Method for evaluation of renovation measures with regard to moisture and emission loads
- Based on risk assessments

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Preface

I would like start by thanking all my supervisors for giving me this great opportunity, and the freedom to expand and divert during the work, allowing me the possibility to explore issues that concerned this research, and supporting me in that exploration. I would like to thank my main supervisor Jesper Arfvidsson for the support and guidance he has provided concerning my studies in general and his highly valuable support and encouragement in writing this thesis. I would also like to thank my co-supervisor Petter Wallentén for participation, help and guidance in the research project on interior insulation on masonry brick walls, in my literature study and as well as his support in my graduate studies and writing this thesis. Furthermore, I would like to thank my co-supervisor Dennis Johansson for participation, help and guidance in the research project on demand controlled ventilation as well as always taking time for the feedback I have requested, as well as his support in writing this thesis. Finally, I would like to thank Åsa Wahlström for supervising me in my literature study, my research on demand controlled ventilation and this thesis, and for always taking the time to provide me with invaluable feedback.

Thinking about the end-result of the project without the cooperation of involved companies does not paint a pretty picture. Therefore, I would like to acknowledge Swegon, and especially Andreas Wackenfors for the possibility to utilize their facilities in Tomelilla, for allowing me to borrow some measurement equipment and for providing the contacts needed for evaluating their demand controlled ventilation system in-field. At Swegon Air Academy, I would like to thank Petra Bednarova for supporting me in acquiring measurement equipment for the research project. In addition, I would like to thank Hyresbostäder i Norrköping, and specifically Magnus Lagerström, for the possibility to freely navigate in the apartment building in which the demand controlled ventilation system was installed, the support with installation of necessities for our measuring equipment, the time he set aside for me and the support with surveys for the evaluation. At Akademiska Hus in Lund, I would like to thank Torbjörn Fischbeck for making measurements possible in the Lund University V-building and for providing access to the measurement site at all times. Finally, I would like to thank ÖrebroBostäder, and especially Lars-Göran Andersson and Mats Andersson for making measurements possible in Örebro, and for their invaluable support with measurement equipment installation, beside their generous hospitality.

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Abstract

Renovating the European building stock has for almost two decades been a matter of importance. For Sweden, it is important to renovate its multifamily buildings in order to achieve a reduced energy use, but also because renovation is needed due to building materials and services reaching (or having passed) the end of their life span. In order to renovate properly, renovation measures must be implemented correctly to avoid negative impact on the building materials and the indoor environment. For this purpose, renovation measures need to be evaluated with regards to moisture and emission loads, and the risks related to these. This thesis has developed a realistically applicable method for this type of evaluation, called RememberL, and tests RememberL on two renovation measures as case studies. Through laboratory tests, in-field measurements, building performance simulations, hygrothermal simulations and surveys, the renovation measures are evaluated according to the methodology. RememberL thereby yields useful results for understanding the impact that these methods have on building materials and the indoor environment and vice versa. Furthermore, through the application of RememberL on these case studies, it is further developed to a method that proves flexible through several alternatives.
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1 Introduction

In this chapter, the background for this research is motivated as well as the aim of the thesis, its limitations, the disposition of the thesis, and finally the publications included in this thesis.

1.1 Background

Renovating the European building stock has for almost two decades been a matter of importance to the European Union, as stated in several directives such as 2002/91/EC (European Commision 2002) and 2010/639/EU (European Commission 2010). Furthermore, recently the Swedish government together with other political parties agreed on an aim to achieve a 50% more efficient energy use in Sweden by 2030, and one of the agreed measures is to reduce the energy use of Swedish houses and businesses (Regeringskansliet 2016). According to IVA (2012), such reduction of energy use for existing buildings can be achieved through applying energy efficiency renovation measures with a high renovation rate. Besides the importance of reaching energy and environmental goals, there is quite a large renovation need in Sweden due to building materials and services reaching (or having passed) the end of their life span (Boverket 2009).

Between 1946-1975 approximately 1.4 million apartments in multifamily buildings were built in Sweden in order to satisfy the needs for housing (Allmännnyttan 2016). Many of these are now (or soon will be) in need of renovating. However, fortunately, many of these buildings share common characteristics that are directly related to the building technology used at the time in order to satisfy the quick building rate needed in order to satisfy the need. Common building characteristics include framework in load-bearing reinforced concrete with exterior masonry walls (often brick) (Boverket 2009). Common ventilation characteristics include mechanical exhaust without heat recovery and natural ventilation, less common is balanced mechanical ventilation with heat recovery, and least common is balanced mechanical ventilation without heat recovery (Boverket 2009). Some of these buildings have culturally protected facades, making it impossible change their appearance, e.g. through applying exterior insulation. Any renovation measure is thereby restricted to the interior of the building, whether it be added insulation to the building envelope or installation of a new ventilation system. Incorrectly implemented, renovation measures can have negative impact on the state of the building materials, the Indoor Air Quality (IAQ) and the Indoor Environmental Quality (IEQ). This in turn affects the occupants’ well-being and comfort and the energy efficiency outcome of the renovation measure, and can result in social, economic and environmental damage to those affected by the renovation measure (Fisk et al. 2010; Coombs et al. 2016; Mudarri & Fisk WJ 2007).

In order to avoid negative outcomes, possible renovation measures need to be evaluated with regards to impact on the building materials and the IEQ. For choices of renovation measures, Lind et al. (2016) argue for technical sustainability, and emphasize that the durability and reliability of the building materials, and the risks connected to implementing them should be prioritized. However, in order to this, moisture and emission loads which are connected to different renovation measures
need to be determined. This, in order to assure minimum impact on the building materials and the IEQ but also for being able to predict the impact.

A multifamily building must fulfill a number of requirements. Besides national, regional, and local municipalities and organizations, such requirements are set by building owners. These requirements do not only control the design, construction and renovation of a building, but also act as guidelines for meeting demands stated by society in general as well as by those most subjected to the impacts of these choices – the occupants. It is obviously of utmost importance that the safety and comfort of the inhabitants is fulfilled – not only out of safety and moral aspects, but also out of sustainability and profitability aspects. The occupants state a number of demands on their dwellings – among them are demands on the indoor environmental quality and thereby the heating, ventilation, plumbing, water, and waste water systems, as well as space, building materials, aesthetics, and the list goes on. Each change (i.e. renovation) in any of these systems or components will therefore directly or indirectly affect the occupants. A considered renovation measure should therefore achieve a sustainable, and safe environment. A part of that safety is the moisture safety in the design, as well as a sustainable indoor environment. The measure should therefore be evaluated, which sometimes can be done through the application of benchmarking procedures or other independent evaluations. Methods for evaluations of renovation measures out of energy, thermal comfort, CO₂-emission reduction, occupant exposure to CO₂, and cost have previously been proposed and tested (Lizana et al. 2016; Ma et al. 2012; Heijmans et al. 2008; Malmgren & Mjörnell 2015; Vilutiene et al. 2015; Ibn-Mohammed et al. 2014). However, only one of these consider the indoor air quality in terms of emission exposure, and none consider the hygrothermal status of the building materials. Besides, they do not focus on evaluation a renovation measure in and of itself, but instead they focus on the choice of renovation measures with regards to the mentioned aspects. Furthermore, it seems to be common to focus on energy aspects and less common to focus on other aspects in research on renovation of multifamily houses, such as hygrothermal and IEQ, as shown by the appended literature review (Paper 3).

1.2 Aim
This thesis aims to propose a practically applicable and realistic method for evaluation of renovation measures, based on empirical data from case studies. This with regards to moisture loads on the building materials and emission loads in the indoor climate based on risks related to these.

Through the application of the proposed method, this thesis also aims to collocate and analyze existing relevant publications on impact of renovation measures, and identify lack of research on specific renovation measures with the hope to fill that gap by determining the impact of such renovation measures.
1.3 Limitations
The empirical base for developing and applying the proposed method was limited to two case studies (two applied and evaluated renovation measures) and a literature review.

Regards to impact of loads were limited to existing mathematical models for determination of risks concerning the building materials as well as guidelines concerning the IEQ. The applied mathematical models treat microbiological growth on biological building materials and corrosion of reinforcement. Existing guidelines for IEQ were regarded for occupants’ well-being, as well as the impact on energy efficiency.

The publications regarded in this thesis have been limited to published literature written in Swedish or English from available digital and printed sources through Lund University library services.

1.4 Disposition
This thesis starts with an introduction, explaining the research motive and aims, and continues with a declaration of the limitations posed on the conducted research. It then describes the proposed method, called RememberL, the motivation for chosen case studies, and the application of RememberL on case studies. Finally, RememberL itself is discussed as well as the application of it, which leads to final conclusions for this thesis.

1.5 List of publications
The following publications are included in this thesis (see appendix C), and are results from applying RememberL in two case studies.

Paper 1

This paper is an analysis of laboratory tests of a demand-controlled-ventilation system for multifamily buildings, and specifically the control design with regards to emission and moisture loads. I contributed through a literature review, study and test planning, arrangement of the possibility for lab-tests in a mock-up apartment provided by Swegon, supervision of the tests as well as part-taking in them, parts of the analyses of the results, and writing the paper.

Paper 2
This paper is a study on the moisture supply set point for a demand-controlled-ventilation system for multifamily buildings, with regards to a sensitive exterior wall construction with interior insulation in existing multifamily buildings. The assessment of the set point for the moisture supply was conducted with regards to interior and exterior moisture loads and the impact of these with regards to the risk for microbiological growth on possible biological building materials in the exterior wall. I contributed through a literature review on moisture supply in correlation with material deterioration risks, study and simulation planning, conducting simulations and analysis, and writing the paper.

Paper 3

This paper is a literature study on renovation of multifamily buildings, conducted mainly in cooperation with fellow Ph.D. student Karin Farsäter. The study served several purposes, among them were to identify the lack of research on renovation of multifamily houses in temperate climates, in order to determine the need for such research. My contribution was conducting searches for, as well as analyzing and writing the parts on status determinations and renovation measures. I also wrote parts of the background, method description, discussions and conclusions.

Paper 4

This paper is a summarizing analysis on a demand-controlled ventilation-system (DCV-system) for multifamily houses, based on a case study. The paper evaluates the DCV-system with regards to interior moisture and emission loads and impact on building materials, building energy efficiency, and occupants’ well-being (IEQ). My contribution was conducting a literature review, planning and conducting parts of the in-field measurements and surveys, simulation study planning and supervision, conducting calculations on thermal efficiency, most of the result analysis, and writing the paper.

Paper 5

This paper is an evaluation of interior insulation on exterior solid-brick-masonry walls in multifamily houses, based on two case studies. The evaluation regards interior and exterior moisture loads and analyzes impact on building materials (mold, corrosion). My contribution was conducting a literature review, planning and conducting parts of
the in-field measurements, planning and conducting all hygrothermal simulations and result analyses, and writing the paper.
2 Methodology

In this chapter, the method for reaching the aim of the thesis is described and named. Furthermore, as the method was applied to two renovation measures for further development based on empirical data, the choice of renovation measures is motivated.

This thesis proposes a realistically applicable method for evaluation of renovation measures based on empirical data collected through case studies. This method is through this thesis named **RememberL**, which is in part an acronym for **Renovation Measure Evaluation Based on Risks from Emission and Moisture Loads**. The initiation of RememberL’s development started from the need to evaluate renovation measures with focus on material durability and indoor environment. There are many methods for evaluation of renovation measures that focus on energy, thermal comfort, CO₂-emission reduction, occupant exposure to CO₂, and cost (Lizana et al. 2016; Ma et al. 2012; Heijmans et al. 2008; Malmgren & Mjörnell 2015; Vilutiene et al. 2015; Ibn-Mohammed et al. 2014). However, only one of these consider the indoor air quality in terms of emission exposure (specifically CO₂), and none consider the hygrothermal status of the building materials. Furthermore, they do not focus on the evaluation of a renovation measure itself, but instead they focus on the *choice* between renovation measures with regards to the mentioned aspects. In contrast, RememberL focuses on evaluating the impact of a chosen renovation measure on moisture and emission loads, and vice versa. In such an evaluation RememberL *prioritizes* the risks related to these loads, and the impact these have on the status of the building materials and the quality in the indoor environment.

RememberL was at first a loosely based method for evaluation of renovation measures. RememberL including the following steps, (which are summarized in Figure 2.1):

- **Literature review**, to ascertain existing knowledge within the field and to find a point of reference to compare the renovation measure against, i.e. a *benchmark* (a standard or point of reference). This benchmark could be a previous evaluation of the renovation measure, a competing measure, a reference value, or the case before the application of the renovation measure.

- **Determination of the loads** that the measure affects or are affected by the measure, with regards to possible relatable risks that are possible to determine through either mathematical models (benchmarking tools) or existing standard values.

- **Choice of benchmarking option** appropriate with regards to the above, and form of data acquisition. E.g. if the measure affects or is affected by the relative humidity in the indoor air, and a benchmark exists for the relative humidity with regards to moisture damage on common indoor items, the choice here would be to choose a benchmarking method were the resulting relative humidity is assessed towards that benchmark.

- **Benchmarking** through comparing results from measure application with a benchmark, thereby considering risks involved. This could be done towards a
previous evaluation of the renovation measure, a competing measure, a reference value, or the case before the application of the renovation measure.

The application of RememberL was limited to renovation of multifamily buildings in Sweden, built 1945-1970. Furthermore, the loads considered in the application of RememberL have been limited to those affecting the hygrothermal status of the building materials, and the indoor environmental quality.

2.1 Renovation measures in case studies
RememberL was applied to two case studies with regards to multifamily buildings in Sweden: interior insulation on exterior solid masonry walls and demand controlled ventilation. Amongst other measures, the literature study (Paper 3) showed a lack of research conducted on these two measures, even though they might be quite attractive measures for improving energy efficiency and indoor air quality.

In the literature review (Paper 3), only a scarce few evaluate interior insulation through application in multifamily buildings (Sjöberg & Wichlaj 2007; Morelli et al. 2012). These evaluate the application through hygrothermal measurements, thermal simulations with regards to moisture loads on the building envelope and mold risks associated with this. Neither of these evaluate the renovation measure through hygrothermal measurements and hygrothermal simulations for Swedish multifamily buildings. Besides these references, several other references evaluate interior insulation on exterior masonry walls (Vereecken & Roels 2014; Vereecken 2013; Toman et al. 2009; Pavlík & Černý 2009; Johansson et al. 2014; Klösheiko et al. 2014). None of the applications are evaluated for Swedish multifamily buildings, which might differ in terms of wall composition and moisture loads.
In the same literature review (Paper 3), only one paper (Pavlovas 2004) was found for specifically evaluating demand controlled ventilation for renovation of multifamily houses. Besides this, another paper evaluates a DCV-system for newly built apartment buildings (Hesaraki & Holmberg 2015). Both of these papers evaluate DCV-systems out of impact on the CO₂-levels, humidity, and VOC-levels in the indoor environment. However, none do so with regards to the risks of the loads on the building envelope, and both do so through simulations but not in-field measurements, thereby not asserting the impact of or on existing loads. Furthermore, neither ventilation system in question is controlled on VOC.
3 Method application in case studies
This chapter describes the application of RememberL in the case studies, and the results of steps of that application, i.e. the empirical data from the application of RememberL for further development and detailing of RememberL.

3.1 Case study - Interior added insulation
Interior added insulation is known to pose material issues due to decreased hygrothermal performance of the existing building envelope, which may lead to increased risks for reinforcement corrosion, microbiological growth, frost expansion, etc. All applications of interior insulations reduce the temperature of an existing unventilated masonry wall, however, that does not mean that all interior insulation increases the humidity content, which is in part due to different functionalities of different insulation types (Vereecken & Roels 2014). For multifamily buildings, research based on effects by interior insulation on masonry walls is scarce, and even more so for Swedish multifamily buildings. None of the references under 2.1 are directly applicable as benchmarks, but do provide insight on the determination of existing loads and benchmarking procedures. Besides the references under 2.1, several references have been found to be useful guidelines for this type of evaluation (D’Ayala & Aktas 2016; Künzel & Kießl 1996; Pavlík & Černý 2009; Toman et al. 2009). The two common impact factors investigated from a hygrothermal perspective is: 1) internal moisture loads, which can be expressed in moisture supply (difference between vapor content outdoors and indoors), and 2) external moisture loads, specifically - wind-driven rain. In this case study, these loads were determined through in-field measurements on masonry walls in a Swedish multifamily building and a building with similar wall composition. Through these measurements, differences in load impact depending on cardinal direction, depth, vertical placement, etc. served as guidelines for further benchmarking through simulations. The results enacted guidelines for further assessment on the impact of the renovation measures with regards to the included loads. The loads’ effect on the outcome of the application of the measure, as well as the measures’ effect on the outcome, were determined through use of existing mathematical models for risks concerning the building occupants and materials.

3.1.1 In-field measurements
Lund University V-building, Lund
A part of the Lund University campus, and the Faculty of Engineering, the V-building hosts offices, lecture rooms, group work rooms, and a large laboratory. The building consist of six floors including the basement, and has exterior walls of solid brick masonry (red brick + mortar), which are 1½ ‘stone’ thick (approx. 375-385 mm). The V-building underwent an extensive renovation during 2014-2016, under which interior surfaces, insulation, windows, electricity, network, ventilation, water and waste water systems were renovated.
The facilitator for this building allowed us to install temperature and relative humidity sensors in the exterior walls of the building for assessment of interior insulation on solid masonry walls (Paper 5). In order to determine the moisture loads on the building envelope for further benchmarking, the sensors were placed in different cardinal directions (north, south and west), separately in brick and mortar, and on different depths from the interior surface (see Figure 3.1.2 to Figure 3.1.4). The building is situated approximately 86 m above sea level, and a 3D-model from Google Earth of the building is presented in Figure 3.1.1. In the attic’s southern and western wall the sensors were placed as shown in Figure 3.1.2 and Figure 3.1.3. In the attic’s northern wall the sensors were placed as shown in Figure 3.1.4.

Figure 3.1.1: V-building, Google Maps.
Figure 3.1.2 Approximate location of sensors installed in southern and western walls. Blueprint provided by Akademiska Hus.

Figure 3.1.3 Approximate vertical location of sensors installed in western wall. Blueprint provided by Akademiska Hus.
Multifamily buildings, Örebro

A block of three multifamily buildings in Örebro (see Figure 3.1.5), were fully renovated 2013-2016, with the addition of two stories (see appendix A1). Each building consists of 29 apartments, and underwent a quite extensive renovation which replaced the elevator, all fill-in walls, interior surfaces, kitchens, bathrooms, fresh and waste water pipes, and the entire electricity, data, heating and ventilation systems.

For the work on Paper 5, hygrothermal sensors were installed in various depths within the masonry wall and in different cardinal directions (see appendix A2). They were also installed in different vertical placements, and as the composition of the exterior walls for these buildings differs from V-huset’s walls, the sensors were installed in each of the different material layers shown in Figure 3.1.6 until Figure 3.1.8. The sensors in the masonry wall were installed at depths in the masonry wall which approximately corresponds to the depths for the sensors in V-huset from the exterior surface.
From the outside in:
- 1 stone (250 mm) solid brick masonry
- 15 mm cavity
- 70 mm mineral wool between steel studs
- 0.2 mm vapor barrier (PE-foil)
- 45 mm mineral wool between wooden studs
- 12 mm OSB
- 13 mm gypsum board

Figure 3.1.6: Wall composition of northern and southern exterior walls for the multifamily buildings in Örebro. Sensor placement in the wall: red – brick, blue – mortar, green – air/mineral wool. Approximate sensor depths from the interior surface of the masonry wall: 90, 150 and 200 mm. Blueprint provided by ÖrebroBostäder.
Load determination results for further assessment

The results from these measurements are described in more detail in Paper 5. Through analysis of the measurement results with regards to the climate in Lund and Örebro (see appendix B1 and B2), the following knowledge was gained for use in further assessment of the renovation measure.

For the case without interior insulation (Lund):

- Differences between materials in an uninsulated wall are season-dependent. Warmer seasons result in higher temperature and humidity fluctuations and differences, especially in warmer walls (south and west).
- Differences between hot and cold months show that uninsulated walls in different cardinal directions should be considered in an evaluation, as the wall towards the north is much more humid during the summer.
- Differences between hot and cold months indicate that the solar driven vapor in the direction which is most subjected to wind driven rain should be considered. The masonry wall to the south in this case is the driest, even though this is the one most subjected to wind-driven rain according to climate analysis (see appendix B1).
- Differences in depth show that sensors closest to the interior surface are the most humid during the summer but driest during the winter. Together with the previous observation, this strongly indicates that solar driven vapor is pushed towards the interior during the summer, making it a considerable load to include in further evaluations.

For the case with interior insulation (Örebro):
- Interior insulation impact on the hygrothermal performance is substantial in comparison with the uninsulated wall in Lund. The differences in spread between the two cases for the sensors in the masonry wall shows much smaller hygrothermal differences for the case in Örebro. This also applies to differences between the materials in the masonry wall, allowing us to disregard material differences in further assessment of internal insulation.
- The humidity is higher in the upper part of the façade than the lower. The height above ground in further assessments should therefore be considered.
- The results show similar seasonal differences in the depth from the interior surface, strongly suggesting solar driven vapor as an important impact factor in further assessment. The results also show that interior loads pose minor or nonexistent risks with an applied vapor barrier.
- The results also show that if any biological material exists between the vapor barrier and the exterior wall, there is a high risk for mold growth.

3.1.2 Hygrothermal simulations

**Internal moisture loads and external**

In Paper 2 internal and external loads on an internally-insulated exterior solid-brick-masonry wall without a vapor barrier were simulated. The results show that both with and without internal moisture loads, external loads are far superior and pose a much larger risk for mold-growth than internal loads. Internal loads do however also pose a significant risk for mold-growth and should not be disregarded.

Paper 2 also compared different geographically bound loads (external climate) to be used for further generalized benchmarking results, showing that some geographical Swedish locations gave a much decreased hygrothermal performance for the same wall. The geographical locations were chosen with the assumption of the existence of multifamily houses built 1945-1970.

**Benchmarking**

For a realistic outcome from the used hygrothermal simulation tool, Paper 5 validated the tool and the model of the V-huset’s wall built within the tool. The validation showed that the simulation tool gives results for the wall model that are worse than actual with regards to risk of microbiological growth. It was however unclear if this was due to the tool itself or the climate data (specifically the solar radiation data), but most likely it was the latter. Nevertheless, the results suggest that the tool and model should provide a safety margin in the benchmarking.

For a determination of risks based on the hygrothermal status of the building envelope, a literature review was conducted in search of mathematical risk assessment tools that can be applied on measurement or simulation results for benchmarking different measures. Although internal insulation of exterior masonry walls is associated with a number of risks, tools for determination of this risk are scarce. Fortunately, two risks can be considered with the tools that exist today: the mold-
growth risk based on relative humidity, temperature and time (Sedlbauer 2002; Viitanen 2007; Mundt-petersen et al. n.d.; Thelandersson & Isaksson 2013) and a newly developed tool for the assessment of corrosion of bed-joint reinforcement of solid-brick masonry walls based on relative humidity, temperature and time (Larsson & Molnar 2014). These two were used for a final benchmarking of different measures for internal insulation considered in Paper 5. Furthermore, as Norrköping was previously (Paper 2) identified to have superior exterior moisture loads in a number of Swedish geographical locations that may contain multifamily buildings in need of renovation, climate data for this location was chosen for a more generalized outcome (see appendix B3).

3.2 Case study – Demand Controlled Ventilation
A Demand Controlled Ventilation (DCV) system has been developed for renovation of multifamily houses. The control strategy for this DCV is novel and bases the regulation of the air change rate (ACR) for each apartment in a multifamily building on continuous measurements of the moisture supply, the difference between vapor content indoors and outdoors, and on the content of Volatile Organic Compounds (VOCs) in the exhaust air. Based on certain set points for these parameters, the air flow is automatically increased or decreased in order to achieve good IAQ and optimal energy efficiency. An example of a setup for this ventilation in an apartment is illustrated in Figure 3.2.1.
To be able to evaluate the controls for the DCV-system, and thereby the set points for the ventilation rates, Paper 1 reviewed literature on indoor air pollutants, technical data on the system and the installed measuring devices, as well as important indoor air parameters (impact factors) such as VOCs and moisture supply in multifamily houses. No previous evaluations of the system were found and neither could sensor readings be related to effects on occupants’ well-being or ventilation air change rate. The only references that were found, were on the sensor used for DCV-control based on VOCs (Herberger et al. 2010). This reference shows correlations between VOCs and CO2 (a widely accepted IAQ-indicator), however, the tests of the sensor by Herberger et al. (2010) were conducted in office environments and therefore the reference was deemed insufficient as a benchmark for evaluation of this DCV-system for Swedish multifamily houses. However, other references (Johansson et al. 2011) have found that the output from the mixed-gas sensor used in the DCV-controls (AppliedSensor n.d.) partly correlates with CO2 –levels in Swedish multifamily houses, but on building level. Although the found references provide guidelines for evaluating the DCV-system through in-field measurements, the DCV-system was analyzed in Paper 1 through laboratory testing. This in order to determine the impact on the system functionality by (VOC and moisture) loads induced by common household activities on apartment-level.
Traditionally, CO$_2$ is used as an indicator of the indoor air quality (IAQ) and is a combustion product as well as a human effluent (Bernstein et al. 2008). CO$_2$ is believed to be an indicator for the indoor air quality because it correlates with higher levels of other indoor-generated pollutants [e.g. VOCs], but should also be considered a pollutant (Satish et al. 2012) that affects cognitive processes. VOCs are a range of pollutants that can be found in numerous products; e.g. building materials, but also a result of daily household activities (Paper 1), and may affect human health negatively in certain concentrations (Herberger et al. 2010). It is therefore imperative to remove these pollutants from the indoor environment, or at least minimize their content in the indoor air so that they do not affect our health negatively. However, the applied VOC-sensor is not cross-sensitive and therefore measured pollutants are not specified. Benchmarking directly towards a known VOC-guideline is therefore not applicable. Output from the sensor has therefore correlated with CO$_2$ values, for determination of the IAQ and system functionality with regards to CO$_2$ guidelines.

Besides VOCs, the system is also run on moisture supply controls. Through a set level for a maximum allowed moisture supply in the indoor air (i.e. a set point), the ventilation increases. However, no benchmark could be found for this specified parameter with regards to moisture safety risks. To be able to evaluate this functionality of the system with regards to loads in the indoor environment as well as risks for the building envelope, a load determination was conducted (Paper 2). A design load was determined with regards to existing mathematical models for mold-growth on biological building materials. This design load was recommended as the moisture supply set point for the system.

Several sources have shown that DCV can result in considerable energy savings in comparison to conventional ventilation systems run with a constant air volume (CAV) (Mysen et al. 2003; Dounis & Caraiscos 2009; Mysen et al. 2005; Jeong et al. 2010; Herberger 2009; Lu et al. 2011; Wachenfeldt et al. 2007; Pavlovas 2004; Laverge et al. 2011), but only one of these is conducted on a multifamily building (Pavlovas 2004). However, Pavlovas (2004) evaluation is not conducted based on measured internal moisture and VOC loads, but on simulated loads based on assumed schedules of the occupants. The loads that actually impact the indoor environment, the building envelope or the operation of the system have therefore not actually been determined. Thereby, none of these references can directly serve as benchmarks. However, the references can act as guidelines for benchmarking procedures, but a load determination is needed in order to simulate the system correctly for an energy and IAQ benchmarking (Paper 4).

### 3.2.1 Laboratory tests – control scheme

The functionality of the sensor in demand controlled ventilation system was analyzed (Paper 1) through laboratory testing in a mock-up apartment. The system response and response time were evaluated with regards to common activities that constitute loads in the indoor environment and induce VOCs and moisture. Results reaffirmed producers’ intentions with the sensors and ventilation system design, and even though
the system could not be fully evaluated with regards to effect on the indoor air quality or the building envelope, the test results implied possible consequences of the demand control design and the system design:

- There is approximately a 5 min delay between pollutant induction and reaction by the system, which allows the pollutant to spread across the apartment a longer time with low minimum ACR than high minimum ACR.
- Idle occupant presence does not constitute a sufficient load for increased ACR.
- Sensors react to a variety of unwanted loads induced in the indoor environment, and some substances that cannot reasonably be considered loads.
- Measurements showed that a undetected pollutant (specifically CO2) kept rising with no response from the system, resulting in a recommendation to increase minimum ACR or decrease the lower threshold for system response.

The test resulted in recommendations to further assess the ventilation system in-field (pilot test).

3.2.2 In-field measurements
A part of Hyresbostäder i Norrköping AB’s building stock, a group of multifamily buildings were finished in 1965, and consist of apartments with 1-2 rooms and with similar layouts. Before renovation, the ventilation was a balanced mechanical ventilation system with supply and exhaust air but without heat recovery, and the supply air was heated with a unit connected to the district heating system. The new DCV-system and cooker hoods was installed for 24 apartments within this building. Distributing boxes, main ducts to and from the AHU in the attic, and serviceable components were installed in the multi-story staircase space (hallway) and in the attic (see appendix A3).

In-field measurements were conducted before and after renovation (see appendix A4), but were predominately used for load determination with regards to the indoor environment (VOC, CO2, relative humidity, temperature) and system functionality (ACR, air flows, temperatures by heat exchanger) for further benchmarking. Unfortunately the in-field measurements could not significantly provide enough data for a complete benchmark of the new system in comparison with the system before renovation. However, in-field measurements gave information on the system functionality (response to loads), and produced data for comparison between MOS-sensor output and CO2 levels, for correlation assessment.
3.2.3 Simulations and calculations

Energy use of the apartments could not be determined through measurements (Paper 4) before and after renovation, as energy measurements were only conducted on district level and not specifically on the 24 apartments that were included in the study. Loads that could affect the operation of the system and thereby the energy efficiency outcome were therefore determined through in-field measurements (Paper 4). These loads were then used in building performance simulation software for energy efficiency and IAQ benchmarking against conventional mechanical ventilation systems with heat recovery, and demand-controlled-ventilation with CO₂ and moisture supply control with (Paper 4). This analysis was complemented with a thermal efficiency calculation for benchmarking against CAV-systems with and without heat recovery (Paper 4). These benchmarking procedures showed considerable energy savings in comparison to the previous system, and in comparison with a CAV running on the maximum air flow that the DCV could supply, while still having achieved good IAQ. In comparison with a conventional CAV running on minimum requirements by Swedish regulations, the benchmarking procedures showed that the energy use was higher for the investigated DCV, however they also showed that a better IAQ could be achieved in comparison with a CAV.

No benchmark was found through the literature study for risks on building materials with regards to the moisture supply (Paper 2). Therefore the moisture supply control was evaluated through mold-growth-risk analysis with regards to interior loads on interior vapor-open insulation on solid masonry walls (a common construction for the investigated houses). This analysis was conducted based on hygrothermal simulations (Paper 2), and resulted in a design load for application to the DCV-system.
3.2.4 Survey
Due to uncertainty in what loads the system considers (see 3.2.1), and as a complement to the laboratory tests (3.2.1), a survey was conducted for benchmarking of the system in comparison to the previous installation (Paper 4). The survey confirmed results from the lab-tests and from benchmarking based on in-field measurements.
4 Results

In this chapter, the results from developing RememberL through the case studies are presented, and a work flow chart for RememberL is proposed based on the empirically collected data.

Through the application of RememberL in the case studies, it was obvious that the loosely defined methodology (described under chapter 2) was insufficient for the cause and needed to be further developed and detailed. The work flow chart for RememberL is presented in Figure 4.1, and is the end-result of RememberL development through case studies. Basically, the flow chart applies to two cases of renovation measure evaluation: one where the measure under evaluation can be benchmarked through at least one of the proposed procedures by comparison with existing research results, and the other case is when the proposed measure cannot. Figure 4.2 shows how the two case studies fits into this flow chart.

The benchmarking procedures included in RememberL compare the resulting effect of applying the measure with a known reference point, a benchmark. This benchmark could be a previous evaluation of the renovation measure, a competing measure, a reference value, a reference value that may be correlated to an effect of the measure application, or the case before the application of the renovation measure. In the case of a found benchmark, sometimes determination of loads that the measure is subjected to is needed in order to choose a benchmarking procedure. An example of this is when a technical measure is to be applied as a renovation measure in a different environment than it is normally applied (e.g. in a reference case), the loads of the new case environment should first be determined in order to assess the impact of that environment on the measure and vice versa. The opposite would be when the loads are known or not needed in order to conduct benchmarking.

In the case of no existing benchmarks, e.g. when evaluating a new innovative measure or a new application of an existing measure, the logical step is to evaluate the measure with regards to the function that it is proposed to have, the consequences thereof, and the consequences of the impact of the loads on the measure and vice versa. This procedure might produce a benchmarking reference (a benchmark).

RememberL conducts benchmarking through a mix of analyses that regard human behavior and perception (e.g. surveys on the IEQ), as well as physically measureable parameters (e.g. relative humidity indoors). Furthermore, research conducted through application of RememberL may be both hypothetico-deductive as well as inductive.
LITERATURE REVIEW
BENCHMARK SEARCH.

NO BENCHMARK FOUND.

BENCHMARK FOUND.

E.G. APPLICATION IN A DIFFERENT ENVIRONMENT.

LOAD DETERMINATION
In order to benchmark a solution, sometimes a load determination is needed with consideration of possible consequences that may emerge from the application of the measure.
Laboratory tests, In-field measurements, Simulations

BENCHMARKING
With regards to loads in the indoor environment or on the building envelope and the risks associated with these.
1. Against results from previously conducted evaluations on the renovation measure.
2. Against performance by similar, related or competing measures.
3. Against benchmark for impact factor(s) affected by investigated measure.
4. Against benchmark for correlating impact factor(s), or impact factors that can otherwise be connected with impact factor of investigated solution.
5. Against case before application of renovation measure (as a benchmark).
Laboratory tests, In-field measurements, Surveys, Simulations

INDEPENDENT EVALUATION
Test of measure function with consideration of possible consequences that may emerge from the application due to its designated functions.
This might be the final step in an evaluation with no benchmarking references. However, the results from this evaluation might produce a reference for further benchmarking (a benchmark).
Laboratory tests – simulation of renovation measure application with regards to the loads that it will be affected by, e.g. test of responsiveness to loads and ability to maintain satisfying qualities.
In-field measurements – with or without applying the renovation measure. Determination through measurements of loads or impact through application.

POSSIBLE PATH (BENCHMARK ACHIEVED)

Figure 4.1: Work flow chart for RememberL.
LITERATURE REVIEW
- Insulation
- DCV
Previous evaluations on Swedish multifamily buildings, or benchmarks for impact factors affected by measure.

NO BENCHMARK FOUND.
DCV
- System functionality based on VOC- and moisture supply.
- Benchmark for moisture supply with regards to risks on the building envelope.
- Benchmark for MOS-sensor with regards to ventilation control and occupants' well-being in apartments, as well as typical household activities.

INDEPENDENT EVALUATION
DCV
- System functionality with regards to loads induced by common household activities.
- System functionality in-field (installed for apartments).

BENCHMARK FOUND.
- VOC in correlation with CO₂
  - CO₂ as IAQ indicator
  - Mold growth on building material mathematical model
  - Corrosion on reinforcement mathematical model
  - VOC benchmark with regards to risks on the occupants
  - Survey for IEQ determination

- CaSi not usually used in Swedish multifamily houses.
- Moisture Supply not usually related to mold growth risks.
- VOC loads in Swedish multifamily buildings have not previously been determined.

Lab-tests suggest impact by system design on IAQ.
LOAD DETERMINATION

*Insulation*
- Moisture loads on the building envelope depending on direction, vertical placement, material, season, etc. Design case determined for benchmarking through hygrothermal simulation based on these loads and risks related to them.

*DCV*
- VCC and moisture supply loads in Swedish multifamily building determined through in-field measurements with regards to system functionality.

BENCHMARKING

2. Against previous evaluations.
   *DCV* - CO₂-VOC correlation, apartments vs offices.

1. Against performance by similiar, related or competing measures.
   *DCV*
   - DCV (VOC+MS) vs DCV (CO₂+MS) vs CAV (low flow) vs CAV (high flow)
     Energy efficiency, IAQ

3. Against benchmarks for impact factor(s).
   *Insulation* - Hygrothermal simulation based on these loads and risks related to them.

4. Against benchmarks for correlating or connecting impact factor(s).
   *DCV* - CO₂-VOC correlation, VOC eq. ppm as IAQ-indicator vs CO₂ as IAQ-indicator.

6. Against case before application.
   *Insulation* - With and without insulation, hygrothermal simulations, hygrothermal measurements in-field.

*DCV*
- Surveys – IEQ perception change
- RH in some apartments
- System response to loads in the indoor environment (qualitative reasoning vs CAV)
5 Discussion

In this chapter, the end-results from applying RememberL in the case studies and the applicability of RememberL are discussed. Besides this, RememberL is compared to other methods for evaluation of renovation measures, and recommendations for further research are stated.

Application of RememberL on the two included case studies gave much information on the measures’ functionality and impact on the building envelope and on the indoor climate, but did not always produce definitive conclusions. The following summarizes the results of the evaluations conducted through the application of RememberL.

Interior insulation does decrease the hygrothermal performance of a building envelope which results in an increase of risks related to this. This decrease depends dominantly on the exterior loads but also on the interior. Demand Controlled Ventilation could be beneficial for the building envelope, the IAQ as well as the energy efficiency of a building, as it considers the individual loads of each apartment and ventilates accordingly. However, the energy efficiency for DCV-systems depends on the interior loads, and with higher loads comes higher ventilation rates, which affects the energy use of the building.

In order to achieve more definitive conclusions from the application of RememberL, the research should be conducted on a larger scale, and the same data acquisition methods should be used in a closely similar manner before and after the application of a renovation measure. The ideal scenario would be to apply the measures to buildings that have reference buildings for comparison after renovation. However, to presume that two buildings and their occupants are exactly the same with regards to each other, is wishful thinking. The same applies to one building in and of itself and its occupants over time - both internal and external loads may vary over the years due to changed occupant habits and/or climate change. Therefore the acquired data from such a scenario may not provide material for entirely accurate evaluations.

RememberL has been developed through application on the included case studies, which were mainly renovations of multifamily buildings. However, since RememberL is defined in general it should be possible to apply on renovation measures for other buildings, and especially domestic buildings. Furthermore, although it is a method defined specifically for renovation measures, some parts might be applied in other cases.

For further development of RememberL, and in order to extend RememberL’s range of application, RememberL should be applied to further case studies. Furthermore, even if the case studies that have been included have applied most of the “steps” within RememberL, surely more steps, benchmarking options, and data acquisition methods can be defined.

As previously mentioned, there are other methods for evaluation of renovation measures (Lizana et al. 2016; Ma et al. 2012; Heijmans et al. 2008; Malmgren & Mjörnell 2015; Vilutiene et al. 2015; Ibn-Mohammed et al. 2014), and one of these consider the indoor air quality in terms of emission exposure (specifically CO₂), but
none (claim to) consider the hygrothermal status of the building materials. Furthermore, these methods are not focused on risk assessments of moisture loads on the building materials or emissions in the indoor climate, but may include risk assessments considering these loads in one way or another for the choice of renovation measures. RememberL focuses on a chosen renovation measure and evaluates this with regards to the mentioned loads and risks. Note that RememberL does not exclude economic, environmental or social impact of the measures, e.g. building energy performance, but prioritizes evaluation of renovation measures based on the risks related to the mentioned loads.

Hopefully, RememberL will be of use to other researchers evaluating measures for renovations of buildings, but also to building consultants when considering renovation measures.
6 Conclusions
The method, RememberL, has been successfully developed and tested through two cases studies. The application of RememberL was successful for providing information on the functionality of the investigated measures in the case studies. Furthermore, the impact of the renovation measures on the building envelope and on the indoor environmental quality could be assessed. Finally, the flexibility of RememberL provides more than one alternative benchmarking option in case something (e.g. a data acquisition method) should fail irreparably.
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APPENDIX A – More on case studies
A1 Renovation of multifamily building in Örebro

Figure A1.1: Exterior masonry wall in an apartment during renovation.
Figure A1.2: Beneath floor boards in living room during renovation.
Figure A1.3: Mold growth in interior insulation layer of an exterior masonry wall.
Figure A1.4: Example of weather protection during renovation.
Figure A2.1: Sensor installation behind new interior insulation with steel studs.
Figure A2.2: Sensor installation on both sides of vapor barrier applied with new interior insulation with steel studs.

Figure A2.3: Taken from Melrose et al. (2015). Hygrothermal monitoring equipment from SensiLog. The sensor case marked Id 11 is for placement inside porous building materials, while the other sensor case is for monitoring air (such as in cavities, indoor air, etc.). Both use sensors of type SHT75 from SENSIRION.
Figure A2.4: Sensor installation on both sides of vapor barrier applied with new interior insulation with steel studs.
A3 Renovation of multifamily building in Norrköping

Figure A3.1: Picture of distribution box in hallway during installation.
Figure A3.2: Picture of sensor and damper box in hallway during installation.
Figure A3.3: Picture of supply and exhaust air ducts in apartment during installation.

Figure A3.4: Picture of covered ducts inside apartments after installation.
Figure A3.5: Pictures of covered supply and exhaust air devices inside apartments after installation.
A4 Measurement equipment installation in Norrköping

Figure A4.1: Picture of sensor placement in ventilation system before renovation.

Figure A4.2: Pictures of sensors placed in ventilation system after renovation.
Figure A4.2: Pictures of sensor placement in ventilation system after renovation.
APPENDIX B – Climate Data

B1 Lund climate, V-building

The V-building is situated approximately 70 meters above sea level, in Lund city, in the Scania province, in the southern part of Sweden. The weather in Lund is described by the table below.

Table B1.1: Monthly average climate data from METEONORM 7, showing typical weather in Lund for a normal year based on a 10-year period.

<table>
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<tr>
<th>Month</th>
<th>Glo. Rad. Horiz., kWh/m²</th>
<th>Dir. Nor. Rad. kWh/m²</th>
<th>Air Temp /°C</th>
<th>Rel. Hum. /%</th>
<th>Wind Sp. /ms⁻¹</th>
<th>Wind Dir. /°</th>
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Figure B1.1: Sunshine duration from METEONORM 7, showing typical sunshine duration in Lund for a normal year based on a 10-year period.
Figure B1.2: Precipitation from METEONORM 7, showing typical precipitation in Lund for a normal year based on a 10-year period.

Figure B1.3: Temperature data from METEONORM 7, showing typical temperatures in Lund for a normal year based on a 10-year period.
Figure B1.2: WUFI analysis of solar radiation and precipitation in Lund in 2014. The brighter color in the left figure indicates a larger annual solar radiation sum, showing stronger intensities in the south than in the north or the west.

B2 Örebro climate
Situated 35 m above sea level.

Table B2.1: Monthly average climate data from METEONORM 7, showing typical weather in Örebro for a normal year based on a 10-year period.

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Figure B2.1: Sunshine duration from METEONORM 7, showing typical sunshine duration in Örebro for a normal year based on a 10-year period.

Figure B2.2: Temperature from METEONORM 7, showing typical temperature in Örebro for a normal year based on a 10-year period.
Figure B2.3: Precipitation from METEONORM 7, showing typical precipitation in Örebro for a normal year based on a 10-year period.

Figure B2.4: WUFI-analysis of typical wind driven rain in and solar radiation Örebro, based on statistically assembled data in METEONORM 7.
B3 Norrköping climate

Building situated 54 m above sea level.

Table B3.1: Monthly average climate data from METEONORM 7, showing typical weather in Norrköping for a normal year based on a 10-year period.

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<td>3.5</td>
<td>85</td>
<td>3.8</td>
<td>270</td>
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<tr>
<td>Dec</td>
<td>10</td>
<td>6.0</td>
<td>0.4</td>
<td>85</td>
<td>3.8</td>
<td>270</td>
<td>32</td>
</tr>
<tr>
<td>Year</td>
<td>113</td>
<td>5.3</td>
<td>7.7</td>
<td>74</td>
<td>3.8</td>
<td>270</td>
<td>414</td>
</tr>
</tbody>
</table>

Figure B3.1: Sunshine duration from METEONORM 7, showing typical sunshine duration in Norrköping for a normal year based on a 10-year period.
Figure B3.2: Temperature from METEONORM 7, showing typical temperature in Norrköping for a normal year based on a 10-year period.

Figure B3.3: Precipitation from METEONORM 7, showing typical precipitation in Norrköping for a normal year based on a 10-year period.
Figure B3.4: WUFI-analysis of typical wind driven rain in Norrköping, based on statistically assembled data through METEONORM 7.
APPENDIX C – Appended papers
EVALUATION OF SET POINTS FOR MOISTURE SUPPLY AND VOLATILE ORGANIC COMPOUNDS AS CONTROLLING PARAMETERS FOR DEMAND CONTROLLED VENTILATION IN MULTIFAMILY HOUSES

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Keywords: Demand, ventilation, multifamily, VOC, moisture.

SUMMARY

The main purpose has been to evaluate existing set points (thresholds) and suggest proper set points, for the regulation of the air change rate in a demand controlled mechanical ventilation (DCV) system. The DCV is controlled by measurements in the supply and exhaust air of the vapor content and volatile organic compounds (VOCs) for each dwelling in multifamily houses. Results have been achieved through a literature review and laboratory tests. The threshold for the maximum ventilation rate (0.8 ac/h) should be set at 1000 ppm (CO₂-eq.). Preferably, a minimum ventilation rate of 0.5 ac/h should be set with current thresholds (800-1000 ppm CO₂-eq.). With a lower minimum ventilation rate (e.g. 0.1 ac/h) the lower threshold should be set at 450 ppm (CO₂-eq). In order to deal with heavy moisture production the threshold for the moisture supply is suggested to be set at 3 g/m³.

INTRODUCTION

A new DCV system for multifamily houses automatically regulates the air change rate for each dwelling according to the actual moisture supply and VOC-content in the indoor air. Outside each apartment, a box is placed including sensors and dampers that regulate the air exchange for the apartment based on the measured parameters. The VOC content is measured in the exhaust air for the whole apartment, while the vapor content is measured both in the supply and exhaust air in order to calculate the moisture supply (the difference in the vapor content). The idea with such design is to ventilate only as much as necessary at all times.

In order to deal with an increased VOC-content, the system increases the ventilation rate and sets it between 0.1-0.8 ac/h depending on the load. The increase of the ventilation rate is linear in a VOC-content interval of 800-1000 ppm (CO₂-eq.). For the moisture supply the threshold is set at 2 g/m³. When the moisture threshold is exceeded the system ventilates at the maximum air change rate (0.8 ac/h) until the moisture supply has reached below the threshold. After that, the system will stepwise decrease the air change rate to the minimum rate or a rate that corresponds to dealing with the VOC-load.

The system sets the highest ventilation rate that is needed to deal with either load. If the moisture supply is lower than the moisture threshold, while the VOC-content exceeds the VOC threshold, the airflow will be adjusted to deal with the VOC-load. However, if at any time the moisture supply is measured to be above the threshold, it does not matter what the VOC-load is at that moment, the ventilation rate will be maximized.
This control scheme gives rise to some questions. In order to achieve good IAQ, where should the set points (thresholds) for the VOC be set? In the case of a too low set point, the ventilation will unnecessarily increase the air change rate and thus result negatively on the energy efficiency. In the case of a too high threshold, the ventilation rate will be inadequate for achieving good IAQ. In addition, what are the maximum values on the measured parameters that we can accept in regards to loads on the building and in regards to the health of the habitants?

As the sensors register the content in the exhaust air for the whole apartment and not the individual rooms, one hypothesis is that the system will not properly deal with the actual loads in the individual rooms. A load in a certain room might be diluted when the exhaust air for the room mixes with the rest of the exhaust air. Therefore, VOC-concentration of e.g. 800 ppm (CO2-equivalent) in the bathroom or kitchen might only register as e.g. 600 ppm (CO2-eq.) in the total exhaust air. Consequently, a smaller load might not be detected as the variations might dampen due to the dilution. Depending on how the system is designed to deal with the measured load, the ventilation rate might become inadequate. The load in the room where the pollution originates or moisture production takes place might be damaging in regards to the habitants health and/ or the durability of the building material.

A recently started research project will evaluate and analyze field installations of the proposed ventilation system from both indoor environmental, energy and economical perspectives. This paper is a part of that project. All of the presented hypotheses in this paper concern the set points and the systems functionality. Therefore, the purpose here has been to evaluate the functionality of the newly developed system, to evaluate existing set points, and to suggest proper set points, for the decrease and increase in the air change rate.

**METHODS**

A literature review on evaluations of the MOS-sensor and literature on VOC, moisture supply and CO2 in correlation to ventilation rates as well as IAQ was made to cover the advantages and disadvantages of the system sensors in regard to the indoor environmental quality.

![Figure 1. Illustration of the laboratory and setup. VOC, RH and temperature were measured by sensors 1-6 and the box. Sensors A and B measured additionally the CO2.](image-url)
apartment is modeled after an existing Swedish 1-bedroom. It has been furnished with 2-hand furniture from a yard sale: among the furniture was a bed in the bedroom, sofas in the living room and a stove with a frying pan in the kitchen. The VOC-interval for the regulation was 800-1000 ppm (CO₂ eq.) and the threshold for the moisture supply was set at 4 g/m³. The tests have been limited to activities that are assumed common practice in multifamily houses. Such as idle presence, cooking, showering, smoking, peeling oranges and painting.

LITERATURE REVIEW

IAQ in regards to VOC and moisture supply

In a literature review, Bernstein et al. (2008) summarized the pollutants that we may encounter in the indoor air. The review mentions the following pollutants: particulate matter, gases, microbial and chemical VOCs, smoke and outdoor ambient air. Bernstein et al. states that many experts recommend that the air pollutant levels are maintained at 50% or less than the USA National Ambient Air Quality Standards (NAAQS) for outdoor air pollutants established by the USA Environmental Protection Agency (EPA, 2014). Numerous of other studies have determined the pollutants that exist in our homes, e.g. Wolkoff & Nielsen (2001). However, none of these studies correlate VOC-content to CO₂-equivalents or to ventilation rates. Therefore, the results are not applicable in this study and set points for the system can thereby not be determined by their presented results. The lack of cross-sensitivity in the MOS-sensor means that we cannot suggest thresholds for the output based on VOC-concentrations that are acceptable in our indoor air. Further research for determining such correlations might be necessary to produce an optimal ventilation strategy in order to achieve as healthy and energy efficient ventilation as possible through DCV.

A study of the sorption of VOCs in residential rooms showed that when the adsorption rate is competitive with the air exchange rate, VOCs are adsorbed into the surrounding building materials (Singer et al., 2006). The results of this study implies that the ventilation should be set so that it adequately deals with this phenomena, in order to decrease the concentrations of VOCs in the indoor air that the habitants are subjected to. A study made by Jørgensen in 2006 concluded that due to sorption of VOCs in building materials, an office should increase the ventilation rate from 0.67 ac/h to 2 ac/h a couple of hours before the work shift starts in order to lower the resulting concentrations. The tests were performed in a test chamber with a nylon carpet (Jørgensen, 2006) which might not adequately reflect multifamily houses, although by simulating the ventilation system in an office building that has higher ventilation rates than Swedish dwellings we believe that the results are on the safe side. Qinjin et al. (2012) also concluded that higher ventilation rates prevent sorption of VOCs in building materials. At lower air change rates≤0.1 ac/h sorption of VOCs are considerable, and at ≥0.5 ac/h some VOCs can be neglected, while at ≥5 ac/h sorption the effect is even weaker, and finally at ≥20 ac/h all sorption is negligible. These studies indicate that in order to deal with the VOC-sinks in our homes we need to have an adequate ventilation rate. We believe that this applies even more for the harmful substances that are not detected by the installed sensor.

A comprehensive study that have been conducted in Sweden, ELIB has determined the average moisture supply in multifamily buildings at 1.2 g/m³ with a ventilation rate of approximately 0.5 ac/h (Boverket, 2009). Johansson & Bagge (2010) have also determined the moisture supply to an average of 1.4 g/m³.

Previous evaluations of the sensors
There is no literature on the relative humidity (RH) and temperature sensor except for the data sheet from the manufacturer. According to this, the sensor can withstand 100% RH and has an inaccuracy of ±2.5% RH. For this evaluation, we will have to assume that this is correct.

The mixed gas sensor detects a variety of substances: alcohols, aldehydes, aliphatic hydrocarbons, amines, aromatic hydrocarbons, CO, CH₄, LPG, ketones and organic acids. It uses micro-machined metal oxide semiconductor (MOS) technology and has a sensing range of 0-2000 ppm (CO₂-eq), and is functional between 5-90% RH (AppliedSensor, 2014).

Herberger et al. (2010) have shown that when measuring VOCs with MOS-technology equivalent CO₂-levels of measured pollutants can be reliably predicted. However, the study was restricted to highly occupied meeting rooms. Another study made by Ulmer & Herberger (2012) has also shown reliable correlation of predicted and measured CO₂-concentrations in indoor spaces where no appreciable human activity takes place. However, this study was restricted to office rooms, meeting rooms and kitchens. In addition, a study made by Johansson & Bagge (2012) has also shown such somewhat of a correlation, although not strong. Of these studies only Johansson & Bagge’s (2012) apply for dwellings, and at the same time their measurements were not for individual dwellings separate from each other, but in the supply and exhaust air for whole apartment buildings. In other words, none of these studies properly reflect a single normally occupied apartment, which might not be a highly occupied environment and therefore the correlations may not be applicable when determining the set points for a healthy ventilation strategy in individual apartment dwellings.

In Herberger et al.’s article (2010) it is also stated that MOS-sensors are not cross-sensitive, which is a fallback. Therefore they also state that this kind of sensor cannot be used for a scientifically correct evaluation of air composition, but that a DCV based on this technology is at least better than a DCV based on CO₂-sensors as the MOS-sensor seems to offer a better correlation with perceived air quality.

DISCUSSION

Ventilation strategy with sensor limitations

Herberger et al.’s states (2010) that a MOS-sensor cannot be used for a scientifically correct evaluation of air composition, but that a DCV based on this technology is at least better than the more common DCV based on CO₂-sensors. They state that the MOS-sensor offers a better correlation with perceived air quality due to the detection of a variety of substances.

Kostianen (1994) found that the most common VOCs are alkylbenzenes, alkanes, terpenes, aliphatic aldehydes, and some chlorinated aliphatic hydrocarbons. In comparison to the specifications for the measuring device (AppliedSensor, 2014), we may deduce that the MOS-sensor used in this ventilation system should detect the majority of indoor air pollutants and therefore be an effective device to indicate the state of the IAQ.

CO₂ is sometimes used as an indicator for IAQ and this device has been shown to correlate somewhat with CO₂. Thereby setting the thresholds after recommended CO₂-concentrations levels might be the only applicable strategy, for now. This is confirmed by Herberger et al. (2010), and would mean that the maximum ventilation rate should be reached when the readings from the mixed gas sensor exceed 1000 ppm (CO₂-eq). Ensuring this CO₂-level will, according to ASHRAE, satisfy a substantial majority of visitors entering the space with respect to human bioeffluents. On the other hand, determining the minimum threshold for when the ventilation rate should start increasing is a bit more complicated. Through the literature review, we might deduce that this depends on how high the minimum air change rate is set. If the minimum air change rate is set to be ≥0.1 ac/h then the lower VOC -threshold should be as low as possible in order to ensure a healthy IAQ by dealing even with smaller
loads. If it is set to be ≥0.5 ac/h then the risk of an unsatisfying IAQ is lower as the ventilation rate might be adequate even for smaller loads. In the latter case, the threshold should be set higher in order to ensure that pollutants due to more significantly polluting activities are dealt with and at the same time ensuring energy efficiency. Preferably, the higher ventilation rate strategy is chosen as there are a number of pollutants that the sensor does not detect, thereby a higher ventilation rate should be applied to deal with such pollutants as well. At the same time, a higher ventilation rate might be the healthiest strategy, considering the other fallbacks that come with relying on DCV.

RESULTS FROM THE LABORATORY TESTS

Note that in Figure 2 the MOS-sensor in the box reached approximately 500 ppm (CO2 eq.) when three idle adults were present in the living room. Sensor VOC1 however reached at that time approx. 800 ppm (CO2 eq). When spraying the air freshener in the shower room, sensor VOC6 increased to a peak of approx. 1800 ppm (CO2) later to be followed (+ 15 min) by the box’s sensor with a peak of 800 ppm (CO2 eq.). This occurred for all tests when comparing the sensor first subjected to pollution and the sensor in the control box. The output from the CO2-sensors reached approx. 600 ppm during idle presence with an insignificant change of about +100 ppm during the spraying activity.

The same test as presented in Figure 1 was remade but with a minimum ventilation of 0.5 ac/h. We found that the box registered a VOC-peak significantly faster (within 5 min) and the VOC-content was reduced in a faster manner to levels existing prior to the spraying.

![Graph](image)

Figure 2. Results from the first test. T = 0 min, presence of three idle adults in the living room. T = 50 min, spraying air freshener in the bathroom. T=65 min, the smell of the air freshener is noticed in the living room. T=80 min, bathroom door is opened.
Figure 3. Results from the first test. T = 0 min, presence of two idle adults. T=9 min, frying activity commences. T=17 min, activity stops. T=41 min, no presence in the apartment.

CONCLUSIONS

Based on the laboratory tests

From the tests conducted in the mock-up apartment we may deduce the following:

1) Due to the system design and the placement of the control box the air is in fact greatly diluted and lower loads are registered with the controlling box’s MOS-sensor. This results in an insufficient ventilation rate in order to deal with the actual load at the source. Thereby also resulting in the spread of the pollutant to the rest of the apartment (as all other sensor outputs consequently followed). However, this did not occur for all tests as some pollutions that originated close to the extract supply resulted in a faster registration with the sensor in the box than the one placed right next to the source of pollution. See Figure 3, and compare VOC4 with VOC-Box.

2) The sensors and consequently the system do react to a variety of both occupant and non-occupant pollutants and increase the ventilation rate according to design. However, the sensors do not detect idle presence. Most likely for two reasons: a) the activity does not constitute a sufficient increase as a pollution, and b) the produced concentration is diluted before it reaches the controlling sensor and therefore not registered as a significant pollution.

3) A higher ventilation rate is preferred in order to deal with the pollutants in the indoor air as quickly as possible, preventing prolonged exposures. This conclusion is based on a remake of the test presented in Figure 2 but with a minimum ventilation rate of 0.5 ac/h.
4) For some tests two CO₂-sensors were logging simultaneously with the VOC-sensors. A thorough analysis of the correlation between these outputs has not been made, but the produced graphs suggest that such a correlation exists, although not entirely. This was expected as the VOC-sensors detect pollutions that the CO₂-sensors do not.

5) Stronger outputs for the VOC-sensors were noted for some activities over others. E.g. peeling oranges gave a higher output than frying eggs or spraying air freshener.

6) In some rooms the output was stronger than in others when no activity occurred in the apartment; compare outputs VOC2 and VOC3 in Figure 2. Most likely due to the emission of VOCs from the furniture as VOC2 was closer to the bed than VOC3.

7) When the threshold for the moisture supply is exceeded, the ventilation rate is maximized.

8) Tests indicate that the VOC-sensor reacts to moisture. However, we have not confirmed if this is the case as it is possible that VOC-emissions form the surface materials in the apartment are increased to a higher relative humidity (Xu & Zhang, 2011).

**Recommendation of set points and ventilation strategy**

The mixed gas sensor registers a variety of substances. However, the sensor does not register all substances that may exist in our indoor environment, to mention some: ozone and sulfur dioxide. Thus, even if the level of these pollutants are high, the system will not increase the ventilation rate in order to deal with them. Therefore, we do not recommend to rely solely on the output from the sensor in order to regulate the ventilation rate. A safer way is to determine a minimum ventilation rate in combination with a minimum threshold for the sensor output.

The literature review has shown that there is a lack of research within this area. Both when it comes to correlations between VOCs and CO₂ as well VOCs and ventilation rates. The recommended thresholds should thereby be based on indirect relations between IAQ and CO₂-concentrations in our indoor air, which is also the strategy suggested by Herberger et al. (2010). In addition, the ventilation strategy needs to consider fallbacks of the system design which is mainly: the effects due to the dilution of the pollution by the time it has reached the controlling sensor, the lack of cross-sensitivity and that not all pollutants that exist in our indoor air are detected by the sensor.

The threshold for the maximum ventilation rate (0.8 ac/h) should be set at 1000 ppm (CO₂-eq.), in coherence with current recommendations of achieving good IAQ based on CO₂-levels. Preferably, a minimum ventilation rate of 0.5 ac/h should be set with current thresholds (800-1000 ppm CO₂-eq.) in order to deal with the fallbacks of the system design and the MOS-sensor. If a lower minimum ventilation rate is instead chosen (e.g. 0.1 ac/h) the lower threshold should be lowered to 450 ppm (CO₂-eq), which was the outdoor lowest outdoor value registered by the system during a 3-month period.

The system provides satisfactory ventilation in regards to moisture supply above 4 g/m³, even though the registered moisture supply is a diluted value in comparison to the loads in the individual rooms. The threshold for the moisture supply is suggested to be set at 3 g/m³ in order to ensure that the system deals with heavy moisture producing activities but does not ventilate unnecessarily. Normal values on the moisture supply are 1.4 g/m³ and as the system regulates the ventilation rate mainly according to the MOS-sensor output with the moisture supply as a supplement, a high value should be set so that the supplement does not interfere with the main control, but at the same time deals with damaging moisture production.
ACKNOWLEDGEMENT

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Moisture supply Set Point for avoidance of moisture damage in Swedish multifamily houses

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Abstract

From 1950 until 1975 approximately 1.3 million apartments were built in Sweden. Now, a considerable part of these are in need of renovation. This paper is part of an evaluation of a new DCV system developed especially for the renovation of these houses. The DCV automatically regulates the air change rate for each dwelling based on measurements of the indoor air. One of the measured parameters is the moisture supply. Simply put, the ventilation rate increases when the measured moisture supply exceeds the set point based on a PI-controller. In this paper, simulations have been carried out to determine an appropriate set point for the moisture supply for avoidance of moisture damage on biological building materials. A worst case scenario has been considered – and the general maximal set point is recommended to be 3 g/m$^3$.

1. Introduction

To fulfill the demands by the directives of the European Union 2020 [1] and 2050 [2], Sweden must retrofit its current building stock in order to achieve a lower energy output. The multifamily buildings in need of renovation consist of more than a million dwellings. These were built from 1950 to 1975, and are in need of renovation or retrofitting mostly due to the building materials and building services having reached, or even passed, the end of their lifespan.

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Keywords: demand control; ventilation; moisture supply; multifamily; Sweden.
With new regulations in Sweden, renovated buildings must fulfill the same requirements as new buildings which means that they usually have to be retrofitted to a higher standard regarding moisture, energy and ventilation.

In order to renovate effectively and properly, new solutions must be developed to solve common issues that arise during and after the renovation process. These solutions must also be properly evaluated for optimization of energy efficiency and a healthy indoor environment. One such solution is a new ventilation system that has been designed especially for alleviating common issues that arise during the renovation process. The new system is a demand-controlled ventilation (DCV) system for multifamily houses, which automatically regulates the air change rate (ACR) for each dwelling. This paper aims to evaluate the set point for the moisture supply of this new DCV.

1.1. A novel DCV and its proper Set Points

A traditional mechanical ventilation system with heat recovery (MVHR) for multifamily houses runs on a constant air volume (CAV) principle. A problem, is that a CAV-system will ventilate unnecessarily much at times and insufficiently at other times. A novel MVHR has been developed to address this issue [3]. This DCV-based system regulates the ventilation rate for each apartment according to two parameters in the indoor air: the moisture supply, and the content of volatile organic compounds (VOCs). Outside each apartment, a box is placed that includes sensors and dampers that regulate the ACR for the apartment based on the measured parameters. The moisture supply, which is the difference between the indoor and outdoor vapor content, is calculated through measurements of the vapor content in the supply and in the exhaust air. The idea is to ventilate only as much as necessary in order to achieve a healthy indoor environment and at the same time reduce the energy output.

An important factor that affects our health is the state of the building and the building materials. For this, and other reasons, we must strive to avoid moisture damage to the building materials by controlling the moisture levels in our houses. It is therefore important to carefully analyze the ventilation strategy, which includes the set points for the ventilation system. In this novel DCV-system, the ventilation rate increases when the measured moisture supply exceeds the set point based on a PI-controller. Shortly after, the ventilation rate reaches its maximum. As long as the set point is exceeded the ventilation system strives to reduce the moisture supply until it reaches below the set point. When the moisture supply set point has not been exceeded, the ventilation rate is adjusted to deal with the VOCs instead. In the case of a too high set point for the moisture supply, the risk for mold growth in the building material increases. In the case of a too low set point, the system’s energy efficiency might be decreased since the system would sometimes ventilate at an unnecessarily high rate, i.e. when the risk for moisture damage is insignificant.

Today, there are no directives from the authorities in Sweden concerning the moisture supply, and we have not found research that suggests a limit on the moisture supply. There are investigations [4] of the indoor environment in the Swedish multifamily buildings that were built between the years of 1965-1975; the so called “million program”. These investigations show that the average of the moisture supply in these buildings is approximately 1.2 g/m³ with a ventilation rate of about 0.5 ac/h. However, these investigations do not address the risk of moisture damage in building materials due to the moisture supply.

In a previous article we have evaluated the set points for the VOC-control and the moisture supply for this DCV, and suggested an adjustment [3]. However, the moisture supply set point was suggested based on the results of the above mentioned investigations [4], and not on the risk for moisture damage. The study presented here has analyzed the most vulnerable situation where the moisture supply is the key factor for moisture damage in the concerned buildings. This, in order to determine a set point that is to be used when implementing this kind of DCV-system.

2. Method

The construction used in the simulations was chosen since it is a typical construction of the building envelope in Swedish multifamily houses from 1950-1975 [5]. Also due to vapor diffusion through the building envelope, the construction represents the worst case scenario for these houses regarding moisture in general. From the exterior to the interior, the material layers in the chosen building envelope are:

- 1 ½ stone solid masonry
- Air gap
- 90 mm Mineral Wool + Wooden Studs
• Vapor barrier (PE-foil)
• 13 mm gypsum board

The air gap is usually very narrow (15 mm) and unventilated, and is thus almost insignificant for the dry-out potential in the wall. However, it does serve the purpose of separating the studs and the insulation layer from the solid masonry, which might absorb rain and transport water inwards by capillary suction.

There are, of course, different versions of the construction in focus. Another example of a poor version is the same construction but without the air gap, letting suction occur between the studs and the solid masonry, which increases the risk of mold growth on the wooden studs. The same risk is posed in the case of a previously placed and later neglected wallpaper on the masonry wall – when internal insulation is added in a renovation. Also, the vapor barrier is in some cases non-existent, or it has degraded through time to what can best be described as a white powder. The state of the vapor barrier in such a case means that the vapor can freely diffuse through the construction and further increase the risk of mold growth. The worst case scenario for moisture damage caused by the moisture supply might therefore be the combination of the chosen construction and the three observed examples. These together form case A, where the moisture supply adds to the risk of mold growth.

Arguably, the mold growth on the wallpaper is caused by the combination of absorbed precipitation and a low temperature, and not due to the vapor diffusion from the interior. The fact that vapor diffusion only accumulates a small amount of water compared to rain-water suction supports this argument. However, a counter-argument is that if the vapor diffusion from the interior is left uncontrolled, it might add to the accumulated rain water and increase the risk of mold growth. The risk due to this phenomenon has therefore been worth investigating. In addition, the risk for mold growth depends on a sufficient relative humidity ($RH$) in combination with a preferable temperature, sufficient time and sufficient nutrition. The $RH$ may be high even though the water content in the material may not be. This means that the risk does not require as high water content as might accumulate from rain absorption. The vapor diffusion alone should therefore be sufficient to cause mold growth since it might increase the relative humidity to a point where the conditions are preferable for mold growth.

In some houses, case A has been modified and become even more sensitive to vapor diffusion from the interior. An example is when vapor resistant paint is applied to the exterior surface of the façade. The idea is that such application will repel rain water, which is true, but it also limits the dry-out possibility for vapor diffusion from the interior. As a consequence, water is accumulated in the wall, making the moisture supply the sole moisture source causing mold growth on the wallpaper. This example will hereby be referred to as case B.

<table>
<thead>
<tr>
<th>Case A (with rain absorption)</th>
<th>Case B (without rain absorption)</th>
</tr>
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<tbody>
<tr>
<td>- 1 ½ stone (375 mm) solid masonry</td>
<td>- Water-repellant-vapor-retarding paint (Latex)</td>
</tr>
<tr>
<td>- Wallpaper*</td>
<td>- 1 ½ stone (375 mm) solid masonry</td>
</tr>
<tr>
<td>- 90 mm Mineral Wool + Wooden Studs</td>
<td>- Wallpaper*</td>
</tr>
<tr>
<td>- 13 mm gypsum board</td>
<td>- 90 mm Mineral Wool + Wooden Studs</td>
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<tr>
<td></td>
<td>- 13 mm gypsum board</td>
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</table>

*not actually simulated, however, results have been assessed with the assumption that this wallpaper or other sensitive material exists here

2.1. Determining the risk for microbiological growth

With hygrothermal simulations of the constructions in WUFI Pro, we have closely studied the risk for microbiological growth on the wallpaper in case A and B, using two recognized mathematical models. There are several such models for determining the risk for microbiological growth, among them are [5-7]. Simply put, these models describe the mold growth rate based on three criteria: temperature, relative humidity and time. Newer models are based on the same criteria as the older models, but also consider mold shrinkage. As an indicative approach, the results have first been compared using a Folos-diagram [8] that compares actual $RH$ with $RH_{crit}$ according to [5] and does not consider shrinkage of the mold. However, this tool is efficient for comparing results between different scenarios. Further assessment has been carried out using the MRD-model [7], which does consider the shrinkage during unfavorable conditions. The MRD-model compares simulation results with experimental results, producing an index. The index should not exceed a so called limit state (MRD-index $= 1$), which indicates visible mold growth under microscope.
2.2. Choice of climate data

Currently, there is no standard test-reference time-period to use for hygrothermal simulations of constructions in Sweden. What is commonly used is the actual climate data for a geographical location, or a normalized climate data over the years of 1995-2005. In comparison to the actual weather data, the normalized data do not include possible extreme values. However, in Meteonorm a normalized year that includes extremes for the temperature data can be synthetically produced. In our simulations, we have used such data based on measurements from 1991-2010.

Since the DCV-system presented in this paper might be installed in any multifamily building in Sweden built between the years of 1950-1975, there is no single specific geographical location to consider in the hygrothermal simulations. Instead, the worst case-scenario for the construction has been considered, and that is where the criteria for mold growth are fulfilled according to [5]. However, this does not directly point out the geographical location where the risk is highest. Therefore, climate data for several locations have been used based on the hypotheses that they are either very humid, very cold or a combination of both. Cities situated along the coast or by a lake have been chosen. Only cities that most likely have multifamily buildings from 1950-1975 have been considered. The locations are: Malmö, Norrköping, Oslo, Karlstad, Örebro, Luleå and Kiruna.

2.3. Convection

The convective transport of moisture into the construction may be an issue when there is an air leakage. Due to the numerous factors that affect this phenomenon, there might exist an over or under pressure indoors which causes an unfavorable air leakage into the construction from the interior. To translate the factors that affect the pressure into a possible air leakage, numerous assumptions are needed and the result will vary very much depending on these assumptions. This paper therefore disregards the effect that the convection may have.

2.4. Simulated dimensions and input data

The number simulated dimensions should be based on the construction composition. In some cases, such as when a thermal bridge poses the greatest risk for mold growth on an interior surface, two dimensional simulations may be needed. In most cases, however, a 1D-hygrothermal simulation is sufficient. In the studied construction, the temperature on the studied wallpaper is lower than any surface temperature that a thermal bridge may result in, and therefore 1D-simulations are sufficient.

Table 2: Chosen material input data from material databases in WUFI.

<table>
<thead>
<tr>
<th>Material</th>
<th>Name in database</th>
<th>Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid masonry</td>
<td>Solid brick masonry</td>
<td>Fraunhofer-IBP-Holzkirchen; Germany</td>
</tr>
<tr>
<td>Mineral Wool</td>
<td>Mineral Wool (heat cond: 0.04 W/mK)</td>
<td>Fraunhofer-IBP-Holzkirchen; Germany</td>
</tr>
<tr>
<td>Gypsum board</td>
<td>Gypsum board, interior</td>
<td>LTH Lund University</td>
</tr>
</tbody>
</table>

All simulated cases are directed towards the orientation where the wind driven rain is the most frequent. Other initial conditions are: top of the façade, wind dependent heat resistance, $T_{\text{interior}} = 20^\circ \text{C}$, case A: 70% adhering fraction of rain, case B: no rain absorption and the surface coating has an sd-value of 3.4 m. The rest are WUFI-default values.

In order for the construction to reach an equilibrium with the surrounding climate, and the results to be unaffected by assumed starting conditions, the simulation has been run for 10 years by repeating the same synthetic climate year. For the assessment with the Folos-diagram the results have then been evaluated with data for the last simulated year, to ensure equilibrium – which has been achieved five years into the simulation. For the MRD-model the results from the last three years have been used in order to include the synergetic effects for the mold growth across the years.

3. Results

Fig. 1 and 2 are Folos-diagrams for all considered locations, with a moisture supply of 1.2 g/m$^3$. The curves in the top of the diagrams show the actual RH, related to the left y-axis. When the critical relative humidity ($RH_{\text{crit}}$) has been
exceeded during a simulated hour an “x” has been plotted, related to the right y-axis. The plotted x:es show the difference between the exceeded RH and RH_{crit}. The results are presented for the last year of the simulation.

A comparison of Fig. 1 and Fig. 2 clearly shows that the effect of rain absorption makes a significant difference. In fact, the difference between the results is so great that case A is not applicable for this analysis. This is because the effects of the rain and that of the diffusion from indoors are on so vastly different scales that the effect of the diffusion does not even begin to compare with the effect of the rain. Further analyses are therefore solely based on case B.

Fig. 2 shows that a moisture supply of only 1.2 g/m³ does not present a risk for microbiological growth. We have therefore run the simulation with higher values. The DCV’s set value of 3 g/m³ produces a significant risk for mold growth based on [9], while higher values further increase that risk. When comparing locations, it is shown that the city of Malmö is the most vulnerable geographical location in Sweden where this phenomenon may occur, even though the differences between the locations are small. Therefore, further results have focused on Malmö.

For Malmö (Fig. 3), it is not until the moisture supply exceeds 1.8 g/m³ that a risk for mold growth begins to appear. However, RH_{crit} is exceeded for a mere 7 h/y (Tab. 3), while the rest of the year the conditions for mold growth are very unfavorable, and possible growth will decay/shrink.

The MRD-model has been applied to the results in Fig. 3 for the last three years of the simulation in order to include synergetic effects across the years. These are presented in Fig. 4, which shows a low MRD-index for moisture supplies of 1.8-2.4 g/m³. Therefore, further simulations with moisture supplies at 3-9 g/m³ have been carried out, showing a drastic increase in risk between 3 g/m³ and 4 g/m³. This lead to even narrower analyses for moisture supplies from 3.0-3.6 g/m³ (Fig. 5). As shown in Fig. 4 and 5, the limit state at MRD-index = 1 is exceeded only when the moisture supply is above 3.0 g/m³. This indicates visible mold growth under a microscope [8] for moisture supplies above this value.

<table>
<thead>
<tr>
<th>Moisture supply (g/m³)</th>
<th>Annual time, RH&gt;RH_{crit} (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>7</td>
</tr>
<tr>
<td>1.9</td>
<td>114</td>
</tr>
<tr>
<td>2.0</td>
<td>115</td>
</tr>
<tr>
<td>2.1</td>
<td>342</td>
</tr>
<tr>
<td>2.2</td>
<td>959</td>
</tr>
<tr>
<td>2.3</td>
<td>1606</td>
</tr>
<tr>
<td>2.4</td>
<td>2514</td>
</tr>
</tbody>
</table>

Table 3: Results from simulation in Fig. 3.
4. Discussion and conclusions

The aim of this paper was to determine a general moisture supply set point for a DCV in Swedish multifamily buildings from 1950-1975, based on the risk for moisture damage. An optimal set point for the system has been determined to $3 \text{ g/m}^3$ through hygrothermal simulations and the latest mathematical mold growth models. The investigation was focused on the impact of different moisture supplies in a construction with pure diffusion. For this reason the construction which was much exposed to wind driven rain was not chosen and also no convection was studied.

Even though the simulations were based on a worst case scenario for the diffusion, we recommend a thorough investigation of the set point to be carried out for each project due to the numerous input parameters that represent uncertainties. Such an uncertainty is the chosen average temperature indoors. More than 97% of the concerned houses have an average temperature of $\geq 20 \degree C$ [4]. Choosing a higher temperature would reduce the relative humidity in all simulation results, and the set point can be raised in proportion to this. What can also differ are the properties of the building materials, and it should also be noted that the assumed wallpaper might not be common, even if it actually exists in some cases. Either way, other biological material can exist in the critical point, such as dust, saw dust or wooden studs. Furthermore, the MRD-model has been applied as it is, with the $D_{\text{cr}}$ set to 39 days. For further information on why that might pose as a problem, please refer to Thelandersson & Isaksson [8].

References

Abstract

In Sweden, approximately 1.4 million dwellings were built 1946-1975. Today, a considerable part of these are in need of renovation for various reasons. Research results, experiences and outcomes from renovation projects could facilitate in performing more efficient renovations. As an aid for further research, this paper aims to compile and review relevant literature that may support in choosing a renovation strategy and making decisions on renovation measures. The focus of this paper is research on status determination, renovation strategies and renovation measures. Differences and similarities within these areas are presented through the analysis of 234 relevant publications. The results show that renovation of multifamily buildings in temperate climate conditions is widely researched. The included research has a strong energy focus, and while other effects of renovation are researched as well, they are not as strongly represented. Status determinations are often based on data from national databases that include useful information that could help alleviate decision making in the renovation process. Further research on the effect of such databases on the renovation process is needed. There numerous renovation strategies, and while there exists both in-depth and broader strategies, these are seldom connected. Finally, there are many publications evaluating the various effects of renovation measures, but some effects and measures are more widely researched than others. This paper lays a strong foundation for further in-depth research on the reviewed publications.

Keywords: multifamily, multiresidential, renovation, retrofit, refurbish, review

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1 Introduction
In Sweden, approximately 1.4 million dwellings were built 1946-1975 [1]. Today, a considerable part of these are in need of renovation for various reasons [2]–[8]. Reasons are mainly that building materials and services are reaching the end of their lifespan, but also the need for adjustment to modern standards. These include: new living habits, spatial demands and accessibility needs of the tenants. Simultaneously, the European Union has published directives demanding an increased energy performance by the current building stock, 2002/91/EC [9] and 2010/639/EU [10]. In order to satisfy the need for renovation based on the reasons above an estimated 50000 apartments per year need to be renovated [3].

Research results, experiences and outcomes from documented renovation projects are needed in order to renovate efficiently. As an aid for further research on the renovation of multifamily houses, this paper aims to compile and review relevant literature that may support in choosing a renovation strategy and making decisions on renovation measures. The aim is also to identify the lack of research within specific areas that concern renovations of multifamily buildings. There are several literature reviews that are relevant for renovation of multifamily buildings. Reviews by Haapio and Viitaniemi [11] as well as by Thuvander et al. [12], treat existing methods for achieving a sustainable built environment. The former [11] focuses on environmental certification systems for multifamily buildings in temperate climate, but not specifically applied to renovations. However, the latter [12] focuses on renovations - and specifically of multifamily buildings in temperate climate. As the former, the latter also includes environmental certification systems, but additionally includes other strategies that may be applied in renovation projects. The strategies included in Thuvander et al. [12] have the aim of facilitating the decision-making process in a renovation project. Besides the above mentioned reviews, there are also reviews that focus on specific issues [13]–[15] that are relevant to renovations, e.g. specific phases of a building’s lifespan [16], or renovation as a process [17]. One such review by Friege and Chappin [18], aims to understand what is needed to increase the number of energy-efficient renovations.
However, Friege and Chappin’s review is not specifically focused on renovation of multifamily buildings, but on research on renovations in relation to homeowners. Another similar review has been conducted by Ma et al. [19] but with a focus on providing a systematic approach for the identification of retrofit options.

This literature review is conducted with a wider approach than the studies mentioned above by including all aspects relevant for renovation of multifamily buildings in temperate climate conditions. This study may also facilitate renovation projects in achieving energy efficient, and healthy environmentally-sustainable buildings. This, along with fulfilling requirements stated by the inhabitants and society, with focus on renovations in temperate climate.

For the renovation of a multifamily building, a typical first step is to determine the status of the building, the second is usually to decide on a renovation strategy, and the third to decide on the specific renovation measure. Therefore, this literature review covers research covering:

- Status determinations - status of single buildings or building stock. This includes research out of many aspects, including technical, economical, and social.
- Renovation strategies - different approaches/methods/strategies for renovation.
- Renovation measures - Technical solutions used in order to achieve energy efficient buildings and healthy indoor environments.

2 Method
We have selected publications that we have found directly or indirectly relevant for renovation of multifamily buildings. We have included: scientific papers, accepted manuscripts, Swedish theses, and reports from projects in Sweden. All literature reviewed has been written in English or Swedish.

2.1 Search strategy
Through preliminary searches, we have compared databases and chosen two that generated specifically relevant results: Science Direct and Scopus. For a coherent search method, the same combinations of search phrases were used in both databases, see Table 1. By limitation of the search to title, Abstract and Key words, the search phrases have yielded in the number of results presented in Table 1, which we have sifted through for relevant articles.
2.1.1 Colleagues
We have also received relevant publications through emails from colleagues at Swedish universities and establishments, as well as professionals working in the building sector. These papers are not included in Table 1.

2.2 Literature analysis
In Table 1, the number of hits in the two databases have been presented. The literature was first sifted on the relevance in regards to renovations in regions with temperate climate, even if they do not focus on temperate climate. Secondly, a sifting was made on the year of publication in relation to its technical relevance to today’s renovations. In this sifting, publications treating renovation measures or status determinations conducted before 1999 have been excluded due to presumed changes in technology and surroundings that make the results irrelevant/outdated. However, for renovation strategies, publications before 1999 have been included if deemed relevant. Also, publications have been excluded if only the abstract could be located and the abstract is insufficient for the analysis.

The references have been analyzed through the following steps:

1) Categorization into (some references have been included in more than one category):
   a. Status determination,
   b. Renovation strategies, and
   c. Renovation measures.
2) Subcategorization – e.g. insulation measures vs ventilation measures. The subcategories have been determined through analysis of the references throughout the review process.
3) Identification of the aim of the research/ renovation project (e.g. improved energy efficiency).
4) Identification of the method used in the conducted research/ investigation (e.g. simulations, interviews, measurements).
5) Thereafter the literature was analyzed from a statistical perspective based 2-4, and on content.
2.2.1 Noteworthy publications

Some publications have been found to be noteworthy by being especially relevant for renovation in temperate climates. These were publications that:

- were directly relevant geographically
- covered an extensive amount of renovation options and the effects of these options on the building and the tenants
- focused on a single renovation option out of multiple perspectives (e.g. not only evaluated at how renovation affects the energy use, but also the indoor air quality)
- covered a rarely researched option or aspect of an option within the context of this paper
- evaluated an option in an actual renovation project (case study) from initiation to finalization, e.g. by (field) measurements before and after a renovation
- evaluated an effect by a renovation measure or renovation strategy that have otherwise been rarely evaluated

The analysis of each category has included a deeper analysis of the content in a selection of the publications found to be noteworthy.

3 Literature distribution

The first sifting of the acquired publications results in 234 publications relevant to renovations of multifamily buildings in temperate climate. The yearly distribution of the publications is presented in Figure 1. A strong increase in the number of publications is noticeable from 2009 to 2013, from seven publications to 38 publications. From 2013 and onwards, the number of publications does not fall below 30 publications per year. Before 1999, only five publications are deemed relevant for this study.

![Figure 1: Yearly distribution of included publications in this study. Publications up until June 22nd 2016 are included.](image)

The geographical distribution of the literature in this study is presented in Figure 1. The publications are divided by the publications’ geographical aims. Each country has been sub-categorized under the macro geographical regions according to a composition by the United Nations [20]. E.g. a publication analyzing a renovation measure for a building in France belongs to the macro geographical region of Western Europe. As shown in Figure 2, the majority of publications belong to the region of Northern Europe.

![Figure 2: The geographical distribution of publications included in this study.](image)
4 Status determinations

A total of 57 references [2]–[8], [21]–[71] conduct one or several types of status determinations on building stocks in various regions. The large majority treats building stocks in Northern Europe, followed by Western and Eastern Europe, and finally North America.

Figure 3 shows that most status determinations focus on the energy performance of the building stocks, followed by aspects that concern the users. “User” aspects include all aspects that directly affect the inhabitants, such as the Indoor Environmental Quality (IEQ). “Other” aspects include buildings’ technical status (e.g. life expectancy of building materials, renovation needs) and typology classification of buildings. “Economy” aspects include economical calculations, such as profit. “Environment” aspects include assessments of the impact on the environment, e.g. CO₂ foot print reduction of different renovation scenarios for entire building stocks.

Research methods that are used in the status determinations vary, but the dominating method are surveys (Figure 4). This might be due to the extensive use of national databases that include nation-wide surveys and measurements. Reviews do not only include literature reviews, but also reviews of statistical data. Interviews are conducted with tenants, building owners and professionals in the industry. Surveys are mostly conducted with the inhabitants of the buildings.

Further analysis of the simulations and/or calculations (Figure 5) conducted for the status determinations shows that the building energy performance is at focus, followed by the economical aspects, and then by assessments of the IEQ.

A deeper look (Figure 6) into the measurements and/or audits conducted in the status determinations, show a strong energy focus. However, other factors are also investigated. Temperatures indoors are measured for identification of thermal comfort issues but also for validation of tools used for energy use determinations. Humidity is measured for the sake of determining the indoor air quality (IAQ), but not for determination of (risks for) moisture damage. CO₂ is measured for determination of IAQ. Air tightness is measured both for determination of IEQ and for energy use. Acoustics and
Illumination are measured for the determination of the IEQ. Finally, other measurements for the determination of the IAQ are conducted on carbon monoxide (CO), volatile organic compounds (VOCs), particulate matter (PM), nitrogen dioxide (NO₂), radon (gas), microbial content in dust, and ventilation air change rates (ACR).

Figure 6: Types of measurements and/or audits conducted in the status determinations.

4.1 Analysis of status determinations
Status determinations on a macro scale (building stocks) as well micro scale (individual buildings) are needed for: support of new legislations and policies, the choice of renovation strategies, as well as the determination of proper renovation measures. Besides being a benefit for the above, thoroughly conducted status determinations can generate valuable input data for simulations and decision support tools. One such status determination by Boverket, the Swedish National Board of Housing, Building and Planning, describes the status of 1800 houses in Sweden [5]. This is done through surveys with tenants, audits and in-situ measurements. Not only does the report give useful input data for comparison and building simulation, but it also describes technical status (damage, building material status, and building services status) and analyses the energy usage. In contrast to this quite encompassing publication, a more energy focused assessment is conducted by Högdal [56] for the same building stock. The assessment analyses planned renovation measures in depth. A similar in-depth study is conducted by Ma et al. [43] for buildings in Southwest China, where noise annoyance has been recognized as a serious problem for the residents health and well-being. Another in-depth study, by Langer et al. [26] focuses on IEQ for 567 French dwellings, showing results for air change rates (ACR) close to those measured by Boverket in Sweden. However, Langer et al. takes the IEQ measurements one step further and measure VOC-concentrations as well.

Most status determinations acquire measurement/audit and survey/questionnaire data from national databases. In some cases collected data might be insufficient for the purpose of the research, but functions instead as input data for calculations/simulations. Furthermore, we found that simulations are heavily energy focused (see Figure 5). If this is due to the tools being limited in their functions, or the input data insufficient for other types of simulations, is unclear. In contrast, the conducted measurements/audits seem to be less energy focused, but energy assessment is still the dominating aim even for these. However, energy data based on measurements should be relatively easy to collect on a large scale through a national poll with building owners, compared to other building performance data, which might affect the choice of measurement data to use in a status determination. To summarize the above, the differences might be explained by difficulties in conducting different types of measurements on large scales, as well as insufficient simulation tools, besides energy focused research funding.

5 Renovation strategies
In this study, the word strategies is used as a collective for methodologies, methods, protocols and approaches. This analysis includes a total of 87 references on strategies for renovation projects. Further analysis of these references results in the identification of 81 different strategies. The analysis includes the following references: [33], [38], [44], [46], [52], [59], [64], [72]–[151]. Environmental
certification systems (e.g. LEED, BREEAM) can also be identified as renovation strategies, however, this analysis does not include such systems as several other studies analyzes them in-depth, e.g. [11], [12], [152], [153].

Of the identified strategies, 23% are both developed and evaluated in the analyzed publications, as shown in Figure 7.

More than half of the identified strategies are meant to be used during the planning phase of a renovation project, see Figure 9. 38% (18 strategies) of these are meant as tools to facilitate the decision-making process before a renovation.

Almost half of the strategies are aimed towards building owners, as seen in Figure 10. The strategies aimed at the community includes local, regional as well as international communities. Others refers to: occupants, investors as well as educational units.

and 39 are calculation models. Other methods used are: work samples, the use of national/international databases and GIS (Geographical Information Systems).
As presented in Figure 11, just over 70% of the analyzed strategies include an energy aspect. The category “social” in Figure 11 includes occupant involvement, occupant interaction with the building that affects the energy usage and occupant preferences on thermal comfort. The environmental category treats reduction of emissions from the buildings and the construction process.

Figure 11: Included aspects in the analyzed renovation strategies. A reference may include more than one aspect.

Figure 12: Analyzed strategies by sustainability aspects: environment, economy and social.

Sustainability is commonly divided into three aspects: environment, economy and social. In Figure 12, the aspects in Figure 11 have been categorized into the three aspects of sustainability. In this case, the environmental aspect also includes energy efficiency, and the social aspect includes IEQ and architecture/culture. Figure 12 also presents the numbers of strategies including two or three aspects of sustainability.

5.1 Analysis on renovation strategies

The energy efficiency focus is by far the strongest in the strategies involving renovation of multifamily buildings in temperate climate conditions, and the dominating type of support tool is aimed at building owners.

There are a total of 18 strategies aimed to facilitate the decision-making process before a renovation, and all target building owners. 14 of the decision-making tools include the application of energy efficiency measures. This is also confirmed by Ferreira et al.’s [93] analysis of decisions support tools, where energy efficient measures is identified as a reoccurring aspect of importance. The analysis is meticulous both in aspects considered in the support tools in and of themselves, as well as the methods for the support tool.

An evident difference between the studies treating renovation strategies is in the depth of focus: broad vs deep. A broad integrated approach risks becoming too shallow to notice the details that matters. Noris et al. [129] show a good example on how to achieve depth and at the same time include all three sustainability aspects: environment, economy and social. In order to do this, the developed strategy by Noris et al [129] takes base in already performed deep research and connects different aspects as well as results within the study. Furthermore, the strategy includes both models and measurements for alleviating the decision-making in construction projects. The chosen retrofit measures are analyzed, through both pre and post-diagnosis. Finally, the main sustainability aspects are limited: the environmental aspect includes only energy efficiency measures for buildings, and the social aspect only includes indoor environment improvements.

Bettgenhäuser and Hidalgo [77] include technical, economical and environmental aspects in their renovation strategy.
publication presents the development of a renovation strategy as well as an evaluation of the strategy out of national (German) and international (EU) positions. The environmental aspect in the strategy considers the greenhouse gas emissions released during the user phase and the embodied energy out of a life-cycle perspective. The study shows the benefits of using the strategy in a broad context but with limited width in the various included aspects. The study also excludes any social aspects. Bettgenhäuser and Hidalgos strategy is one of the few found strategies highlighting the technical aspects of a renovation.

In a publication, Hejmans, Wouters and Loncour [105] have evaluated the Energy Performance Building Directive’s (EPBD) ability to include innovative ventilation systems. The evaluation shows an understanding for the broad perspective of the process as well as the in-depth issue of calculating the influence of innovative ventilation systems. Through a probabilistic approach the authors conduct an energy performance assessment in order to give a more reliable result. With the more specific deeper focus in their study, Hejmans, Wouters and Loncour investigate a specific issue as well as the issue’s impact in a broader perspective.

A strategy aimed at contractors, consultants, building owners or other parties actively involved in a renovation project needs a strong link with the community, municipalities and policy makers. Koo et al. [117] analyzed the potential of renovation measures to fulfill the national goal of carbon emissions reduction with consideration of the economic aspects of renovation projects. The economic aspects include initial cost, net present value and saving to investment ratio. For this aim, Koo et al. developed an integrated multi-objective optimization model linking renovation strategies for building owners to the national goal of emissions reduction.

Only a few strategies are aimed towards building entrepreneur and consultants. These strategies focus on everything from the organizational and economical aspects of a renovation, to the building design and improvement of specific processes or calculation models. Of the community aimed strategies 22 of 29 include energy aspects.

Three different studies, from three different countries, evaluate how Energy Performance Certifications (EPC) can be used. Two of them from UK [154] and Denmark [155], involve a survey with dwelling owners that has performed EPCs. The survey includes questions on how the EPC has affected the dwelling owners, and if it has led to them performing energy efficiency measures on their buildings. The two studies show that the EPC has not had that effect. This leads to improvement suggestions aimed for policy developers in order to increase the effect of the EPCs. The third study [89] (Ireland) used the data in the EPC system to perform energy calculations for the Irish building stock and analyze the indoor temperatures influence of the calculations.

6 Renovation measures

In total, 115 references [3], [4], [8], [51], [52], [56], [92], [103], [106], [127], [134], [143], [156]–[262] that treat renovation measures. Figure 13 shows how many of these references consider renovation measures on different building components. The majority of the references consider renovation measures that somehow affect the building envelope, e.g. exterior insulation. Measures on the building services are also quite often considered, such as: upgrades to mechanical ventilation systems with heat recovery, installation of hot water consumption measurements, replacement of old heat pumps, and airtightness improvements. Other measures consist dominantly of solar technology, both photovoltaics and thermal. Other measures also include other energy saving technology such as LEDs and automatic control, but also “softer” solutions such as aesthetical changes, tenant behavioral change and tenant involvement.
The main aim of the references, is to evaluate renovation measures’ effect on the energy use (Figure 14). However, as can be seen in Figure 14, other effects are also evaluated. Economical evaluations contain various different kinds of assessments, such as cost efficiency, life cycle costs, profitability, payback time, etc. Environmental evaluations are mostly done by calculating CO2-reductions, and occasionally emissions of other pollutants as well as the impact that these have on the environment. Assessments of the moisture safety risks are done on mold growth risks, water penetration risks and moisture recycled through air handling units (AHUs). The users (inhabitants) are considerably often considered as well, through assessments of the IEQ and legionella risks. Finally, other aims include evaluations on aesthetics and spatial demands, assessment of government policy measures, and improvement of building owners’ proficiency.

Figure 15 shows that building performance simulations and/or calculations are most frequently used by the included references. References including measurements are less frequent than those conducting simulations/calculations. Of these, approximately a third (16) are conducted for calibration/validation of a simulation model/tool. Measurements conducted both before and after a renovation measure are few (9).

Figure 16: Types of simulations/calculations conducted by the references on renovation measures. A reference may conduct more than one type of simulation/calculation.

A further division into subcategories of simulations and calculations (Figure 16), shows a variety of considered effects with renovation measures. Also here, the energy focus is dominating, followed by economic effects. Only a few references consider environmental effects of the renovation
measures (besides energy reduction), and even fewer consider the hygrothermal effects.

A further division into subcategories of measurements/audits is shown in Figure 17. The figure shows that references that conduct energy measurements (22) are not quite as many as references that include simulations/calculations (Figure 16) conducted on energy (65). In contrast, measurements on temperature are dominating (Figure 17). However, measurements on energy come in close second place while all other measurements are comparable.

6.1 Building envelope

Further analysis of the measures applied on the building envelope (Figure 18), show that most references apply measures on the walls/facades, and approximately half of the references apply it on the roof. However, effects on/of thermal bridges are rarely evaluated.

Figure 17: Types of measurements/audits conducted by the references on renovation measures. A reference may conduct more than one type of measurement/audit. *I.e. air pressurization tests.

Figure 18: Types of envelope improvements researched by the references. A reference may have researched more than one type of envelope improvement. *Includes Crawl Space/Slab.

Figure 19 shows that airtightness improvement measures are applied on window frames, door frames and draught stripping. However, most references that evaluate the effect of airtightness improvements, do not specify what measures have been taken. Usually these references have conducted simulations, in which such details are unknown and estimated.

Figure 19: Airtightness improvements researched by the references. A reference may have researched more than one type of airtightness improvement. *Includes draught stripping.

Improvements on windows and doors are quite often considered. Details on window improvements can be found in Figure 20. The figure shows that upgrading to 3-pane and 2-pane windows are equally sought/evaluated measures. This paper does not differ between window replacement and refurbishment.
6.1.1 Analysis on building envelope
Improving the building envelope is important in order to get durable, sustainable and energy efficient housing with improved IEQ. Publications showing that renovation measures on the building envelope can do this are abundant. However, as the above analysis states, not many show this by measurements before and after a renovation (9/115).

Among the references on improvements of building envelopes, there are several that are quite extensive and detailed. Six of these conduct measurements before and after a renovation, [106], [205], [263]–[265], [204]. Gillott et al. [204], and Sinnott [265] conduct thermal comfort measurements before and after a renovation in relation to dwelling air tightness and draught. These show that draught can be reduced by 30% [204] / 22% [265] with retrofit measures, that the energy use is thereby reduced by approximately 9% [204] / 361 kWh/(annum and dwelling) [265], and that occupants are generally pleased with the draught improvements [265]. Hong et al. [106] also focuses on thermal comfort, through insulating measures and interventions on the heating system. This reference shows an improvement in the mean indoor temperature, significantly increasing the amount of thermally ‘comfortable’ inhabitants.

Only one of all references evaluates the effect of reduced thermal bridges. However, even this single [165] reference does not evaluate a specific renovation measure’s effect on thermal bridges. Normally, thermal bridges are seen as the weakest thermally insulated part of the building envelope, which makes this result remarkable.

A durability aspect that is quite important for renovations in temperate climate is moisture safety. This is even more important for measures on the building envelope that separate the indoor and outdoor climate. The intervention applied should not increase the moisture risks in the existing fabric nor become a moisture risk itself. As mentioned above, publications that consider hygrothermal effects of renovation measures for multifamily buildings are few. There are even fewer that actually analyze the moisture risks for building envelope interventions. Martinsson et al. [187] conducts measurements in an in-situ project for hygrothermal assessment of an external prefabricated system for exterior insulation. The measurements showed initial moisture issues caused by rain water penetrating through the exterior surface. An intervention improved the situation, later showing much lower risks for moisture damage. In contrast to exterior insulation, interior insulation is analyzed by Sjöberg and Wichlaj [236] through hygrothermal calculations, showing an increased risk for moisture damage with interior mineral wool insulation without a vapor barrier on the inside. Analysis on interior insulation is also done by Morelli et al. [266] in Denmark, but with in-situ hygrothermal measurements for the assessment of interior aerogel-stone wool mixture vs vacuum insulation panels. They state that interior insulation increases the risk for mold growth through measurements, and especially if any biological material exists between the interior insulation and the wall, emphasizing the meticulous removal of such material.
6.2 Ventilation, heating and plumbing

Conventional balanced (continuous) mechanical ventilation with heat recovery (MVHR) is the most researched ventilation improvement (see Figure 21). What is very rarely investigated, are natural ventilation techniques and demand controlled ventilation systems.

Figure 21: Types of ventilation measures researched by the references. A reference may have researched more than one type of ventilation measure. A reference may have researched more than one type of ventilation improvement. *Exhaust Air Heat Pump. **Balanced mechanical ventilation with heat exchanger, centralized.

Measures on the heating and plumbing systems, quite often researched. These include a numerous amount of technical measures, shown in Figure 22 and Figure 23.

Figure 22: Heating system measures researched by the references. A reference may have researched more than one type of improvement on the heating and/or plumbing system. *Ground Source Heat Pump (GSHP), Central Solar Heating System (CSHS), Downhole Heat Exchanger (DHHE), External Air Source Heat Pump (EAHP), Ground Water Source Heat Pump (GWSHP), Air to Air Heat Pump (AAHP). Heat Cost Allocators (HCA), Low Temperature Heating System (LTH), Solar Water Heating System (SWHS). *Included: "all", adjustment, insulation, thermostatic valve, zonal heating.

6.2.1 Analysis on ventilation, heating and plumbing

Although continuous MVHR is the most often considered HVAC renovation measure, references that assess the effect of the MVHR before and after a renovation through measurements are very few. Noris et al. [264] conducts IAQ measurements before and after renovations, and show that comfort conditions are generally improved in apartments where retrofit measures are taken to improve the IEQ. This applies even more so for the apartments that have a continuous mechanical ventilation system installed. Improvement of the IAQ was also shown by Coombs et al. [205], where comparisons of the IAQ before and after a renovation showed a decrease in pollutants that originate both indoors and outdoors. The authors state that this is most likely due to the decrease in the frequency of window opening post-renovation vs pre-renovation. Gillott et al. [204] (see section 6.1.1) state that intervention by draught measures required the installation of a continuous MVHR as the building envelopes air tightness improved. While they show that energy reduction can be achieved with the installation of an MVHR, they also show with thermal imaging that the MVHR created
exposed gaps within the building envelope and thereby additional leakage paths. Thomsen et al. [159] and Wahlström et al. [220] also show that energy reduction can be achieved by installing a MVHR, as well as other positive results as increased perceived IEQ.

Almost as frequently considered as continuous MVHR, is the EAHP (Figure 22). These two are often considered as competing techniques as both can be used for renovation of the ventilation system in a building, including heat recovery.

Natural ventilation measures seem only to be researched in terms of overheating issues [267], [210], [267], [257]. Other attributes are not considered, indicating a lack of research on natural ventilation in renovation of multifamily buildings in temperate climate. An argument against such research could be that natural ventilation often is the starting-point (ventilation strategy existing pre-renovation) and that mechanical ventilation systems are the upgrade that ensure energy reduction with improved IAQ. However, the lack of research is not only on natural ventilation as a stand-alone measure, but also as a complementary measure to mechanical ventilation systems. As such, it can provide a “boost” in the air change rate when needed, e.g. to get rid of odors or excess moisture in the indoor air. Furthermore, as shown in the above mentioned references it can provide passive cooling.

Demand Controlled Ventilation is also very rarely evaluated in terms of renovation of multifamily buildings. Which is to be expected, as it is hard to determine the ventilation need in apartments, and as the air change rate cannot vary as much as in offices/ industrial buildings. The publication that does exist evaluates it through simulations and not through measurements [197], indicating a need for such evaluations.

6.3 Other measures

Figure 24 shows measures not included in 6.1-6.3. Electrical measures include: LEDs, lighting, automatic control, and measures improving electrical efficiency. Policy measures include changes in political policy. Other technical measures include non-insulative façade improvements, improvement of thermal bridges, phase change material, active cooling measures, renewable (non-solar) energy systems, and rain water collecting/ harvesting. Social measures include: behavioral change, and tenant involvement in the renovation process. Shading measures are passive cooling techniques. Solar tech includes: photovoltaics (PVs), thermal solar systems and glazing (of e.g. balconies).

6.3.1 Analysis on other measures

As noted above, solar technology seems to be the most considered measure between “other measures”. Among the 26 references that consider solar technology, four focus on solar energy measures as the main renovation measure. Among these, Voss [256] has reviewed experiences from solar energy building renovations out of an international context, following fourteen demonstration projects (with solar focus) in the 1990’s. Already in the year 2000, Voss states that cost competitiveness of solar concepts need to be improved in relation to other renovation measures. However, in contrast to Voss, Silva [232] (year 2016) shows how solar systems in combination with nZEB/ ZEB design concepts...
can be “cost-effective with attractive payback times” for multifamily buildings in Portugal. Also, out of an environmental perspective Silva as well as Krstic et al. [216] show how solar systems can be used to successfully reduce CO₂ emissions in two case studies.

In the “other technologies” category, rarely observed (effects of) renovation measures have been evaluated. One such effect is spatial quality, and for assessing this in dwelling renovations, Acre and Wyckmans [268] developed a tool for combining practice and theory. Another rarely evaluated effect is phase changing. Ramakrishnan et al. [257] have evaluated the effect of phase change material in reducing heat related risks in Australian non-ventilated dwellings, with good results. This both with and without cooling by natural ventilation.

Besides technical measures, sociotechnical measures have been evaluated. One of them being behavioral change by Ben and Steemers [166]. Through simulations, they show a drastic improvement in energy savings (62-86%) through behavioral change, stating that this far exceeds any physical improvements.

Tenant involvement in the renovation process for social sustainability is the second sociotechnical measure that has been evaluated. Gustavsson and Elander [103] point out numerous insights on such a process, but most importantly the difficulties posed by both tenants and authorities.

7 Discussion

Generally, the dominating aim for the research in the included publications is for energy reduction. The cause for energy reduction globally is without question a cause for all humanity. With reduction of the energy consumption, inherently pollutant emissions are also reduced, and so is the effect that these have on the environment. Thereby this aim can also be considered an environmental aim, but not solely. The goal for a better environment might be driving this sort of research, but is it the only driving factor? The larger part of the included publications are from the year 2007 and onward indicating a rising interest on renovation of multifamily buildings in temperate climate, see Figure 1. From 2010 the inclination is more evident, peaking in 2013. The same peak is then reached again during 2015. During this time period the EU declared several energy strategies. These strategies state the need for renovation of existing European buildings, but it is unclear if it is the directives that are causing the rising interest or if the directives are affected by it.

Simulations conducted are energy dominated. Even here it is unclear if this is caused by focus of the research, or if commonly used building performance simulation software is insufficient for other purposes than energy evaluations.

Measurements seem to be conducted mostly on temperature and energy. This applies to both status determinations and research on renovation measures. In the analyzed renovation strategies, it is uncommon to include measurements. The measurements that are included are on IEQ, such as temperature, ventilation rates, and relative humidity. It is unclear why, in all three categories, other measurements are not as frequently conducted. It could be that the mentioned measurements are not too invasive for the tenants in multifamily buildings, thus indicating a general difficulty in achieving other in-situ measurements. This might also be why researchers more often resort to simulations. However, the “measurement” category does not only reflect in-situ measurements but also ex-situ (in lab), begging the question if this is a funding issue rather than a process difficulty.

Status Determination

Many status determinations (almost all) have included one or several kinds of surveys. Many use national databases containing data on country specific building stocks. These databases contain useful data for policy work,
but also input data for building performance simulations that might be used for assessments on the effect of different types of renovation measures. Such data bases have proved to be quite useful for research and legislative purposes. However, even though they are quite beneficial, not all countries have databases that include extensive information on building details, renovation measures and their effect on the IEQ. This raises a few questions: How do these data bases affect the renovation process/ rate in the countries that have such databases? And how encompassing is the included data?

In contrast to status determinations on country building stocks that encompass a large quantity of buildings, the searches yielded no results including building specific status determinations. Although status determinations on macro scales give useful data, such data is insufficient for decision making on specific buildings. However, this should not be a cause for concern, as an explanation for the lack of status determination on single building level is that such status determinations might not be publication-worthy. It does not mean that they are not conducted.

Renovation Strategies

It is difficult to establish (but yet of importance) if the same strategy is treated in several publications or if it is several different strategies. This study shows that there is a large number of different strategies that are aimed to be used in renovations. The need for several different strategies are supported by the variety of actors involved in different parts of the renovation process and the need for flexibility for adapting to different circumstances. Due to the complexity of a renovation project, both broad and more in-depth strategies can be beneficial when performing a renovation. How well these strategies are implemented in renovation projects, beyond case studies, are not evident in the analyzed publications. However, without practical usage of the strategies the benefit of them are lost.

Knowledge from earlier research and performed renovations could prevent future projects from repeating old mistakes. Our study show that a total of four, of the found strategies, include literature reviews as part of the strategies methodology. This is an indication that knowledge from earlier research is not emphasized in developed strategies. There are other ways of benefiting from knowledge from earlier research but how well this is spread is not evident in this study.

This study focuses on renovation of multi-family buildings, with the search terms chosen to achieve this direction. The chosen search terms can, to some extent, explain the limited inclusion of the user/maintenance phase in the found publications but not completely. The user/maintenance phase make up the largest part of a building’s lifespan. The renovation phase is highly influenced by the user/maintenance phase and should therefore be more included in strategies aimed towards renovations.

It is widely/generally known that any construction project benefits economically from a well-defined project plan at an early stage. This could be one of the reasons to why most of the found strategies aim towards building owners since they are the initiating actor in a renovation. It is therefore important that to have knowledge of and support for the whole renovation process in an early stage for building owners.

Renovation Measures

Combined, active measures (HVAC + solar tech + electrical) are more researched than passive (building envelope + airtightness + shading + other technical + natural ventilation). Separately, building envelope measures are most considered, and among them those applied on the façade. Logically, the façade is the largest surface compared to other
surfaces that have possibility for improvement. This might be the reason why façade measures are the most considered. Façade measures are more attractive if applied externally than internally when it comes to residential buildings, as internal measures are linked to the reduction of rentable living space as well as possibly decreased hygrothermal performance. However, not any external façade improvement on any building should be considered a safe choice out of a moisture safety perspective. Out of this perspective, an unsafe structure can not only cause microbiological growth, but also reduce the performance of the building material. It is therefore quite alarming that hygrothermal effects of/on building envelope improvements are so rarely evaluated in relation to renovations.

Recycling energy used on heating the indoor environment should be quite beneficial. This might explain the heavier research on continuous MVHR and EAHP. Why other options are not as researched is hard to say. Two options that are rarely researched where discussed under 6.2.1 – demand controlled ventilation and natural ventilation. Considering energy reduction as well as improved IAQ, in general the latter is usually not considered an improvement. However, the former should be. This because demand controlled ventilation should be developed to satisfy the need for a good IAQ as well as the reduction of the energy consumption by satisfying the need for increased air exchange only when it arises. Therefore it is surprising not to see more research on this subject.

7.1 Scope of review
With the chosen search method, not all literature published on renovations can be found, particularly older non-digitalized studies. However, not all older studies are relevant for this article, since many old techniques and methods are outdated due to new manufacturing methods and societal changes. Also, we have only included publications that are accessible through the chosen data bases and colleagues. As previously mentioned, the databases were chosen through preliminary searches. However, there are other databases that also are relevant for our search such as Google Scholar, but in order to make the work load manageable we have excluded these databases and thus not accounted for the publications found thereby. Figure 1 could indicate that the research performed on renovation projects have increased since 2007 but due to the mentioned search method this increase could also be due to the easier access of newer publications.

By querying colleagues for publications, we have limited the search to their experience and knowledge within the researched area. Thereby, we have also limited the search to their language skills. This means that relevant research from languages and countries not covered by their skills and experiences has been excluded.

Even though the restrictions mentioned above shape the outcome of this review, they have made the work load manageable and still generated many relevant publications. With the restrictions we might not have covered all publications possible, but we believe that the results still reflects the current situation within the given context of this review.

By narrowing our search to Abstract, Title and Key words, we believe that the searches has generated results that are most relevant to this paper. Doing the search in a different manner, e.g. including search in the text of each article, or only searching on the title, would either 1) include references that just mention one of the phrases that we have used, thus producing an unmanageable amount of irrelevant literature, or 2) given us a very short list of literature insufficient for this review. Even this was concluded after pilot searches.

Since we have conducted several searches throughout the work with this paper, a few
renovation strategies might be represented more than once since a publication might have been included in the analysis more than one version. The material has been thoroughly analyzed to avoid this issue but errors cannot be completely ruled out.

Publications made before 1999 on renovation measures and status determination have been excluded from the analysis due to presumed changes in technology and surroundings that make the results irrelevant/outdated. This concerns 12 available references published between 1985-1996 [269]–[280]. However, a look at these references show that similar concerns were raised then as are raised today: energy efficiency measures, solar technological measures, domestic hot water consumption measurements, measures against draught and for thermal comfort, the inhabitants health (IAQ), social measures such as public participation in house planning and financial costs.

The workload for the presented study has been quite extensive, even if the scope was limited to be manageable. Surely more and deeper analyses can be performed on the included publications, and thereby the conclusions can be extended.

8 Conclusions
The aim of compiling and reviewing publications on renovation of multifamily buildings, has resulted in a review including 234 publications. The complexity of renovation of multifamily buildings in temperate climate is widely researched. The reviewed material covers many important aspects of renovation. Research conducted provides much useful information for alleviating choices in the renovation process.

Overall, a strong energy focus has been noted throughout the review. Other aspects have not been equally researched although they might be just as important for achieving energy efficient, and healthy environmentally-sustainable buildings through renovation. For example, follow-up of performance after renovation, well-being of tenants, and hygrothermal effects of renovation measures.

Looking at the analyzed strategies, they cover all presented aspects of sustainability. Most focus on a specific aspect and some cover all the mentioned aspects. The strategies that treat several sustainability aspects, show limitation in the depth of each aspect. Some of the in-depth and the broad strategies are connected to each other, but this is needed on a larger scale.

Some measures are rarely researched, although they might be viable options. Some aspects of measures are also very rarely researched, even though these might be important for the well-being of the tenants. Examples of some of these measures are demand controlled ventilation, natural ventilation, interior insulation, and insulation of thermal bridges and basement walls.

In order to improve the accuracy of the results, further studies can...
- ...be conducted including more databases.
- ...be conducted on country specific research.
- ...be conducted on non-renovation specific research that might be implemented on renovations.
- ...research the implementation of renovation strategies in the renovation process.
- ...research the implementation of renovation research in the renovation process.
- ...research existing national databases for country specific building stocks, and their effect on the renovation process in these countries.
- ...perform deeper analyses on the publications included in this review.

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Dual-mode DCV for renovation of multifamily houses

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Abstract

A dual mode demand control ventilation system has been developed for alleviating the renovation process for multifamily houses. With a central fan, but decentralized control boxes including dampers placed outside each apartment, the system regulates the air change rate for each apartment individually based on two indoor air parameters: moisture supply, and volatile organic compounds (VOCs). The idea with this control scheme is to remove pollutants emitted by materials and common household activities that might be harmful or cause discomfort in the indoor environment, as well as reduce the moisture load on the building materials and the building envelope in order to reduce the risk for harmful microbiological growth. This article evaluates the system through laboratorial tests in a mock-up apartment, hygrothermal simulations of the building envelope, building performance simulations, surveys with tenants in a case study before and after renovation, and in-situ measurements in a case study before and after renovation. Furthermore, we have determined the correlation between the used VOC-sensor’s output and a conventional CO₂-sensor’s output. The evaluations show that the system functions as intended with improved IAQ after renovation and a decreased moisture load on the building materials and thereby the building envelope. Calculations show that this has been achieved together with significant energy savings with regards to heating the supply air. At the same time, simulations indicate that these results have been achieved in exchange for a marginally higher energy use than a conventional mechanical ventilation with heat recovery.

Key words: ventilation, carbon dioxide, VOC, moisture, indoor air quality.

1 Introduction

Several EU directives over the past two decades have stated the need for renovation of the European housing stock, e.g. 2002/91/EC [1] and 2010/639/EU. So has numerous other publications, for various reasons [2]–[9]. While one reason can be the need to reduce the energy use for environmental purposes [9], other reasons can be the need for replacement of building materials and services that are reaching the end of their lifespan [5]. Another important reason can be a need to improve the indoor air quality (IAQ) for the residents in existing dwellings. A solution that can fulfill some of these needs is the installation of a balanced mechanical ventilation system with heat recovery (MVHR).

As a renovation measure, a MVHR-system can reduce the energy use through heat recovery and improve the IAQ through filtered supply air. What can be considered a step further in energy efficiency is a demand controlled MVHR-system (DCV-system). In contrast to a conventional MVHR-system that supplies a constant air volume (CAV), the idea with a
DCV-system is to regulate the ventilation rate in order to more appropriately deal with the demand [10]. This control strategy has previously been used in commercial buildings, offices and industrial buildings, but is (to our knowledge) rare among multifamily buildings. This might be because air change rates (ACRs) in offices and industrial buildings are usually much higher than in multifamily buildings, furthermore the buildings are not constantly occupied which allows the ventilation to be turned off for example in night times.

Conventionally, DCV-systems are controlled with CO₂-sensors placed in the occupancy zone. CO₂ is often considered an indicator of the IAQ, as it can be related to human activity, combustion processes and other pollutant producing activities. Nevertheless, CO₂-sensors do not detect other pollutants, such as those produced from activities that do not produce CO₂, e.g. mopping using common chemicals. Neither do they detect pollutants emitted from building materials, such as linoleum carpets, glues, paint, etc. Many type of volatile organic compounds (VOCs) on the other hand, are compounds that we actually want to get rid of, emitting from activities and materials. Also, as “VOC” is an umbrella term for numerous compounds, a VOC-sensor reacts to many more compounds than a CO₂-sensor. A VOC-sensor could therefore prove more sensitive to changes in the indoor environment, thus a DCV-system based on VOC-sensor control should also react more swiftly to the need for an increased air change rate. Furthermore, the VOC-sensors used in this system are quite cheap compared to conventional CO₂-sensors and has previously proven to give output correlating to conventional CO₂-sensors [11]–[13] (except for emissions that CO₂-sensors cannot detect) which makes them an attractive option for determining the IAQ.

A dual-mode DCV-system for renovation of multifamily buildings [14] has been developed with the goal of alleviating the transition from existing ventilation systems, as well as incorporate the above ideals. The system automatically regulates the air change rate for each apartment in a multifamily building according to two indoor air parameters: moisture supply expressed in g/m³, and volatile organic compounds (VOCs) expressed in correlated CO₂-equivalent ppm. For the determination of the moisture supply, temperature and relative humidity (RH) sensors are placed in the air handling unit’s (AHU) supply air duct, as well as in the exhaust air duct of each apartment. The moisture supply is thereby calculated as the difference in vapor content in the exhaust and supply air flows. For regulation of VOC concentrations, a metal oxide semiconductor (MOS-sensor) [11]–[13], [15], [16] is also placed in the exhaust air. As CO₂ is often regarded as an indicator for IAQ and as the conventional option for DCV are CO₂-sensors, the VOC-sensor output is correlated to CO₂-levels in order to determine the IAQ based on the VOC-sensor output.

Two previous publications [17], [18] evaluate control strategies for the DCV-system mentioned above. The first article [17] analyzes results on the system’s functionality through tests in a laboratorial mock-up apartment. The second article [18] analyzes the risk for mold growth on a typical (but risky) exterior wall composition. Both publications result in recommendations for control strategies for this DCV-system. This article further builds upon our previous publications, and evaluates the ventilation through a pilot project. The DCV-system is installed in a multifamily building as a trial, and through measurements and surveys before and after the renovation we aim to determine the effect of the system on the indoor environmental quality (IEQ), which includes the indoor air quality (IAQ), thermal comfort and acoustics. In addition, through simulations based on measurements from the system itself, we determine the energy efficiency of the system compared to an ordinary MVHR-system with a constant air
volume (CAV) ventilation strategy. Furthermore, through calculations based on the conducted measurements, the energy efficiency of the system is compared to the previously installed system for the determination of possible energy savings in such a conversion.

1.1 Air Change Rate and Set Points
Depending on chosen set points, the system will increase/decrease the ventilation rate to adjust for the demand. For this there are two types of control strategies integrated in the system – one based on VOC in the indoor air and the other based on the moisture supply, thus making it a dual mode DCV. The system always prioritizes the strategy that, at a given moment, results in a higher ACR.

For the air flow regulation based on VOC-control, the control is based on a proportional (P) controller where the set minimum air change rate (ACR) is increased proportionally to the demand if the minimum VOC set point is exceeded, and the maximum ACR corresponds to the maximum VOC set point. E.g. if the minimum VOC set point is at 500 ppm CO₂-eq. with a minimum ACR at 0.5 air changes per hour (ac/h), and the maximum VOC set point is at 900 ppm CO₂-eq. with a maximum ACR at 1 ac/h, the ACR would be 0.75 ac/h if the VOC would be at 700 ppm CO₂-eq. Recommendations for specific set points are presented in our previous publication based on the tests in the mockup-apartment [17]. The tests include common household activities which produce pollutants that we do not want in our indoor air as well as emissions that might be uncomfortable, e.g. tobacco smoke, deodorant spray, paint fumes, and emissions produced when frying food or when cleaning with chemicals. During testing, the minimum VOC set point was set at 800 ppm CO₂-eq. and the maximum at 100 ppm CO₂-eq., with a minimum ACR of 0.1 vs 0.5 ac/h to a maximum ACR of 0.8 ac/h. The tests show that the chosen VOC-sensor [15] reacts to these pollutants, resulting in an increased ACR when necessary and ventilating as designed for a better IEQ. However, the results also show that due to the (practical) placement of the system’s VOC-sensor in a exhaust box outside the apartment there is a latency in the registration of the pollutant as well as a diminished sensor output compared to the sensor output in the room of the pollutant’s origin. This latency is further increased with a lower ACR, allowing the pollutant to spread during a longer time period which extends its reach within the apartment. In the publication [17], this issue leads to a recommendation of a minimum ACR of 0.5 ac/h or a lower minimum VOC set point of 450 ppm CO₂-eq which corresponds to the lowest value measured in the outdoor air within a three month period. A lower set point means a more sensitive system which increases the ventilation rate more often, while a higher ACR accounts for undetected pollutants in the indoor air. A higher minimum ACR also accounts for loads that are not measured, such as heat loads.

For the air flow regulation based on moisture control, the control is based on a proportional-integral controller (PI), where (simply put) the maximum ACR is increased (until maximized) as long as the chosen set point is exceeded. Due to insufficient data on recommendations for the moisture supply set point, we further analyze the set point for the moisture supply in another publication [18]. The analysis is based on the risk for visible mold growth on a typical (but risky) exterior wall composition, as a design case scenario. The results lead to a recommended set point for the moisture supply at 3 g/m³ in order to avoid moisture damage based on a design case scenario for Swedish multifamily buildings.

1.2 VOC correlation with CO₂
As mentioned above, CO₂ is often regarded as an indicator for IAQ and is the conventional option for DCV. The VOC-sensor [15] output is therefore correlated to CO₂-levels in order to determine the IAQ based on the VOC-sensor output. This is done by relating the sensor
output to recommended CO₂-levels. Several sources [11]–[13] have shown that the VOC-sensor output does correlate with CO₂-levels for offices, but none have shown this for apartment dwellings (where the demand is different from that of offices). The correlations found are also far from deterministic.

1.3 Pilot project
In the beginning of 2014, the DCV-system was installed as a renovation of the ventilation system for a part of a multifamily building finished 1965 in Norrköping. The building consists of apartments with 1-2 rooms and with similar layouts, and the DCV-system was installed for 24 apartments accessible through the same entrance (staircase space), and is still up and running. Before renovation, the ventilation was a balanced mechanical ventilation system with supply and exhaust air but without heat recovery, and the supply air was heated with a heating unit connected to the district heating system. The ventilation rate was estimated to 0.5 ac/h by the building owner and 1 ac/h by another source. However, building regulations valid when the building was raised do not have a set ACR for dwellings but for specific rooms [19]. Based on building regulations, and an assumed room height of 2.5m, the apartments should have an ACR of 0.53-1.65 ac/h depending on system design choices, apartment layout and surface area. Unfortunately, blue prints do not specify the ACR, and no measurements were conducted to confirm the reported or calculated ACR, not even the report from the latest obligatory ventilation control (OVC) required by Swedish regulations [20]. Besides the new DCV-system, the single other renovation measure was the installation of cooker hoods in each apartment. Otherwise, no other measures were taken.

Distributing boxes, main ducts to and from the AHU in the attic, and serviceable components have been designed to be installed in the multi-storey staircase space (hallway) and in the attic. Outside each apartment, and in the attic, control boxes including sensors and dampeners are placed for the regulation of the airflow. The placement of the components in these areas has been chosen in order to alleviate the renovation process by reducing the time needed inside the apartments and thereby also the imposition on the tenants. Another intended benefit of placing the control boxes outside each apartment is the possibility for maintenance without the need to bother the tenants.

2 Method
2.1 Simulations DCV vs CAV
Collected energy data was insufficient to precisely assess the total energy use of the affected apartments, as the energy data that has been collected by the property owner is specified for the whole block. The apartments were simulated in IDA ICE [21], a validated building performance simulation software. With IDA ICE, the DCV-system was compared to a conventional balanced mechanical ventilation system with heat recovery (MVHR) and a constant air volume (CAV) ventilation strategy. This in order to determine if the DCV is more or less energy efficient than the conventional option. Furthermore, the simulations included parametric tweaking of the VOC set points and ACRs presented in Table 1 for reaching optimal energy efficiency and IAQ.

The simulations of the DCV-system were based on measurement data collected through the DCV-system itself within a year after installation. The data from the system was collected for each five minutes for each apartment on exhaust and supply air: temperature, RH, VOC-content and air flow. Furthermore the moisture supply for each apartment was calculated for each five minutes (by the system itself). This data set the basis for an advanced adaptive model of the DCV-system, which was created in IDA ICE and able to realistically mimic the actual setup [21]. In order to get a model suitable for the parametric analysis, the measurement data
was first converted to hypothetical moisture and VOC loads through retracing calculations. The model was validated through comparisons of simulated and measured ventilation flows for an apartment, showing a coherence but with some accuracy deviations. However, as the main aim was to compare simulation results and thereby relative differences, the simulation model was accepted despite the accuracy deviations.

The parametric analyses included possible control strategies (Table 1). Multiple scenarios based on DCV-strategies (B-D) were compared with a scenario where the ventilation was run with a CAV with the minimum ACR required by Swedish Building Regulations (A). Furthermore, the CO2-content in the exhaust air for eight apartments were measured during the same time period and the system was simulated based on these measurements as well (H), and compared to CAV for these eight apartments (D). CAV for these eight apartments was also compared with control only VOC (F), and control on VOC plus moisture supply (G).

<table>
<thead>
<tr>
<th>Setup</th>
<th>Air flow strategy</th>
<th>ACR (/ac/h)</th>
<th>VOC Set Points /(CO₂-equiv. ppm)</th>
<th>Moisture Supply Set Point /(g/m³)</th>
<th>No. of apartm.</th>
<th>Simulation period</th>
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<td>DCV</td>
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<td>0.1-0.8</td>
<td>700 – 1000</td>
<td>3</td>
<td>8</td>
<td>2014-11-11 until 2015-05-12</td>
</tr>
<tr>
<td>H</td>
<td>DCV (CO₂)</td>
<td>0.1-0.8</td>
<td>700 – 1000</td>
<td>3</td>
<td>8</td>
<td>2014-11-11 until 2015-05-12</td>
</tr>
</tbody>
</table>

2.2 Heat recovery calculation
Since measurements of energy use before and after could not be conducted, we measured the temperatures of the exhaust, supply, outdoor and indoor air flows within the AHU. Together with the summarized air flows the thermal efficiency of the AHU could be calculated since the supply and exhaust air flows were balanced, as well as its dependency on the air flows. This was done for hourly calculated averages of data that was measured with 15 seconds to 5 minute intervals.

The thermal efficiency has been calculated according to:
$$\eta = \frac{T_{\text{supply air}} - T_{\text{outdoor air}}}{T_{\text{indoor air}} - T_{\text{outdoor air}}}$$

Where the thermal efficiency $\eta$ is calculated as the ratio between the increase in temperature for the supplied air and the maximum possible increase for the supply air, which is the difference between the temperature in the indoor air and the outdoor air.

Energy used for heating air flow can be calculated as:
$$P = q \cdot \rho \cdot c \cdot \Delta T$$

Where $P$ is the power needed for heating (W), $q$ the air flow (m³/s), $\rho$ the density for air (kg/m³), $c$ the specific heat for air (kJ/(kg·°C)) and $\Delta T$ the difference in temperature (°C) before and after heating.

2.3 Survey before and after
In order to evaluate the indoor climate, a survey regarding experiences of the indoor
environment were tucked into the tenants’ mail boxes before and after the renovation. The survey was handed out in envelopes including a pre-paid response envelope. The survey is known as the BETSI survey [22], developed by the Swedish National Board of Housing, Building and Planning, and consists of questions regarding the status of the building, the indoor environment and the tenants’ health. Questions identified to be relevant for the renovation project were chosen for further analysis. Both before and after renovation the same amount of surveys were handed out, as well as incentives offered for survey participation. Furthermore, reminders of both the importance of the survey and the incentives were sent to those who did not respond at first.

2.4 Measurements IAQ before and after

Before the renovation, measurements were conducted through placement of sensors in the collective supply and exhaust air ducts for all apartments. Temperature and relative humidity (RH) were measured in both the supply and exhaust air. In the exhaust air, a conventional CO₂-sensor, as well as the VOC-sensor mentioned under were used to measure the IAQ for the collective apartments.

After the renovation, the DCV-system logged values relevant for the IAQ, device controls, air flow and energy use from apartment control boxes and from the AHU. Among the logged system-data, apartment-specific data relevant for this analysis was collected on supply and exhaust air: temperature, relative humidity, VOC-content, and air flow. Furthermore the moisture supply for each apartment was calculated for each five minutes (by the system itself). This data has been compared with data collected before the renovation, for a comparison of the IAQ. In addition to the sensors in the system itself, we placed CO₂-sensors in the exhaust air ducts for eight apartments in order to determine the correlation between the VOC-sensor and CO₂-sensor output.

Measurement data from the system were collected for over a year before the simulations were conducted, as well as a year after. During most of the year before simulations, the placement of one of the RH-sensors in the AHU was incorrect, giving much higher calculated than actual moisture loads. This resulted in higher ACR than representative for the chosen control design during this time period, and therefore this data was disregarded in the IAQ-comparison. Furthermore, the comparisons have compared data collected during the same seasons before and after renovations in order to exclude the effects of seasonal variations.

3 Results

3.1 Simulated difference

The building performance simulations show a correlation between energy use and the improvement of the IAQ. The higher the energy use, the better the IAQ is on the sense of lower values for VOC-concentrations as well as for the relative humidity. This applies to all the suggested control strategies. The simulations also show that the chosen DCV strategy (B-D) provides a significantly better IAQ than the conventional ventilation system based on CAV-principle (A). Furthermore, the simulations show that the control strategies based on “safer” approaches (C and D) in regards to less pollutants in the indoor air do require higher energy use than the chosen strategy in the actual case (A), but at the same time result in a lower moisture load on the building materials. However, it must be emphasized that the option with a higher minimum ventilation rate (D) in combination with the DCV-controls might deal with pollutants that are not detected by the system more appropriately than the other strategies. A higher minimum ACR also accounts for loads that are not considered in the DCV-strategy, such as heat loads during the summer.
Controlling only on VOC (F) results in a lower energy use and a significantly higher humidity content in the indoor air, thus increasing the risk for microbiological growth on biological material. This in contrast to running with moisture controls (G) which deals with the humidity indoors and also results in an increased energy use in comparison with CAV (A). Air flow regulation based on CO₂-controls (H) instead of VOC-controls (G) resulted in marginally lower energy use and approximately the same humidity content, but a lower VOC-content.

### Table 2: Results from simulations in IDA ICE. Energy and IAQ in the apartments based on control strategies in Table 1. The relative energy use is in comparison with CAV, e.g. energy use for option A divided by the energy use for option A = 100%, and optionB/optionA =101%, etc. The energy use of setup A-D has been compared with the energy use of A, while energy use of setup E-H has been compared with the energy use of E. Results for simulation period 2014-11-11 until 2015-05-12, and for simulations including all 24 apartments, as well as only 8 apartments with CO₂-measurements.

<table>
<thead>
<tr>
<th>Setup / No. of Ap.</th>
<th>Strategy</th>
<th>ACR (ac/h)</th>
<th>VOC Set Points (CO₂ eq. ppm)</th>
<th>Moisture Supply Set Point (g/m²)</th>
<th>Relative energy use of CAV</th>
<th>VOC (CO₂ eq. ppm)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A /24</td>
<td>CAV</td>
<td>0.5</td>
<td>N/A</td>
<td>N/A</td>
<td>100</td>
<td>3271</td>
<td>876</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>519</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10%</td>
<td>8</td>
</tr>
<tr>
<td>B /24</td>
<td>DCV</td>
<td>0.1-0.8</td>
<td>700 – 1000</td>
<td>3</td>
<td>101</td>
<td>2468</td>
<td>791</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>347</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8%</td>
<td>8</td>
</tr>
<tr>
<td>C /24</td>
<td>DCV</td>
<td>0.1-0.8</td>
<td>450 – 1000</td>
<td>3</td>
<td>102</td>
<td>2474</td>
<td>767</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>347</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8%</td>
<td>8</td>
</tr>
<tr>
<td>D /24</td>
<td>DCV</td>
<td>0.5-0.8</td>
<td>700 – 1000</td>
<td>3</td>
<td>105</td>
<td>2475</td>
<td>753</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>355</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8%</td>
<td>8</td>
</tr>
<tr>
<td>E /8</td>
<td>CAV</td>
<td>0.5</td>
<td>N/A</td>
<td>N/A</td>
<td>100</td>
<td>3275</td>
<td>1014</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>581</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8%</td>
<td>8</td>
</tr>
<tr>
<td>F /8</td>
<td>DCV</td>
<td>0.1-0.8</td>
<td>700 – 1000</td>
<td>N/A</td>
<td>97</td>
<td>2480</td>
<td>942</td>
</tr>
<tr>
<td></td>
<td>(only VOC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>359</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10%</td>
<td>15</td>
</tr>
<tr>
<td>G /8</td>
<td>DCV</td>
<td>0.1-0.8</td>
<td>700 – 1000</td>
<td>3</td>
<td>103</td>
<td>2480</td>
<td>890</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>386</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8%</td>
<td>7%</td>
</tr>
<tr>
<td>H /8</td>
<td>DCV</td>
<td>0.1-0.8</td>
<td>700 – 1000</td>
<td>3</td>
<td>102</td>
<td>1842</td>
<td>725</td>
</tr>
<tr>
<td></td>
<td>(CO₂ instead of VOC)</td>
<td>0.1-0.8</td>
<td></td>
<td></td>
<td></td>
<td>229</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40%</td>
<td>7%</td>
</tr>
</tbody>
</table>

### 3.2 Calculated thermal efficiency and energy savings

Figure 1 shows calculated thermal efficiency of the AHU in the case study, with fitted curves in the first and second degree. Results show that the thermal efficiency varies with the air flow, and is between 77-85%.

**Figure 1:** Calculated thermal efficiency of the AHU in the case study. Based on hourly averages of measurement data. 2014-11-12 until 2015-02-25.
For each hourly average air flow shown in Figure 1 the energy needed for heating the supply air could be calculated according to formulas presented under chapter 2.2. Unfortunately, since the air flow before renovation is uncertain, the energy use for heating the supply air with the previous balanced mechanical ventilation (without heat recovery) system could not be calculated with certainty. Assuming that the previous system had a maximum air flow that equals the new system (0.8 ac/h), the hypothetical energy use could be calculated for the previous system for the time period presented in Figure 1. The same could be done for the DCV-system under the same time period with air flows presented in the same figure. With a supply air temperature set to 19°C, the difference in energy use could be calculated between not utilizing a heat exchanger with a CAV, utilizing a heat exchanger with CAV, and utilizing a heat exchanger with a DCV. Results from energy calculations (Table 3) show significant energy savings through heat recovery (83%), and further savings with DCV on dual-mode (86%).

Table 3: Calculated energy use for heating the supply air from 2014-11-12 until 2015-02-25, using different options. CAV with/without heat recovery and dual-mode DCV (VOC + moisture supply controls) with heat recovery.

<table>
<thead>
<tr>
<th>Ventilation strategy</th>
<th>Heat exchanger</th>
<th>ACR/ h⁻¹</th>
<th>Air flow/ l/s</th>
<th>Thermal efficiency</th>
<th>Energy use/ kWh</th>
<th>Relative energy use/ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAV</td>
<td>No</td>
<td>0.8</td>
<td>523</td>
<td>N/A</td>
<td>26915</td>
<td>100</td>
</tr>
<tr>
<td>CAV</td>
<td>Yes</td>
<td>0.8</td>
<td>523</td>
<td>0.83</td>
<td>4665</td>
<td>17</td>
</tr>
<tr>
<td>DCV</td>
<td>Yes</td>
<td>0.1-0.8</td>
<td>189-523</td>
<td>0.75-0.91</td>
<td>3618</td>
<td>14</td>
</tr>
</tbody>
</table>

3.3 Perceived change

Apartment-wise, the response rate before the renovation was 11/24 (46%), and after the renovation 6/24 (25%). It is therefore difficult to draw any deterministic conclusions from this survey, and the results should therefore only be seen as indicative. As incentives and reminders were offered for survey participation we cannot find a cause by the execution for the low participation rates.

Survey answers shows that those who answered the survey after were slightly less pleased with their dwelling standard and comfort than those who answered before. However, Figure 2 shows that the frequency of natural ventilation is lower among those who answered after than those who answered before, which is an indication of improved IAQ. Figure 3 indicates a lower (thermal) comfort through slightly increased issues with draft, and increased issues with high room temperature. At the same time, Figure 3 confirms indications from the results in Figure 2 of improved IAQ by showing decreased issues with: static electricity and odors. Otherwise no changes can be confirmed in Figure 3.

Figure 4 further details thermal comfort before and after the renovation and shows improvement with discomfort due to cold during the summer. At the same time Figure 4 shows slightly increased issues with varying room temperature shifts with temperature shifts outdoors, confirming indications from Figure 3. Otherwise the satisfaction is basically the same after as before.

Figure 5 shows a slight increase with issues due to the spread of cooking fumes that the tenants themselves generate, and a slight
decrease with issues due to cooking fumes from neighbors. Otherwise, issues with odors do not seem to have changed.

**Figure 3:** Questions on IEQ discomforts within the past three months before the time of the survey. Answers by inhabitants who answered before and who answered after the renovation (not necessarily the same).

**Figure 4:** Detailed questions on thermal comfort in the dwellings. Answers by inhabitants who answered before and who answered after the renovation (not necessarily the same).
Survey answers show no significant changes in discomfort issues due to ventilation issues, but indicate that the system handles moisture in the indoor air better than the previous ventilation system, as no one reports condensation on the windows when cooking after the renovation - in contrast to before renovation where approximately 40% report such issues. This is confirmed by results in Figure 6 showing a significant improvement with condensation on the bottom part of the interior surface of window-glass during the winter.

Survey answers show that no significant change in regards to acoustics in the dwelling can be determined. Neither is there any significant change in noise issues due to the ventilation.

Overall, the inhabitants who have answered after renovations report less health issues after than before the renovation, see Figure 7. All of these health issues can be connected to the IEQ, showing that the IEQ is improved or the same compared to before renovation.

A summary of the conclusions of indications that can be deduced from the survey results is presented in Table 4.
Figure 7: Health issues reported by the inhabitants. Answers by inhabitants who answered before and who answered after the renovation (not necessarily the same).

Table 4: Summary of changes before and after renovation, based survey results.

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In general:</strong></td>
<td><strong>In general:</strong></td>
</tr>
<tr>
<td>+ lower moisture load on the building materials</td>
<td>- slightly lower apartment comfort</td>
</tr>
<tr>
<td>+ less health issues</td>
<td>- slightly lower apartment standard</td>
</tr>
<tr>
<td><strong>IAQ:</strong></td>
<td><strong>IAQ:</strong></td>
</tr>
<tr>
<td>+ less issues with odors</td>
<td></td>
</tr>
</tbody>
</table>

**Pros**
- + less frequent use of natural ventilation
- + less issues with static electricity
- + decrease with issues due to cooking fumes from neighbors

**Cons**
- - increase with issues due to the spread of cooking fumes that the tenants themselves generate

**Thermal comfort:**
- + less issues with cold during the summer
- + slight improvement with draft from the windows

**Thermal comfort:**
- - slightly less pleased in general
- - slightly increased issues with draft
- - significantly increased issues with high room temperatures
- - slightly increased issues with varying room temperature shifts with temperature shifts outdoors

**Acoustic comfort:**
- No improvement.

3.4 Measurement results

3.4.1 Before vs after

Figure 8 shows results on RH before versus after the renovation. Before the renovation, sensors were placed in living room and in the hallway in these apartments, which does not completely represent the overall IAQ for the whole apartment. In contrast, after the renovation the ventilation system measured the RH for the collected exhaust air from the whole apartment which is a more accurate representation of the overall IAQ in the apartment. The difference in measuring methods makes a direct comparison less than accurate. However, differences in measurement results still indicate a lower spread in the RH for all apartments after the renovation than before through the difference in median, as well as a marginally lower RH in general for apartment 2220 and a significantly higher RH for apartment 3240.
Figure 8: Boxplots on measured RH in two apartments before and after renovation. Showing 25th percentile, median, 75th percentile, whiskers (1.5 · interquartile range) and outliers. Also showing ‘notch’ which represents the 95% confidence interval over the median.

Figure 9 shows measured CO2 and VOC-content for all apartments before versus after the renovation. Before the renovation, CO2 and VOC-sensors were placed in the collective exhaust kitchen air-duct for all apartments. Unfortunately, we could not measure VOC-content after renovation in the exhaust air for the AHU, due to space limitation. Therefore, VOC-content before renovation in the main exhaust air duct has been compared to VOC after renovation for exhaust air from all 24 apartments separately. Here a direct comparison between these two data sets is less than accurate, however indications of change should still be possible. Comparing VOC in the exhaust channel for the kitchens with all apartment exhausts after, the median is lower. However, for the bathrooms, the median is higher. The spread is larger after though, but as the time series interval before renovation is much larger than after (30 versus 5 minutes) this is to be expected. However, the main exhaust measurements before renovation should represent diluted VOC-content as these values represent the collected exhaust air from all apartments, in contrast to the measurement data after renovation that represent the collected data for all apartments separately. Fortunately, we could measure the CO2-content after renovation in the exhaust air for the AHU. A direct comparison with both measurements is more valid here, but at the same time we have two exhaust channels before renovation in comparison with one after. The average for the collected air flow from all apartments can therefore not directly be compared with the average for the one after. Either way, separate comparisons with both measurements show that the CO2-levels after are higher than before, which means that the ACR has been lowered.

Figure 9: Boxplots on measured VOC before and after renovation. Refer to Figure 8 for details on the boxplot.

3.4.2 VOC vs CO2

Figure 10 shows that CO2 and VOC sensors are in good agreement, however, the VOC-sensor shows much higher peak values. An
explanation for this can be the higher sensitivity in the VOC-sensor, as it measures VOCs that normally occur in ppb-concentrations, in contrast to CO₂-concentrations which normally are usually larger than 390 ppm. The output of the VOC-sensor is amplified in order to express it in CO₂ equivalent ppm –small changes are thereby also amplified and become relatively larger than actual, which might explain the large differences in peak amplitudes between CO₂ and VOC-values. However, the VOC-sensor reacts to a range of pollutants in contrast to the CO₂-sensor, which might be another explanation to the difference in peak amplitudes, as it might be reacting to more than one pollutant during peaks. For several apartments the correlation seen in Figure 10 is confirmed, and as for the one in Figure 10 the peak differences are larger and occur often depending on living habits.

Figure 10: VOC vs CO₂ for one apartment during two weeks. Hourly average values.

Figure 11 confirms the observations from Figure 10, but for all eight apartments in which CO₂ was measured in the exhaust air. The width between the whiskers is much larger for the VOC-sensors than the CO₂-sensors, showing a larger spread. This is due to VOC peaks more often resulting in higher values than simultaneous corresponding CO₂ peaks, which further confirms the higher sensitivity of the VOC-sensor. This is evident for all but apartments 4230 and 6230. Furthermore, apartment 4230 and 6230 are the only apartments showing lower VOC medians than CO₂ medians. For the majority of the apartments this means that running a DCV on VOC should result in higher average ACR than running on CO₂, which in turn should result in lower exposure to pollutants produced in the indoor environment.

Correlation coefficients for hourly average VOC-values against hourly average CO₂-values during the first 20 weeks for all eight apartments have been calculated. Correlation coefficients for between VOC (as dependent) and CO₂ (as independent) are: 1) Pearson’s: 0.4312 (95% CI 0.4199-0.4424), 2) Spearman’s: 0.3729, with VOC-outliers excluded. Showing both a linear correlation (Pearson’s) as well as a monotonic (Spearman’s) correlation between the two types of measurements, but not strong ones. However, with the outliers there is no significant correlation between the two. Furthermore, besides erroneous values VOC-outliers also represent the variations in the indoor climate that the CO₂-sensor cannot detect. In conclusion, this means that the output of the VOC-sensor correlates with CO₂.
overall, and whatever differences might be explained in the VOC-sensors superior sensitivity through amplification as well as its superior function to detect a range of pollutants that the CO₂ sensor doesn’t. This should make the VOC sensor the superior choice of the two, in regards to the IAQ-performance of the ventilation system.

3.4.3 Overall IAQ and system functions

Figure 12 shows the calculated (through differences in measurements) moisture supply by the system. Outliers reach very high values, and some apartments show quite high median values as well. The average for this type of apartments is 1.2 g/m³ according to Boverket [23] and several show a median close to this, but many show significantly higher medians. In addition, we have shown that the risk for mold growth is substantial as long as the moisture supply exceeds 3 g/m³ for a sensitive construction [18]. This assessment was however based on constant 12-h average values, while Figure 12 shows results for 5-min intervals making the guideline difficult to apply. However, based on the above, Figure 12 confirms the need for moisture-based ventilation controls as the ACR should be designed to adapt to each apartment’s specific load. Measurements of relative humidity in the exhaust air for each apartment also shows that some apartments have high RH (>75%), and that most have outliers beyond this value. However, in general the RH in the indoor air is within an acceptable range (low risk for mold growth <75%).

Figure 13 shows boxplots on measured VOC-content in CO₂ eq. ppm for each apartment. Some apartments have much higher loads than others, which should mainly be caused by habitual differences but may also indicate material emission differences. Nevertheless, these differences confirm the need for individual ACR for each apartment. The system’s response to these loads as well as moisture loads shown in Figure 12 through regulation of the ACR has been calculated for all 24 apartments. The ACR has been calculated based on measured air flow for each apartment and each apartment’s volume with an apartment height assumed to 2.5 m. The ACR for the apartments strongly varies corresponding to the VOC and moisture loads, as shown in the following analysis.

Figure 12: Measured moisture supply for each 5 minutes, all 24 apartments. The moisture supply is calculated as the difference between the measured vapor content in the exhaust air and the supply air. Refer to Figure 8 for details on the boxplot.
Data for a million measurements have been used to calculate correlation coefficients for:

1. VOC (independent) – ACR (dependent),
   a. Pearson’s: 0.7674 (95% CI 0.7644-0.8447),
   b. Spearman’s: 0.4483
2. Moisture Supply (independent) – ACR (dependent),
   a. Pearson’s: 0.6173 (95% CI 0.5821-0.6503),
   b. Spearman’s: 0.6868

For both cases the outliers have been deleted, as outliers in these cases do not represent realistic data for the determination of the correlation coefficient. The calculated correlation coefficients show that both a linear correlation (Pearson’s) as well as a monotonic (Spearman’s) correlation exists for both relations. However, for VOC – ACR (Figure 14) a linear correlation fits better than a monotonic correlation (0.76>0.45), while for Moisture Supply – ACR (Figure 15) a monotonic fits slightly better than a linear (0.69>0.62). This means that both graphs and correlation are in strong agreement with the described control strategy (VOC controlled with P-regulators and moisture supply controlled with PI-regulators), and the system runs as intended. The correlation coefficient partly describe to what degree the ACR is controlled by each independent variable. The ventilation is controlled less on moisture supply than on VOC-content, but both affect the ACR significantly and neither should be excluded.
4 Discussion

A higher rate in survey participation is desirable. As we cannot accurately determine the amount of residents in the studied location, the response rate has been determined apartment-wise. The response rate after the renovation is thereby deemed too low for deterministic conclusions and the results from the survey can only be considered as indicative. Due to the low response rate, each answer carries weight and singular overall dissatisfied respondents can have a strong impact on the results. Furthermore, due to displacement of the RH-sensor for the supply air, the moisture supply was calculated to be much higher than it actually was for almost a year after installation. This contributed to higher ACR than intended during a long time period. Fortunately, the surveys were handed out more than two months after the issue was corrected, but the erroneous placement could nevertheless have affected the opinions of the survey responders. In addition, data collected during this time period has been disregarded in the evaluation of the IAQ through measurements, as it does not represent the system functionality. However, data from this time period has been used for the calculation of the correlation between CO₂ and VOC outputs. Hopefully, it will serve as a valuable lesson for further installations that it is important to conduct checkups post-installation in order to ensure that the intended purpose of the ventilation system is fulfilled.

The ACR for the case study before renovation is unclear, but if it was based on valid building regulations at the time of construction it should have been higher before than after the renovation (0.53-1.65 ac/h before vs 0.1-0.8 ac/h after). The transition to a lower ACR might explain why survey results indicate “the spread of cooking fumes” within the apartments after renovation (as the tenants were used to a higher ACR before renovation). In addition, a low minimum set point (0.1 ac/h) for the ventilation rate might amplify the issue with spread of cooking fumes as this increases the reaction time for the ventilation system, thereby allowing fumes to spread a longer time extending their reach. Furthermore, the sensors read diluted concentrations of the pollutants as the air leaves the apartment, giving a lower than needed response at the source of the pollutant – allowing it to spread in the apartment. The cause for this is the practical placement of the VOC and moisture sensors in the collective exhaust air duct for each apartment. This means that the concentration at the place of origin will be registered lower by the sensors in the control box. Complaints concerning “old air” might be caused by the low minimum set point for the ventilation rate which stays low in regards to undetected pollutants. As the system does not react to all existing pollutants it allows concentrations of undetected pollutants to increase (unintentionally). Furthermore, the system does not react to heat load, and (to our knowledge) the existing heating system was not readjusted after the renovation. This might also be a cause for complaints on “old air”, as the heating system was adjusted for the heating need that existed before the
ventilation – which should be lower after renovation than before renovation since the ACR was higher before. Thus, even though the IAQ might just be fine, the heat load might result in this type of sensation. Slightly increased issues with high room temperatures, and significantly decreased issues with cold during summer supports this reasoning. However, at the same time the surveys show slightly increased issues with draft which contradicts the issues that might be caused by a lower ACR. Increased issues with draft may therefore be due to other reasons, such as supply device design and placement or increased infiltration through the building envelope. Increased infiltration might in turn be caused by a changed pressure profile over the building envelope. Despite slightly increased issues with old air, spread of fumes, and thermal comfort, the survey indicates that the IAQ is significantly improved though less issues with odors, static electricity, and cooking fumes from neighbors as well as less frequent use of natural ventilation. The survey also indicates a significant improvement in the tenants’ health. Furthermore, the survey indicates that moisture loads on building materials seem to have decreased as well, causing less concern for microbiological growth and issues caused therefrom.

Simulations show that a higher minimum ventilation rate (0.5 ac/h vs 0.1 ac/h) increases the energy use slightly (4%) but at the same time improves the IAQ. Both laboratorial and survey results support this conclusion by indicating issues that might be increased due to lower minimum ventilation rate. Thereby our previous recommendation of a minimum ventilation rate of 0.5 ac/h is confirmed.

However, survey results only indicate slight increase with (comfort) issues due to a lower ventilation rate after renovation versus before renovation in contrast to improved health and IAQ, which is also confirmed by measurement results. A lower minimum ventilation rate for the DCV-system should therefore not be seen as harmful, as the system either way seems to deals with pollutants that we want to get rid of.

In comparison to a conventional MVHR, simulations show that the DCV-system improves the IAQ in regards to VOC-content in the indoor air no matter what control strategy is chosen. This in exchange for a slight change in the energy use. Running only with VOC-control saves energy (3%), while dual-mode control increases energy use (1-5%). Simulations based on dual-mode control as well as conducted measurements show the need for controls based on moisture in order to deal with high humidity contents in the indoor air.

Even though comparisons with conventional MVHR through simulations do not show much difference in energy use, the transition to a heat exchanger in the case study undoubtedly saves considerable amounts of heat energy with regards to heating the supply air to a set temperature (in comparison to having heating the supply air without a heat exchanger). A system with a variable air volume (VAV), such as a DCV-system, further saves energy through varying air flows, which we have confirmed through calculations based on measurement results from temperatures and air flows in the AHU. Energy calculation savings show that the DCV-system is at an advantage over conventional CAV MVHR, even though the thermal efficiency diminishes with a decreased air flow.

Measurements show a need for individual ventilation for each apartment with ACR for specific loads at all times. They also show that the installed VOC-sensors can be used instead of conventional CO2-sensors both for ventilation controls as well as indicators of IAQ, which is also confirmed by simulation results. However, an important addition to the controls has been the moisture controls, which are the cause for a decreased moisture load on the building materials. Even if the Swedish building code demands an airflow per
floor area, it is apparent that this will not suit both an apartment with one occupant and another apartment with ten occupants equally well. The only reasonable way to design the airflow of an apartment block, where it is impossible to know how the future amount of inhabitants, is to aim for the highest reasonable occupancy and by that the corresponding relevant airflow in all apartments. Even if the design is not made that way in Sweden today, as well as in the pilot project of this study, in case of such a design, there will be a huge energy saving from the demand control. As it is today poor indoor climate in apartments with high occupancy is simply accepted.

5 Conclusions
The system functions as intended, and responds to regarded VOC and moisture loads by increasing or decreasing the air change rate when needed, i.e. gets rid of pollutants that we want to get rid of. Measurements and simulations show that IAQ has improved with lower VOC-content and moisture loads. Surveys show that IAQ has improved as issues with static electricity, odors, and tenants’ health have decreased. However, due to design practicalities - the combination of sensor placement, the choice of measurement interval - with the combination of a low minimum ventilation rate some issues with spread of cooking fumes seem to have increased according to surveys. This phenomenon is supported by findings from laboratory tests. Surveys also indicate that overheating issues also seems to have decreased during the summer as well as draft issues, which might be caused by the choice of set points or lack of heating system readjustment rather than due to the ventilation system functionality or design.

Comparison of a DCV system with a CAV-MVHR system with maximum air flow (0.8 ac/h) shows that the DCV system saves energy. However, the energy efficiency of this system in comparison to conventional CAV-MVHR systems is recommended to be further investigated through case-study energy-measurements.

6 Acknowledgements
We would like to acknowledge the Swedish Research Council FORMAS for their financial support in this project. We would also like to acknowledge Swegon and Hyresbostäder i Norrköping for the use of their facilities.

7 References
inom IVAs projekt Ett energieffektivt samhälle,” Kungl. Ingenjörsvetenskapsakademien (IVA), 2012.


Abstract

To renovate efficiently and properly we must understand the behavior of the existing buildings and thereby building materials. An analysis of hygrothermal measurements in two case studies, one with and one without an internally added thermal insulation system, identifies critical factors for further assessment through simulations. This leads to validation of a hygrothermal simulation model of a solid masonry brick wall for further assessment of different types of internally added thermal insulation systems. Assessment of mold risks based on the MRD-model shows that the risk for mold growth with all internally added thermal insulation systems is significant, if biological material is present in two critical points with regards to solar driven vapor from the exterior: 1) the boundary between the thermal insulation and the existing masonry wall, and 2) the boundary between the thermal insulation and the exterior surface of an internally added vapor barrier. Furthermore, assessments of corrosion risks are conducted for two critical depths of placement for the bed-joint reinforcement. For the corrosion risk at 30 mm from the exterior surface, capillary-active vapor-open systems can improve the situation in comparison to no thermal insulation at all while other systems increase the corrosion risk. For the corrosion risk at 90 mm from the exterior surface, all thermal insulation systems increase the corrosion risk. The exclusion of precipitation uptake eliminates all risks, showing that this is the rain is the most crucial factor. Solutions that limit this uptake or increase the dry-out rate should therefore be considered beneficial.

Key words: hygrothermal, insulation, masonry, brick, renovation, moisture.

1 Introduction

To renovate efficiently and properly we must understand the behavior of the existing buildings and thereby building materials. Status determinations should therefore be used as pointers for decisions on renovation measures. These can be conducted through measurements which describe the situation at hand through analysis. However, the effect of a renovation measure cannot be determined through measurements but requires other methods, such as simulations. If we expect simulations to accurately describe the situation at hand, accurate input data is needed as well as validated models. Status determinations, and thereby measurements can produce such data. Furthermore, if the purpose with a simulation is to determine possible risks with renovation measures, it should be based on a design case scenario. In such a scenario, a proposed renovation measure is analyzed through the use of a combination of variables that produce the least beneficial situation, based on the posed risk. However, these affecting factors should be chosen as realistically as possible for a fair analysis, and deeper analysis of in-situ monitoring data might provide pointers toward the choice of such factors – which include: interior moisture production, climate, cardinal direction, height above the surrounding ground, building material, as well as solar- and precipitation absorption factors.

There are several publications treating both in-situ and in-lab measurements and simulations on solid masonry brick walls,
with/without exterior/interior thermal insulation. D’Ayala and Aktas [1] present results from measurements in the UK. In their paper, they link wind-driven-rain (WDR) with the relative humidity (RH) in a masonry wall and compare the results against hygrothermal simulation models, finding the models to be accurate. Similar measurements are presented by Klõšeiko et al. [2], with evaluations of different types of thermal insulation placed on the interior surface of the external walls. Their results show that the thermal comfort increases but that the risk for mold growth between the thermal insulation and the exterior masonry wall is significant. Vereecken and Roels [3] also evaluate different types of thermal insulation, but in-lab with an X-ray projection method. Their results show that capillary active systems contribute to higher increase of the moisture stored inside the walls, in contrast to traditional vapor tight systems. Johansson et al. [4] present an evaluation of vacuum thermal insulation panels in-lab, showing a decreased hygrothermal performance of the wall. Künzel and Kießl evaluate façade impregnation in combination with interior thermal insulation [5] showing that the impregnation improves the dry-out process of the wall but recommends that interior thermal insulation should be applied some time after impregnation. Pavlík and Černý [6] as well as Toman et al. [7] evaluate hydrophilic mineral wool as interior thermal insulation instead of conventional mineral wool with a vapor barrier. Both show that the hygric function of the thermal insulation improves the hygrothermal performance of the wall.

None of the above mentioned publications evaluate interior thermal insulation on exterior solid masonry brick walls in Sweden through in-situ measurements and validated simulation models. This paper aims to accurately analyze two case studies in Swedish multifamily houses through hygrothermal measurements in exterior solid brick masonry walls. The aim is to determine the design case simulation scenario by identifying differences between materials, depths, heights and cardinal directions. The aim is also to produce a validated simulation model in the hygrothermal simulation tool WUFI Pro, for further assessment of interior thermal insulation.

This paper does not consider risks that cannot be determined by existing risk models that can be based on data from hygrothermal simulation programs. Neither does it evaluate energy, economical, social, or environmental impact of the investigated options.

2 Method
2.1 Measurements
Measurements were conducted in Lund and Örebro, Sweden. SHT75 [8], a sensor by SENSIRION, was used for monitoring of temperature (accuracy ±0.3°C) and relative humidity (accuracy ±1.8%) in the walls and the air. It has been applied by SensiLog [9] in a complete set for hygrothermal measurements. For placement in porous building materials, the sensor has been coated with a filter. This was done to protect the sensor from being damaged/corroded by substances in the surrounding building materials.

2.1.1 Lund, V-building
In the beginning of 2014, we installed 26 sensors of type SHT75 (read above) in the exterior walls and the indoor air of the V-building’s attic. The sensors measured temperature and relative humidity each 10 minutes for 6 months.

The V-building in Lund is part of the Faculty of Engineering at Lund University and is used for various activities normally found at a university. It hosts offices, lecture rooms, group work rooms, and a large laboratory. The sensors mentioned above were installed in the attic walls. On one hand, this means that the sensors should’ve been unaffected by the activities in the rest of the building. On the other hand, the attic hosts the building’s air
handling unit (AHU), which might’ve leaked air exhausted from the formerly mentioned rooms. For this and other reasons, the attic’s indoor air conditions were carefully monitored with the SHT75, but without a filter – which placed the sensor in direct contact with the indoor air.

The exterior walls consist mainly of solid brick masonry (red brick + mortar), and are 1½ ‘stone’ thick (approx. 375-385 mm). Also worth noting is that the attic was unventilated, that the floor consists of a painted concrete slab, and that the roof consists of a painted (on the interior surface) light weight concrete.

2.1.1.1 Sensor placement
The sensors were placed in the northern, southern and western walls on different depths, separately in brick and mortar and on different depths from the interior surface: 200-220, 285 and 330 mm. As the wall is approximately 385 mm thick, this places the sensors 140-160, 100 and 50 mm from the exterior surface.

The setup was chosen for an analysis of the moisture flux through the wall, through different materials and in different cardinal directions. This in order to more clearly understand how to model masonry walls in building performance simulation programs, and to alleviate choices in the renovation process.

In the attic’s southern wall the sensors were placed as shown in Figure 1, and were approximately 86 m above sea level.

2.1.1.2 Indoor and Outdoor climate
The indoor climate was monitored in both the northern and southern part of the attic. Both temperature and relative humidity were measured each 10 minutes.

For the analysis, outdoor climate has been acquired through the use of services provided by the Swedish Metrological and Hydrological Institute (SMHI). Most of the climate data could not be acquired for Lund, so these values have been taken from climate stations in nearby locations. Air temperature, relative humidity, wind direction and wind speed was acquired from Sturup (Malmö Airport) climate station. Data on precipitation was acquired from a climate station in Malmö. The only climate data that was acquired from a climate station in Lund was for global radiation. Direct solar radiation has been calculated through SMHI’s service Strång [10]–[12]. Diffuse solar radiation has been calculated using the following formula:

\[ E_{\text{dif}} = E_{\text{glo}} - E_{\text{dir.norm}} \cdot \sin(\alpha_{\text{sol}}) \]
Where: $E_{df}$ is the diffuse solar radiation [W/m$^2$], $E_{glo}$ is the global radiation [W/m$^2$], $E_{dir,norm.}$ is the direct normal solar radiation [W/m$^2$], and $\alpha_{sol}$ is the solar elevation angle [degrees]. The solar elevation angle was calculated based on the latitude, longitude and the elevation of the simulated location. Missing data have been interpolated.

Unfortunately, as the precipitation data was for Sturup and not for Lund it was insufficient for a deeper analysis on the effect of precipitation on the wall. The same applies to the effect of the direct solar radiation, as this was calculated and not measured.

2.1.2 Örebro, Karmen 15

‘Karmen’ is a block of buildings in Örebro. Three buildings within the block consist of towerblock buildings, each consisting of 29 apartments. These were renovated during 2013-2016. We installed the same type of sensors here as for V-huset. This was done for one of the buildings in the beginning of 2015. Measurements started in the middle of summer 2015 and are still ongoing.

In the renovation the exterior walls were rebuilt to the combination shown in Figure 2.

2.1.2.1 Sensor placement

Similarly to V-huset, the sensors were installed in various depths within the masonry wall and in different cardinal directions. However, they were also installed on different stories, and as the composition of the exterior walls for these buildings differs from V-huset’s walls, we also had the opportunity to install the sensors in each of the different material layers shown in Figure 2. The sensors in the masonry wall were installed 90, 150 and 200 mm from the interior surface of the masonry wall, which approximately corresponds to the depths for the sensors in V-huset from the exterior surface. In this case, the depths from the exterior surface were: 140, 100 and 50 mm.

Figure 2: Wall composition of northern and southern exterior walls for Karmen 13-17. Sensor placement in the wall: red – brick, blue – mortar, green – air/mineral wool. Approximate sensor depths from the interior surface of the masonry wall: 90, 150 and 200 mm. Blueprint provided by ÖrebroBostäder.

2.1.2.2 Indoor and Outdoor climate

Unfortunately, the indoor climate could not be monitored as the indoor air sensors were dead on arrival. Furthermore, the tenants did not agree to the installation of new sensors at a later occasion. The closest sensors to the indoor climate would be those placed on the interior surface of the vapor barrier. However, the climate at this location is strongly affected by the thermal thermal insulation as well as the airtightness of the interior surface (OSB + gypsum board). Therefore, using the readings from these sensors as indicators of the indoor air would be inaccurate.

Figure 3: Approximate location of sensors installed in exterior walls. Blueprint provided by ÖrebroBostäder.
Outdoor climate for Örebro has been acquired from SMHI, with the method described under 2.1.1.2. However, in contrast to the climate data for Lund, most of the data was acquired from stations within Örebro. Nonetheless, as for the climate data in Lund, the data for precipitation was acquired for a nearby location (thus not Örebro), and the data for solar radiation was calculated. However, daily precipitation data for the actual location was obtained from SMHI which is at least enough for indicative comparisons.

2.2 Simulations
Hygrothermal 1D-simulations were conducted in WUFI Pro for analysis of internally added thermal insulation. The basic model consisted of a solid brick masonry wall, based on the wall in the V-building. As we didn’t have the material data (e.g. sorption curves) for the wall, the first step was to create a model of the wall in WUFI and validate that model.

In order to reach equilibrium with the surrounding climate, and to minimize the effect of assumed starting conditions, all simulations has been run for 10 years by repeating the same climate year. The results from the last three years in the simulation runs have then been used for further risk assessment using models described under 2.2.3.4.

2.2.1 Input data, all simulations
Unless otherwise specified, all simulations have used default WUFI Pro values and the following input data:

- Driving rain coefficient for a tall building’s upper part, +20 m.
- No explicit radiation balance.

2.2.2 Validation of simulation model
Initial simulations were conducted for the selection of the material type appropriate for further analysis.

2.2.2.1 Weather Data, Indoor Climate and Other Input Data for validations
For the validated model, hourly weather data for Lund was assembled as described under 2.1.1.2. Under the same section, we have also mentioned that the indoor climate was monitored in both the northern and southern part of the attic. However, WUFI requires data for the whole year in a data file but the indoor climate data was only measured for six months. Therefore the indoor climate was chosen according to an annual sinus function fitting the indoor acquired climate data.

2.2.2.2 Material type selection
The first step consisted of simulations of 21 different types of brick, mortar and combined brick-mortar materials found in various WUFI databases. As the measurement results showed quite large fluctuations in RH for the monitoring-position closest to the exterior surface, the materials with results showing low fluctuations in the same monitoring position were discarded. The table below presents the materials chosen for further analysis.

<table>
<thead>
<tr>
<th>Sensor name</th>
<th>Material name</th>
<th>Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>Solid Brick Masonry</td>
<td>Fraunhofer-IBP Holzkirchen, Germany</td>
</tr>
<tr>
<td>F5</td>
<td>Aerated Clay Brick (density 672 kg/m³)</td>
<td>MASEA</td>
</tr>
<tr>
<td>F6</td>
<td>Expanded Clay</td>
<td>MASEA</td>
</tr>
<tr>
<td>F7</td>
<td>Solid Brick ZD</td>
<td>MASEA</td>
</tr>
<tr>
<td>F8</td>
<td>Brick (old)</td>
<td>North American</td>
</tr>
<tr>
<td>F10</td>
<td>Portland Cement-Lime Mortar – Type S</td>
<td>North American</td>
</tr>
</tbody>
</table>

2.2.3 Comparison of internally added thermal insulation
From the analysis of the measurements in V-huset and in Örebro (under sections 3.1 and 3.2) and in consideration of the risks assessed through 2.2.3.4, the following critical points were identified:

- For analysis of the effect of solar driven vapor, the wall is oriented towards the
cardinal direction in which the wind driven rain is the most intense.

- For analysis of mold risk, the boundary between the thermal insulation and the solid brick masonry wall is the most critical point. In the case of combination between vapor-open and vapor-tight materials, the boundary between the external vapor-open thermal insulation layer and the internal vapor-tight material is another critical point.

- For analysis of corrosion risk, the location of the bed joint reinforcement at 30 mm and 90 mm from the exterior surface poses the greatest corrosion risks [21].

2.2.3.1 Thermal insulation systems

There are several different types of thermal insulation that can be applied on the interior surface as renovation measures. Vereecken [22] categorizes these in capillary active (i.e. hydrophilic) and standard (i.e. conventional) materials, where capillary active materials include capillary suction in contrast to standard materials. The standard materials can further be sub-categorized into vapor open and vapor tight materials. Vapor open materials should however be combined with a vapor barrier to reduce the moisture flux through the wall from the interior. We have previously shown [13] the risks the interior moisture flux poses if a vapor barrier is not used with conventional interior thermal insulation (mineral wool between wooden studs). Therefore, we have refrained from analyzing such solutions in this paper.

When a vapor barrier is used, the risk for moisture damage due to solar driven vapor is also quite significant (as shown under 3.2), if there are any biological materials in the boundary between the vapor barrier and the material layers further towards the exterior. The same issue might be faced with a vapor tight thermal insulation layer on the inside. Since it is the precipitation uptake that is the main cause for this phenomena, a solution to this issue could be impregnation with a vapor-open water repellant to the exterior surface, if a ventilated air gap is not possible to achieve. However, it is not always practically possible to achieve a ventilated airgap for an existing masonry wall. Furthermore, the application of a ventilated air gap for a thick masonry wall will practically render the existing wall’s heat resistance insignificant.

We have previously shown that precipitation is the most contributing factor to the moisture risks for this kind of setup [13]. In the case of an exterior water repellant, it is important for it to have a lower vapor resistance than the interior vapor barrier in order to allow the material between these two membranes to dry out.

The comparative simulations have included all options mentioned in the paragraphs above, this is shown in the following table. Each thermal insulation type has been chosen with a thickness that gives an equal amount of heat resistance as the other types, with a U-value of 0.25W/(m²·K) including the solid masonry wall.

Table 2: Thermal insulation systems assessed in simulations.

<table>
<thead>
<tr>
<th>Case</th>
<th>Solution</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Calcium silicate (λ=0.05W/(m·K), d=0.149m)</td>
<td>Capillary active, Vapor open</td>
</tr>
<tr>
<td>2</td>
<td>EPS (λ=0.04W/(m·K), d=0.115m)</td>
<td>Vapor tight</td>
</tr>
<tr>
<td>3</td>
<td>Mineral wool - PE-foil - Mineral wool (λ=0.04W/(m·K), d=0.115m)</td>
<td>Vapor open with vapor barrier</td>
</tr>
<tr>
<td>4</td>
<td>3 + water repellant* (λ=0.04W/(m·K), d=0.115m)</td>
<td>VO + VB + WR</td>
</tr>
</tbody>
</table>

*rain water penetration =0%, exterior surface

2.2.3.2 Weather data for simulations

There is no standard test-reference time-period to use for hygrothermal simulations of constructions in Sweden. Instead, normal year
climate data are usually chosen for hygrothermal analyses. For conclusions that might be applied generally, a design case scenario is sought. For generalized results, the design case scenario should have the toughest normal year for realistic Swedish locations. In a previous publication [13], normal year weather data files for multiple locations were acquired through METEONORM 7 for WUFI Pro simulations. METEONORM 7 provides statistically based normalized climate data for any geographical location. This data is based on measured data from climate stations all over the world, and interpolation between these stations [14]. However, normalized data might underestimate the effect of extreme hourly climate variations. Therefore the option to include extreme hourly values with regards to temperature was chosen.

In our previous publication [13], climate files for relevant Swedish locations were analyzed out of an identified design case scenario (based on a realistic construction type) with regards to internal moisture loads and interior thermal insulation on multifamily buildings with exterior brick-walls. The analysis showed that the weather for the Swedish city Malmö posed the greatest mold growth risk. However, in the same article, the Swedish location that showed the highest mold growth risk including the effect of rain absorption was Norrköping. Based on those results, the climate file for Norrköping was used in this publication for the final analysis of interior thermal insulation of exterior brick walls.

2.2.3.3 Indoor climate, input data and design choices

Indoor climate was chosen according to EN13788. Humidity class 1 was used, as this accurately represents the indoor climate measured in Swedish multifamily houses according to a survey conducted by Boverket [15] (the Swedish National Board of Housing, Building and Planning). The source states that the temperature and moisture supply indoors was measured to 22°C and 1.2 g/m³ on average, respectively.

For a design case scenario, the driving rain coefficient was chosen for a tall building’s upper part with a height of 20 meters above ground.

For Norrköping, the wall was oriented towards the west, as a WUFI-analysis of the climate data has shown that this was the most intense cardinal direction for the wind driven rain.

2.2.3.4 Risk assessment

Added interior thermal insulation poses a risk for increased relative humidity in existing walls, due to the decreased heat flux and thereby lower temperature. The hygrothermal conditions of the wall have been related to several risks: 1) microbiological and biological growth, 2) corrosion of the bed joint reinforcement above openings, and 3) frost decay in the form of frost expansion as well as deterioration due to repeated freeze-thaw cycles. In this paper, we have refrained from explaining the mechanisms behind these occurrences in detail, as there are numerous references that do [16]–[21]. Existing models for damage risk assessment based on hygrothermal conditions have so far covered mold and corrosion risks. We have not found any model for risk assessment of frost decay. This might be due to the difficulty in modeling the complexity of the problem, as the occurrence of frost decay depends not only on surrounding climate, but also on the chemical and structural composition of the building material, which for bricks can vary from brick to brick. Add to that the combination with different types of mortar, and the difficulty to attain such a model increases.

2.2.3.4.1 Microbiological growth

With the right conditions, microbiological growth may occur on biological material in the form of mold. It is known that emissions from mold may cause health problems. Therefore, mold growth causing emissions in the indoor environment should be avoided. There are several models for the determination of mold growth on biological building material, but for
this paper the risk of mold growth in sensitive locations within the wall is determined through the use of the MRD-model [16]. This model describes the mold growth rate based on three criteria: temperature, relative humidity and time. As with most new models, the MRD-model considers the shrinkage of mold during unfavorable conditions, which in comparison with laboratory analyses give realistic results[16]. The model compares the hygrothermal simulation results with experimental measurement results, producing an index. If the index exceeds 1, the results indicate visible mold growth under microscope.

2.2.3.4.2 Corrosion
Cracking of the brick masonry can be caused by corrosion of the bed joint reinforcement over windows and other openings in the façade. This can lead to the need to replace the reinforcement due to aesthetic and structural damage. The risk of corrosion on the bed joint reinforcement within the masonry wall, can be assessed through an empirical model proposed by Larsson and Molnar [21]. The suggested model is based on corrosion models for reinforcement in concrete based on accelerated laboratory tests. The data used for the model can be hourly average data, and the corrosion rate calculated for each hour. The model accounts for temperature (T), relative humidity (RH) and oxygen supply in the vicinity of the reinforcement. According to the model, there is no corrosion if the temperature is below 0°C, and the corrosion rate increases with increasing temperature and relative humidity. However, at the same time the model accounts for oxygen supply by considering the moisture saturation of the masonry over time, diminishing the corrosion rate for as long as the relative humidity exceeds 90%.

3 Results and Discussion
3.1 Measurements in V-huset
The sensors were named after placement in material and depth into the construction. S-B1 means in the southern façade, in the brick, first sensor from the interior surface. In other words, the first letter stands for the cardinal direction of the wall, the first number for the level above ground, the second letter for the material, and the final number for the order of placement from the interior surface of the brick wall.

Throughout the measuring period, the southern indoor sensor has registered a bit higher RH than the one in the north. This might be because the average indoor temperature in the south has been lower, according to the data analysis. However, the analysis also shows that the temperature in the south has a larger spread, even though the same cannot be said for the RH. The larger spread might be explained in a larger annual solar radiation and driving rain sums for the southern wall in relation to the northern wall - causing larger fluctuations.

![Boxplots on measured RH for southern sensors in the V-building’s attic wall. Showing 25th percentile, median, 75th percentile, whiskers (1.5 interquartile range) and outliers. S=South, B=Brick, M=Mortar.](image)
3.1.1 General comparison - Lund

There is a distinct difference both between materials and depths when it comes to the RH. In the southern wall (Figure 4), the further out the sensor is installed into the construction the larger the spread is and the higher the median is (more humid). However, this phenomena is more apparent for the sensors in the mortar than those in the brick. The same relationship between spread, depth and material can be found in the temperature readings for the all walls (e.g. southern wall, see Figure 5), as well as the RH readings for the western wall. However, the RH readings for the northern wall show the opposite relationship (see Figure 6) – the further out into the wall towards the exterior, the more humid it is. According to a WUFI-analysis of the climate data, the southern and western walls are more frequently exposed to sun and wind driven rain. The solar radiation should therefore account for the higher range temperature and RH-ranges together with the superior exposure to the wind driven rain. Without the wind driven rain, it would simply be dryer in these walls than in the northern wall. Another difference between the orientations of the walls is that the western wall is on average colder (15.0 °C) than the southern wall (16 °C), and the northern wall is on average colder (14.1 °C) than the western wall, but the same cannot be said for the relative humidity (RH₅avg=90.3%, RH₆avg =95.8%, RH₇avg =90.7%). The difference in the average RH between the south and the west might be explained in the difference between the average temperatures, and the difference in average temperatures can only be explained by the difference in exposures to sun and wind driven rain as the sensors west and the south share the same indoor climate. The northern wall is generally colder, but the average RH for the northern wall seems to be almost equal to the average RH for the southern wall, meaning that if the temperature in the northern wall was warmer then it would on average be drier than the southern wall. Nonetheless, the fact remains that these measurements show that the northern wall is colder and more humid than the southern wall, even though the indoor air temperature in the northern part of the attic.
is warmer and drier than in the southern part of the attic.

3.1.2 Cold month comparison - Lund

When comparing the RH and T for the different wall setups for a cold month, the above noted difference between depths is confirmed, i.e. the further out into the wall the colder and more humid it is. But, further comparison of the averages for the whole measuring period shows a different relation. The coldest wall is on average the one to the west (7.82°C), second coldest to the south (8.16°C), and the warmest to the north (8.86°C). Furthermore, the RH for the northern wall is the lowest (88.9%), while the southern is the most humid (99.6%), although the western does not fall far behind (99.0%). That the northern wall is the warmest, likely relates to the temperature difference in the indoor air where the northern indoor air sensor registers a higher temperature than the southern sensor throughout the whole month (average: 20.4 °C vs. 16.7 °C). That the southern wall is the most humid might be explained by an exceeded exposure to rain.

3.1.3 Warm month comparison - Lund

Looking at a warm month instead, the previously noted relation between depth and temperature can no longer be established with certainty (Figure 7 and Figure 8). Due to, what can only be deduced to be the influence of solar radiation, fluctuations are much stronger the further out into the wall for both RH and T. The effect of these fluctuations echoes throughout the whole month, making the wall drier towards the exterior than the interior. This applies especially to both brick and mortar in the southern and western wall, but is not evident for the northern wall. If this means that vapor is pressured towards the interior, or if this simply describes the effect of solar radiation cannot be deduced due to insufficient climate data. However, the difference in measurements between the cold and the hot month insinuate that vapor is pressured towards the interior. This can only be confirmed by measurements of precipitation in relation to solar radiation, which we currently do not have with required accuracy.

During the summer month, the temperature and relative humidity between the two indoor sensors are approximately in coherence (average: 23.3°C vs. 23.2°C) Therefore, these should not significantly contribute to the differences between the walls. A quick comparison of the average temperature shows that the southern wall is the warmest (22.5°C), the western second warmest (21.8°C), and the northern the coldest (20.0°C). A quick comparison of the average RH shows that the southern wall is the driest (92.2%), the western second driest (93.4%) and the northern the most humid (93.5%). The clear reason for this is differing exposures to sun and wind driven rain.

3.1.4 Summary - Lund

- Mortar and brick behave approximately similar during the cold month, but not during the warm month. Depending on the orientation of the wall, larger fluctuations can be found in either brick (south) or mortar (west).
- Northern and western walls are on average colder and more humid than the southern wall during the summer month, but the same cannot be said for the whole time period and for the winter month.
- During the whole measuring period, and especially during cold months, the further out into the wall the colder and more humid it is. The same cannot be said for the summer months, where the opposite has been observed. It is unclear if this is due to the vapor being pressured towards the interior due to solar radiation, as the weather data is insufficient for such an analysis. However, measurements in relation to acquired weather data indicates that such is the case.
3.2 Measurements Örebro

The sensors in Örebro were named after placement in material and depth into the construction and level placement, e.g. S5-B1 means in the southern façade, on the fifth level, in the brick, first sensor from the interior surface. In other words, the first letter stands for the cardinal direction of the wall, the first number for the level above ground, the second letter for the material, and the final number for the order of placement from the interior surface of the brick wall.

As previously mentioned, we have not been able to acquire indoor air measurements for the apartments in Örebro. The closest thing to
these would be the sensors placed on the interior surface of the vapor barrier marked “BI” in the following boxplots. However, between this sensor and the indoor environment is a layer of mineral wool and a gypsum board, and observed on site (at least in some cases) an OSB. This means that the sensor is placed in a thermally and aurally different position from the indoor climate, making it insufficient for the assessment of the indoor air and the effect that this has on the hygrothermal situation in the wall. Also, this makes it quite difficult to achieve a validated model for this scenario, therefore such a model has been based on the measurements in Lund.

Figure 9: Boxplots on measured T for sensors in the southern wall on level 5. Showing 25th percentile, median, 75th percentile, whiskers (1.5 x interquartile range) and outliers. N = North, S = South, FO= façade exterior surface, B = brick, M = mortar, Ca = cavity, BO = barrier exterior surface, BI = barrier interior surface.

Figure 10: Boxplots on measured RH for sensors in the southern wall on level 5. See Figure 9 for details.

Figure 11: Boxplots on measured RH for sensors in the northern wall on level 5. See Figure 9 for details.
3.2.1 General comparison - Örebro

The same relation between spread, depth and median can be noted for the measurements in the solid masonry brick wall in Örebro as for the corresponding in Lund. In general, the further out into the wall, the more humid it is and the colder it is. However, there are some differences to be noted here as well. The differences in temperatures between depths within the masonry wall is not as distinct for the setup in Örebro as it is for the one in Lund (see B1-B3 and M1-M3 in Figure 9). This might be caused by the decreased influx of heat from the interior due to the thermal insulation. Also, there are differences that can be related to the height above the ground. Sensors on level 5 register, in median, higher relative humidity than those on level 3 (e.g. compare S3-B3 and S5-B3 in Figure 12 and Figure 10), but marginal differences in temperature. This applies to both northern and southern walls. A reason for the humidity differences might be a superior exposure to wind driven rain on higher levels – where possible obstacles have less influence for the rain. This can however not be confirmed with current measurements.

There are also similarities with the results for the wall in Lund to be noted. One such similarity is that the northern wall is in median more humid than the southern wall (compare S5-B1 to 3 and N5-B1 to 3 in Figure 11 and Figure 10). An analysis of the climate data assembled with METEONORM 7 for a 10-year period shows that the southern side of the building is usually the most exposed side both when it comes to wind driven rain and solar radiation, similarly to Lund. These comparisons show that the solar radiation has a superior influence on the hygrothermal conditions in the wall, even more so than the wind driven. Furthermore, the difference in median between the northern and southern walls at the most critical point is marginal (compare S5-BO and N5-BO in Figure 11 and Figure 10). However, for the same sensors the whiskers for the southern side is marginally higher. In conclusion, this means that the more exposed an exterior surface is to direct sunlight – the drier the material closer to that surface will be, even if it is most subjected to wind driven rain. Consequently, the critical point in regards to solar driven vapor (from the facade to the interior during a hot month), represents the highest risk in this cardinal direction.

3.2.2 Cold and Hot month - Örebro

Fluctuations are clearly stronger for the southern wall than the northern, even during the winter. Also, as for Lund, the sensor that is most humid during the winter, the one closest to the exterior surface (S5-B3), becomes the driest sensor during summer days without precipitation. During some summer days the opposite is observed, which might relate to the precipitation. Hourly precipitation data (in location) could not be acquired, making a thorough analysis of this impossible. However, daily precipitation data has been acquired from SMHI, which is at least good enough for an indicative analysis. During days with precipitation, sensor S5-B3 registers the highest relative humidity in relation to other sensors within the wall. This can be observed in 2015-07-06, which is right after precipitation from 2015-07-
06. Note that when this happens the sensor on the exterior surface (S5-BO) of the vapor barrier drops (2015-07-03), indicating a lower moisture flux from the exterior, only to rise again when the RH for S5-B3 drops again (compare S5-BO with S5-B3 2015-07-12 until 2015-07-17).

Something that can also be noted in Figure 13 is the heightened risk for moisture damage in the form of microbiological growth, where the RH for S5-BO as well as S5-Ca far exceeds 75% while the temperature is approximately at 20°C. The posed risk is clear without further analysis, but fortunately the chosen solution is impervious to mold growth due to the choice of steel frames instead of wooden studs. However, in case of contamination (e.g. in the form of sawdust) the risk persists. Therefore, for such an application, it is of the utmost importance to keep this space clean from biological material.

3.2.3 Summary - Örebro
- The results confirm noted behaviors in the analysis on previous results from Lund, but differences between the measurement results in relation to the placement of the sensors appear in some aspects, which can be deduced to the effect of the interior thermal insulation and vapor barrier.
  - The results show that the upper part of the façade is more humid than the lower, implying a higher exposure to precipitation in comparison with the lower part, making it more vulnerable out of a moisture safety perspective.
  - The results indicate the effect of wind driven rain on the hygrothermal status of the wall in relation to the cardinal direction, resulting in a ‘reversed’ moisture safety risk where the most critical point is the exterior surface of the vapor barrier.
  - If the most external thermal insulation layer is combined with wooden studs instead of steel studs, the risk for moisture damage due to solar driven vapor is quite significant.

![Figure 13: Temperature and relative humidity registered in the southern wall for a winter month. Dotted lines represent T. S=’south’, B=’brick’, M=’mortar’, Ca=’cavity’, FO=’facade’, BO=’barrier’s exterior surface’, BI=’barrier’s interior surface’, number=order of placement from the interior surface.](image-url)
3.3 Simulations

3.3.1 Validation of model
As previously described, the first step was to validate a model of the wall in WUFI Pro, for use in further simulations for assessment of interior added thermal insulation in relation to the risks stated under 2.2.3.4. Consecutively, summarizing conclusions from measurements and the validated model has been applied in the simulation.

Initial simulations show a quite accurate thermal coherence for cold months between measurement and simulation results for all the chosen materials in Table 1. However, temperature (and thereby RH) fluctuations, due to what may be deduced as solar radiation, are larger for measured data than the simulation results (see Figure 15). This is most likely because thermal data (i.e. solar radiation data) isn’t entirely accurate, due to the form of acquisition (described under 2.1.1.2). However, this also depends on the chosen surface properties of the façade. For the exterior surface the short wave solar radiation factor was set to 0.91 (Tiles, concrete, black). Using this factor instead of 0.68 (Brick, red) generates results closer to measurements (∆T 2-3°C). However, for a design case scenario it is safer to choose a setup that results in a more humid wall with the use of 0.68 (Brick, red).

For some of the simulated months, some materials generate results that are close to the measured results, while the same materials produce results that are quite off for other months. The strongest contender is material F7 (see Table 1). During some months material F7 generates higher simulated RH than measured in average, which places the simulation results on the safe side when assessing the moisture safety risks. Therefore further simulations for assessment of interior thermal insulation are conducted with this material.

Figure 14: Measured vs simulated RH for April 2014, at approximately 330 mm depth. See Table 1 for material details.
3.3.2 Thermal insulation comparison

3.3.2.1 Posed risks

As shown in Figure 16, only option no. 4 (exclusion of precipitation uptake) produces results with a marginal risk for mold growth between the thermal insulation and the masonry wall, in case of pre-existing biological material or contamination. Any other option requires meticulous (almost flawless) cleaning of the boundary between the materials. Furthermore, option no. 3 further poses a risk in the boundary between the thermal insulation and on the vapor barrier’s exterior surface (3b). It is therefore extremely important to remove any biological material from the interior surface of the masonry wall if such solutions are chosen, and not to use wooden studs. It is also important to choose materials that can handle high relative humidity without a decrease in performance or deterioration of the material itself.

Even for the corrosion risk, the exclusion of precipitation uptake is the most beneficial option, see Table 3. For the rest, depending on the depth from the exterior, the different thermal insulation types generate diverse corrosion results. CaSi shows approximately the lowest increase in corrosion depth in comparison to an uninsulated masonry wall, making it the superior option between the investigated solutions. At d=30 mm, CaSi even improves the situation, generating a smaller corrosion depth of the reinforcement.

Table 3: Calculated corrosion depth (over three years) in bed joint reinforcement above openings in the facade. Refer to Table 2 for thermal insulation system specification.

<table>
<thead>
<tr>
<th>Thermal insulation system</th>
<th>d=30 mm from exterior surface</th>
<th>d=90 mm from exterior surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>15.78</td>
<td>15.50</td>
</tr>
<tr>
<td>1</td>
<td>14.02</td>
<td>15.59</td>
</tr>
<tr>
<td>2</td>
<td>16.27</td>
<td>14.77</td>
</tr>
<tr>
<td>3</td>
<td>16.98</td>
<td>16.72</td>
</tr>
<tr>
<td>4</td>
<td>0.341</td>
<td>0.216</td>
</tr>
</tbody>
</table>

For both calculated risks, a vapor-open water repellent on the façade improves the situation drastically. Such hydrophobic function could be achieved by applying vapor open impregnating materials on the façade, e.g. silane or siloxane. However, these have varying repelling-efficiencies depending on manufacturer and might even degrade over time. Also, such impregnations have a risk of discoloring the façade, which might not be accepted in cases where the building is protected by cultural heritage laws.

4 Conclusions

Measurements show clear differences between geographical locations, cardinal directions, depth and vertical placement. Marginal differences are also noted between materials. The measurements also indicate the effect of known physical phenomena, and the significance of precipitation and solar radiation on the hygrothermal status of exterior masonry walls. With regards to the applied interior vapor-open insulation and vapor barriers, the results clearly show that there is a risk for microbiological growth due to solar driven vapor if biological materials
exist by the exterior surface of the vapor barrier.

In general, current simulation guidelines have been confirmed. Furthermore, simulations generate worse-than-actual end results, forcing the end-user to make decisions that ultimately should benefit the outcome. Simulations are also deemed to give close-enough results for hygrothermal assessments of exterior masonry walls, and even though the actual material data might not exist, substitutes can be found in the existing databases.

The mold risk is only significant if biological material is trapped between the thermal insulation and the exterior masonry wall, or between the thermal insulation and the exterior surface of an internally added vapor barrier. It is therefore of the utmost importance to avoid any biological materials by these boundaries, or reduction of the precipitation uptake as it is identified as the most contributing factor to the mold risk.

The corrosion risk exists with or without thermal insulation. Standard types of thermal insulation seem to increase the corrosion risk, while capillary active types perform better. As for the mold risk, elimination of precipitation uptake also eliminates the corrosion risk. However, if and how the corrosion risk poses a threat to the structural stability, aesthetics or other potential issues has not further been investigated.

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6 References


