings can you adjust? (Decentral ventilation system)”

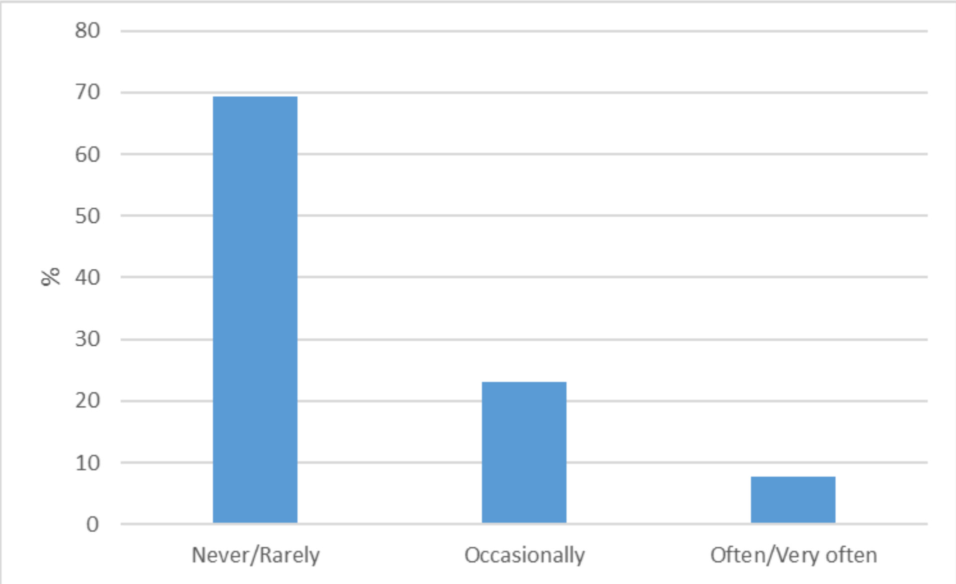

Figure 11 Answers to the question “How often do you adjust settings on your ventilation panel?”

The occupants were also asked questions related to parameters or settings that can be adjusted to control the installed decentral ventilation systems in Figure 10. The survey results show that 11.8% and 52.9% of residents can make adjustments to supply air temperature and air volume respectively. Whereas 5.9% responded ‘other things’ and 29.4% went with no responses.

The occupants were asked additionally related to the frequency of adjusting ventilation-related settings on their ventilation panel. Figure 11 shows that 69,3% responded “Never/Rarely”, 23,1% “Occasionally” and 7,7% “Often/very often”.

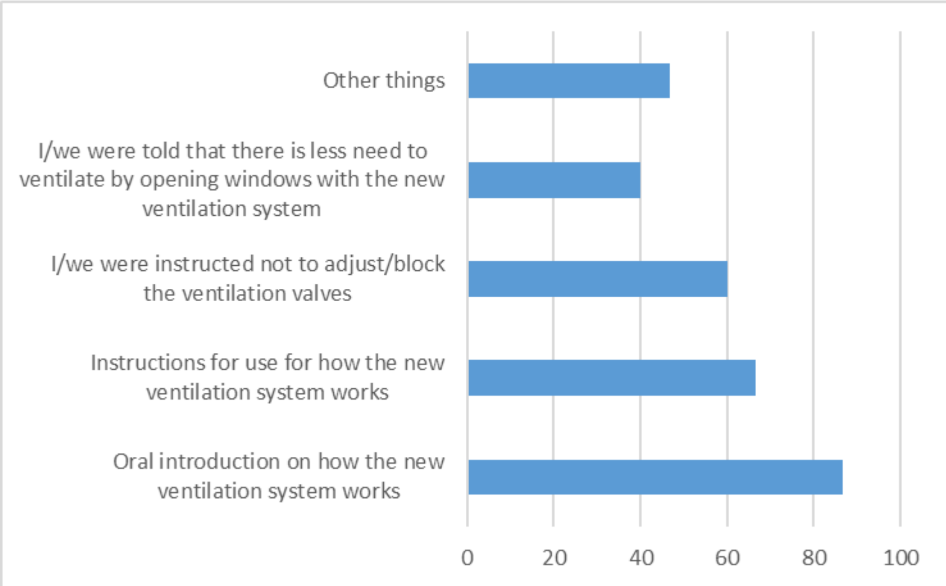

Figure 12 Answers to the questions regarding if they have received instruction of how to regulate and adjust the ventilation system.

Figure 12 shows that 86,6% responded that they were given an introduction orally on how the new ventilation system works, 66,7% got instructions for the use of the new ventilation system, 60% were instructed not to adjust/block the ventilation valves, while 40% were informed the need of opening fewer windows with the new ventilation system. 46,7 % chose ‘other things’ in the survey. From analysis by use of Mann Whitney U-tests is it shown that only occupants which have received a users manual in writing (66.7%) are significant satisfied with the ventilation system ($p=0.016$).

How is the relation between satisfaction with the indoor climate and satisfaction with the ventilation system?

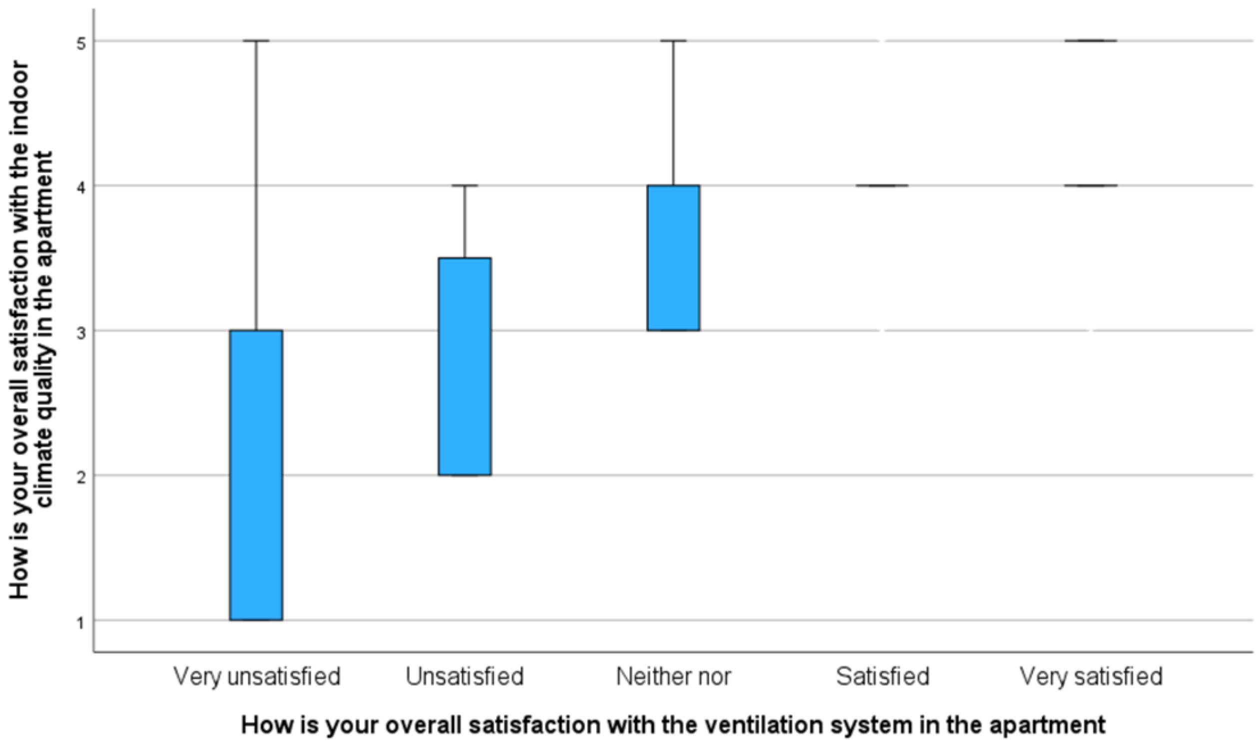

Figure 13 The correlation between satisfaction of the indoor climate and satisfaction with the ventilation system shown. The Correlation analysis: Mann Whitney U-test is used to test significance of this correlation.

Test variables: How satisfied are You with the ventilation system (decentral)? vs How satisfied are you with the indoor climate. Population: n=89. Correlation coefficient: 0.721**: p<0.000. Correlation is highly significant at the 0.01 level (2-tailed).

Part results:

The overall results are the following:

1. The indoor climate is becoming more uniform after renovation and installation of decentralized ventilation system – that is manifested in less occupants are unsatisfied and less is satisfied with the indoor air after installation of the decentral ventilation system.

2. Occupants with the decentral ventilation system report more dry air (summer and winter) as well as symptoms such as headaches, dry eyes, etc.). In addition to experiencing noise and draft from the ventilation system – than before installation of the decentral system. On the other hand, is the presence of the decentral ventilation system related to a 5-fold reduction in mold in the indoor climate.

3. There is a high correlation between the assessment of indoor climate quality and satisfaction with the ventilation system

4. Satisfaction with the (decentralized) ventilation system depends on whether the occupants have received written instructions for use beforehand and whether they have a sense of control over the system. The latter again depends on whether they have tried to (or regularly) adjust the system.

Part discussion:

This report’s results are based on 116 respondents’ answers. A response rate of 9% which might seem low but is to be accepted based on the necessary but also complicated method for data collection based on delivery and re-collection of completed questionnaires using local building managers. A higher response rate would give greater security for representativeness and greater security in the data analyses. Even so the investigation is suitable for showing new correlations between resident satisfaction, indoor climate, and ventilation systems, which in itself lead to new clarifications about why the results look as shown.

The overall evaluation of the system from them shows that less of them is very satisfied, but also that less among them are unsatisfied with the decentral ventilation system compared to the assessment of the old central system, which might be related to on the one hand more annoyances in the indoor climate and on the other hand benefits from reduction in molds?

Some of the results indicate that it is very important that the occupants feel that they have control over the ventilation system and that they dare to throw themselves into regularly regulating the system so that they experience satisfaction with the ventilation system and thus with their indoor climate, as satisfaction with the ventilation system is linked to satisfaction with the indoor climate. Another result shows that guiding and especially a written users’ instructions for the system and for its regulation is very important for people to dare to venture into regulating the ventilation system – which only a few of the residents have received. This investigation does not show anything about whether the ventilation system is difficult to see through or if it is difficult to regulate the system itself. But in any case, it is recommended that a written user manual be drawn up and distributed and preferably with contact options for local people who can help the occupants with regulating the system so that they achieve a sense of control over the decentral ventilation system.

finally, it is thought-provoking that 2/3 of the residents have not changed their window -opening behavior after switching to a new decentralized ventilation system. Only 19% have changed this behavior and thus open their windows to a lesser extent than before the renovation, while conversely 10% ventilate more than before the renovation. It seems a little strange and should perhaps be seen in the context of the increased assessment of dryness in the indoor climate, and perhaps in extension of this that many occupants lack the feeling of control over their decentralized ventilation system. Again, the solution seems to be distribution and guiding in how the system is regulated, as the feeling of control over the ventilation system is linked to a positive assessment of the indoor climate.

Phase 2 (Fault impact detection)

In this section, the results obtained from the fault impact analysis are shown. The results are illustrated by highlighting thermal (TER) and electric (ECR) energy use comparison between the free-fault system and the with-fault system model.

Sensors faults

In Figure 14, the results of the fault sensors' impact are presented. The sensor after the heat recovery unit (ACF), which controls the air fraction passing the heat exchanger, has a strong influence on the thermal energy use. With a positive offset of 4°C, the thermal energy use is about 27% higher than the free-fault case. On the other hand, small electric energy savings are achieved.

Regarding the temperature sensor after the heating coil (AHC), which controls the hot water flow rate inside the heating coil, a 15% increase of thermal energy use is found in correspondence of a negative offset of -4°C.

		TER_{tot}	ECR_{AHU}
ACF sensor	-1 °C	-1%	1%
	-2 °C	-1%	2%
	-3 °C	-1%	3%
	-4 °C	-1%	4%
	1 °C	5%	-1%
	2 °C	11%	-3%
	3 °C	19%	-5%
	4 °C	27%	-7%
AHC sensor	-1 °C	3%	-0%
	-2 °C	7%	-0%
	-3 °C	11%	-0%
	-4 °C	15%	-0%
	1 °C	-0%	-0%
	2 °C	-0%	-0%
	3 °C	-0%	-0%
	4 °C	-0%	-0%

Figure 14 Impact of ACF and AHC sensors offset with different intensities. The ratios are related to the free-fault scenario (Thermal energy use = 3106 kWh/y, Electric energy use = 400 kWh/y

Bypass faults

The poor operation of the bypass damper has a strong impact on the total energy use. Both thermal and electric energy are affected by faults in the bypass, as this component regulates the airflow passing through the heat exchanger. As shown in Fig. 15, the leakage can increase the thermal energy use by 30%, while reducing the electric energy use by 7%. A completely stuck bypass (value of 1) almost doubles the thermal energy use.

		TERtot	ECRAHU
Leakage	0.1	1%	-0%
	0.2	10%	-3%
	0.3	19%	-5%
	0.4	30%	-7%
Stuck	0	-1%	7%
	0.2	10%	1%
	0.4	30%	-5%
	0.6	63%	-11%
	0.8	86%	-16%
	1	90%	-18%

Figure 15 Impact of bypass leakage and stuck fault. The ratios are related to the free-fault scenario (Thermal energy use = 3106 kWh/y, Electric energy use = 400 kWh/y

Duct faults

Faults in the ducts can be related to leakage or thermal losses. As shown in Fig. 16, leakage slightly influence only electric energy use. In contract, thermal losses have a strong influence on thermal energy use. Poor insulation of ducts may lead to about 50% increase of thermal energy use.

		TERtot	ECRAHU
Leakage	0.14	0%	-2%
	0.2	0%	-2%
	0.26	0%	-3%
	0.33	1%	-3%
	0.4	1%	-4%
Thermal Losses	0.005 mm	48%	1%
	0.01 mm	30%	0%
	0.02 mm	18%	0%
	0.03 mm	13%	0%

Figure 16 Impact of ducts' leakage and thermal losses. The ratios are related to the free-fault scenario (Thermal energy use = 3106 kWh/y, Electric energy use = 400 kWh/y

Fans and filters faults

Faults affecting fans and filters involve changes only in electric energy use. As shown in Fig. 17, increased pressure drop in filters has a small impact on electric energy use (5%), while degradation of fans (lower efficiency) can lead to 40% increase of electric energy use.

		TER_{tot}	ECR_{AHU}
Both Fans	$\eta_{el} = 0.5$	0%	40%
	$\eta_{el} = 0.55$	-0%	27%
	$\eta_{el} = 0.6$	-0%	17%
	$\eta_{el} = 0.65$	-0%	8%
Supply Fan	$\eta_{el} = 0.5$	-0%	20%
	$\eta_{el} = 0.55$	-0%	14%
	$\eta_{el} = 0.6$	-0%	8%
	$\eta_{el} = 0.65$	-0%	4%

		TER_{tot}	ECR_{AHU}
Both Filters	ΔP = 45 Pa	0%	1%
	ΔP = 50 Pa	-0%	3%
	ΔP = 55 Pa	-0%	4%
	ΔP = 60 Pa	-0%	5%
Supply Filter	ΔP = 45 Pa	-0%	1%
	ΔP = 50 Pa	-0%	1%
	ΔP = 55 Pa	-0%	2%
	ΔP = 60 Pa	-0%	3%

Figure 17 Impact of fans' electrical efficiency drop (lefy) and filter fouling (right). The ratios are related to the free-fault scenario (Thermal energy use = 3106 kWh/y, Electric energy use = 400 kWh/y

Discussion

Phase 1 (Perception of mechanical ventilation system)

The survey has provided a wide spread of opinions and statements regarding the newly installed balanced mechanical ventilation in renovated apartment buildings. The interviewed group have expressed negative and positive statements concerning the installation process, commissioning period, daily operations, and on the impact of ventilation system that has on the indoor environment. The most common topics that were part of interviews are discussed below.

Changes after renovation

Indoor Environmental quality

The indoor environmental quality (IEQ) in a building is based on the indoor environmental performance of buildings, such as air quality, access to daylight and views, pleasant acoustic conditions, and occupants' control over lighting and thermal comfort [1, 2]. A key factor for achieving a satisfactory indoor environment in residential buildings is providing an acceptable indoor environmental quality for its occupants, based on levels of physical parameters that contribute to IEQ. A Danish study showed that there was a tendency for residents, in residential buildings with balanced mechanical ventilation systems, to experience fewer problems with unpleasant odors from their apartments along with less visible mold. In addition, the residents perceived often air dry [3]. The authors concluded that residents with decentralized mechanical ventilation often experience more problems with noise from their ventilation systems especially when the ventilation systems are not correctly designed. In the present study, among all occupants, draught and noise from the ventilation system were found most disturbing parameters from which occupants were observed dissatisfied with the ventilation systems.

Perceived air quality

Indoor air quality is often defined by the details involving the level of concentrations of particles and gases in the air, and thermal conditions that may negatively affect the health, comfort, and performance of a building's occupants. Insufficient ventilation rate in buildings is considered as the most common reason for pollutant buildup. It means that the growth of molds and bacteria, and the off gassing of chemicals from building materials can be significant. Therefore, the purpose of ventilation systems is to reduce the concentrations of pollutants, simultaneously, along with providing satisfactory indoor air quality and thermal comfort in buildings. Human subjects are used for characterizing the quality of air as it is perceived by people indoors. Different methodologies for sensory evaluations of indoor air quality exist [4], but two methods have been used extensively: sensory assessments of odor intensity and acceptability of air quality. In the present study, the majority of the residents were found to be less satisfied with the perceived air quality after the renovation of the ventilation systems.

Dry air in winter

The relative humidity of an indoor environment usually varies throughout the year depending on the evaporated water of the outdoor air, which is highest in summer and lowest in winter in Denmark. This leads to the absolute moisture content in the air to lowest in winter. When the dry outdoor air enters our buildings and is heated, it results in a low relative humidity. In a home, moisture is added from people and their activities, e.g., cooking and bathing, which reduces the drying out of the indoor climate during the heating season. Low relative humidity in the indoor air can cause an experience of irritation and itching among residents during the heating season [5]. Low-energy single-family houses have been previously studied in Denmark [6]. This study has focused on issues related to having a mechanical ventilation system i.e. satisfaction with the air quality, does the air feel dry in winter, and does the ventilation system make noise, and how the indoor air behaves during winter. The authors concluded that 7% of the problems were associated with dry air on daily basis and 11% on weekly or monthly basis. The present study showed that the percentage of residents who never perceived dry air in winter (before the renovation) was approximately 60%, while this figure was dropped to 30% after the renovation. This means that the perceived dry air in winter increased by 30% because of the installation of the ventilation systems. In addition, the percentage of residents who perceived dry air often/ very often before and after the renovation was found approximately 8% and 18%, respectively.

Draught
Another factor that may cause thermal discomfort is draught which is defined as unwanted local cooling of the human body [6] and is usually caused by high air velocity or air movement in the occupied zone. According to the ISO 7730 Standards [7], the draught model is used to evaluate draught risk that involves a group of people dissatisfied with draught. The results obtained by [8] showed that only a few house owners experienced problems with draught, leading to up to 94%-96% of residents feeling satisfied without experiencing draught problems in winter or summer. Only 3% found the draught conditions unsatisfactory in winter and 2% in summer. Draught was only mentioned in connection with the opening of windows and near the inlet of the ventilation system. In the present study, the occupants were asked questions related to the perceived draught in the apartment before and after the installation of the new ventilation system. The results showed that approximately 50% of residents never/rarely perceived draught before the renovation and 46 % after the renovation. The percentage of residents who perceived draught often/ very often before and after the renovation was approximately 16% and 26% respectively.

Mold
Mold is small micro-organisms that can be disease-promoting while some are harmless. Mold occurs and thrives in moist environments. One of the most efficient ways to prevent humid air in the building is ventilation. Adequate air change rates dry wet areas and help to remove water vapor produced by washing and cooking. In the present study, the results showed that approximately 8% of the residents reported the occurrence of mold and it was approximately 34% before the installation of the ventilation systems. This means that the installation of the ventilation systems had a positive influence on the reduction of mold in the residential buildings.

Individual control
Centralized ventilation systems: The ventilation unit in a central ventilation system is typically placed in the building's attic, and the unit serves several storey dwellings through a vertical main duct system and horizontal branch ducts in the dwellings. The main advantages of a central system are that it is easy to achieve central monitoring of the operation, there is only one unit that needs to be serviced, there is a relatively low material and man-hour consumption associated with service, and the hood can be included as an integral part of the ventilation system. The disadvantages of the system are that space must be set aside for the unit, ducting – especially vertically – which can be a challenge, and it is not possible to achieve individual user adaptation of the ventilation in a simple way. Furthermore, there is a risk that the system may cause the transfer of sound between dwellings.

Decentralized ventilation systems: With decentralized ventilation, there is a ventilation unit in each individual home. The unit can be placed in a cupboard, for example in the home's entrance hall or in the kitchen, or it can be placed above a suspended ceiling in the entrance hall or in the bathroom. From the unit, horizontal ducts are led to the individual rooms in the home. The advantages of a decentralized ventilation system are better possibilities for individual adaptation of the performance, fewer ducts, and generally simpler ducting compared to a central system. However, a decentralized ventilation system may entail a risk of noise nuisance in the home from the unit itself. Furthermore, from the property's operating staff point of view, there can be an increased time consumption associated with service and maintenance due to the many units in such a system, and it may get difficult to monitor the operation of the individual facilities.

Here is the question about the ability to control the ventilation systems. Individual control means relating to “the perceived ability to significantly alter events” [9]. A high individual control in indoor environments corresponds to a belief that one can change the course of events, whereas a low individual control represents the lack of such belief.

The occupants were asked questions related to their satisfaction with the amount of control they have over the ventilation system AFTER the installation of the new central/decentral ventilation system. The results showed that 47,9% were found satisfied with the ability to control the decentral ventilation systems, while 22,2% reported their satisfaction with the central ventilation systems.

The occupants were asked questions related to the ability to adjustment of ventilation-related settings on the ventilation panel AFTER the installation of the new decentral ventilation system. The results showed that approximately 69% never/rarely had the ability to make adjustments of ventilation-related settings on the ventilation panel, and approximately 8% answered ‘very often’.

Window-opening in residential buildings provides residents with the ability to control indoor air quality through natural ventilation and have the potential to provide a satisfactory indoor climate. On other hand, window-opening practice may have a significant impact on energy use. A Danish study focused on window-opening practice in residential buildings [10]. The results showed that space heating energy demand is underestimated, and it results in buildings where the windows are controlled with a probabilistic function consuming up to 58% more energy than a building where the control of windows is regulated by a fixed schedule related to the temperature. Another study [11] conducted a questionnaire survey in Danish Dwellings and showed that approximately 53% slept with an open window during autumn while 25.2% had a window open during the night in the wintertime, which in most situations ensure an air change rate of more than 0.35 h^{-1}. The authors concluded that the residents use window openings to ensure satisfactory indoor air quality. The results from the present study also showed that approximately 74% of the residents opened the window daily/several times a day before the renovation and that 67% did not change this behavior after the renovation of the ventilations systems.

Specific questions related to the decentral ventilation systems
The occupants responded that approximately 49% were ‘Satisfied/very satisfied’ with the amount of control over the decentral ventilation system after the installation of new ventilation systems, while approximately 22% were found satisfied with central ventilation systems. The occupants were also asked if they turned their decentral ventilation system on and off. The residents who responded “yes” were approximately 27% and 58% of residents responded with “No” option. The response related to parameters or settings that can be adjusted to control the installed decentral ventilation system was approximately 12% for supply air temperature, and approximately 53% for air volume. The occupant’s responses regarding the frequency of adjusting ventilation-related settings on their ventilation panel were approximately 69% for “Never/Rarely” and approximately 8% for “Often/very often”. The question regarding the instruction manual was according to the following: approximately 89% got an oral introduction on how the new ventilation system works, 67% responded that they got instructions for use of the new ventilation system, 60% responded that they were instructed not to adjust/block the ventilation valves, 40% responded that they were told that there is less needed to ventilate by opening windows with the new ventilation system and 46,7 responded with ‘other things’ option. The interesting part showed that only occupants that have received instructions in writing were significant satisfied with the ventilation decentral system. Further, that satisfaction with the indoor climate is highly related to the satisfaction with the ventilation system.

Phase 2 (Fault impact detection)

The presence of faults in HVAC components affect the overall system operation. In the following sections the discussion of results is presented.

Sensor offset
The ACF sensor detects the air temperature after mixing the bypass and the heat recovery path and controls the bypass flow to reach the setpoint temperature value (18°C). When a positive offset occurs, the detected temperature is higher than the real one, and the control system opens the bypass damper more than needed. The consequence is that less heat is recovered, and the missing amount is supplied by the heating coil. Therefore, an increased thermal energy use is obtained (Fig. 14). The negative offset involves a longer time for the bypass damper to stay closed and a lower opening level. This has a very limited effect on the thermal energy use. The changes in electrical use are due to the different airflow rates crossing the heat recovery unit, which causes higher pressure losses.

The AHC sensor detects the air temperature at the heating coil outlet and controls the water flow rate to reach the air supply temperature setpoint (18°C). The positive offset causes a higher detected air temperature than the real one, leading a lower temperature of supply air into the building. The reduction of the thermal energy use of the heating coil is balanced by an increase in heating system use. Therefore, the

AHC sensor positive offset does not increase the total energy use (Fig. 14) but involves a different balance between the two systems. On the other hand. the negative offset increases the water flow rate and the thermal energy use in the heating coil, resulting in a higher temperature inside the building with the risk of overheating.

Bypass faults
The leakage fault occurs when an undesired airflow ratio bypasses the crossflow heat exchanger due to unsealed damper closing. The electric energy use decreases, as less air flow passes through the heat recovery unit. However, this leads to a lower heat recovered and an increasing need for integration provided by the heating coil (Fig.15).

The stuck fault corresponds to a situation where the damper is at a fixed position for the whole simulation time. Despite this difference, the results are like those presented for leakage fault: the thermal energy use increases, as the heating coil provides the whole amount of energy to reach the supply air temperature setpoint.

Ducts faults
As shown in Fig.16, the ducts' leakage fault does not greatly impact thermal energy use. However, the heating coil increases energy use due to the inlet leakage of air colder than that coming from the heat recovery process. This fault involves a lower airflow inside the ducts and supplied to the room. The impact of a lower flow is also reflected in the electrical consumption, which is lower than the free-leakage simulation (Fig. 16), but it also entails a lower IAQ level inside the building, as it is shown in Fig. 18.

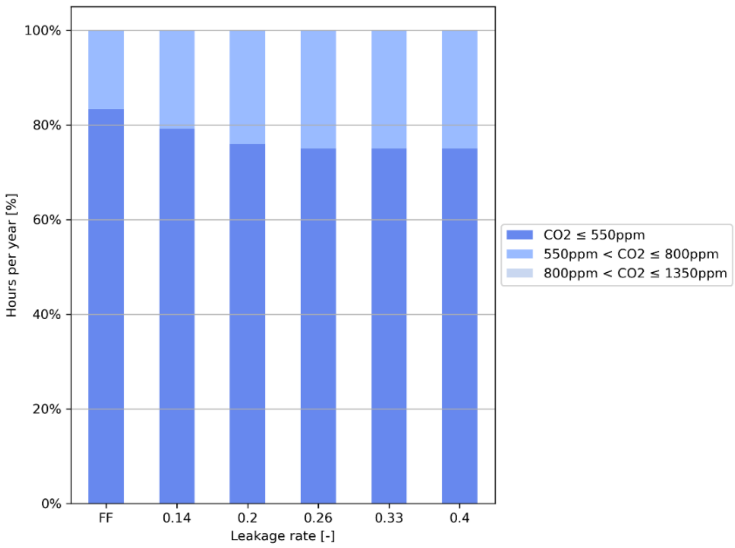

Figure 18 variation of IAQ class as a function of leakage rate in ducts

The ducts' thermal losses affect all the air paths and components operations. The thermal energy use increases because of the colder air flowing in the ventilation system. For high thermal losses, in the most critical hours of the year, the systems cannot provide the needed energy to keep the indoor temperature setpoint. Therefore, an increase of unmet hours for thermal comfort is found, as shown in Fig. 19.

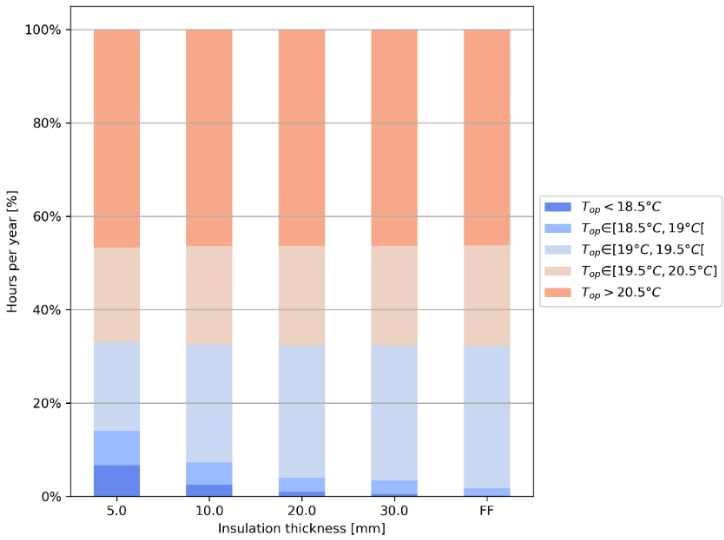

Figure 19 Variation of hours in each operative temperature range for different insulation scenarios

Conclusions

Phase 1 (Perception of mechanical ventilation system)

This study shows that occupants with the new ventilation system experience more noise and dry conditions compared with before the renovation. On the other hand is the new decentral ventilation system related to a five-fold lower incidens of mold in the apartments. These results reflect an overall lower satisfaction but also lower dissatisfaction with the new ventilation system.

After renovation (installation of the new ventilation system), perceived indoor air quality has not improved, which might be related to the increased experience of dry air in the winter and draught and noise from the ventilation system.

Satisfaction with the indoor climate is related with the satisfaction with the ventilation system. Further, satisfaction with the decentral ventilation system is related with receiving a user's-guide in writing for functionality of the ventilation system and occupants experience with adjusting the system and their feeling of having control over the system.

By obtaining a larger pool of data, the results might be changed, thereby other conclusions would be drawn from the survey.

Phase 2 (Fault impact detection)

The presence of faults in a typical Danish ventilation system can lead to an increased energy use. In this study, a simulation-based investigation was carried out. The following conclusions can be drawn:

Poor bypass damper operation is main cause of thermal energy increase (up to 90% in case of fully open stuck).

Other impactful faults on thermal energy use are poor insulation of ducts (up to 48% increase) and sensor faults (up to 27%).

Fans' efficiency degradation may lead to increased electric energy use (up to 40%).

The results obtained can be useful for producers and manufacturers of these systems. The results give awareness of the impact that poor design and operations (installation, improper design, inadequate maintenance) can have on systems' energy use.

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Appendix 1

Presentation of Phase 1 was carried out in the “DANVAK Temamøde”.

Appendix 2

An article is submitted to a scientific journal “Energy and Buildings” for peer review.

Improving Occupants' Satisfaction with Mechanical Ventilation using Technical and Non-Technical Solutions

This project is financed by Landsbyggefonden and focuses on evaluating the occupants' and building management's experiences with mechanical ventilation in renovated residential buildings in Denmark. The report proposes technical and non-technical solutions related to increased satisfaction with the ventilation system and with the indoor climate among occupants and staff. The project is divided into two phases:
In Phase 1, the importance of a new and adjustable mechanical ventilation system on the residents' satisfaction with the indoor climate and with the ventilation system is examined, as well as the inconveniences and functionality experienced by the new ventilation system.
In Phase 2, the effects of faults in a CAV AHU system on thermal and electrical energy consumption, thermal comfort and on indoor air quality are investigated. In the study, error models were developed that define KPIs and evaluate how errors can affect energy consumption and indoor climate conditions.

This project is financed by Landsbyggefonden