Field Measurements for Verification of the Impact of Renovation and Maintenance Measures on Buildings

- regarding Energy Efficiency, Indoor Environment and Moisture Safety

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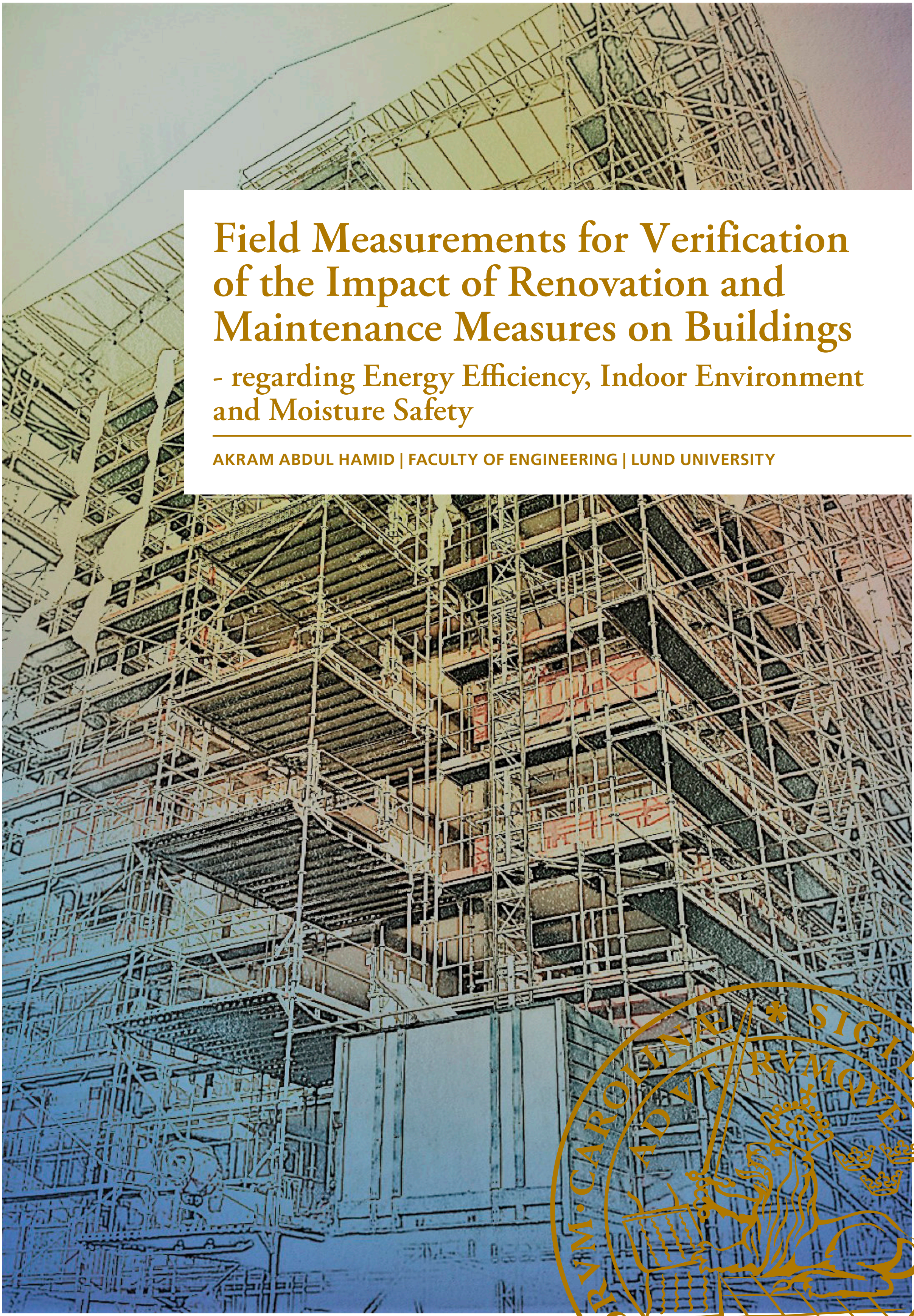
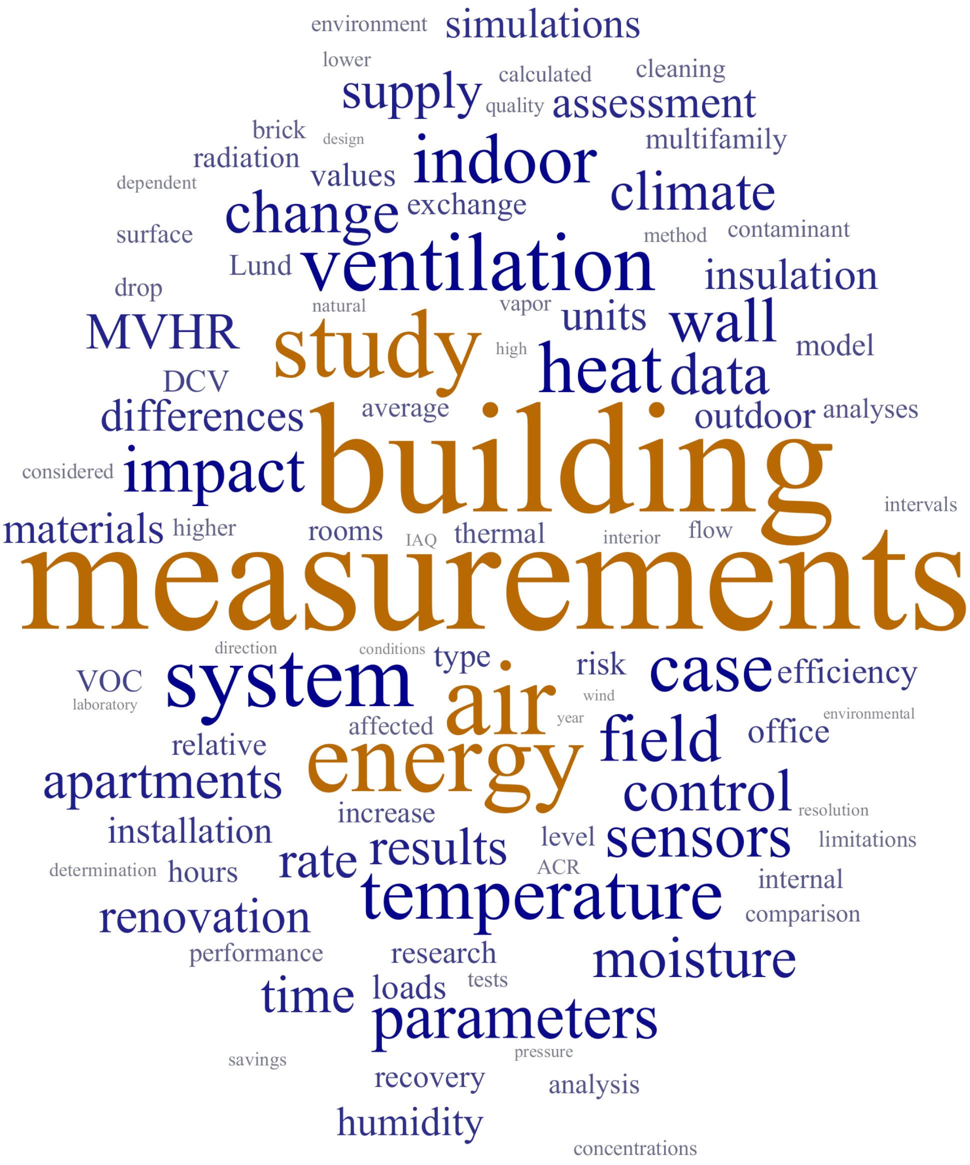


Field Measurements for Verification of the Impact of Renovation and Maintenance Measures on Buildings

- regarding Energy Efficiency, Indoor Environment and Moisture Safety

AKRAM ABDUL HAMID | FACULTY OF ENGINEERING | LUND UNIVERSITY



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Fältmätningar för verifiering av den inverkan som renoverings- och underhållsåtgärder har på byggnader

- avseende energieffektivitet, inneklimat och fuktsäkerhet

Akram Abdul Hamid

Lund University,
Faculty of Engineering,
Department of Building and Environmental Technology,
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Field Measurements for Verification of the Impact of Renovation and Maintenance Measures on Buildings

- regarding Energy Efficiency, Indoor Environment and Moisture Safety

Akram Abdul Hamid

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Abstract

Renovating the European building stock has for almost two decades been a matter of importance to the European Union. Reduction of energy use for existing buildings can be achieved through applying energy efficiency renovation measures. Besides this, there is quite a large renovation need in Sweden due to building materials and services reaching (or having passed) the end of their service life.

Incorrectly implemented, renovation measures can have negative impacts on the state of the building, and so can the lack of maintenance measures. In order to avoid negative outcomes, impacts of possible renovation and maintenance measures need to be evaluated. It is also important to be able to predict these impacts and therefore important to acquire data on them, but also more knowledge on how to isolate the impacts of such measures through field measurements.

This thesis aims to assess the impact of relevant and applicable renovation or maintenance measures for buildings in temperate climates, primarily through field measurements. This thesis also aims to illuminate the process of field measurements for acquiring data for the assessment of renovation and maintenance measures. The empirical base for this has included five case studies on renovation or maintenance measures that are relevant for Swedish buildings, and a literature review.

In order to illuminate the process of field measurements for the assessment of the impact that renovation and maintenance measures has on a building, this thesis has analyzed the research procedure in five case studies that have included such assessments. These case studies included measures that impacted on the energy use, the indoor environmental quality, and/or the moisture safety of a building.

The thesis compares the setups of the field measurements in the case studies, discusses the details of the field measurements, the limitations in each study and the consequences thereof, and the knowledge that was gained through the analyses that were conducted. This empirical data, gained from these analyses, formed the basis for the illumination of the overall method for the assessment of renovation and maintenance measures through field measurements.

The results in the included case studies show that the measures that have been evaluated have a beneficial impact on the energy use, and some also on the indoor environment. However, it is important to consider possible risks with implementing the measures in order to avoid negative outcomes. The case studies show that it is possible to determine the impact through field measurements, with accuracy. The analysis of the procedures in the case studies in this thesis shows that different measurement setups require different types of analyses in order to determine the impact of the measure. If field measurements are conducted on an object (e.g. a building) before and after the implementation of a measure, control parameters should be measured simultaneously in order to determine the impact of changes in these parameters on the object and thereby isolate the impact of the measure. If measurements are conducted solely after the implementation of the measure, simultaneous measurements should be conducted on a control object, that is comparable to the object on which the measure has been implemented (the main object) and preferably has not undergone any changes during the study.

The combination of the case studies shows that the design of the field measurements is often based on a hypothesis. The design considers limitations of the case study, possible impact of control parameters, if it is possible to conduct measurements on a control object, and if it is possible to retrieve data from other sources. The combination of the case studies also shows that, most likely, a deviation (e.g. sensor failures) will occur, or a limitation will exist, which will require supplementary analyses to be conducted in order to answer the hypothesis and/ or other questions related to the determination of the impact of the measure.

Key words renovation, maintenance, measures, field measurements, energy, moisture, ventilation

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The knowledge of anything, since all things have causes,
is not acquired or complete unless it is known by its causes.

- Avicenna (Ibn Sīnā), c. 1020.

Preface

I would like to start by thanking all my supervisors for giving me this great opportunity. I would like to thank my main supervisor Jesper Arfvidsson, as well as my co-supervisors, for the support and guidance they have provided in my studies and in my research. Special thanks also go to my co-supervisors Dennis Johansson, Hans Bagge, and Petter Wallentén for their cooperation and support in the case studies, and for giving me the opportunity to work with them. Thanks also go to Åsa Wahlström for supervising me in the literature study, the case study on demand-controlled ventilation, and for always taking the time to provide me with valuable feedback.

There have been numerous occasions in which I have received highly valued support from my esteemed colleagues and fellow PhD students at the department. This, both regarding my work environment at Lund University and through discussions regarding my research and studies. For this I'd like to thank them all, as well as for their pleasurable company at the office and outside of it.

I would like to thank my parents for their love and support. I would also like to express my appreciation for my wife supporting me and being patient with me during my studies (but also ever since I met her).

Finally, as always, for all things:

الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ

Praise be to God, Lord of the Worlds.

This doctoral thesis is part of my graduate studies at Lund University, Faculty of Engineering, Department of Building and Environmental Technology, Division of Building Physics. The research was done in cooperation with, and support from, the Division of Building Services.

The division of Building Physics

In English-speaking countries, building physics is sometimes referred to as building science. It is the knowledge of the state and the operation of the building's envelope [1]. Heat transport, moisture transport and air flow are the physical processes that are in focus within this research area. These processes occur in the building materials, within the buildings and in relation to the surrounding environment.

At the Division of Building Physics [2] we deal with the design of building components such as the foundation, the outer walls, the windows, the roof, and their connections. This, with regard to their hygrothermal functionality and status, the conservation of energy and resources, as well as their impact on the indoor climate. We deal with the physical processes that occur in the building envelope and within the building. We also develop programs, codes and applications for building physics based on mathematical models.

The division of Building Services

This research area comprises the functions of all building services equipment in a building, the interaction of the equipment with the occupants and their activities, the building itself and the climate within and surrounding the building. The research has a systematically analytical and method developing orientation. Its purpose is to develop energy efficient equipment that gives a good indoor climate and has a guaranteed functionality.

The Division of Building Services [3] deals with HVAC (heating, ventilation and air condition), as well as water services such as tap water, drainage and plumbing systems. The research also includes the indoor environment and the well-being of the occupants due to the built environment.

Research disciplines & interdisciplinarity

There are many opinions and argumentations for when and where the discipline originated as a structuring mode for academic practice. There also differentiating definitions of what defines a discipline depending on the level of detail and sophistication [4].

The word discipline stems directly from the Latin *disciplina* "instruction given, teaching, learning, knowledge" [5]. But defining an academic discipline is not that simple, because then we need to ask ourselves: What is being taught? What instructions are given? Which knowledge is passed? What makes this discipline unique? I believe the answers to these questions are what defines a discipline.

In Chettiparamb's literature review [4] the author presents definitions on what a discipline is according to other sources. I find that Boisots (1972) is the easiest to apprehend and most agreeable with my own perception of how to define a discipline. According to Boisots, three elements structure an academic discipline:

- *observable and/or formalized objects, both manipulated by means of methods and procedures*
- *phenomena that are the materialization of the interaction between these objects*
- *laws – whose terms and/or formulation depend on a set of axioms. These account for the phenomena and make it possible to predict how they operate.*

If I would define the discipline of Building Physics with the help of Boisots's definition of a discipline, the object would be the building and the building envelope, the phenomena would be the physical processes that occur in/ to the building, and the laws would be the physical laws that account for the physical processes.

The word *inter* is Latin and is translated to "among, between, betwixt, in the midst of" [5]. The word interdisciplinarity would, in Latin, be *inter disciplinam*, which literally translated would mean "between instructions". This on the other hand does not explain what interdisciplinarity means to us in practice. For that, we need to look at the practical use of the word.

Chettiparamb [4] mentions that Roberta Frank (1988, cited in Klein, 1996, p. 8) "places the origin of the term interdisciplinarity within the Social Science Research Council, when the term was used as a kind of 'bureaucratic shorthand' for research involving two or more professional societies." I interpret this to mean that the practical meaning of the word interdisciplinarity is the involvement of two or more academic disciplines with each other in a certain event (education or research). The degree of mixture can then be even further assessed and different types of interdisciplinarity defined. For more details on this the reader is referred to Chettiparamb [4].

Interdisciplinarity within my research

The Division of Building Physics cooperates closely with the Division of Building Services. In fact, they work so closely together that they could be considered to be one division in practice, since they share courses, resources, division meetings, research projects, etc. This is because the two research fields are so closely connected and complement each other.

I believe that in order to do proper research in either field one must possess knowledge within the other. This is also strived for within the research that I have conducted in this thesis.

Akram Abdul Hamid, Lund

September 23, 2019

Sammanfattning

Renovering av det europeiska byggnadsbeståndet har varit en sakfråga för Europeiska Unionen i mer än två decennier. Ett av de mål som Sverige har tagit sig an är reduktionen av energianvändningen i Sverige med 50% före år 2030, och en av de överenskomna åtgärderna är att reducera energianvändningen i det svenska byggnadsbeståndet. Enligt IVA kan sådan sänkning av energianvändningen uppnås i befintliga byggnader genom applicering av energieffektiva renoveringsåtgärder, i en hög takt.

Felaktigt tillämpade, kan renoveringsåtgärder ha en negativ inverkan på byggnadens tillstånd, och det kan även brist på underhåll. För att minska riskerna med tillämpningen av renoveringsåtgärder, behövs det fler utvärderingar av sådana åtgärders inverkan på byggnader. Det är dessutom viktigt att kunna prognostisera den inverkan som relevanta åtgärder har på byggnadsbeståndet. Därför är det viktigt med kunskap om inverkan av olika renoverings- och underhållsåtgärder, men också kunskap om hur sådana åtgärder bör utvärderas.

Avhandlingens mål är att utvärdera inverkan av relevanta och tillämpningsbara renoverings- och underhållsåtgärder för byggnader i Sverige. Syftet med denna avhandling är dessutom att klargöra fältmätningar som metod för att skaffa data för bedömning av renoverings- och underhållsåtgärder. Den empiriska basen för detta har inkluderat fem fallstudier om renoverings- eller underhållsåtgärder som är relevanta för svenska byggnader, samt en litteraturstudie.

För att klargöra fältmätningar som metod för bedömning av den inverkan som renoverings- och underhållsåtgärder har på en byggnad har denna avhandling analyserat forskningsförfarandet i fem fallstudier som har inkluderat sådana bedömningar. Dessa fallstudier inkluderade åtgärder som påverkade energianvändningen, innemiljön och/eller de berörda byggnadernas fuktsäkerhet:

- Invändig tilläggsisolering på tegelytterväggar
- Behovsstyrd ventilation för flerbostadshus
- Från- och tilluftssystem med värmeväxling för flerbostadshus
- Rengöring av värmeväxlare
- Ventilationsåtgärder för kulturhistoriska byggnader:
    - I en skorsten dolt från- och tilluftssystem med värmeväxling
    - Spjäll för att reducera självdragsflödet utanför kontorstid

Avhandlingen har analyserat utförandet av fallstudierna, diskuterat detaljerna i fältmätningarna, begränsningarna i varje studie och konsekvenserna av dessa, samt den kunskap som har erhållits genom analyserna som genomfördes i fallstudierna. Den empiriska data som har framställts genom denna analys har legat till grund för klargörandet av fältmätningar som utvärderingsmetod av renoverings- och underhållsåtgärder.

Resultatet i fallstudierna i denna avhandling visar att åtgärderna som har utvärderats har en god inverkan på energianvändningen, och att vissa även har en god inverkan på inneklimatet. Det är dock viktigt att ta hänsyn till möjliga risker med åtgärderna för att de inte ska ha negativ inverkan på inneklimatet eller fuktsäkerheten. Fallstudierna visar att det är möjligt att bedöma inverkan av renoveringsåtgärder genom fältmätningar, med noggrannhet. Analysen av utförandet av fallstudierna visar att olika mätuppställningar kräver olika typer av analyser för att bestämma effekten av mätningen. Om fältmätningar utförs på ett objekt (t.ex. en byggnad) före och efter utförandet av en åtgärd, bör kontrollparametrar mätas samtidigt för att bestämma inverkan av förändringar i dessa parametrar på objektet. Därigenom kan inverkan på objektet av dessa förändringar, samt renoveringsåtgärden, bestämmas. Om mätningar görs enbart efter åtgärdens implementering, bör samtidiga mätningar genomföras på ett kontrollobjekt, vilket ska vara jämförbart med objektet som åtgärden har implementerats på (huvudobjektet), och helst oförändrat under studien.

Kombinationen av fallstudierna visar att utformningen av fältmätningar ofta bygger på en hypotes. Planeringen av fältmätningarna bör fokusera på besvarandet av denna hypotes, men bör också beakta begränsningar för mätningar i fallstudien, möjlig inverkan av andra parametrar, och om det är möjligt att utföra mätningar på ett kontrollobjekt, samt om det är möjligt att hämta data från andra källor. Kombinationen av fallstudierna visar också att det är troligt att avvikelser (t.ex. sensorfel) inträffar i mätningarna, och att dessa, tillsammans med begränsningar i fältmätningarna, kan kräva kompletterande analyser för att besvara hypotesen och/ eller andra frågor relaterade till bestämningen av effekten av åtgärden.

Abstract

Renovating the European building stock has for almost two decades been a matter of importance to the European Union. Reduction of energy use for existing buildings can be achieved through applying energy efficiency renovation measures. Besides this, there is quite a large renovation need in Sweden due to building materials and services reaching (or having passed) the end of their service life.

Incorrectly implemented, renovation measures can have negative impacts on the state of the building, and so can the lack of maintenance measures. In order to avoid negative outcomes, impacts of possible renovation and maintenance measures need to be evaluated. It is also important to be able to predict these impacts and therefore important to acquire data on them, but also more knowledge on how to isolate the impacts of such measures through field measurements.

This thesis aims to assess the impact of relevant and applicable renovation or maintenance measures for buildings in temperate climates, primarily through field measurements. This thesis also aims to illuminate the process of field measurements for acquiring data for the assessment of renovation and maintenance measures. The empirical base for this has included five case studies on renovation or maintenance measures that are relevant for Swedish buildings, and a literature review.

In order to illuminate the process of field measurements for the assessment of the impact that renovation and maintenance measures has on a building, this thesis has analyzed the research procedure in five case studies that have included such assessments. These case studies included measures that impacted on the energy use, the indoor environmental quality, and/or the moisture safety of a building:

1. Interior added insulation on external Solid Brick Masonry walls
2. Demand Controlled Ventilation for multifamily buildings
3. Mechanical Ventilation with Heat Recovery (MVHR) for multifamily buildings
4. Air-side cleaning of heat exchangers in ventilation systems
5. Ventilation measures for heritage buildings:
   - MVHR through a duct-in-duct solution installed in a chimney pot
   - Dampers that restrict the buoyancy in a natural ventilation system out-of-hours in order to reduce energy use

The thesis compares the setups of the field measurements in the case studies, discusses the details of the field measurements, the limitations in each study and the consequences thereof, and the knowledge that was gained through the analyses that were conducted. This empirical data, gained from these analyses, formed the basis for the illumination of the overall method for the assessment of renovation and maintenance measures through field measurements.

The results in the included case studies show that the measures that have been evaluated have a beneficial impact on the energy use, and some also on the indoor environment. However, it is important to consider possible risks with implementing the measures in order to avoid negative outcomes. The case studies show that it is possible to determine the impact through field measurements, with accuracy. The analysis of the procedures in the case studies in this thesis shows that different measurement setups require different types of analyses in order to determine the impact of the measure. If field measurements are conducted on an object (e.g. a building) before and after the implementation of a measure, control parameters should be measured simultaneously in order to determine the impact of changes in these parameters on the object and thereby isolate the impact of the measure. If measurements are conducted solely after the implementation of the measure, simultaneous measurements should be conducted on a control object, that is comparable to the object on which the measure has been implemented (the main object) and preferably has not undergone any changes during the study.

The combination of the case studies shows that the design of the field measurements is often based on a hypothesis. The design considers limitations of the case study, possible impact of control parameters, if it is possible to conduct measurements on a control object, and if it is possible to retrieve data from other sources. The combination of the case studies also shows that, most likely, a deviation (e.g. sensor failures) will occur, or a limitation will exist, which will require supplementary analyses to be conducted in order to answer the hypothesis and/ or other questions related to the determination of the impact of the measure.

Contents

1 Introduction

In this chapter, the background for the research conducted in this thesis is motivated as well as the aim of the thesis, its limitations, the disposition of the thesis, the publications included in this thesis, and finally, the abbreviations used 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 [6] and 2010/639/EU [7]. Not so long ago, 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 [8]. According to the Royal Swedish Academy of Engineering Sciences [9], 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 fulfilling 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 service life [10].

A number of historic events resulted in great needs for housing in Sweden [11], and therefore there are large segments of the building stock that are built during specific time periods in which the building technology is similar [12]. Several references [13]–[18] state the need for renovation of the buildings that were built during the so called "record years" (1946-1975). The buildings that were built then consist of apartments, but also offices. There are also buildings built before this era that are also in need of renovation [19], of which some are considered culturally and historically valuable, i.e. heritage buildings [20]–[22]. Besides renovating, the building stock also needs to be maintained in order to preserve the performance of the building materials and service equipment [23]–[28].

Correctly implemented, renovation measures can improve the status of existing building materials (e.g. the hygrothermal status), the energy use of buildings and the indoor environmental quality. Incorrectly implemented, such measures may affect the result in social, economic and environmental damage to those affected by the renovation measure [29]–[31]. In order to alleviate decision-making in the renovation process, the impacts of possible renovation measures need to be assessed. For this, data on the impact of different design choices (renovation measures) needs to be acquired, since such data can be used in renovation strategies [32], e.g. [33]. Even though there are many publications that conduct evaluations for this reason, more data is needed [32].

Data on the impact of renovation measures can be acquired through field measurements, laboratory studies, simulations and surveys [32]. There are some arguments for conducting field measurements, such as that it is conducted in the real world (the natural setting) and thereby observes the natural state of things [34], and that it intends to observe and analyze what exists instead of manipulating a factor under study [34]. Field measurements focusing on determining the impact of renovation measures might be considered field experiments, since experiments involve: 1) a strategic manipulation of a system to 2) create an organized response, in order to 3) answer a specific question [35]. Harrison and List [36] argue for field experiments since it is possible to observe a subject in a controlled setting in which the subject cannot perceive any of the controls as unnatural or the experiment as deceptive. These arguments suggest that data produced through field measurements have a high external validity, i.e. that they are generalizable to environments outside an experimental setting [34]. However, there are some issues pertaining to the process of field experiments which might diminish the internal validity of the results, such as the existence of uncontrolled extraneous variables [34], e.g. the weather or the behavior of the inhabitants. What is meant by internal validity, is the condition that observed differences on the dependent variable are a direct result of manipulation of the independent variable [34], e.g. the impact on energy use (dependent) by the thermal resistance of the building envelope (independent). Besides extraneous variables, what can also impact on the results in field measurements are differences in field-measurement designs. Recently Ahn and Park [37] conducted a comparison of spatial resolutions for predictability of building occupancy, which showed that the assessment was significantly influenced by varying this resolution. Furthermore, two other sources show that a too low temporal resolution might impact on the assessment by diminishing the impact of potential peaks of a parameter [38], [39].

The above implies that different methodologies for field measurements will impact the results of a study, and even though some regulations require the verification of the fulfillment of some demands, e.g. the energy use [40], no specific method for measurements is recommended in order to verify that impact with certainty. For this, guidelines have been developed by some actors in the building sector [41], [42]. One of these includes a systematic approach for assessing the impact of renovation measures on the energy use of a building [42]. All the above argues for a systematic approach when using field measurements for the determination of the impact of different renovation measures, since a systematic approach can be used to produce relevant and useful information on the technical status of a building [43], [44]. Several studies have been made on how to evaluate renovation measures regarding energy, thermal comfort, CO_2-emission reduction, occupant exposure to CO_2, and cost [45]–[50], but these do not focus on field measurements as a method for data acquisition. However, recently, Ganguly et al. [51] suggested a method for the assessment of renovation measures through measurements, with regard to the impact on the indoor environmental quality. They propose an index that is based on the indoor temperature and relative humidity, but do not consider changes to other factors that might have impacted on the results. Nevertheless, none of these references focus on how to conduct field measurements in order to isolate the impact of a measure (i.e. increase the internal validity of the results).

1.2 Aim

This thesis aims to assess the impact of relevant and applicable renovation or maintenance measures for buildings in temperate climates, primarily through field measurements. This in order to provide professionals and academics data for future decision-making and research. Such data will hopefully improve decision-making in the renovation process, and thereby increase the renovation rate in Sweden.

This thesis also aims to illuminate the process of field measurements for acquiring data for the assessment of renovation and maintenance measures. This based on empirically acquired data from the analyses of the research procedures in five case studies focusing on field measurements. The main aim of the case studies has been to determine the impact of a measure on at least one specific parameter per case study. Therefore, this thesis also aims to highlight possible deviations (e.g. loss of data) that may occur in the field-measurement process which impact on the assessment process. It also aims to highlight possible supplementary analyses that can be applied in order to compensate for the uncertainties that such deviations might imply. In this thesis, supplementary analyses are defined as analyses conducted besides analyses that were possible to make only using the data acquired through field measurements.

The thesis is aimed at researchers within the research fields of Building Physics and Building Services, but also at professionals within the building industry who conduct assessments of renovation and maintenance measures, through field measurements.

1.3 Limitations

The empirical base for illuminating the process of field measurements, for assessment of renovation and maintenance measures, was limited to the included case studies and a literature review. The choice of renovation and maintenance measures for the case studies was limited to needed research on renovation or maintenance measures that are relevant for Swedish buildings. The research within the case studies was limited to the application of the measures in Swedish buildings, and each case study was (obviously) limited to the time and resources allocated to it.

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 theoretical background for the work in the case studies and in the thesis, and then the method used in the thesis and in the case studies. The thesis then summarizes and discusses the conclusions made in each case study based on the field measurements and compares the conclusions from other analyses in the case studies. Then, the thesis describes the execution of each case study considering the theoretical background of the thesis, after which a synoptic discussion follows. Based on the analysis of the case studies, the thesis then illuminates the overall method for assessments of renovation and maintenance measures, primarily through field measurements. Finally, conclusions are made.

1.5 List of publications and relevance

The following publications are included in this thesis (see appendix B).

Paper 1

Abdul-Hamid, A., El-Zoubi, S. and Omid, S. (2014) *'Evaluation of set points for moisture supply and volatile organic compounds as controlling parameters for demand controlled ventilation in multifamily houses'*, in The 13th International Conference on Indoor Air Quality and Climate 2014.

This paper is an analysis of laboratory tests on a demand-controlled-ventilation system for multifamily buildings, and specifically the control scheme. The analysis focused on potential emission and moisture loads in Swedish apartments.

I conducted the literature review, designed the laboratory study, enquired after the possibility to conduct laboratory tests in a mock-up apartment provided by

Swegon, arranged the measurement equipment used for testing, supervised the tests, part-took in the tests, conducted parts of the analyses that were included in the paper, and wrote the paper. I wrote the draft of the paper.

Paper 2

Abdul-Hamid, A., Wallentén, P. and Johansson, D. (2015) *'Moisture Supply Set Point for Avoidance of Moisture Damage in Swedish Multifamily Houses'*, Energy Procedia. Elsevier B.V., 78, pp. 901–906. doi: 10.1016/j.egypro.2015.11.016.

This paper is a study on the moisture supply set-point for a demand-controlled-ventilation system for multifamily buildings. The setpoint is determined with consideration of a sensitive (but possible) external-wall construction with internal insulation in existing multifamily buildings. The determination of the setpoint for the moisture supply was based on simulations that compared interior and exterior moisture loads and their impact on the hygrothermal status of the wall. The assessment considers the risk for microbiological growth on possible biological building materials in the external wall.

I contributed through a literature review on moisture supply as a guideline for the examined risks. I planned the study and simulations, conducted the simulations and the analyses. I wrote the draft of the paper.

Paper 3

Abdul Hamid A., Farsäter K., Wahlström Å., Wallentén P., 2016 *'Literature review on renovation of multifamily buildings in temperate climate conditions.'*, Energy and Buildings, 172. doi: 10.1016/j.enbuild.2018.04.032.

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 extent of research on renovation of multifamily houses in temperate climates, in order to determine the need for such research.

I conducted searches for, as well as analyzed, and wrote, the parts on status determinations and renovation measures. I also wrote most of the background, method description, discussion and conclusions. I estimate to have produced at least half of the content in the paper.

Paper 4

Abdul Hamid A., Johansson D., Wahlström Å., Fransson V., 2019 *'The impact of a DCV-system on the IAQ, energy use, and moisture safety in apartments - a case study'*. Submitted 2019-08-14.

This paper is an analysis on a demand-controlled ventilation-system (DCV-system) for multifamily houses, with focus on field measurements made in a case study. The paper evaluates the DCV-system with regard to interior moisture and emission loads and the potential impact of these on the building materials as well as the indoor air quality. The paper also determines the impact of the DCV-system on the energy use in the building, through calculations on the thermal efficiency of the system and the energy saved on heating the supply air.

I conducted a literature review, planned and conducted large parts of the field measurements, conducted calculations on thermal efficiency and energy saved on heating the supply air, analyzed the results, as well as wrote the draft of the paper.

Paper 5

Abdul Hamid, A. and Wallentén, P. (2017) *'Hygrothermal assessment of internally added thermal insulation on external brick walls in Swedish multifamily buildings'*, Building and Environment, 123, pp. 351–362. doi: 10.1016/j.buildenv.2017.05.019.

This paper is an evaluation of internal insulation on exterior solid-brick-masonry walls in multifamily houses, based on two case studies. The evaluation considers interior and exterior moisture loads. The paper analyzes (mold, corrosion) risks, due to the loads and different types of insulation, on the building materials in the solid-brick-masonry walls.

I conducted the literature review, planned and conducted parts of the field measurements, planned and conducted the hygrothermal simulations and result analyses, and wrote the draft of the paper.

Paper 6

Abdul Hamid, A., Bagge, H. and Johansson, D. (2019) *'Measuring the impact of MVHR on the energy efficiency and the IEQ in multifamily buildings'*, Energy and Buildings. Elsevier B.V., 195, pp. 93–104. doi: 10.1016/j.enbuild.2019.05.004.

This paper is an assessment of the impact that conventional MVHR has on multifamily buildings' energy use, based on field measurements in a case study that aimed to isolate the impact of the measure.

I conducted a literature review, analyzed the field measurements, and wrote the draft of the paper.

Paper 7

Abdul Hamid, A., Johansson, D. and Lempart, M. (2019) *'Determining the impact of air-side cleaning for heat exchangers in ventilation systems'*, Building Services Engineering Research and Technology, p. 014362441985000. doi: 10.1177/0143624419850005.

This paper assesses the impact of a maintenance measure (cleaning) on heat exchangers in ventilation units. This, through field measurements and a laboratory study as well as through mathematical models.

I conducted a literature review, and planned, conducted part of, and assessed the field measurements. I was also responsible for planning, conducting and assessing the laboratory measurements, analyzing the results, planning and producing the models, and writing the draft of the paper.

Paper 8

Akram Abdul Hamid, Johansson D., Bagge H., 2019 '*Ventilation measures for heritage office buildings in temperate climate for improvement of energy performance and IEQ'*. Submitted to Energy & Buildings, under revision.

This paper determines the status of 12 heritage buildings in Sweden in order to acquire data for decision-making in renovation projects that concern the energy efficiency and the indoor environment. The paper also assesses two innovative ventilation measures especially developed for reduction of the energy use.

I conducted a literature review, acquired access to most of the buildings, conducted most of, and assessed the field measurements. I wrote the draft of the paper.

1.5.1 Other related publications by the author

Abdul Hamid, A., Johansson, D., Bagge, H., Kristoffersson, J. (2019) *'Mätningar av inneklimat i kulturhistoriska byggnader med kontor.'* Internal LU & Sustainable Innovation report made in project for The Swedish Energy Agency, project number: 42309-1. Unpublished.

Abdul Hamid, A., Bagge, H., Johansson, D. (2018) *'Energi- och inneklimatåtgärder på ventilation i kulturhistoriska byggnader – Mätningar och analys.'* Internal LU report made in project for The Swedish Energy Agency, project diary number: 2015-001986. Unpublished.

Abdul Hamid, A., Johansson, D., Bagge, H. (2018) *'Metod för optimal rengöring av värmeväxlare.'* The Swedish Energy Agency - E2B2, project number: 41832-1, report 2018:02.

Abdul Hamid, A., Bagge, H., Johansson, D., Kristofersson, J. (2018) *'Installation av FTX i miljonprogramshus - Analys av energibesparing och inneklimat.'* Lund University, report TVIT-18/7114.

Kristoffersson, J., Bagge, H., Abdul Hamid, A., Johansson, D., Almgren, M., Persson, M-L. (2017) *'Användning av värmeåtervinning i miljonprogrammet.'* The Swedish Energy Agency - E2B2, project number: 39394-1, report 2017:17.

Abdul Hamid, A. (2017) *'Method for evaluation of renovation measures with regard to moisture and emission loads - Based on risk assessments.'* Lund University, licentiate thesis, TVBH-3067.

Hilliaho, K., Nordquist, B., Wallentén, P., Abdul Hamid, A., Lahdensivu, J., (2016) *'Energy saving and indoor climate effects of an added glazed facade to a brick wall building: case study'*, Journal of Building Engineering. Elsevier, 7, pp. 246–262. doi: 10.1016/j.jobe.2016.07.004.

Farsäter, K., Johansson, D., Strandberg-de Brujin, P., Abdul Hamid, A. (2013) *'Erfarenhetsåterföring vid renovering'*, Bygg & teknik 2/17.

1.6 Abbreviations and terminology

ACR	air change rate
CAV	continuous air volume
CO_2	carbon dioxide
DCV	demand-controlled ventilation
h^{-1}	per hour
IAQ	indoor air quality
IEQ	indoor environmental quality
MBV	mechanical balanced ventilation
MEV	mechanical exhaust ventilation
MVHR	(balanced) mechanical ventilation with heat recovery
NV	natural ventilation
RH	relative humidity
SBM	solid brick masonry
SMHI	Swedish Metrological and Hydrological Institute
T	temperature
VOC	volatile organic compound

2 Theoretical background

This chapter summarizes the theoretical basis for the work conducted in this thesis as well as in the case studies. The chapter focuses on the author's area of research.

2.1 Research methodology

This section describes the different research concepts that are relevant to this thesis and the case studies included in it. The section intends to provide knowledge on what a researcher might consider when designing a study, e.g. in order to show causation or acquire data to form a hypothesis. Section 3.1 describes how these are used in this thesis.

Proving the cause to an effect through research might not be a straightforward task. A researcher that aims to do so, might choose one or several different paths when designing a study, which might depend on the circumstances of, and possibilities within, the study. What might also affect that choice is existing knowledge about the subject of the study. Since this thesis aims to analyze the research procedures in the included case studies, the following describes the relevant methodological concepts which form a part of the base knowledge deployed in the analyses.

2.1.1 What is a case study?

In a review paper, Gerring [52] aims to explain and illuminate the case study as a method. He argues that it is:

> *…best defined as an intensive study of a single unit with an aim to generalize across a larger set of units.*

Gerring [52] further states that case studies can be defined into three different types:

Type 1 (single unit) - Examination of variations in a single unit - over time, i.e. with temporal variations included.

Type 2 (across units) – A primary unit is divided into subunits which are subjected to covariational analysis, synchronically (i.e. at a particular moment).

Type 3 (across units) – A primary unit is divided into subunits which are subjected to covariational analysis, diachronically (i.e. over time).

However, Gerring [52] points out that case studies also can be hybrids, and often of type 1 and 3. Furthermore, different research designs for case studies of type 2 and 3 in [52] can be:

- **Cross-sectional:** without temporal component
- **Time-series cross-sectional:** with temporal component
- **Hierarchical:** across and within units in the same research design

Depending on the type of research designs, different tradeoffs and affinities can be identified [52]. Single-unit case-studies (type 1) give descriptive knowledge, define causal mechanisms (note: do not show causation), and are exploratory which can generate a theory. Across-unit case-studies (type 2 and 3) give causal knowledge, define causal effects, and are confirmatory which means that they can test a theory. For more information on this matter, the reader is referred to Gerring [52].

2.1.2 The hypothetico-deductive method

This method requires us to formulate guesses, hypotheses and theories as initial conditions. These are then used as an aid to help us answer the how, what and why questions. Because the method is deductive it says that we, from our hypotheses, shall derive empirically testable consequences [53].

The hypothesis accuracy is tried through the derivation of one or several consequences. These are often called observational theorems, test implications, empirical consequences or predictions [35]. In other words, the truth of the empirical consequence is concluded through observations or other empirically accepted test-methods. If the theorem is judged to be false, then it is refuted, and the hypothesis rejected. A new hypothesis is created in its place. If it is judged to be true then further trials can be done with smaller variations or by completely new test implications [35]. This is called a falsification test, however, in order for such test to work it has to be theoretically possible to disprove.

2.1.3 Inductive method

Unlike the hypothetico-deductive method, this method does not require a guess or hypotheses to be formed before the research. Persson & Sahlin [53] argue that the ideal inductive method is useless for scientific research. For it to be useful the researcher must at least have some kind of outset before the research is begun. Acquiring data for everything or anything for no reason would just be a waste of time and resources.

The inductive method aims to find a conclusion, an inductive argument through a finite number of specific facts that becomes a generalization (a law) [54]. Therein lies a problem that has been identified by Empricus 200 B.C. and Humes later on (it is now attributed to Humes). Humes' problem is that the observation "Some As are B" does not give us grounds to claim that "All As are B" [53]. According to Persson & Sahlin [53], we aim to confirm the general effect of the inductive argument and not its absolute truth. They further claim that it is the reliable process itself that does this and not the data that creates the basis for the generalization. Chalmers [54] says that a good inductive argument must satisfy three conditions:

1. The number of observations that are forming the basis of the argument must be large.
2. The observations must be repeated under a wide variety of conditions.
3. No accepted observation statement should conflict with the derived law.

Chalmers [54] continues to explain why these conditions are a must and claims that they can be summed up by the following statement, called "The principle of induction":

> *If a large number of **A**s have been observed under a variety of conditions, and if all those **A**s without exceptions possess the property **B**, then all **A**s have the property **B**.*

Persson & Sahlin [53] describe two more problems with inductive research. One of them is that some objects of a created law can change its properties with time. For example, if we observe that all *As* possess the property *B* and then at a given time *t* they suddenly possess the property *C* instead of *B*. The other problem is that when a law created through inductive research is falsified, we can always blame the falsification on underlying assumptions or theories. So, in other words we say that what really is falsified is the underlying theories for the law and not the law itself. For now, I will not dig deeper into what this might mean and instead refer those who are interested to Persson & Sahlin [53].

2.1.4 Causation

The following represents my interpretation of Persson & Sahlin's [53] chapter on causation. Simply, a cause can be expressed by the following: *B* happens because A happened. In other words, if *A* exists then *B* will exist as well. However, it is not that simple. I believe that it is rarely that one cause *A* is sufficient on its own for *B* to happen, and that often more than one cause is needed – "If *A1, A2, A3* and *A4* happens then *B* happens". The causes can be related to each other or just as well completely unrelated. The nature of a cause can in other words be either (1) or (2):

1. The cause as a *necessary* condition for the effect – Without *A*, then *B* will not happen. No matter what else happens.

2. The cause as a *sufficient* condition for the effect – If *A* happens, then *B* will always happen. Even if nothing else happens, *B* can also happen even if *A* does not happen.

When a cause is necessary but not sufficient, other conditions need to be met to achieve the specified effect. When a cause is sufficient on its own but not necessary, other causes can achieve the same effect. When a cause is sufficient and necessary, then only it alone can achieve the effect and no other causes are needed.

2.1.5 Uncertainties

Persson & Sahlin [53] state (p.162) that knowledge and information are important for taking decisions, but that we often mix the two terms and do not really differentiate between them. Persson & Sahlin [53] state that knowledge per definition is truth, while information can be false, misleading, or even pure lie.

We say that we have knowledge if we have sound evidence, but evidence can be of highly different qualities. It is therefore important to be careful when talking about knowledge uncertainty. Uncertainty might exist because of the lacking quality in our evidence. There are also other reasons for uncertainty, such as those that are due to the (causal) relationship between a hypothesis and the evidence. How certain can we be about our chosen method? How good is the scientific evidence? What are the missing pieces and what evidence can we not achieve with present science [53]? Can we ever be certain of the knowledge that we possess? Persson & Sahlin [53] quote Betrand Russell from his work "The Triumph of Stupidity" (p.161):

> *One of the painful things about our time is that those who feel certainty are stupid, and those with any imagination and understanding are filled with doubt and indecision.*

Persson & Sahlin [53] describe a few chosen factors of that which can create knowledge uncertainty - one of them they call "the incomparable". Due to moral or practical reasons it is sometimes hard to do controlled experiments - we do not subject humans to certain experiments, of obvious reasons. In such cases we must rely on indirect instead of direct knowledge. It is therefore important not to disregard the uncertainty that our values create. Also, the limitations to our methods create knowledge uncertainty. In some cases it is practically impossible to do the kinds of experiments that are required in order to get satisfying results [53]. Another factor for uncertainty that Persson & Sahlin [53] describe are "time limitations". Some research projects need a very long time to be completed due to the speed of the process that is being researched. For some examples of this, please refer to Persson & Sahlin [53].

2.1.6 Knowledge types

Öivind [35] state that knowledge acquired from research is either descriptive or explanatory, which depends on if the research is hypothetical or non-hypothetical (e.g. inductive), respectively. Descriptive knowledge comes either from data mining or black-box testing, while explanatory knowledge might come from epidemiology and certainly from hypothesis testing by experiments.

Öivind [35] further states that the type of study, if observational or experimental, determines a type of relationship that is either correlative or causative, respectively.

2.2 The building as a system

This section describes the intricacy of the building as a system and thereby the parameters and components that might affect that system. The section intends to provide knowledge on what a researcher within the research discipline might consider when designing a field study and when the researcher derives which parameters are affected by changes in the different components that constitute a building.

A building's performance relies on an intricate web of physical and technological parameters that forms a system and affects the building and its indoor environment. Renovation and maintenance measures intervene with the building as a system through changes in parts of the system (parameters), e.g. the fabric of the building or the building service equipment. Since different parameters of the system are connected to each other, more than one parameter of the system may be affected by a measure, and more than one parameter may affect the measure or the impact of the measure. The impact that a measure has on one parameter may echo through this web and therefore impact other parameters. In a building, different balances of air, energy, and moisture, can be identified. By understanding these balances, and the components of a building that affect these balances, the impact of a measure on these balances might be derived and parameters that are affected as well. The following lists summarizes this but might be more exhaustive than presented.

Energy balance

Factors in a building that can affect the energy balance, and therefore the energy use, are listed in the following [55], [56].

1. Architectural design
    - Geometry
        - E.g. window size and placement
        - Spaces, heights, volumes
        - Form, and thereby pressure coefficients
    - Shading
    - Orientations
    - Colors
2. Building technology
    - Thermal capacity of the building materials
    - Building envelope
        - Insulation
        - Airtightness
        - Structural design
        - Thermal bridges
        - Ground properties

Changes to these components and climatic conditions affect the energy balance of a building, and therefore impact on the following measurable parameters within the building related to the energy balance [55], [56], [41]:

1. Air change rates
    - Airflows
    - Infiltration rates
2. Air temperatures
3. Temperatures in the materials
4. Surface temperatures
5. Effect of heating or cooling devices
6. Electricity use
7. Water flows
8. Water temperatures
9. Geometry
10. Irradiance
11. Presence/ Occupancy

Energy balance

3. Ventilation system
    - Heating or cooling of the supply-air
    - Air flow
    - Heat recovery
    - Set points or schedule
4. Cooling system
    - Set points
    - Flows
    - Temperatures
    - Insulation
5. Heating system
    - Set points
    - Flows
    - Temperatures
    - Insulation
6. Plumbing
    - Insulation
    - Flows
    - Temperatures
    - Heat recovery
    - Hot water circulation
7. Inhabitants/ occupants/ users
    - Activities & habits
        - E.g. window opening,
        - cooking,
        - hot water usage.
    - Number
    - Presence
8. Electrical equipment

Energy balance

  - Usage
  - Energy efficiency

1.

Besides the abovementioned factors, the following climate conditions outdoors can also affect the energy balance:

1. Temperature
2. Relative humidity
3. Solar irradiation
4. Cloudiness
5. Wind speed & direction
6. Location

Indoor air

Factors in a building that can affect the indoor air quality are [55]:

1. Building technology
   - Emissions from the building materials
   - Emission sinks in the building materials
   - Building envelope – Airtightness
2. Ventilation system
   - Ventilation rates
   - Distribution strategy and flow pattern
   - Set points or schedule
   - Filtration
3. Inhabitants/ occupants/ users
   - Activities
   - Number

Changes to these components and climatic conditions affect the air balance of a building, and therefore impact on the following measurable parameters within the building related to this balance [55]:

1. Infiltration rates
2. Ventilation system air change rates
3. Air distribution
4. Air temperature
5. Relative humidity in air

Indoor air

- Presence

4. Equipment (appliances, furniture, etc.)
   - Usage
   - Emissions

Besides the abovementioned factors, the indoor air quality in a building is affected by outdoor air's contribution of outdoor pollutants [55].

6. Relative humidity in materials
7. Water content in the materials
8. Indoor air pollutants
   - Gases, e.g. CO_2, VOCs
   - Particles

Moisture

Factors in a building that can affect the moisture balance, and therefore the moisture safety of the building materials, are [57]:

1. Building technology
   - Airtightness of the building envelope
   - Construction design with regard to dry-out, drainage, run-off and capillary action
   - Vapor permeability of the building materials
   - Moisture capacity of the building materials
   - Capillary activity within the building materials
2. Ventilation system
   - Ventilation rates
   - Set points or schedule
   - Heating or cooling of the supply-air
3. Cooling system
   - Set points
   - Technology, e.g. evaporative vs. refrigerated
4. Heating system
   - Set points
   - Technology, e.g. radiative vs. convective
5. Inhabitants/ occupants/ users
   - Activities

Changes to these components and climatic conditions affect the moisture balance of a building, and therefore impact on the following measurable parameters within the building related to this balance [57]:

1. Infiltration rates
2. Ventilation system air change rates
3. Air distribution
4. Air temperature
5. Relative humidity in air
6. Temperatures in materials
7. Relative humidity in materials
8. Water content in the materials

Depending on the building technology and

▪ E.g. window opening, cooking, showering o Number o Presence Besides the above factors, the following climate conditions outdoors can also affect the energy balance: 1. Precipitation 2. Groundwater level 3. Temperature 4. Relative humidity 5. Solar irradiation 6. Cloudiness 7. Wind speed & direction 8. Location	the building services equipment, some moisture sources can be much less impacting than others, or even insignificant.

An example that illustrates the impact that a change to a component can have on more than one parameter, is the addition of internal insulation on external walls. This solution should reduce the transmission losses through the building envelope which in turn will reduce the energy use of the building. However, this is not all that is affected, since the reduction of transmission losses will affect temperatures on interior surfaces. Thus, surface temperatures might increase, and sequentially increase the operative and the equivalent temperatures. If technical systems, such as the heating system or the ventilation system (e.g. the supply-air temperature or the supplied heat) are not adjusted to this change in the building envelope, the change might impact on the inhabitants' perception of the indoor environmental quality, e.g. causing them to feel that the indoor environment is too warm, which might cause them to open the windows more often in order to get rid of the excess heat, which in turn contributes to the energy losses. The increased air change rate due to window opening might itself impact on the indoor air quality and the air humidity indoors, and so on.

2.2.1 Field measurements and measures

What is meant by field measurements within the research disciplines of building physics and building services, is building assessment surveys and evaluations of the non-structural performance of structural design, building materials or building services equipment, as well as of the indoor climate. Field measurements focusing on determining the impact of renovation or maintenance measures, however, might be considered field experiments, since Öivind [35] states that an experiment involves:

1) a strategic manipulation of a system to
2) create an organized response, in order to
3) answer a specific question.

Renovation or maintenance measures correspond to these points as following:

1) the implementation of a renovation measure can be considered *a strategic manipulation of a system* (the building), that,
2) impacts on specific parameters in the building as a system (e.g. the transmission losses of the building) and thereby *creates an organized response*, in order to
3) *answer a specific question*, on e.g. the extent of the reduction of energy used for space heating.

A search was conducted for literature that specifically deals with the procedure of field measurements in buildings for assessment of renovation measures, in a scientific study. The search only found a protocol by the United States Environmental Protection Agency (EPA) [58] on how to conduct field measurements in buildings in general. However, within the field of econometrics, Harrison and List [36] have published a paper on field experiments in general, in which they categorize different types of field experiments depending on their setting. One of them is the *natural field experiment*, in which the subjects naturally undertake tasks and do not know that they are in an experiment. Such experiments compare the impact of a treatment on a naturally occurring comparison group that mimics a control group. The difference between the outcome for the treated group is compared to the outcome of the nontreated group before and after the treatment. In the determination of the *treatment effect* (i.e. impact) a number of factors are also taken into account [36]:

- Number of units in the observation.
- Time of measurement.
- The outcome in cross-section.
- A vector of controls.
- A binary variable.
- The difference-in-differences (DID) average treatment effect.

Harrison and List [36] also describe the use of the propensity score matching (PSM) method in field experiments, by P. Rosenbaum and Donald Rubin. This method relies on the researcher selecting observable factors to measure in two individuals, who should have the same value for these factors and will display homogenous responses to a treatment regarding these factors. According to Harrison and List [36], this type of setup can eliminate bias in the measurements. They further state that in order to identify such individuals, statistical methods can be applied, and a vector of covariates found.

The final method that Harrison and List [36] describe is the instrumental variables method (IV). This method relies on exclusion restrictions and assumes that some components of the field measurement data are random. The problem with this method is to find variables that do not affect the treatment status and has no direct association with the outcome.

Based on the analysis of the references in the literature study, common procedures for assessments of the impact of renovation measures (using field measurements) can be described as either of the following [32]:

1. Condition assessment before or after the implementation of the measure, and further assessment of the impact of the renovation measure by other means (36 out of 47, e.g. simulations or calculations).
2. Validation of computer simulation software, simulation models or calculation models through field measurements for the complete assessment, e.g. [59], [60] (number of references using this method not determined).
3. Comparisons of condition assessments on one or several parameters before and after the implementation of the measure (9 out of 47).

A purpose with building status assessments can be to describe reality in order to be able to assess different maintenance needs [44]. Comparison of the status of a building before and after a measure is implemented, or with and without the measure, is the common theme of the references that were included in the literature review that assess renovation measures [32]. However, the literature review shows that only a few references measure before and after [30], [60]–[67] the implementation of a measure. Most of these [60], [62]–[64], [66] consider changes in other parameters that might impact on the results. Such parameters might be called extraneous variables [34], and based on the abovementioned methods for field experiments described by Harrison and List [36] the impact of extraneous variables should be controlled or excluded if comparisons are made between a treated object before and after a treatment. This, since the existence of uncontrolled extraneous variables [34], e.g. the weather or the behavior of the inhabitants, might diminish the internal validity of the results. What is meant by internal validity, is the condition that observed differences on the dependent variable are a direct result of manipulation of the independent variable [34], e.g. the impact on energy use (dependent) by the thermal resistance of the building envelope (independent).

> *An ideal field experiment not only increases external validity, but does so in a manner in which little internal validity is foregone. Harrison and List [36].*

In order to assure that a measure (treatment) has been successful, or has had an impact on a specific parameter, the impact of a measure should be evaluated in consideration of the above. A field study should be designed in order to isolate the impact of the measure on a (or several) specific parameter(s), and thereby increase the internal validity [34].

> *If controlling all extraneous influences is successfully accomplished, any change observed in the subjects is presumed to be caused by the variable that has been manipulated. Aziz [34].*

This is easier said than done, since in contrast to laboratory studies, field research cannot exert the same control on the object of a study or the parameters that impact on it [34].

When conducting field measurements in buildings, several critical factors can be imagined to be partly, or completely, out of the researcher's control, such as:

- the weather,
- the number and presence of the inhabitants,
- the activities of the inhabitants,
- the operation of the building,
- the existing fabric of the building,
- and the existing building services equipment.

Therefore, experience with field measurements, knowledge on how a building functions as a system, and knowledge in building physics and building services equipment, might help with the derivation of parameters to measure in field measurements.

3 Method

This chapter describes the method used for the analysis of the procedures of the case studies included in this thesis. The analysis of the procedures is mainly presented in chapter 4. Then the work conducted within this thesis is discussed based on the research methodologies, terms and theories described in chapter 2.

This thesis has analyzed the research procedure in five case studies that have included assessments of the impact of renovation and maintenance measures on one (or several) specific parameter(s) in a building. This, in order to illuminate the process of field measurements for acquiring data. What is meant by "procedure" is the way that the process in each case study has been undertaken and the consequences thereof. This has been analyzed with consideration of the theoretical background presented in chapter 2. The analyses of the case studies have entailed the identification of the research methodology in each case study and the derivation of which main parameters can be impacted by the renovation measure, as well as which control parameters might be measured. In this thesis the parameters that are relevant to measure in the case studies are divided into *main parameters* and *control parameters*. Main parameters are defined as parameters that are directly impacted by the renovation or maintenance measure, while control parameters are defined as parameters that impact the main parameters. For each case study, the field measurements have been described, and the details regarding the design of the measurements have been discussed. The thesis has also discusses how causation was shown, what type of knowledge was gained through the research, the necessity of the parameters that were measured in order to make the conclusions, and the necessary arrangements and prerequisites that were required in order to conduct the study. This led to a comparison of the different types of study setups that were deployed in the case studies, a discussion on the choice of data resolutions in the field measurements, as well as a discussion on the parameters that could not be measured and the consequences thereof. The empirical data gained from this analysis, formed the basis for the illumination of the overall method for the assessment of renovation and maintenance measures through field measurements.

A variation of case studies has been included on different renovation measures installed for different reasons, and measures that are relevant for the Swedish market (or similar markets). This, in order to gain insight on possible setbacks or deviations (e.g. in the case of missing data, or a disturbance) that can occur when conducting field measurements but also to include possible supplementary analyses to be made. Such analyses can be in the form of simulations, calculations or surveys [32].

Five case studies, with focus on field measurements, were conducted. These included measures that are partially meant for the improvement of the energy use of a building. These measures were chosen since they are relevant for the improvement of the Swedish building stock. Besides impacting on the energy use, these measures might also impact on the indoor environmental quality, and/or the moisture safety of a building:

1. Interior added insulation on external Solid Brick Masonry (SBM) walls
2. Demand Controlled Ventilation (DCV) for multifamily buildings
3. Mechanical Ventilation with Heat Recovery (MVHR) for multifamily buildings
4. Air-side cleaning of heat exchangers in ventilation systems
5. Ventilation measures for heritage buildings
   A. MVHR through a duct-in-duct solution installed in a chimney pot
   B. Dampers that restrict the buoyancy in a natural ventilation system out-of-hours in order to reduce energy use

The general aim of these case studies was to assess the impact of the measures. In general, this was to be done through of the following procedure:

1. The main parameters that was to be impacted by the measure were derived based on knowledge of the building as a system (section 2.2). This step included a literature review.
2. The control parameters that were to impact the results were derived based on knowledge of the building as a system (section 2.2).
3. The study setup and measurements were designed focusing on 1-2, as well considering the limitations of the premises and the case study, i.e. financial, spatial and temporal restrictions.
4. Measurements were conducted before and after the implementation of the measure, or with and without, and data acquired.
5. An assessment of the impact of the measure was conducted based primarily on the results from the field measurements.

In the abovementioned procedure, details regarding the execution of the field measurements were considered. Furthermore, in several case studies, limitations and deviations (setbacks) resulted in the need to conduct supplementary analyses in order to answer the hypotheses of the studies as well as research questions regarding the impact of the renovation measure.

3.1 Research methodology in this thesis

The following discusses the research concepts used in the thesis and/or in the case studies, considering what is described in chapter 2.

3.1.1 Are they case studies?

This thesis is based on research projects that can, in one way or another, be identified as case studies based on Gerring's [52] definition, since they were intensive studies of single measures/ buildings (units) with an aim to generalize the results across a larger set of units (building stock). Primarily, the type of case studies dealt with in this thesis are what Gerring's [52] has identified as type 3, i.e. diachronically across units. All have been time-series cross-sectional in one way or another, and some even hierarchical. In some cases, the field measurements alone would classify the case study as type 3, however, in others as type 1, unless supplementary analyses were conducted. This means that without supplementary analyses, such case studies (type 1) would give descriptive knowledge and not causal knowledge. The following table identifies the types of the case studies.

Table 3.1: Classification of case studies in this thesis. Type 1 – single unit, temporal variations. Type 2 – primary unit with subunits, covariational, synchronic. Type 3 - primary unit with subunits, covariational, diachronic. CS= Cross-Sectional, non-temporal. Time-Series CS= temporal. H=hierarchical, across and within units in the same research design.

Case study	Type 1, 2 or 3	CS, TSCS, H	Comment
1. Interior added insulation on external SBM walls	Type 3 *Primary unit:* Two buildings. *Subunits:* SBM walls - insulated and non-insulated. Covariational analysis between subunits at similar time periods – with and without measure implementation.	Hierarchical: Across and within SBM walls; different materials, directions, depths, heights. TSCS Covariational analysis at similar time periods, comparisons of SBM walls to each other as well as details above.	Hierarchical also through supplementary analyses: hygrothermal simulations of different types of simulations.

Case study	**Type 1, 2 or 3**	**CS, TSCS, H**	**Comment**
2. DCV for multifamily buildings	Type 1 *Primary unit:* Apartments in one staircase. *Subunits:* Apartments. Covariational analysis between subunits over time – only after implementation.	TSCS Comparison of apartments to each other and results with guidelines, for a long time period after renovation.	Type 3 through supplementary analyses - calculations of DCV vs MVHR vs MEV.
3. MVHR for multifamily buildings	Type 3 *Primary unit:* Buildings. *Subunits:* Ventilation systems. Covariational analysis over time – before and after measure implementation.	Hierarchical Buildings with different ventilation systems compared to each other, apartments within buildings compared to each other. TSCS Comparison of buildings and apartments to each other and guidelines, over time.	Hierarchical through control object.
4. Air-side cleaning of heat exchangers in ventilation systems	Type 3 *Primary unit:* Cleaning procedure. *Subunits:* Heat exchangers. Covariational analysis over time – before and after cleaning.	TSCS Measurements before and after cleaning compared to each other.	Type 3 also through supplementary analyses (laboratory study and calculations). *Primary unit:* Heat exchanger *Subunit:* With different amounts of contaminant.

Case study	**Type 1, 2 or 3**	**CS, TSCS, H**	**Comment**
5. Ventilation measures for heritage buildings	Type 3 *Primary units:* Buildings. *Subunits:* With/ without measures. Covariational analysis over time – before and after measure implementation.	Hierarchical Buildings with different building technology, geographical locations and ventilation systems compared to each other. TSCS Comparison of buildings and offices to each other and guidelines, over time.	Hierarchical also through simulations: NV vs dampers, NV vs MVHR.

3.1.2 Inductive or hypothetico-deductive?

The work within the case studies is largely hypothetico-deductive. In each case study there has been an assumed impact on the results, which has been proven or disproven through analyses of field measurements or through other supplementary analyses. However, each case study required some inductive research in order to determine the significance of parameters that might have impacted on the results. The type of research conducted in each case study is further discussed for each case study in chapter 3.1.5.

The thesis itself is inductively written, since there is no need for a hypothesis in order to fulfill its second aim - the process of field measurements as a method. For this, no hypothesis is needed.

3.1.3 Proving causation

The matter of proving causation within this field of study has partially been described in chapter 2. In all but one case study, in order to prove the cause (the implemented measure), a measure has been implemented to an otherwise largely unchanged system (building) and a response has been measured. At the same time, precautions were taken in order to discern the impact of the cause from the noise due to changes in other parameters or due to reading errors in the measurement equipment. Causation is further discussed in each case study, in chapter 3.1.5.

3.1.4 Uncertainty

Limitations to methods and time.

The methods used in each case study must be reasonable with regard to resource efficiency – i.e. time and cost. They should also respect social, ethical and humanitarian concerns. In a field study, limited resources will limit the method used and the researcher can therefore not measure all considered parameters with the highest possible precision. Furthermore, in a field study within this field of research, social and ethical concerns with regard to the owners, users or inhabitants of the buildings can limit the extent of the research since some actions are prohibited, e.g. subjecting the inhabitants of a building to a change that is meant to affect them physically or mentally and entails obvious risk for harm physically or mentally, without their consent. Besides the inhabitants' consent, a number of legal requirements must be fulfilled in order to conduct such research [68]. These necessary limitations affect the quality of the results which creates knowledge uncertainty.

Besides the above, an unknown and changing future increases the uncertainty in the knowledge gained from our research [69]. Even in climate data that has been recorded so far, variations exist from hour to hour, day to day, year to year, decade to decade, and so on. This might have an impact on future applicability of the results that we produce today [70], and conclusions might either underestimate or overestimate parameters that describe the reality. Underestimating such parameters could lead to serious consequences that could even be life threatening, for instance: underestimating the weight load of snow on a roof, which could lead to the roof collapsing. Overestimating such parameters on the other hand can lead to unnecessarily oversized measures and thereby increased expenses as well as waste of natural resources. A balance between these two options should be sought [71].

Technological limitations.

An example of technological limitations is the equipment's accuracy. Take for example the measurement of the surface temperature of a wall. When measuring with a given device, we do not say that the surface temperature is exactly a certain degree, but we say that it is a degree ± an error. However, uncertainty in our results due to our methods or our equipment should be accounted for when we decide which methods or equipment to use and when we make our conclusions based on achieved results.

3.1.5 Research in the case studies

According to Andersson [35], research includes a system that is manipulated by an input which generates an output. Furthermore, Aziz [34] states that research is a systematic method of inquiry in order to obtain information pertaining to some question or set of questions. In every case study, there has been a system. i.e. one or several building(s), building component(s), or building services equipment. The system has been manipulated by an input (measure), which generated an output (result) based on the laws of nature that govern the physical and chemical processes which were relevant to the system. It has therefore been important to understand the system as well as the laws of nature that govern it in order to understand the impact of the measure on the system in each case study. The following table summarizes the case studies with regard to the changes that were made (the input), the systems that were affected, which laws governed the systems, and the generated output.

Table 3.2: Summary of changes (renovation measures) to the systems that were affected in the case studies, the laws that govern those systems, and the impact that these changes made with regard to the systems.

Input	Measure	Case study 1: Interior added insulation on external SBM walls	Case study 2: DCV for multifamily buildings	Case study 3: Mechanical Ventilation with Heat Recovery
Systems affected	**Building Technology**	X	Indirectly	Indirectly
	Building HVAC	Indirectly	X	X
	Human Physiology	X	X	X
Related laws of nature	**(Building) Physics – Heat, Air and Moisture transport and storage.**	X	X	X
	Human Biology & Psychology	Indirectly	X	X
Output assessed	**Energy use**	X	X	X
	Temperatures	X	X	X
	Relative humidity	X	X	X
	Air flows		X	
	Pollutant concentrations		X	
	Inhabitant perception	X		X

Input	**Measure**	Case study 4: Air-side cleaning of heat exchangers in ventilation systems	Case study 5: Ventilation measures for heritage buildings
Systems affected	**Building Technology**	Indirectly	Indirectly
	Building HVAC	X	X
	Human Physiology	Indirectly	X
Related laws of nature	**(Building) Physics – Heat, Air and Moisture transport and storage.**	X	X
	Human Biology & Psychology	Indirectly	X
Output assessed	**Energy use**	X	X
	Temperatures	X	X
	Relative humidity	X	X
	Air flows	X	X
	Pollutant concentrations		X
	Inhabitant perception		Only without measures

3.1.6 Experiments?

According to Öivind [35], an experiment involves: 1) a strategic manipulation of a system to 2) create an organized response, in order to 3) answer a specific question. It can therefore be argued that the methodology used in most of the case studies is an experimental methodology, since a measure (strategic manipulation) was implemented that impacted on a specific or several specific parameters (an organized response) which answered a specific question (the extent of the impact). Furthermore, Öivind [35] states that in order to obtain relevant information from an experiment, we need to create conditions that are relevant to the specific questions. In all case studies, measurements were conducted in "conditions that are relevant to the specific questions" since the impact was measured in "live" conditions. However, in order to discern the impact due to the measures, control (through measurements or supplementary analyses) of factors that could potentially affect the impact on the system was needed as a precaution. Different types of measurements and assessments also complemented each other, which lead to explanatory knowledge. However, not all is black or white, and in all case studies descriptive knowledge of the system was needed before the implementation of the measure (strategic manipulation). This in order to obtain the explanatory knowledge that was acquired through the implementation of the measure. Therefore, the research methods in the case studies were not purely hypothetico-deductive but also inductive.

4 Case studies – methods, results and discussions

This chapter first summarizes the aims and the conclusions in each case study. It then describes each case study, in detail, with the aim of identifying the research methodologies used in the case studies. For each case study, the materials and methods used in order to answer the hypotheses, or acquire descriptive knowledge through inductive research, are summarized. Then, the conclusions based on the analysis of the field measurement results and the supplementary analyses are stated. Finally, the chapter finishes with a synoptic discussion on the combination of the case studies.

The following subsections first deal with the methods and measurements conducted in order to reach the conclusions in each case study. Each case study is described in the following order:

- Derivation of possible main and control parameters relevant to the measure that might impact the results, based on knowledge presented in section 2.2 and literature studies.
- After deriving the relevant parameters, the thesis describes the actual measurement setup, as well as considerations that were made regarding the details of the field measurements in relation to the impact that was to be assessed:
    - The **timespan** of the measurements, i.e. the time period during which measurements took place in order to make a representative assessment of the impact of the measure, both length and time of year. E.g. if it was necessary to measure equally as long before and after the measure was implemented, and when during the year the measure was assumed to have an impact.
    - The **accuracy (proximity to value)** of the measurement setup and the tools, i.e. the error readings of the sensors, and the placement of sensors, in order to make a representative assessment of the impact of the measure considering the proximity of the measurements to the true value of the measured parameter. Also, the spatial resolution (i.e. proximity to point of impact, and what might be referred to as "level of analysis") of the measurements was considered. Should measurements be conducted on building-level, or in the apartments? Should measurements of the indoor climate in an apartment be measured in the exhaust air, or in a specific room in the apartment?
    - The **precision (proximity of values to each other)** of the measurements, i.e. the quantity of measurement and data points, i.e.

    the temporal resolution (i.e. time intervals) of the readings as well as the number of measurement points. High temporal resolutions and a higher number of measurement points might give better precision, or more noise, but what was the necessary temporal resolution for the assessment that was to be made?
  - If an **induced reaction** was necessary or not in order to assess the impact of the measure on the system, i.e. the necessity of giving rise to a reaction by the system to a significant change in a specific parameter. The variations of a parameter might be too small for the assessment of the impact that a measure has on that parameter. In such a case an induced reaction maybe needs to be considered – in which the operator causes the reaction by manipulating the system in order to achieve a significant and controlled change in the measured parameter, e.g. increasing the moisture content in the air in order to test a dehumidifier. Thereby making it possible to assess the reaction of the system to this change, in comparison to the system before the implementation of the measure, or a system without the measure.
  - If measurements on a **control object** were possible in order to exclude other changes to the system due to control parameters that might affect the results, i.e. changes that were not directly affected by the renovation measure (e.g. environmental parameters). The possibility of measuring on a control object that is comparable to the object of renovation, was discussed. This, in order to assess the impact of control parameters (e.g. weather), or miscellaneous disturbances.
- The need for supplementary analyses due to limitations and deviations in the case study.
- The conclusions based on the field measurements.
- The conclusions based on the supplementary analyses.
- Finally, each case study is discussed regarding:
  - how causation was shown in the case study,
  - the analyses that were possible to achieve with the included parameters,
  - and the arrangements and prerequisites that were necessary in order to conduct the field measurements.

4.1 Summary – assessments and conclusions

The following subsections give a brief overview of the work conducted in the case studies, the conclusions that followed based on field measurements as well as the supplementary analyses that were conducted in order to achieve the aim of the study.

4.1.1 Impact assessed

In each case study, the impact of the measure was assessed with regard to the energy efficiency, indoor environmental quality and/ or the moisture safety. The following table summarizes the impact that was determined in each case study and refers to the made publication(s) that include(s) the details and results. The focus of each study is highlighted with **bold** text.

Table 4.1: Summary of impact assessed in case studies. Bold text = focus of study.

Case Study (measure)	*Impact*			*Paper (in order of relevance)*
	Energy Use	*Indoor Environmental Quality*	*Moisture Safety*	
1. Interior added insulation on external SBM walls	Not assessed. This was not the focus of this case study.	Not assessed. This was not the focus of this case study.	**Assessed through field measurements as well as hygrothermal simulations based on the field measurements.**	5, 2, 3
2. DCV for multifamily buildings	**Assessed through calculations based on field measurements, comparing DCV to other options.**	**Assessed through analysis of field measurements.**	**Assessed through comparing results of field measurements to results from supplementary analyses.**	4, 1, 2, 3

Case Study (measure)	*Impact*			*Paper (in order of relevance)*
	Energy Use	*Indoor Environmental Quality*	*Moisture Safety*	
3. MVHR for multifamily buildings	**Assessed through analysis of field measurements on energy supplied for heating as well as analyses of other impacting parameters.**	**Assessed through analysis of IEQ-survey response.**	Assessed through analysis of field measurements as well as IEQ-survey.	6, 3
4. *Air-side cleaning of heat exchangers in ventilation systems*	**Assessed through analysis of field measurements, with support of laboratory experiments.**	Not assessed, not the focus of this study.	Not assessed, not relevant for the measure itself.	7
5. Ventilation measures for heritage buildings	**Assessed through building performance simulations using field measurement data.**	**Assessed for MVHR through comparison of field measurements.** **Not assessed for dampers, since these do not affect the IEQ during office hours.**	**Assessed through comparison of field measurements.**	8

4.1.2 Conclusions based on field measurements

In the following table, the results acquired through the field measurements are summarized for each case study, together with the parameters that were measured.

*Table 4.2: Summary of field measurements conducted in the case studies and the results gained through these measurements. *From SMHI* [72]*, not local. 1. Only before the implementation of the renovation measure. 2. Not used in the assessment.*

Case Study	Field measurements	Conclusions from field measurements
1. Interior added insulation on external SBM walls	**In the wall:** Temperatures Relative humidity **Outdoors:** Temperatures Relative humidity Global radiation* Precipitation*	Comparisons between an insulated an uninsulated SBM wall showed that the relative humidity in an SBM wall increases due to mineral wool being added on the interior, which in turn increases the risk of microbiological growth on biological building materials and increases the risk of corrosion on bed-joint reinforcement.
2. DCV for multifamily buildings	**Indoors^{1}:** Temperatures Relative humidity MOS-sensor readings (VOCs) CO2 concentrations **Outdoors:** Temperatures Relative humidity Global radiation*^{2} Precipitation*^{2}	Field measurements show that the DCV system provides good IAQ in most apartments included in the study, and that low moisture loads are achieved in most apartments. In some apartments, the settings for the ventilation system might need to be adjusted in order to respond to the higher-than-expected need in those apartments. Field measurements also show that the VOC-sensor in this DCV-system is an appropriate alternative to conventional CO_2-sensors. The combination of field measurements and energy calculations shows that the DCV provides substantial energy savings compared to MBV, and slightly larger savings compared to conventional MVHR.

Case Study	Field measurements	Conclusions from field measurements
3. MVHR for multifamily buildings	**Building level:** Energy supplied **Indoors:** Temperatures Relative humidity **Outdoors:** Temperatures Relative humidity Global radiation* Precipitation*	Comparisons of field measurements on the buildings that were affected, as well as the control (reference) buildings, show that the MVHR provides substantial energy savings compared to MEV and MBV. The analysis also shows that other factors that might impact on the energy use such as solar radiation, outdoor temperature, and adjustments to the heating system, should not be disregarded.
4. Air-side cleaning of heat exchangers in ventilation systems	**In the AHUs:** Pressure drops Temperatures Relative humidity Air flows	The analysis of field measurements showed that cleaning has a significant impact on the heat transfer by the heat exchangers, and that the pressure-drop decreases over the heat exchangers due to cleaning. Field measurements also show that there are differences between different types of buildings, units and geographical locations.
5. Ventilation measures for heritage buildings	**Indoors:** Temperatures Relative humidity **Outdoors:** Temperatures Relative humidity Global radiation* Precipitation*	Field measurements allowed the determination of the latent heat exchange efficiency and the change in ACR. These show that the MVHR provides substantial energy savings compared to NV, while reducing the CO_2 concentrations in the offices that were affected by the measure. Field measurements allowed the determination of the impact of the dampers on the offices that were affected, through the determination of the difference in ACR. These show that the ACR was greatly reduced in the offices that were affected by the measure. Measurements also show that the RH was not affected in the offices with dampers.

4.1.3 Conclusions based on supplementary analyses

In the following table, the conclusions made based on the supplementary analyses, such as laboratory studies, calculations and simulations, are summarized for each case study.

Table 4.3: Summary of supplementary analyses conducted in the case studies and the results gained through these.

Case Study	Supplementary analyses	Conclusions from supplementary analyses
1. Interior added insulation on external SBM walls	Hygrothermal simulations comparing interior and exterior loads.	This analysis showed that exterior loads far outweigh interior loads, and therefore the interior loads were not as important to consider when assessing this type of measure but are significant if no vapor barrier exists on the interior.
	Hygrothermal simulations on different types of insulation.	This analysis showed that different conventional insulation (mineral wool, EPS) may increase the posed risks on the building materials, while CaSi and impregnation might reduce them.
2. DCV for multifamily buildings	Hygrothermal simulations comparing moisture loads.	An analysis on a wall construction sensitive to both interior and exterior moisture loads resulted in a recommendation of a moisture supply set point.
	Laboratory study for determining the reaction of the DCV-system to household pollutants.	The laboratory study showed that the system reacts to common indoor air pollutants and responds well to these, but that there is a response delay due to the system design.
3. MVHR for multifamily buildings	IEQ survey for the assessment of the impact of the MVHR.	The survey showed that the IEQ does not diminish due to the MVHR. No change in the IEQ was perceived regarding most issues. Regarding some issues, the IEQ was experienced to have been improved.

Case Study	Supplementary analyses	Conclusions from supplementary analyses
4. Air-side cleaning of heat exchangers in ventilation systems	Laboratory study for determining how the amount of accumulated contaminant affected the pressure drop and heat exchange.	The laboratory study showed that the pressure-drop increased with the amount of accumulated contaminant, and that the heat exchange diminished.
5. Ventilation measures for heritage buildings	Building energy performance simulations for determining the impact of MVHR and dampers out-of-hours on the energy use.	The analysis shows that the MVHR provides substantial energy savings compared to NV, and that reducing the air change rate out-of-hours in an NV-system can result in significant energy savings.
	Survey for the assessment of the impact on the IEQ.	The IEQ survey could not produce data that was statistically significant for any deterministic conclusions, due to the lacking number of responders. However, the survey did show that buildings with NV clearly had issues with the thermal comfort.

4.2 Case study 1 - Interior added insulation on external SBM walls

Insulation can be added on the interior of external walls as a measure for reducing the energy use of a building. This case study evaluates the impact of such measure on the hygrothermal status of external solid brick masonry (SBM) walls. *Paper 5* aims at accurately evaluating a conventional moisture-safety risk-analysis-procedure, with regard to exterior SBM walls and internal insulation, through the identification of factors that are critical to the results.

This case study used an approach between the hypothetico-deductive and the inductive. The hypothesis was that internal insulation diminished the hygrothermal performance of the existing wall, which was determined through differences in measurements between an insulated and a non-insulated SBM wall. However, even if answering the hypothesis gave explanatory knowledge on the impact of internal insulation, it did not describe how other differences impacted on the results. In order to acquire such knowledge, sensors were installed in different materials, on different depths, on different heights, and in different cardinal directions. This gave information on the impact of these parameters. Furthermore, in order to determine the differences between different types of insulation materials, a hygrothermal mathematical model of an SBM wall was validated in a commercial software in order to simulate the impact of different insulation materials.

4.2.1 Derivation of parameters

There are several main parameters that this measure can directly affect in the building as a system:

- The energy use of a building, since transmission loss through the building envelope is reduced.
- The temperatures on the interior surfaces, since transmission losses through the building envelope is reduced. This can affect the perception of the indoor environmental quality (IEQ), since surface temperatures affect the operative temperature and the risk for draft occurring.
- The hygrothermal performance (temperatures & RH) of the existing building envelope. Due to a decreased heat flux through the wall, building materials beyond the internal insulation will be exposed to lower temperatures. This in turn may lead to increased risks for high relative humidity or condensation and thus reinforcement corrosion, microbiological growth, and frost expansion.

- Among the things that should impact the determination of the walls' performance is the material in which the measurements take place, since a SBM wall mainly consists of a combination of brick and mortar.

Field measurements were primarily focused on parameters that could affect the impact of the internal insulation on the hygrothermal performance of the external wall. Control parameters, that can indirectly affect the end results, are surrounding environmental parameters:

A. Temperatures outdoors.
B. External moisture loads, which are comprised of:
    1. Specifically - wind-driven rain, which is dependent on:
        i. Precipitation.
        ii. Wind speed.
        iii. Wind direction.
    2. Relative humidity outdoors.
C. Electromagnetic radiation outdoors, which can be expressed in:
    1. Global Radiation, which can be divided into:
        i. Direct Solar Radiation.
        ii. Diffuse Radiation.
D. Temperatures indoors.
E. Internal moisture loads expressed in either of the following:
    1. *Moisture supply* (difference between vapor content indoors and outdoors).
    2. Relative humidity indoors, which is affected by:
        - Air change rate indoors.
        - Moisture production indoors.
        - Temperatures indoors.
        - Vapor content outdoors.

4.2.2 Materials and field measurements

Field measurements were conducted in two different units placed in different geographical locations (Lund & Örebro). In both units, differences between cardinal directions, depths in wall, vertical (façade) placements, and between building materials, were investigated. In one unit, Lund, measurements were conducted with no internal insulation. In the second unit, Örebro, measurements were conducted with internal insulation (mineral wool + vapor retarder).

4.2.2.1 Lund University V-building, Lund

The V-building is a part of the Lund University campus, and the Faculty of Engineering. The building is situated approximately 86 m above sea level, and a 3D-model from Google Earth of the building is presented in Figure 4.1. The owner of this building allowed temperature and relative humidity sensors to be installed in the external walls of the building for assessment of internal insulation on solid masonry walls (*Paper 5*). In order to determine differences in 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. In the attic's southern and western wall, the sensors were placed as shown in Figure 4.2 and Figure 4.3. In the attic's northern wall, the sensors were placed as shown in Figure 4.4. For more information on the building and the measurement setup, the reader is referred to *Paper 5*.

Figure 4.1: V-building, Google Maps.

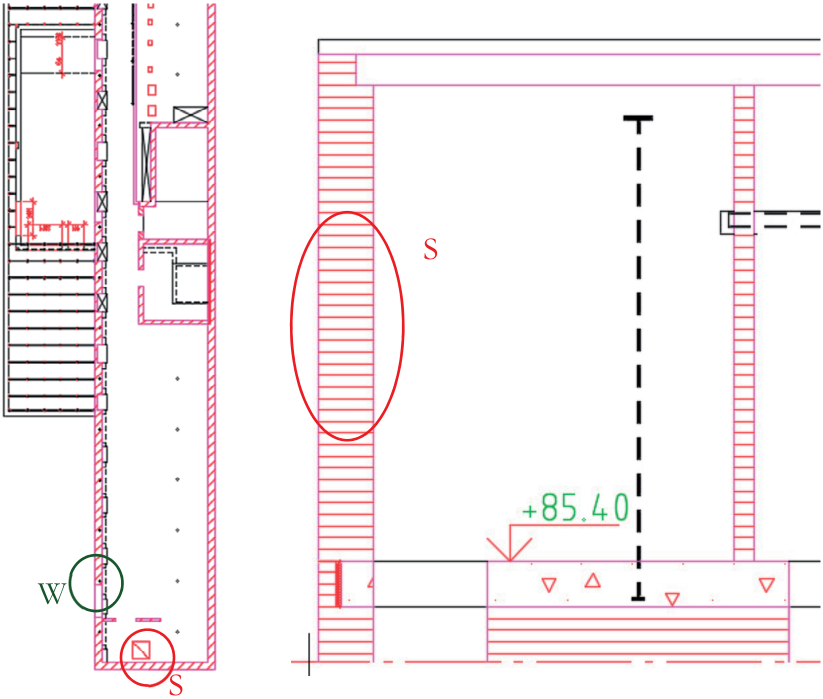


Figure 4.2 Location of sensors installed in southern and western walls. Blueprint provided by Akademiska Hus.

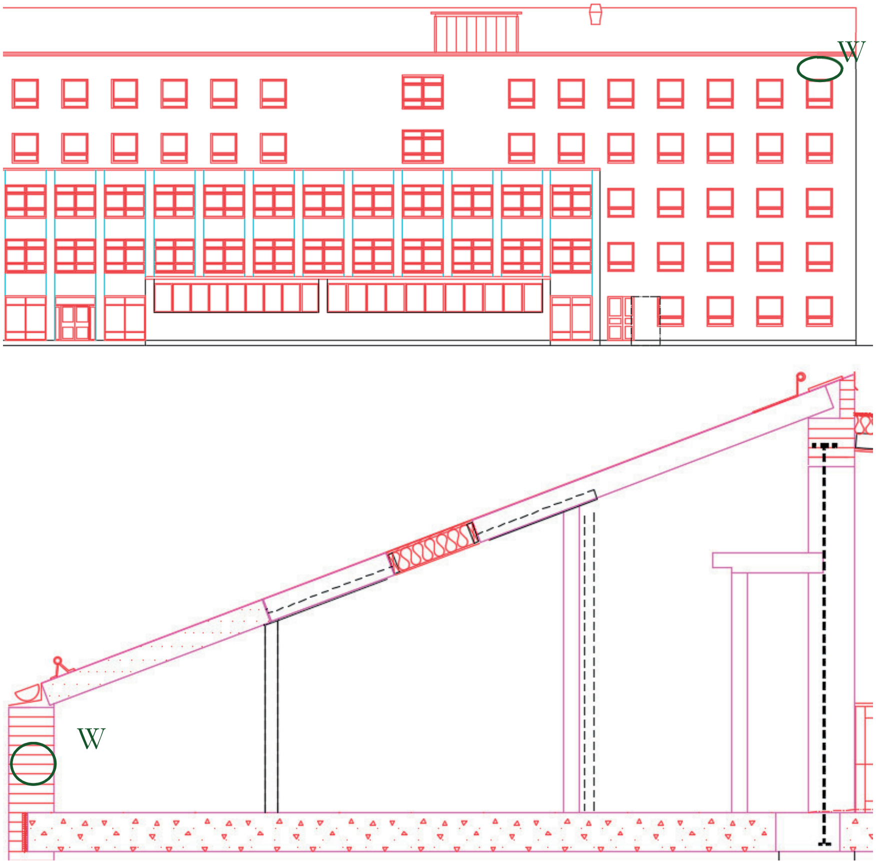


Figure 4.3 Approximate vertical location of sensors installed in western wall. Blueprint provided by Akademiska Hus.

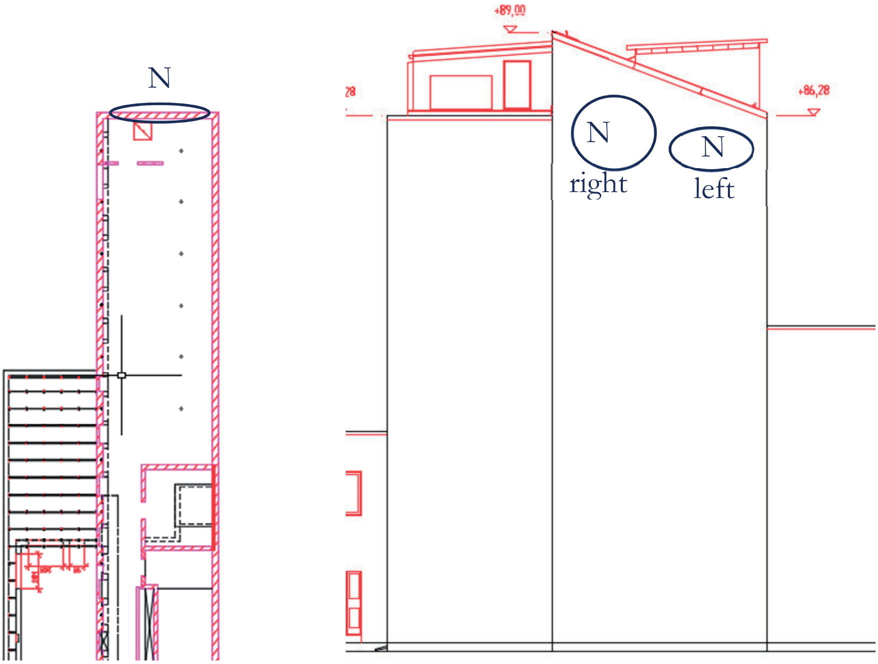


Figure 4.4 Approximate location of sensors installed in northern wall. The sensors in the northern wall consist of two sets of sensors, left and right (interior view). Blueprint provided by Akademiska Hus.

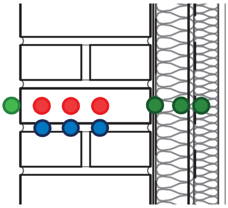
4.2.2.2 Multifamily buildings, Örebro

A block of three multifamily buildings in Örebro (see Figure 4.5), were fully renovated 2013-2016. Each building consists of 29 apartments, and underwent an extensive renovation which replaced the elevator, all fill-in walls, interior surfaces, kitchens, bathrooms, fresh and wastewater 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. They were also installed in different vertical placements, and since the composition of the external walls for these buildings differ from V-huset's walls, the sensors were installed in each of the different material layers shown in Figure 4.6 until Figure 4.8. The sensors in the masonry wall were installed at depths, from the exterior surface, which correspond to the depths of the sensors in V-huset.


[redacted]

Figure 4.5: Multifamily buildings included in case study, shown in a 3D-model from Google Earth.



From the exterior to the interior:

surface sensor

- 1 stone (250 mm) solid brick masonry (3x sensor in brick + 3x sensor in mortar)

surface sensor

- 15 mm unventilated cavity
- 70 mm mineral wool between steel studs

sensor between

- 0.2 mm vapor barrier (PE-foil)

sensor between

- 45 mm mineral wool between wooden studs
- 12 mm OSB
- 13 mm gypsum board

Figure 4.6: Composition of northern and southern external walls for the multifamily buildings in Örebro. Approximate sensor depths of "blue" and "red" sensors from the interior surface of the masonry wall: 90, 150- and 200-mm. Blueprint provided by ÖrebroBostäder.

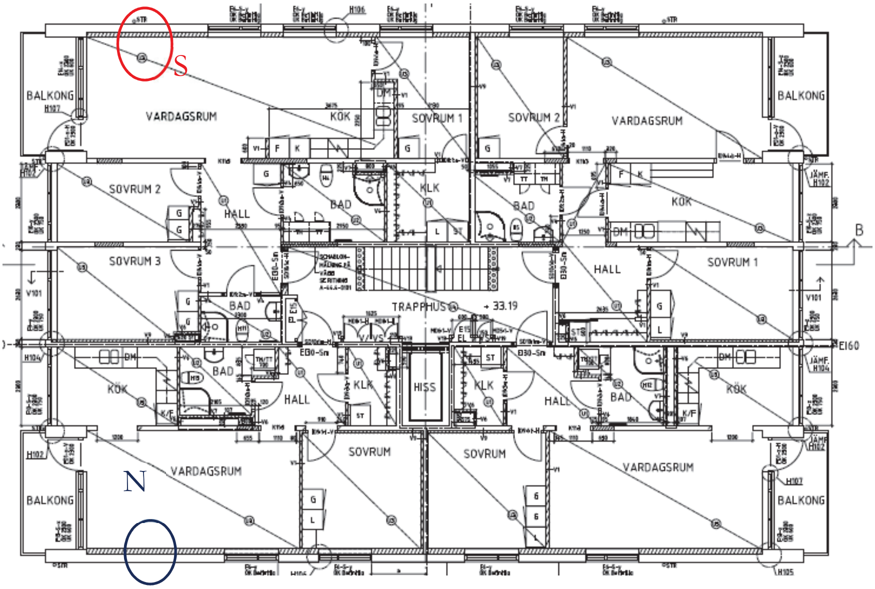
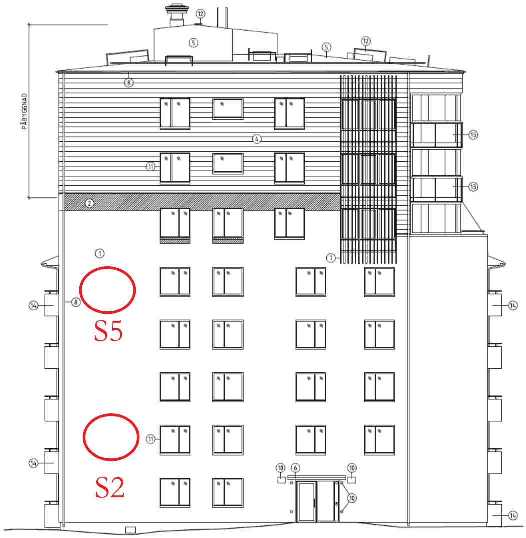


Figure 4.7: Approximate horizontal location of sensors installed in southern and northern wall. Blueprint provided by ÖrebroBostäder.

FASAD MOT NORR



FASAD MOT SÖDER

Figure 4.8: Approximate vertical location of sensors installed in northern and southern walls. The sensors in the northern wall consist of two sets of sensors on level 2 and 5. Blueprint provided by ÖrebroBostäder.

4.2.2.3 Measurement details

The following deals with the measurements of the main parameters that are affected by the renovation measure.

Timespan.

In order to minimize the effect of the seasonal variations of the control parameters, the measurements were conducted during the same seasons before and after the renovation measure. Since seasonal variations change over time due to climate change [73]–[75] the ideal setup might be to cover a timespan before and after renovation that includes all seasons yet be as short as possible in order to minimize the effect of climate change on the end results. This might mean that measurements should include data for a year before and year after the measure. However, considering variations in climate data, the chance of acquiring measurements during comparable climates before and after he measure is implemented might increase with an even longer time span. However, it is probably not often that studies have the possibility of measuring for much longer time periods (several years both before and after), due to resource and time limitations, or due to deviations (e.g. sensor error). In Lund, measurements were conducted for nine months starting 2014, before sensors failed, which means that the measurements at least covered a cold part of the year and a warm part of the year. In Örebro, the measurements continued for at least a year, starting summer 2015, and are still ongoing.

Accuracy.

A masonry brick wall is a composition of at least two building materials – mortar and brick – therefore measurement results might vary quite strongly depending on the material. Therefore, measurements were conducted both in mortar and brick. Furthermore, since capillary and diffusion processes within both materials might differ, the effects of any event should reverberate differently through the depths of the materials – so therefore measurements on different depths were conducted. Finally, since different parts of the exterior of a building are exposed differently to certain events (e.g. wind-driven rain, solar radiation), measurements were conducted in different cardinal directions in order to determine this parameter's impact on the results. For the same reason, measurements were also conducted on different heights (in Örebro).

Precision.

All the parameters within the wall were measured with a time interval (5-10 min) that was assumed to detect all fluctuations due to the hygrothermal processes within the wall. Fluctuations in materials such as masonry, brick, wood, etc.

depend on the distance of the material from the surrounding climates (i.e. depth into the material). They also depend on (the exposure to) different events in the surrounding climate. E.g. if a brick is exposed to a variation in the outdoor air-temperature the surface of that brick would almost immediately vary with the outdoor air temperature, however, such a variation would not immediately be noticed deeper into the brick due to the thermal resistance and thermal capacity of the brick. The same applies to variations in RH and exposure to precipitation. Furthermore, the brick in an external wall is affected by changes in the indoor environment as well, and both changes will affect the results differently on different depths within the brick. Nevertheless, a careful approach with time intervals of 5 minutes (Örebro) and 10 minutes (Lund) was chosen in order to safeguard for unexpected variations as well. Furthermore, these time intervals were also chosen to cover uncertainties regarding the materials' properties, since material data was not acquired for the materials. An argument for this approach is the impact that the time interval has on the maximum value of the measurements, and the amplitude of the fluctuations. The impact of differences in time interval, with longer intervals resulting in loss of peaks, has been shown by Bagge and Johansson [38]. However, this precision could not be achieved on parameters that were not measured by the involved researchers but were acquired from other sources, such as the Swedish Meteorological and Hydrological Institute.

Induced reaction.

Since some materials in the wall, mainly the insulation and possible remnants of biological materials from the previous construction, were sensitive to high RH, the impact of the extremes of the seasonal variations that could affect the hygrothermal performance of the wall (i.e. precipitation and solar radiation), were considered. To wait for the extremes was necessary, since it would be practically quite difficult to do induce a reaction, if not impossible. The timespans in the units were long enough to measure the impacts of such extremes (precipitation, solar radiation, high temperatures, low temperatures).

Control object.

Field measurements were conducted in two buildings – a building on which internal insulation was not applied on the external walls, in Lund, and another one on which it was, in Örebro. However, although the building in Lund was used as a control object (reference building) for the measurements in Örebro, the geographical distance between the buildings, the limitations in the field study (e.g. the type of insulation), as well as differences in construction, required supplementary analyses in order to determine the risks related to the impact of internal insulation on the hygrothermal status of SBM walls.

4.2.2.4 Supplementary analyses

Field measurements were conducted in two buildings – a building on which internal insulation was not applied on the external walls, in Lund, and another one on which it was, in Örebro. The masonry wall in these two buildings had the same color on the bricks, were built during the “record years”, and had the same brick-bond, but did not have the same thickness, and the buildings were located approximately 500 km apart, which means that they were subjected to different climates during the measurements. Furthermore, measurement equipment was installed amid the renovation processes, and access to the buildings were given during a limited timespan. The installation of sensors in the buildings could therefore only be conducted in walls without internal insulation in Lund, and walls with internal insulation in Örebro. The limited access also prevented reparation and replacement of faulty sensors in the walls (Lund) and in the indoor climate (Örebro). For this reason, the internal moisture loads could not be measured in Örebro. Furthermore, due to faulty sensors, measurements could not be conducted in Lund after implementation of insulation. Therefore, impact of insulation was assessed through hygrothermal simulations. Also, usually the application of internal insulation reduces the temperature of an existing masonry wall, however, that does not mean that all internal insulation increases the humidity content, which is in part due to different functionalities of different insulation types [76]. Thus, since only one type of insulation was applied on the walls in Örebro – mineral wool – the assessment through field measurements could only be conducted on this type of insulation.

To compensate for the limitations and deviations mentioned above, sensors were installed on the same depth from the exterior surface of the exterior of the walls in both buildings. This, so that a direct comparison could be made between the sensors and thereby the impact of internal insulation could be assessed. Also, since the internal moisture loads could not be measured in Örebro, a comparison was made between internal and external moisture loads through hygrothermal simulations, see *Paper 2*. This in order to assess the significance of the impact of internal moisture loads on the final construction. Finally, since the impact of only one kind of internal insulation could be assessed through the measurements, a set of supplementary analyses using hygrothermal simulations were conducted in order to assess the impact of different types of insulation, see *Paper 5*.

4.2.3 Conclusions from field measurements

Field measurements show differences between different cardinal directions, depths in material, vertical (façade) placements, and between building materials – all should be considered in a damage risk-assessment. The measurements also show that there is a significant impact from precipitation and solar radiation on the hygrothermal status of the wall, and that internal insulation poses a significant risk for mold growth on biological materials in SBM walls due to solar-driven vapor from the exterior to the interior. The results can be found in detail in *Paper 5* and *Appendix A1*.

Impact of control parameters

Measurements show the following impact of control parameters, for the unit without internal insulation (in Lund):

- Differences between warm 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 warm and cold months indicate that the solar driven vapor has a substantial impact in the direction that is most subjected to wind driven rain. The masonry wall to the south is the driest in this case, even though this is the one most subjected to wind-driven rain according to the climate analysis (see *Appendix A1*).
- Differences in depth show that sensors closest to the interior surface have the highest humidity levels during the summer but the lowest 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 consider in further evaluations. This also indicates that the precipitation during the winter is considerably less frequent and that the temperature difference is the most impacting factor (warm inside, cold outside – dry inside, humid outside).
- The RH is higher in the upper part of the façade than in the lower. The impact of the height above the ground should therefore be considered.

For the unit with internal insulation (Örebro):

- The results show seasonal variations similar to the ones in the wall in Lund.
- Interior loads have almost no impact on the masonry wall with an interior vapor barrier.

- If biological materials exist between the vapor barrier and the SBM wall, there is a high risk for mold growth due to solar driven vapor.

Impact of main parameters

For the unit without internal insulation (in Lund):

- Differences between materials in an uninsulated wall are season dependent. Warmer seasons result in higher temperature and humidity fluctuations and differences, especially in walls more exposed to solar radiation (south and west).

For the unit with internal insulation (Örebro):

- Comparisons between the insulated wall in Örebro and the uninsulated wall in Lund shows that the impact of internal insulation on the hygrothermal performance of a wall is substantial. The differences in spread in temperature and RH between the sensors within each wall is much larger in the uninsulated wall than the insulated wall, and this is shown both in brick and mortar. The differences are so small between mortar and brick in the insulated wall, that the impact of the specific material on the results can be disregarded.

4.2.4 Conclusions from supplementary analyses

Impact of internal vs. external moisture loads

In *Paper 2* internal and external loads were simulated on an internally insulated exterior solid-brick-masonry wall, without a vapor barrier. 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, unless a vapor barrier is applied internally.

Paper 2 also compared different geographically bound loads (external climate) to be used for further benchmarking, showing that the use of data for some locations resulted in a much diminished hygrothermal performance by the same wall. The geographical locations in the paper were chosen with the assumption of the existence of multifamily houses built between 1945-1970.

Impact of different types of insulation, and associated risks

Besides analyzing the field measurement data, *Paper 5* validated the tool and a model of the wall in Lund. The validation showed that the model generates results that are worse than the measurement results with regard to risk of microbiological growth. It was however unclear if the differences between simulation results and measurement results were due to the tool itself or the quality of the climate data (specifically the solar radiation data), but most likely it was the latter. Nevertheless, this suggest that the tool and model provide a safety margin in the benchmarking, i.e. the model produced results that were "on the safe side". See *Appendix A1*.

Supplementary analyses with hygrothermal simulations show that different types of insulation impact the hygrothermal status of the SBM differently, and that some types of insulation may reduce the risk for mold growth and corrosion of the reinforcement bars (e.g. CaSi), while others will increase it.

4.2.5 Discussion

4.2.5.1 Causation

One of the main causes for the difference in results between the insulated and uninsulated walls was identified as the application of the internal insulation. However, is this a necessary or sufficient condition for the effect? I would argue that it is a necessary condition, since it is possible but highly unlikely for changes in surrounding parameters to cause the differences that have been noted between the wall in Örebro and the one in Lund. It is more likely that, through the application of the internally added insulation, the heat flux from the interior was decreased, which in turn decreased the temperatures in the SBM wall in Örebro and cushioned the fluctuations. One way to achieve the same impact through changes in control parameters, without interior insulation, is to decrease temperatures indoors. However, this did not happen in either building.

4.2.5.2 Necessary measurements

In the table below, parameters that were could impact on the results are presented together with (from left to right) 1) their time intervals, 2) a qualitatively assessed degree of relevance within the study based on the outcome, 3) each parameter's dependency on other parameters, 4) the dependee parameters' time intervals, as well as 5) the limitation in the measurements of the dependent or the dependee parameters.

Table 4.4: Time intervals and limitations for parameters measured in field in the units that were included in the case study.

Parameter	**RH_{wall}**	**T_{wall}**	**$T_{outdoors}$**	**$RH_{outdoors}$**	**$T_{indoors}$**
Time interval	Lund: 5 min Örebro: 10 min	L:5 min Ö:10 min	L:5 min Ö:10 min	L:5 min Ö:10 min	L:5 min Ö:10 min
Relevance (1-5)	5	5	4	4	3
Dependency (see section 4.2.1)	A-E	A, C, D	C	A, B	A, C
Time interval – dependee	5-10 min, 1 h, 1 day	5-10 min, 1 h	1 h	1 h	5-10 min, 1 h
Limitations – Unit in Lund	B-1-i: Close by, but not local. E-1, E-2: Attic environment, housing AHU. E-3: Not measured.				
Limitations – Unit in Örebro	B-1-i: Daily precipitation, low temporal resolution. C: Radiation not measured but calculated. D,E: T and RH not measured indoors, but in the internal layers of the wall.	C: Radiation not measured but calculated. D: T not measured indoors, but in the internal layers of the wall.		B-1-i: low temporal resolution for daily precipitation.	This parameter was not measured; however, measures were conducted in wall layers close to the indoor environment. C: Radiation not measured but calculated.

Parameter	$RH_{indoors}$	Precipitation	Global radiation	Wind speed & direction
Time interval	L:5 min Ö:10 min	1h, 1 day	1 h, -	1 h, -
Relevance (1-5)	3	4	4	4
Dependency (see section 4.2.1)	A, B, E.			
Time interval – dependee	5-10 min, 1 h, 1 day			
Limitations – Unit in Lund	B-1-i: Close by, but not local. E-1, E-2: Attic environment, housing AHU. E-3: Not measured.			
Limitations – Unit in Örebro	This parameter was not measured; however, measures were conducted in wall layers close to the indoor environment.	Low temporal resolution.	Not measured but calculated.	

None of these limitations were critical for the outcome of the study since the conducted measurements made it possible able to assess the differences in the hygrothermal status of the walls and compare the measurements in the walls to each other. The conducted measurements also made it possible to validate a hygrothermal simulation model in order to compare different insulation types through. In order to do these analyses, the most important measurements in this case study were (in order of degree of importance):

1. Temperatures in the wall + Relative humidity in the wall.
2. Temperature outdoors + Relative humidity outdoors.
3. Temperature indoors.

4. Precipitation + Global Radiation.
5. Wind speed and direction.
6. Relative humidity indoors / Moisture Production + Air Change Rate.

With the first two parameters, the impact of the measure on the hygrothermal status of the SBM wall was determined. Without these two parameters, the impact of the measure on the wall would be an estimation (a calculation). With measurements on the other parameters, the impact of changes in the environment could be assessed. Furthermore, the different placements of the sensors allowed differences between materials and cardinal directions to be identified.

The hygrothermal status of the wall is dependent on the temperatures, therefore the impact of changes in temperatures indoors and outdoors are significant and therefore needed to be considered. The impact of precipitation and global radiation were also significant on the results, and even if measurements of these are not crucial for the assessment, they do increase the accuracy of the results since they allow for determination of how different events impact on the hygrothermal status of the wall. Precipitation together with wind speed and wind direction allowed for wind-driven rain to be determined, even if this factor can also be estimated. The indoor moisture loads have been shown to have a low impact on the results, as long as these are handled properly (e.g. with a vapor barrier). Even if they aren't, the outdoor moisture loads far outweigh the impact of indoor moisture loads.

As for the time intervals, the chosen time intervals for the sensors in the SBM walls allowed for the visualization of the differences in variance at different depths. This showed how the impact of different occurrences reverberated throughout the wall and how different materials at different depths were affected by weather events. It also allowed for a comparison in variance between the insulated and uninsulated wall, as well as between different materials. The chosen interval was therefore beneficial for these analyses. However, for the mathematical models that were used in order to determine the risk for mold growth and corrosion, 12-hour average values were sufficient. Thus, fluctuations by the minute might not be needed for the assessment of these risks. However, measurements with the chosen time intervals have provided insight on the heat and moisture fluxes within the wall, which contributed to the understanding of the hygrothermal performance of the wall, which in turn aided the assessment of the impact that the renovation measure had on the wall. The time intervals are further discussed in section 4.7.3.2.

4.2.5.3 Necessary arrangements and prerequisites

In order to be able to conduct the field measurements, a continuous contact with professionals in the industry who gave access to the buildings was necessary, i.e. the property owner or a representative of the property owner (i.e. project manager). The comparisons through field measurements would probably not have been possible if a need for applying the measure on at least one of the included buildings didn’t exist and the plan to implement it as well. Since the properties were up for a deep renovation either way, due to expired building materials and issues with the heating system, such a need did exist. Furthermore, the property owner wanted to verify the hygrothermal status of the walls, as well as the impact of the measures on the buildings, and therefore helped in acquiring the necessary time and access to the buildings in order for the measurement equipment to be installed. For this, the involved building entrepreneur needed to be communicated with, and supportive of the research projects, which they were. Furthermore, the measurement equipment that was used required electricity and a place for the computer that collected the data. The wiring between the sensors and this computer, in one of the case studies, was conducted by electricians on-sight and financed by the property owner.

Besides the above, preparations by the research team were conducted through preparations of the measurement equipment. The team was also active in the design phase of the renovation project in order to inform those involved of their participation as well as receive information on the timeline of the renovation project in order to identify when the measurement equipment could be installed in the buildings. The research team then requested updates on the status of the renovation project in order to dispatch and install the equipment. During and after installation the research team controlled the equipment for faulty sensors and acquired internet access so that remote access to the computers existed. The sensors that could be accessed remotely were checked regularly so that data acquisition was ensured, while sensors that couldn’t be accessed remotely were checked on site. Finally, data that could not be acquired through field measurements was acquired from the property owner in one of the case studies (since they had a climate station) and otherwise SMHI [72].

4.3 Case study 2 – DCV for multifamily buildings

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 control 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 4.9. The main aim of this project (*Paper 4*) is to determine the potential for this DCV-system - through field measurements - to achieve: 1) good IAQ, 2) good moisture safety with regard to the moisture loads on building materials, and 3) good energy efficiency in multifamily buildings.

This case study used an approach that was between the hypothetico-deductive and the inductive. It was unclear how DCV would affect the energy use and the indoor climate in an apartment building, since research on this is scarce. Implementation of MVHR had previously been shown to improve the IEQ and energy efficiency in comparison to mechanical exhaust ventilation (MEV), mechanical balanced ventilation (MBV) and natural ventilation (NV). DCV has been shown to further improve both IEQ and energy performance in office buildings and industrial buildings. However, DCV based on this type of control was untested in apartment buildings. A number of hypotheses were therefore made based on the system design and findings in previous publications:

- This system reacts to normal household activities (see *Paper 1*).
- However, since the system reads the pollutant concentrations with a sensor that is placed in a control box through which the main exhaust duct exits the apartment, the system readings might be diluted and the system will react to changes in the indoor environment in a less optimal manner, allowing the pollutant to spread in the apartment (see *Paper 1*).
- Since the system reduces the air-change rate when the sensor readings are low, pollutants that aren't detected by the system might increase to harmful levels (see *Paper 1*).
- The system will reduce the energy use of the building in comparison to other systems, since the ACR will be reduced at times when high ACRs aren't needed (see *Paper 4*).

- The system will reduce the moisture loads on the building materials, since it has an adaptive ventilation rate based on a threshold for the moisture supply (see *Paper 4*).

Some questions were to be answered through an inductive approach, since some of the hypotheses above were yet to be answered, and some could not be answered. One question that was approached in this manner was the impact that the system had on the inhabitants' perception of their IEQ in comparison to conventional balanced ventilation. The aim was to answer this through the analysis of survey responses. Another question was how high the threshold for the moisture supply was to be set, since there were no guidelines for this parameter in regard to the risk for mold growth (see *Paper 2*). A third question was if the VOC-sensor readings did correlate with CO_2, since it was supposed to do so according to previous findings. This in order to compare the readings with conventional CO_2 limits and guidelines. Simultaneous field measurements of the VOCs (sensor readings) and CO_2 (sensor readings) were therefore conducted in eight apartments, see *Paper 4*.

4.3.1 Derivation of parameters

There are several main parameters that this measure can directly affect in the building as a system:

A. Energy use of a building, since:
    1) The energy use for heating the supply air is reduced through recovery of heat from the exhaust air, and the reduction of ACRs when high rates are unnecessary.
    2) The pressure profile over the building envelope might be changed, thereby reducing the air leakage through the building envelope.
    3) Usually, simultaneous airtightness measures are usually performed (or at least they should be) which reduces the air leakage through the building envelope.
B. Indoor temperature, since:
    - The supply air is heated, which might increase the indoor air temperature if all other things remain unchanged.
    - The air flow is controlled, which should dampen variations in the indoor temperature, as well as issues with draft.
C. Indoor relative humidity, since the supply-air is heated and controlled this should improve the system's response to moisture production (loads) and thereby also dry-out rates. Furthermore, when needed, the ACRs are increased in order to deal with high moisture loads.

D. Indoor emission concentrations, since the ACR is controlled, in contrast to a NV system. Furthermore, when needed, the ACRs are increased in order to deal with high emission loads.
E. The electrical use of the building, since fans require electricity to run.

Field measurements were primarily focused on the impact that the measure had on the indoor climate, but also on the energy use. Control parameters, that can directly or indirectly affect the energy use of the building, are surrounding environmental parameters as well as parameters depending on user behavior:

F. Temperatures outdoors.
G. Wind speed and Wind direction, which can impact on the air leakage through the building envelope.
H. Electromagnetic radiation outdoors, which can be expressed in:
    1. Global Radiation, which can be divided into:
        i. Direct Solar Radiation.
        ii. Diffuse Radiation.
I. Temperatures, indoors. Which are affected by:
    1. Temperatures outdoors.
    2. Electromagnetic radiation.
    3. Air leakage.
    4. Internal heat production (gains), from:
        i. Appliances.
        ii. Inhabitants.
        iii. Activities.
    5. Window opening.

Changes in the following parameters can impact changes in the indoor air quality (IAQ):

J. Emissions, indoors. Which are affected by:
    1. Air change rates
    2. Internal emission production (loads), from:
        i. Inhabitants
        ii. Activities
        iii. Building material
        iv. Furniture
        v. Equipment
    3. Window opening

Changes in the following parameters can impact changes in the moisture loads:

K. Relative humidity outdoors, which can impact on internal moisture loads.
L. Internal moisture loads expressed in either of the following:
    1. *Moisture supply* (difference between vapor content indoors and outdoors).
    2. Relative humidity indoors.

…and are affected by:

- Air change rate indoors.
- Moisture production indoors.
- Temperatures indoors.
- Vapor content outdoors.

4.3.2 Materials and field measurements

The field measurements in this study were conducted in Norrköping, in a multifamily building that was built in 1965. The building consist of apartments with 1-2 rooms and with similar layouts, and before the installation of the renovation measure, 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 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 A2*).

Field measurements were conducted before and after renovation and were used for determining the IEQ as well as the moisture loads on the building envelope (VOC, CO_2, moisture supply), as well as for determining the system functionality (ACR, air flows, temperatures by heat exchanger). For more details on this the reader is referred to *Paper 4* an *Appendix A2*.

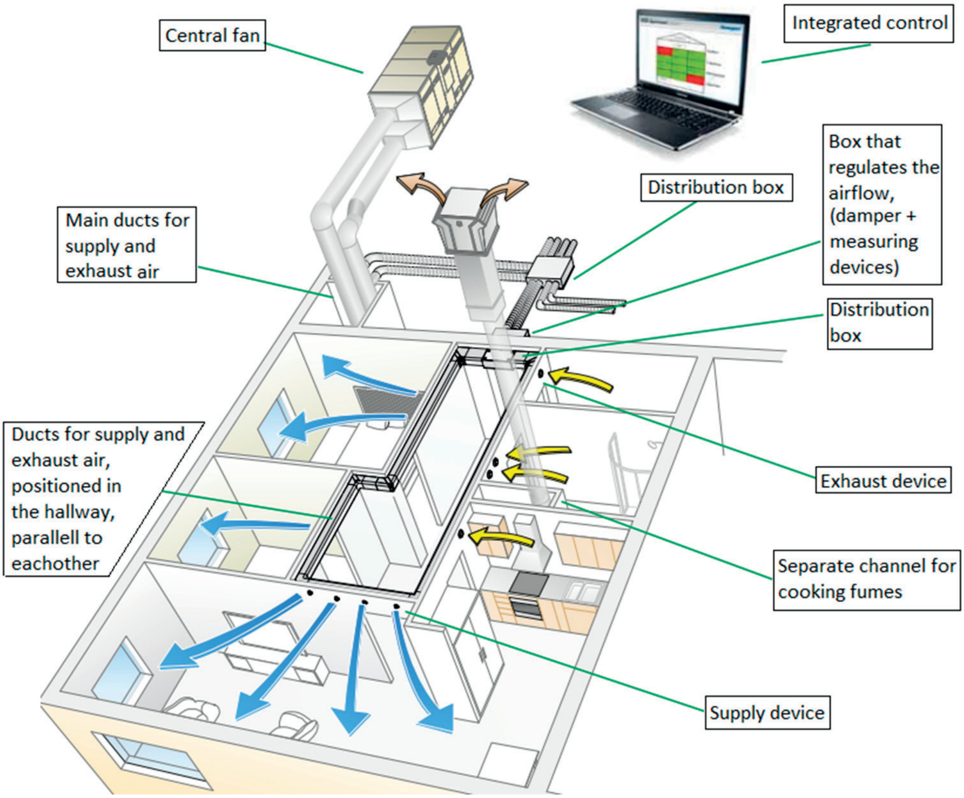


Figure 4.9: Illustration of DCV system in an apartment building, based on illustration by Swegon.

4.3.2.1 Measurement details

Timespan.

In order to minimize the impact of seasonal variations, the plan was to measure during the same seasons before and after the implementation of the renovation measure, according to the same reasoning as in section 4.2.2.3. Furthermore, since one of the aims was to assess the impact on the energy use, and it was assumed that a thermal wheel primarily recovers heat from the exhaust air in Swedish dwellings, the plan was to measure during the time of the year in which space heating was relevant. Nevertheless, measurements were conducted for six months before the implementation of the measure and almost for a year after.

Since the measure is highly dependent on the inhabitants and their habits, it was also important to conduct measurements when they were present in the building, doing normal household activities. However, there was no way certainly of knowing which activities were performed in the building except through measurements of pollutants that the inhabitants and their habits would emit.

Accuracy.

The expected impact that this type of measure has on the energy use is on the energy used for space heating. Measurements on this parameter might therefore be conducted on the supplied heat to the building, i.e. on the heat carriers. Furthermore, such measurements can be conducted on the heat carriers to the parts of the building that are affected by the renovation measure. However, such measurements were not conducted by the researchers since the property owner was already conducting measurements on the heat supplied to the building. Besides, installing equipment for such measurements in a building should be conducted by someone certified for such work. However, existing measurements on the building's heat carriers turned out to be on building level, and since the impact of the measure was only on the apartments found in one out of several staircases, the impact of the DCV-system on those apartments' energy use could not be discerned from the acquired energy data.

Since the IEQ can vary between rooms depending on the usage and occupancy of each room, a detailed approach would be to measure in at least one point of reference in every room. However, access to the apartments would be required in order to at least install measurement devices to log the indoor climate. Such access was not acquired, since the apartments were inhabited during the entire project. Before the installation of the renovation measure, measurements of temperature and RH were therefore only conducted in two apartments to which the researchers were granted access. Also, measurements were conducted in the attic, in the main supply air duct to the apartments that were affected, and in two separated exhaust air ducts that were extracting (collecting) air from the kitchens and the bathrooms respectively. These measurements on staircase level were also conducted in the neighboring apartments. After installation of the DCV-system, control boxes connected to the AHU, and connected to the main exhaust duct for each apartment, measured the temperature, RH, VOCs, and airflows. This data was deemed sufficient for assessing the indoor climate after the implementation of the measure.

In order to assess the impact that the DCV-system has on moisture safety in the apartments, a careful approach might be to conduct measurements that consider the highest risk of moisture damage to the building materials or building envelope. However, in order to determine such a placement, detailed status determinations assessing the moisture safety of the apartments is required, which would also require access to the apartments as well as detailed drawings of the construction design, which were not available. Such a status determination requires analyses of the building structure and materials and should consider the existing moisture loads. However, besides the limited access to the inhabited apartments, what also limited such possibilities was the project's resources and deadlines. Therefore, the assessment of the moisture loads was based on the acquired data from the control boxes placed outside each apartment, as well as the central AHU.

Precision.

The fluctuations in the airflow for the DCV-system should affect the energy use, and the system adjusts this airflow based on the VOC-sensor readings in the exhaust air, as well as measurements of the moisture supply, conducted with a 5-minute interval. These measurements were also logged and were sufficient for the calculations on the energy use and thereby the potential energy savings due to this control.

In order to assess the system functionality (controls), measurements on the IEQ as well as the moisture loads should consider the activities and events that affect the controls. Such activities can be common household activities, such as cleaning, cooking, exercising, window opening, appliance use, and the presence of the occupants. Such events can be changes in the outdoor temperature, RH, precipitation, solar radiation and wind. Since it might have been possible that such variations occur during short time intervals (minutes) the measurement interval of the system (5 minutes) was determined to be appropriate for the assessment.

Measurements conducted by the DCV-system on the indoor air parameters, with a time interval of 5 minutes, were also deemed appropriate for use in the assessment of the impact that the system had on the IAQ, or the resulting IAQ with the system. However, it is unclear to the author what a representative time interval is for assessing the quality of the indoor environment. What time interval is representative of the IAQ and determination of potential risks or discomforts that follow if the IAQ is inadequate? Are values of parameters measured in the indoor air with a 5-min time interval representative of the IAQ and such risks? Take for instance the Pettenkoefer limit for CO_2 of 1000 ppm, it is generally regarded as a limit that should not be exceeded in order to maintain a good IAQ [77], [78]. However, is it never to be exceeded, even momentarily? Not even for 5 minutes? Or is this a limit for an average value of CO_2 in the indoor air for a specific time period? Norbäck et al. [77] associated the average value of CO_2 measured between October 1991 and April 1992 with asthmatic symptoms that the population within the study had experienced. Also, some rules and guidelines suggest that a value of 1500 ppm should not be exceeded on an average for a certain time interval, e.g. daily [77]. A more recent study has however shown that an exposure to 1000 ppm 2.5h three times in one day significantly affected decision-making performance [79]. Nevertheless, it seems safe to say that measurements each 5 minutes should be more than adequate to assess the IAQ. An argument for this approach is the impact that the time interval has on the maximum value of measurements, and the amplitude of the fluctuations. The impact of choosing a too high time interval has been shown by Bagge and Johansson [38]. However, as for the assessment itself, it is not clear which timescale is representative of the IAQ. Therefore, in the analysis of the impact that the system had on the IAQ, 5-min measurements were used for the assessment of the system's response to pollutants, while 1h averages were used for the assessment of the IAQ. The latter simply assumed that the hourly average value is more representative of the IAQ than the 5-min values.

A number of models exist for the determination of mold growth risks [80]–[85]. None of these models require data on shorter time intervals than 1h. Therefore, in order to assess the resulting moisture-loads' impact on the mold growth risk it seems safe to say that the system's measurements of values in the indoor air each 5 minutes should be more than adequate.

Induced reaction.

An induced reaction in field probably would have provided knowledge on how the system reacted to changes to specific parameters. A part of the aim of the study was to determine how this system reacts to such changes and determine the risks with the control scheme that was set to reduce the ACR when a high ACR was not needed. However, access to the apartments was highly restricted, so it was not possible to conduct such tests in the apartments. Furthermore, it was unnecessary to expose the inhabitants to such tests since the system reactions were already tested in a laboratory study in order to determine the risks with the control scheme. For more on this, see *Paper 1*.

Control object.

No control objects (neighboring apartments without DCV) were accessible for the assessment, due to limited access to the apartments. Furthermore, other staircases still had the previous ventilation system which differed in design to the new system (separated exhaust air ducts), and therefore comparable values could not be acquired.

4.3.2.2 Supplementary analyses

Field measurements after installation of the DCV-system, gave information on the DCV-system functionality (response to loads) and produced data for comparison between MOS-sensor output and CO_2 concentrations for correlation assessment. These field measurements also provided enough data for the assessment of the resulting IAQ and moisture loads. They also provided data for the calculation of energy saved for heating of the supply-air. However, even though measurements both before and after installation of the system were conducted, data collection points did not correspond to each other. The reasons for this were:

- The restricted access to the apartments. Before installation of the DCV-system, access was granted by inhabitants in as few as two out of 24 apartments, while data was collected from all 24 apartments after the renovation measure. This difference in quantity makes a direct comparison less than accurate.
- The difference in ventilation design before in contrast to after installation of the DCV-system. Before the installation of the DCV-system, measurements were conducted in the main supply and exhaust air ducts for the 24 apartments connected through one staircase, as well as a control staircase (object). However, the main exhaust ducts were separated into two ducts – one from the bathrooms and one from the kitchens. In contrast to this, the DCV-system did not separate the exhaust air in this manner. It was therefore deemed to be inaccurate to compare this separation of the airflows with the union of all exhaust airflows after installation of the DCV-system.
- The difference in measurement setup before and after installation of the DCV-system. Before installation of the DCV-system, temperature and RH sensors were placed in the living rooms and in the hallways in two apartments, which does not represent the overall IAQ in the apartments. In contrast, after the installation of the DCV-system the ventilation system measured the temperature, RH, VOC and airflows of the exhaust air from the entire apartments which should be a more accurate representation of the overall IAQ in the apartments.

To remedy the consequences of these limitations and deviations, the impact on the IEQ was to be assessed through the IEQ-survey handed out before and after the implementation of the measure. To remedy the consequences of other abovementioned limitations and deviations: 1) no possibility to assess the impact of the inhabitants activities on the ventilation rates, in field, and 2) low spatial resolution of energy measurements, a 1) laboratory study was conducted as well as 2) building performance simulations.

Assessment of perceived IEQ.

In order to evaluate the impact that the DCV-system had on the inhabitants' perception of the indoor climate, a survey was conducted with the inhabitants before and after the installation of the DCV-system. The survey is known as the BETSI survey [86], developed by the *Swedish National Board of Housing, Building and Planning (Boverket)*, 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. The same surveys were handed out both before and after the installation of the DCV-system, and incentives were 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, to no avail. However, the survey response was too low after the implementation of the renovation measure, and a direct comparison was therefore not relevant to make. Apartment-wise, the response rate before the renovation was 11/24 (46%), and after the renovation 6/24 (25%). This was also the number of inhabitants who answered the survey, and the true number of inhabitants in these apartments was unknown but is assumed to be higher than the number of apartments.

Laboratory study and literature review.

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 such as VOCs and moisture supply in multifamily houses.

No previous evaluations of the system that were related to apartments were found, and neither could sensor readings be related to occupants' well-being or ventilation ACRs. The only references that were found, were on the sensor used for DCV-control based on VOCs [87]. This reference shows correlations between VOCs and CO_2 (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 buildings. However, other references [88] have found that the output from the mixed-gas sensor used in the DCV-controls [89] partly correlates with CO_2 –levels in Swedish multifamily buildings, but on building level.

In order to determine the system's functionality in a mock-up apartment (a typical two-bedroom apartment) a test of the systems' response to VOC- and moisture loads was conducted in *Paper 1*. The tests were conducted in in a laboratory and included common household-activities that produce emissions that we do not desire in the indoor environment, e.g. tobacco smoke, deodorant spray, paint fumes, and emissions produced when cooking or when cleaning with chemicals. During testing, the minimum VOC set point was at 800 ppm CO_2-eq. and the maximum at 1000 ppm CO_2-eq., with a minimum ACR of 0.1 vs 0.5 ac/h to a maximum ACR of 0.8 ac/h. The system response to the pollutants and response time were evaluated.

Building Performance Simulations.

Since the impact on the energy used for space heating could not be determined directly through field measurements, the DCV-system was simulated in IDA ICE [90], [91], a building performance simulation software, in order to assess these potential energy savings. The simulations were based on retracing calculations for determination of moisture and emission-loads and included parametric tweaking of the VOC set-points and ACRs. However, the model's validity was assessed and was deemed inappropriate for the assessment of the DCV-system.

Simulations for determination of moisture supply set point.

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. To evaluate this functionality of the system with regard to risks on the building envelope, a load determination was conducted (*Paper 2*). Through hygrothermal simulations, a design load was determined using an existing mathematical model for mold-growth on biological building materials. This resulted in a moisture supply set point for the DCV-system. Read more about this in *Paper 2*.

4.3.3 Conclusions from field measurements

Analysis of the field measurements show that there is a need for apartment-specific ACR due to differences in VOC and moisture loads between the apartments, and that the system responds to the loads as intended. Furthermore, field measurements show that the VOC-sensors are more sensitive to changes in the indoor climate than conventional CO_2-sensors and that the readings are "on the safe side" when related to conventional CO_2 indicators or guidelines. This even though correlation between the two sensors could not be determined due to too many "outliers". The VOC-sensor used in this system is therefore an appropriate alternative to conventional CO_2-sensors, as an IAQ-indicator. Due to using both VOC and moisture sensors, the system is deemed to be able to achieve acceptable IAQ and moisture loads in most apartments within the case study. However, some apartments have been identified to have a higher need than the system is set to fulfill, and their ventilation settings might need an adjustment. See *Paper 4* for further details on these assessments.

Calculations on energy saved for heating the supply air, based on the measured airflows and temperatures in the AHU show that considerable energy savings can be achieved with MVHR with a continuous air volume (CAV), and that even higher savings can be achieved with DCV. See *Paper 4* for further details on these calculations.

4.3.4 Conclusions from supplementary analyses

The precision of the IEQ-survey and the accuracy of the building performance simulations were deemed too low for appropriate assessments. The following summarizes

Set point for moisture supply

A set point for the moisture supply at 3 g/m^3 was determined for the system considering risks for mold growth in the building envelope. This set point was further used as a reference in the determination of the system's performance through field measurements (*Paper 4*), showing that the risk was low for most apartments affected by the measure in the case study.

Laboratory tests – assessment of control scheme

Results reaffirmed producers' intentions with the sensors and ventilation system design, and even though the system could not be fully evaluated with regard to effect on the IAQ 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 produce 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 an undetected pollutant (specifically CO_2) 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 field (pilot test). See *Paper 1* for further details on these tests.

4.3.5 Discussion

4.3.5.1 Causation

In the field measurements, causation could not be determined due to the differences in the field measurement setup before and after installation of the system, and differences between the studied object and the control object. Discrepancy in sensor placement, due to the apartments' inaccessibility before renovation, made a direct comparison between the units (before vs after) imprecise.

The system's reaction to the undesired pollutants (causation) was however tested in a laboratory study, and the impact on the energy efficiency (causation) was shown through calculations based on the field measurements. Within these analyses the implementation of the measure itself was the only parameter that caused a change to the indoor environment or the energy efficiency. With regard to the pollutants (*Paper 1*) and the moisture load (*Paper 2*), the measure is deemed to be a necessary cause for the change in the indoor environment, since these are what trigger the system's increase in airflow. However, in field, the measure would be a sufficient but not a necessary cause with regard to the indoor environment, since a similar impact (increase of airflow) can be caused by the users through e.g. window opening or sealing of supply-air devices. With regard to the improvement in energy efficiency in comparison to the previous system (MBV), the measure (DCV) can be seen as a sufficient cause, but not necessary, in order to achieve a reduction of energy use, since the conventional option (CAV) can achieve the same effect. However, with regard to the improvement in energy efficiency in comparison to a CAV, the DCV is a necessary cause in order to improve the energy efficiency further while maintaining a good indoor environment, due to controls decreasing the airflow when the demand is low.

4.3.5.2 Necessary measurements

In the table below, parameters that might impact on the results are presented together with (from left to right) 1) their time intervals, 2) a qualitatively assessed degree of relevance within the study, 3) each parameter's dependency on other parameters, 4) the dependee parameters' time intervals, as well as 5) the limitation in the measurements of the dependent or the dependee parameters.

Table 4.5: Time intervals and limitations for parameters measured in field in the units that were included in the case study.

Parameter	**Energy supply**	**$T_{outdoors}$**	**$T_{indoors}$**	**$RH_{outdoors}$**	**$RH_{indoors}$**
Time interval	1h	5 min	5 min	5 min	5 min
Relevance (1-5)	5	4	4	4	3
Dependency (see section 4.3.1)	F	C	A, C	A, B	A, B, E.
Time interval - dependee	1h	1 h	5 min, 1 h	1 h	5 min, 1 h, 1 day
Limitation	Only measured on building level, not specified to the part of the building that was affected by the measure.		**Before:** Only in two apartments and on building level, in bathroom and kitchen exhaust ducts. **After:** 24 apartments. **Control:** Different exhaust design.		**Before:** Only in two apartments and on building level, in bathroom and kitchen exhaust ducts. **After:** 24 apartments. **Control:** Different exhaust design.

Parameter	**Wind speed**	**Global radiation**	**Mix-gas (VOC)**	**CO_2**
Time interval	1h, 1 day	1 h, -	5 min	7-15 min
Relevance (1-5)	4	4	5	4
Dependency (see section 4.3.1)			J.1-3	J.1-3
Time interval - dependee			-	-
Limitation	Regional, not local.	Regional, not local. Horizontal, not vertical.	**Before:** Only on building level, in bathroom and kitchen exhaust ducts. **After:** All apartments. **Control:** Different exhaust design.	**Before:** Only on building level, in bathroom and kitchen exhaust ducts. **After:** For 8 out of 24 apartments. **Control:** Different exhaust design.

As shown, there are several limitations to the measurements. As stated previously, these limitations did not allow for comparisons before vs. after installation of the IAQ, energy use and inhabitant perception. Nevertheless, system functionality and controls, resulting energy savings, resulting IAQ and resulting moisture loads were possible to assess (see *Paper 1*, *Paper 2* and *Paper 4*). In order to be able to make the conclusions in these assessments, the following field measurements were needed:

1. Emissions
    a. VOC-sensor readings
    b. CO_2 concentrations
2. Relative humidity & Temperatures indoors and outdoors/ Moisture supply
3. Airflows

4. Temperatures within the unit (& Rotational frequency)

With the first three parameters (1-a & 2-3), the impact of the measure on the IAQ and the moisture safety was possible through benchmarking against references. With data on 1-b the impact on the IAQ could be determined since the values of 1-a and 1-b could be compared and the values of 1-a then related to guidelines for 1-b. With data on 4, the thermal efficiency of the DCV-system could be determined and contrasted to the conventional option, MVHR, as well as the previous option, MBV.

As for the time intervals, 5-minute and simultaneous values on parameters 1-3 were necessary for the determination of the system's response to existing loads, since it was with this time interval that the system responded to the loads. However, for assessment of the IAQ, hourly average values were used, and for the assessment of the risks related to the resulting moisture loads 12-hour average values were used, see *Paper 4*. The time intervals are further discussed in section 4.7.3.2.

4.3.5.3 Necessary arrangements and prerequisites

In order to conduct the field measurements, the involvement a property owner or a representative of a property owner (e.g. property manager), that was willing to install the system in a pilot project, was required. However, the field measurements would probably not have been possible if a need for applying the measure on the included apartments didn't exist and the plan to implement it as well. According to the project manager, there were complaints about the IAQ in the apartments before installation of the DCV, which was the main reason for testing the DCV-system on the apartments that were included in the study. For the measurements to take place before installation of the system, access was required to the previous system's (MBV) main supply and exhaust air ducts, which was granted by the property owner. However, since the inhabitants have the right to choose to grant access to their apartments or not, the property owner could not grant access to their apartments without their consent. Nevertheless, after installation of the DCV-system, this was not required since measurements took place in the control boxes placed outside the apartments. However, in order to assess the impact on the energy use, as well as in order to compare the VOC-sensor readings with conventional CO_2-sensor readings, access was required to control boxes with an electrical socket nearby. This was granted, by the property owner, to the equipment that was available in the attic, and thereby a total of eight apartments besides the AHU.

Besides the above, in order to acquire data, access was needed to the DCV-system's computer, which was granted at several occasions. Furthermore, in order to ensure that data was correctly logged, an analysis shortly after data logging was started in the DCV-system, an analysis was made on the acquired data. This enabled detection of a faulty sensor in the AHU that resulted in an erroneous calculation of the moisture supply, and thereby extremely high values for it, and thereby in higher than representative airflows in the apartments, i.e. overventilation. Data collected during this time period was not included in the analysis, and only data collected after the sensor was repaired was.

4.4 Case study 3 – MVHR for multifamily buildings

Conventional balanced mechanical ventilation with heat recovery (MVHR) can improve a building's energy performance and be a solution for issues with the indoor air quality (IAQ) or the indoor environmental quality (IEQ). The aim of *Paper 6* is to isolate the impact of a MVHR-system, as a renovation measure, through detailed field measurements that enable the exclusion of the impact of other factors that can affect the studied parameters.

This case study used an approach that was between the hypothetico-deductive and the inductive. What had been shown previously was that implementation of MVHR improves the IEQ and energy efficiency in comparison to MEV, MBV and NV. The hypotheses were therefore that:

- This system will improve the IEQ through the introduction of heated supply air in the buildings with MBV, as well as through the introduction of filtered supply air in the buildings with MEV.
- This system will improve the energy performance of the building through the introduction of heat recovery, in all buildings.

At the same time, some questions were to be answered through an inductive approach, since previous studies has not isolated the impact of the MVHR through a study in which only MVHR was applied to a building or a set of buildings. The main question was – how large is the impact of heat recovery on the energy use? Another question was – how large is the impact of control parameters on the end results?

4.4.1 Derivation of parameters

There are several main parameters that this measure can directly affect in the building as a system:

A. Energy use of a building, since:
    1) The energy use for heating the supply air is reduced through recovery of heat from the exhaust air.
    2) The pressure profile over the building envelope might be changed, thereby reducing the air leakage through the building envelope.
    3) Usually, simultaneous airtightness measures are usually performed (or at least they should be) which reduces the air leakage through the building envelope.

B. Indoor temperature, since:

    - The supply air is heated, which might increase the indoor air temperature if all other things remain unchanged.
    - The air flow is controlled, which should dampen variations in the indoor temperature, as well as issues with draft.
- C. Indoor relative humidity, since the supply-air is heated and controlled this should improve the system's response to moisture production (loads) and thereby also dry-out rates.
- D. Indoor emission concentrations, since the air change rate (ACR) is controlled, in contrast to a natural ventilation (NV) system.
- E. The electrical use of the building, since fans require electricity to run.

Field measurements were primarily focused on the impact that the measure had on the energy use, but also on the IEQ. Control parameters, that can directly or indirectly affect the energy use of the building, are surrounding environmental parameters as well as parameters depending on user behavior:

- F. Temperatures outdoors.
- G. Wind speed and Wind direction, which can impact on the air leakage through the building envelope.
- H. Electromagnetic radiation outdoors, which can be expressed in:
    1. Global Radiation, which can be divided into:
        - i. Direct Solar Radiation.
        - ii. Diffuse Radiation.
- I. Temperatures, indoors. Which are affected by:
    1. Temperatures outdoors.
    2. Electromagnetic radiation.
    3. Air leakage.
    4. Internal heat production (gains), from:
        - i. Appliances.
        - ii. Inhabitants.
        - iii. Activities.
    5. Window opening.

Changes in the following parameters can impact changes in the IAQ:

- J. Emissions, indoors. Which are affected by:
    1. Air change rates
    2. Internal emission production (loads), from:
        - i. Inhabitants
        - ii. Activities
        - iii. Building material
        - iv. Furniture

            v. Equipment
    3. Window opening

Changes in the following parameters can impact changes in the moisture loads:

K. Relative humidity outdoors, which can impact on internal moisture loads.
L. Precipitation.
M. Internal moisture loads expressed in either of the following:
    1. *Moisture supply* (difference between vapor content indoors and outdoors).
    2. Relative humidity indoors.

…and are affected by:

- Air change rate indoors.
- Moisture production indoors.
- Temperatures indoors.
- Vapor content outdoors.

4.4.2 Materials and field measurements

Field measurements were conducted in four buildings in Linköping, that were built in 1965. These were all in the same neighborhood, see Figure 4.10. See details on the buildings in *Paper 6*. Before the installation of the MVHR-system, one of the buildings had a Mechanical Exhaust Ventilation System (*MEV-system*) while the other building had a Mechanical Balanced Ventilation System without heat recovery (*MBV-system*), see Table 4.6. The new MVHR-systems were designed to achieve the same air-change rates (ACR) in the apartments as the previously installed ventilation systems (MEV/MBV).

Measurements of global horizontal radiation were conducted on the roof of one of the buildings. Other data for the outdoor climate was acquired through SMHI [72]. Measurements of the district heating were conducted on each building. Data on domestic electricity use was acquired on building level. Measurements on temperature and relative humidity (RH) were conducted on apartment level, in the hallways. For further details on how the measurements were conducted, the reader is referred to *Paper 6*.

No airtightness improvements were made to any building before or after the installation of the MVHR. Building 3 already had a mechanical ventilation system with supply and exhaust channels, changes made to this building were therefore not significant in terms of penetration through the building envelope. The airtightness of the building is therefore assumed to be similar before and after installations of the MVHR. With regard to the degree of leakiness it does not seem to be a leaky building according to the analysis conducted in the paper.

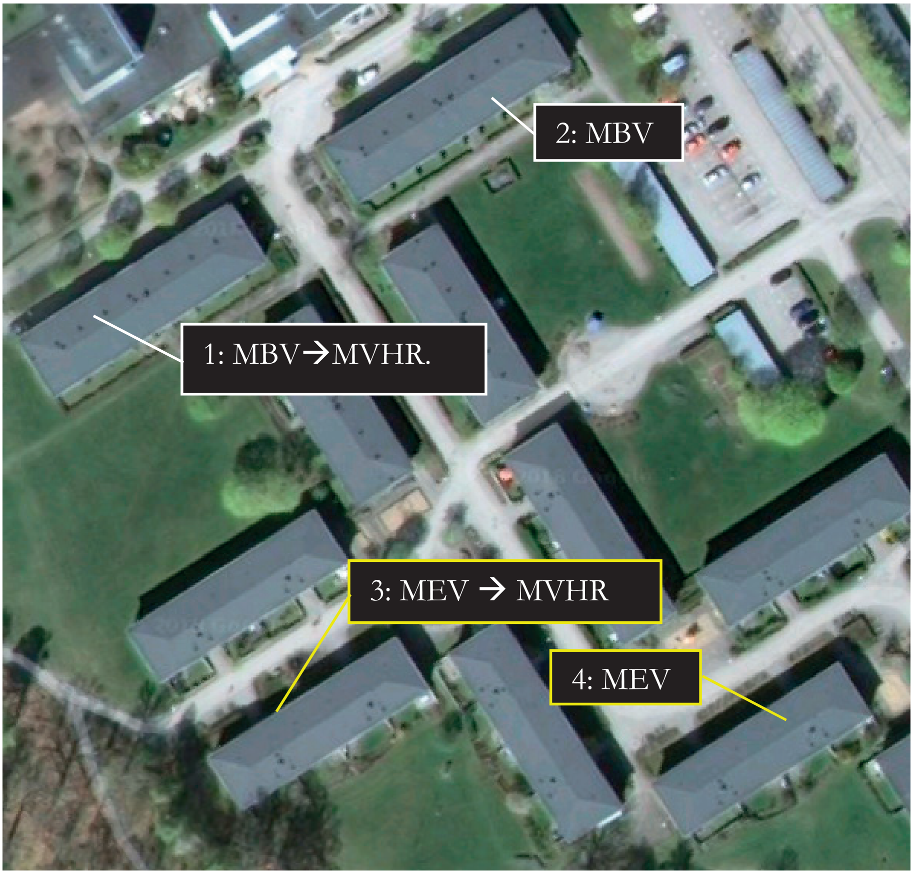


Figure 4.10: Satellite-view of the buildings included in the case study, screen dump from Google Maps (2018-07-31). From Paper 6.

Table 4.6: Summary of transition and type of building in this study. From Paper 6.

Building Number, type	System, 'Before'	System, 'After'
1, modified	MBV	MVHR
2, control for 1	MBV	MBV
3, modified	MEV	MVHR
4, control for 3	MEV	MEV

*Table 4.7: Summary of transition and type of building in this study. From Paper 6. *Error in paper 6, which says '1,2' in this cell.*

Measurement	Building number	Measurement period	Temporal resolution
District Heat	1, 2	2015-10-20 - 2017-05-01	1h, building level
District Heat	3, 4*	2015-12-21 - 2017-05-01	1h, building level
Temperature and RH	All	2015-07-20 - 2017-05-01	5 min, apartment level
Global Horizontal Radiation	All	2015-11-23 - 2017-05-01	5 min, on site
Outdoor Climate (Temperature)		2015-07-01 - 2017-05-01	1h, regional level

4.4.2.1 Measurement details

Timespan.

In order to minimize the impact of seasonal variations, measurements were conducted during the same seasons before and after the implementation of the renovation measure, according to the same reasoning as in section 4.2.2.3. Furthermore, since one of the aims was to assess the impact on the energy use, and it was assumed that a thermal wheel primarily recovers heat from the exhaust air in Swedish dwellings, the plan was to measure during the time of the year in which space heating was relevant. Measurements were therefore conducted for at least three cold months before and after the implementation of the measure.

Accuracy.

The expected impact that this type of measure has on the energy use is on the energy used for space heating. Measurements on this parameter were therefore conducted on the supplied heat to the building, i.e. on the heat carriers. Furthermore, these measurements were conducted on the heat carriers to the parts of the building that were affected by the renovation measure.

Since the IEQ can vary between rooms depending on the usage and occupancy of each room, a detailed approach would be to measure in at least one point of reference in every room. Since the main purpose of the measurements in the indoor climate were to function as control parameters, measurements on temperature and RH were conducted in a reference point that was assumed to be the least impacted by changes in outdoor environmental parameters (such as solar radiation), and mainly impacted by the installation of the MVHR. Besides, project financial resources and time limit, as well as the extent of the project (number of apartments included) limited the extent of indoor climate measurements to one reference point per apartment. The hallways in the apartments were protected from external factors such as direct sunlight and window opening, since they had no windows, and therefore this was position was chosen. What further increased the validity of the placement of the sensor is that most of the mechanically driven exhaust air is assumed to have passed through the hallway. This, since supply devices were placed in the living room and bedrooms while exhaust devices were placed in the bathroom and in the kitchen. All the rooms were connected through the hallway as can be seen in the following figures. This is the case both before and after renovation, however, in the buildings with MEV the supply devices consisted of fresh-air vents, instead of supply devices, in the living room and bedrooms.

In order to assess the impact that the MVHR-system has on moisture safety in the apartments, a careful approach might be to conduct measurements that consider the highest risk of moisture damage to the building materials or building envelope. However, in order to determine such a placement, a detailed status determination regarding the moisture safety of the apartment is required. Such a status determination might require analyses of the building structure and materials with regard to the existing loads. However, besides the limited access to the inhabited apartments, what also limited such possibilities was the project's resources and deadlines. Besides this, another aim of the project, was to determine the impact of the MVHR-system on the IEQ through comparisons of field measurement results before and after the installation of the system. Therefore, it was more important to measure in a reference point within the apartments that was deemed to represent the average indoor air in the apartments before and after the renovation measure.

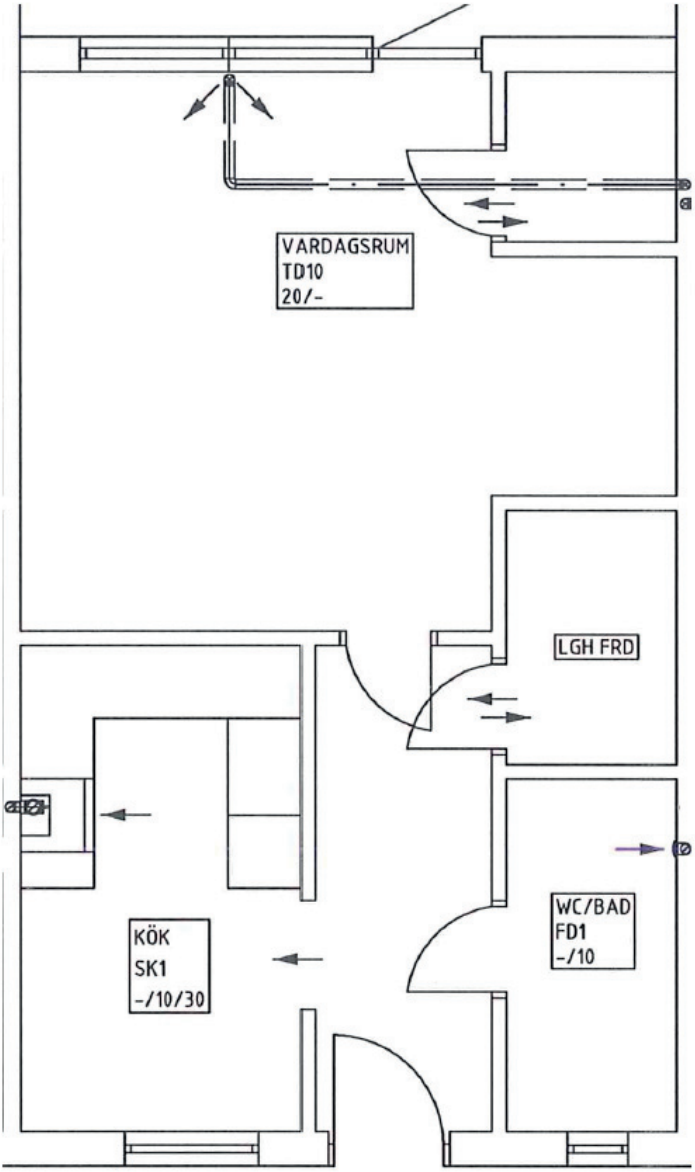


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Figure 4.11: Airflow in a 1-bedroom apartment with MEV. Provided by Riksbyggen AB.

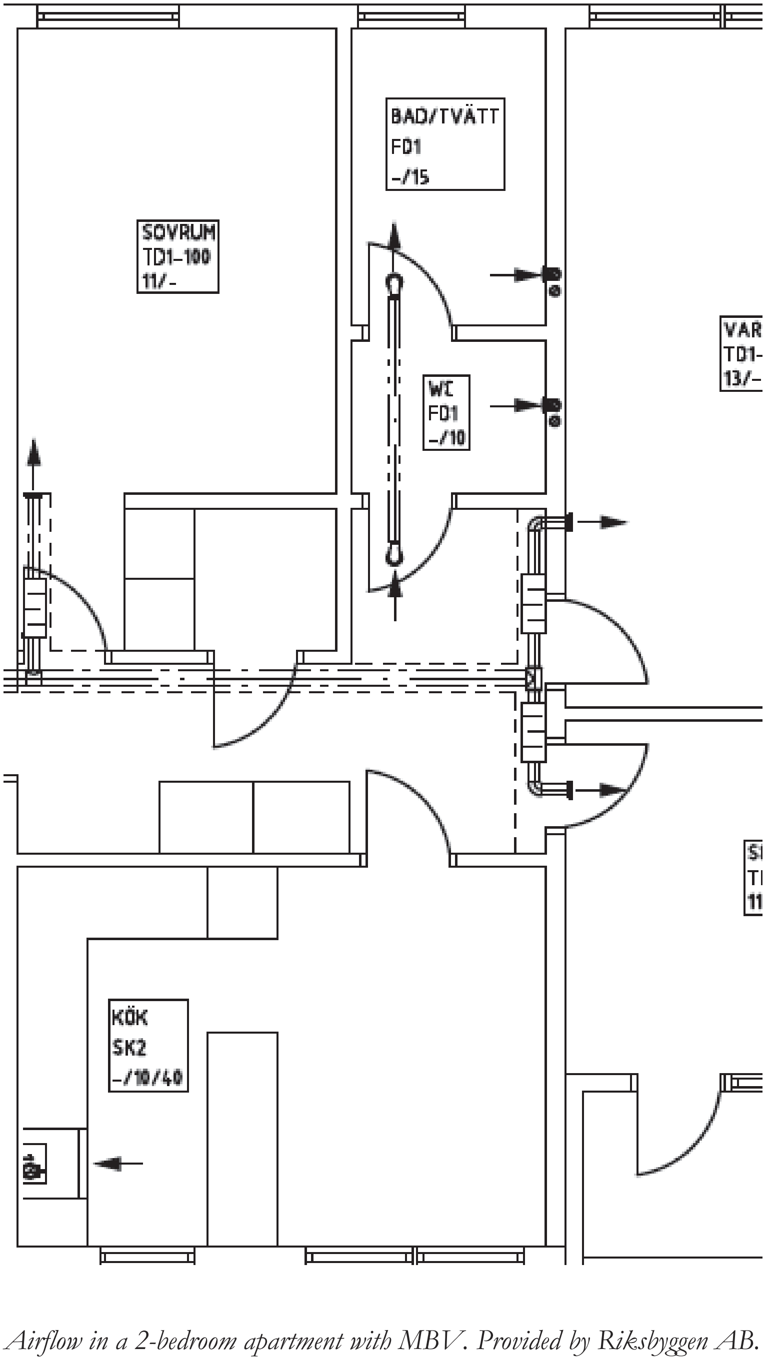

Figure 4.12: Airflow in a 2-bedroom apartment with MBV. Provided by Riksbyggen AB.

Precision.

Due to the thermal capacity of the building, the building has a response time to changes in the outdoor temperature. Therefore, measurements on the energy supplied to the building considered this with regard to the time interval chosen. Measurements of energy supplied to the building as well as indoor air temperature and outdoor air temperature were made hourly. Measurements on other parameters that were considered were also made or acquired with at least the same or a higher temporal resolution (shorter time intervals).

The time interval for the measurements of indoor air parameters (temperature and RH) were conducted each 5 minutes. Following the reasoning in section 4.3.2.1, this time interval should be more than sufficient. However, in order to compare values of indoor air parameters with changes in the outdoor climate (mainly outdoor temperatures), average hourly values were used, since hourly values is what SMHI [72] provides for the climate station in this location.

Induced reaction.

Since the aim of the study was to isolate the impact of the ventilation measure on the energy use for space heating, an induced reaction was not necessary. What was prioritized was to measure the energy use during a timespan in which space heating was necessary.

Control object.

In order to assess how changes in other parameters impacted on the energy use for space heating, measurements were conducted on control objects. The control objects were buildings that were identical in composition to the buildings that got an MVHR installed and were assumed to produce homogenous responses to a treatment.

4.4.2.2 Supplementary analyses

Field measurements could not determine the impact on the IAQ since measurements of emissions were not conducted in the apartments. However, the measure should not have impacted on the IAQ since the same ACR was achieved with all ventilation solutions. Nevertheless, surveys were simultaneously handed out as measurements were conducted in order to determine the impact on the IEQ.

4.4.3 Conclusions from field measurements

The measurements show that the installation of a conventional MVHR system can result in significant energy savings. However, the measurements also show that the impact in changes of other parameters that might affect the results should be considered in such an evaluation, e.g. global radiation, indoor temperature, and outdoor temperature. In *Paper 6*, the results of these measurements are described in greater detail. Through analysis of the measurement results and in consideration of the climate in Norrköping, the following knowledge is gained.

Main parameters:

- Building 1 has a higher energy signature than building 2 before the installation of the MVHR but building 1 has a lower energy signature than building 2 after installation of MVHR. This shows that the MVHR had a significant impact on the energy use of the building.
- Building 3 and 4 had identical energy signatures before the installation of the MVHR but building 1 had a lower energy signature than building 2 after installation of MVHR. This shows that the MVHR had a significant impact on the energy use of the building.
- Building 2 had a slightly higher energy signature during the second measurement period. Which might be due to an adjustment of the heat supplied to the building, or due to a change in weather.
- Building 4 had a slightly lower energy signature during the second measurement period. Which might be due to an adjustment of the heat supplied to the building, or due to a change in weather.
- There is almost no difference in the temperature indoors before and after MVHR, which suggests that there was no impact of the MVHR on the thermal conditions indoors. However, temperatures increased (slightly) in building 4 that did not undergo any changes, which indicates that something that affects these indoor temperatures have changed. This is most likely the Global Radiation.

Control parameters:

- Temperatures outdoors were slightly higher after installation of MVHR, which should have impacted on the energy use of the building after MVHR.
- RH outdoors were not much different after installation of the MVHR, which means that vapor content was slightly higher outdoors after MVHR.
- Global horizontal radiation was higher with MVHR.

- Airtightness testing as well as an analysis of wind speed connected to outdoor temperature, shows that the buildings were insensitive to wind both before and after MVHR.
- Buildings that received MVHR have approximately the same household electricity use before and after.
- There is a slight lower RH in all buildings after MVHR.

4.4.4 Conclusions from supplementary analyses

Survey

A survey with the inhabitants before and after the implementation of the renovation measure shows that the renovation measure has no negative impact on the IEQ, which seems to improve it with regard to the thermal comfort. The survey also shows that the MVHR-system seems to improve some matters concerning the IAQ. See *Paper 6* for more details on the results of the survey.

4.4.5 Discussion

4.4.5.1 Causation

The impact of MVHR on the parameters that were affected was assessed through field measurements, and a significant impact was determined on the energy use. However, a difference in presence of inhabitants or their habits might have impacted on the results, therefore it was important to assess if such changes had occurred. One way to do this is to measure CO_2 concentrations, which are affected both by presence and different household activities. However, CO_2 measurements were only conducted on building-level and were not conducted before renovation or insufficiently so (too short time span, and one building only). Therefore, the possibility of changes in the population were assessed through the analysis of RH-levels before and after renovation, which showed no meaningful differences that could be suspected to have occurred due to changes in inhabitants. In addition to this, information was received from the property manager, who confirmed that the same people inhabited the apartments both before and after the installation of the MVHR. Furthermore, electricity use on building level was also used in order to determine if the inhabitants had changed their habits and if the internal heat production had changed, and it seemed to not have done so. Finally, analyses of temperatures outdoors, temperatures indoors, global radiation, wind, and air leakage for the affected buildings as well the reference buildings (control objects) determined the changes in these parameters and how the energy use or the indoor temperature changed with them. This allowed showing how much of the change in energy use was caused by the implementation of the renovation measure, thereby showing causation, and improving the internal validity of the assessment.

It is possible that the shade configuration might differ during winter when the sun is very low, which may have affected the energy use in the buildings. However, with the conducted measurements it is not possible to determine to what extent this is, and to what extent this possible difference impacts on the end results. Also, since this should mostly be relevant during winter and when the sun is quite low, it is difficult to say if there is a noticeable difference in impact on the energy use due to this possible difference in shading configurations. Especially since the number of sunshine hours during the winter in Sweden are quite low. However, even if measurements that are needed in order to accurately determine this were not conducted, simulations can be conducted of the buildings with the surrounding objects that shade the buildings in order to determine the impact of this parameter. However, as in all research projects, resources and deadlines limited the extent of the analyses, and this had to be considered out of scope for this case study.

The impact on the IEQ (causation) could not be shown through measurements, since detailed measurements (of e.g. CO_2 levels and radiant temperatures) regarding this were not conducted. However, temperature and RH did not change significantly in order to imply that there has been a significant change in the IEQ. Furthermore, since ACR was measured to be the same before and after the implementation of the measure, the measure's impact on the IAQ was assumed to be minimal. Nevertheless, a survey was conducted in order to determine the impact of the measure on the perceived IEQ, which showed no negative impact but only positive.

Finally, like in case study 2 and 5, window opening in this case study could not be recorded in order to assess its impact on the results. Proper and efficient methods for this should be investigated.

4.4.5.2 Necessary measurements

In the table below, parameters that might impact on the results have been presented together with (from left to right) 1) their time intervals, 2) a qualitatively assessed degree of relevance within the study, 3) each parameter's dependency on other parameters, 4) those (the dependee) parameters' time intervals, as well as 5) the limitation in the measurements of the dependent or the dependee parameters.

Table 4.8: Time intervals and limitations for parameters measured in field in the units that were included in the case study. Regional = from a station within the same city. Local = from the neighborhood.

Parameter	Energy supply	$T_{outdoors}$	$T_{indoors}$	Wind speed	Wind direction	Global radiation	Electricity use
Time interval	1h	1h	1h	1h	1h	1 min	1 month
Relevance (1-5)	5	4	4	3	1	4	4
Dependency (see section 4.4.1)	F, G, H, I	E	See I	-	-	-	-
Time interval dependee	1 min, 5 min, 1h	1 min	1 min, 5 min, 1h	-	-	-	-
Limitation			Not all affected apartments, but enough.			Not vertical, but horizontal.	Building level, including facility energy use (building services equipment). Errors in daily apartment level.

Parameter	Time interval	Relevance (1-5)	Dependency (see section 4.4.1)	Time interval dependee	Limitation
$RH_{outdoors}$	1h	3	(L) F	1h	
$RH_{indoors}$	1h	3	K-M	5 min, 1h	Not all affected apartments, but enough.
Precipitation	1h	3	-	-	Not local, but regional.

There were very few limitations in this study, and they were not critical for the outcome. The conducted measurements were enough to determine the impact of the MVHR on the building's energy use, partially the IEQ (indoor air temperature), as well as the moisture loads on the building materials. The most important measurements in this case were (in order of degree of importance):

1. Energy supply
2. Temperature outdoors
3. Temperatures indoors
4. Global radiation
5. Airtightness testing
6. Wind speed
7. Electrical use (household)
8. Relative humidity indoors
9. Relative humidity outdoors
10. Precipitation

With the first two parameters, the impact of the measure was determined on the energy use. The energy use is dependent on the difference in temperatures, therefore if changes in (average) temperatures outdoors and indoors occur, the impact of such changes on the results would be significant. Since changes in other factors (3-8) might have impacted on the energy use as well, determination of potential changes in 3-8 increased the precision of the assessment and allowed for corrections (see *Paper 6*).

With parameter 3 (indoor air) the impact on the IEQ was possible to assess, while with parameters 2 and 4, the impact of changes in the outdoor climate in the IEQ was possible to assess.

With parameter 8 (RH indoors), the impact on the moisture loads was possible to assess, while with parameter 2 this assessment was possible to be narrowed down to the same outdoor climate (cold period). An analysis of 9 before and after the implementation of the renovation measure contributed to the accuracy of the assessment.

As for the time intervals, then daily values on energy use, and outdoor temperature, were used for the determination of the building energy signatures. Hourly average values were used for the assessment related to indoor temperature, since the temporal resolution for the outdoor climate data was 1h. The time intervals are further discussed in section 4.7.3.2.

4.4.5.3 Necessary arrangements and prerequisites

In this study, the field measurements were primarily conducted by professionals in the building industry, working for the property manager or hired by the property manager. However, the field measurements would probably not have been possible if a need for applying the measure on at least one of the included buildings didn't exist and the plan to implement it as well. Furthermore, the property owner wanted to verify the impact of the measure on the buildings, in order to have data for future decision-making in similar cases and was therefore quite invested in carrying out the measurements as per instruction. Therefore, the property owner also involved the building entrepreneur in the project meetings, and they were quite supportive of the research project.

Besides the above, the research team was active in the design phase of the renovation project in order to inform those involved of their participation as well as receive information on the timeline of the renovation project and help plan the installation of the measurement equipment. During and after installation, the research team controlled the received data from the equipment in order to detect faulty sensors or lacking data. Finally, data that could not be acquired through measurements was acquired from SMHI [72].

4.5 Case study 4 – Air-side cleaning of heat exchangers in ventilation systems

The energy efficiency of heat exchangers in ventilation systems can reduce with the accumulation of contaminants. Air-side cleaning of such exchangers can therefore be a means to improving (or restoring) a building's energy performance. The aim of *Paper 7* is to build upon existing knowledge concerning the contamination of coils and heat-recovery units with field measurements, and to determine the impact of contamination on their energy use.

This case study used an approach that was between the hypothetico-deductive and the inductive. What had previously been shown was that implementation of contamination on heat exchangers impacted on the: heat efficiency, pressure drop, as well as emissions, see *Paper 7*. The hypotheses were therefore that:

- Air-side cleaning of heat exchangers would improve (i.e. restore) their energy performance through restoration of the pressure drop over the component (to installation) and the heat conductivity between the exchanger and the air that runs through it.
- It is the accumulation of contaminant that affects the heat exchangers energy efficiency.
- The accumulation of contaminant correlates with the runtime of the AHU.

However, even if answering the hypotheses gave explanatory knowledge on how the accumulation of contaminant affected the energy efficiency, it did not describe how other factors impacted on the result. In order to acquire such descriptive knowledge, a laboratory study and a literature review were conducted which were to answer the following questions:

- Do different types of contaminants affect the heat exchange?
- How much contaminant must accumulate on a heat exchanger before it is profitable to clean it?

4.5.1 Derivation of parameters

There are several main parameters that might be affected by the accumulation of contaminant on a heat exchanger in a ventilation unit:

A. Energy use of a building, since:
    1) The energy use for heating the supply air is increased through the diminished heat recovery of heat from the exhaust air.

    2) The pressure drop over the ventilation unit might be increased, thereby demanding the fan to increase the power output.

B. Indoor emission concentrations, since the contaminants might emit pollutants to the indoor air.
C. For units that are controlled by fan-rpm (rare), the indoor air quality (IAQ) might be affected by the accumulation. This, since the contaminant will increase the pressure drop over the ventilation unit, which will reduce the supply airflow to the building.

Field measurements were therefore primarily focused on the impact that cleaning had on the energy use of the air handling units (AHU). Other changes to control parameters can directly or indirectly affect the energy use. These control parameters are:

D. Air flows
    1) Indoor air
    2) Exhaust air
    3) Outdoor air
    4) Supply air
E. Air temperatures
    1) Indoor air
    2) Exhaust air
    3) Outdoor air
    4) Supply air
F. Moisture recovery in thermal wheels (relative humidity)
    1) Indoor air
    2) Exhaust air
    3) Outdoor air
    4) Supply air
G. Heating/ Cooling fluid temperatures & flows in coils
    1) Supply
    2) Return
H. Rotational frequency in thermal wheels
I. Time since cleaning/ installation of the unit
J. Accumulation of contaminant and the type of contaminant
K. Information about the premises, i.e. the location of the facility, the type of unit that was cleaned, etc.

4.5.2 Materials and field measurement

Measurements in field were conducted, as far as reasonable with regard to time and resources, according to *Appendix A3*. Measurements were conducted before and after abrasive blasting of coils and heat-recovery units with dry ice (frozen carbon dioxide). Details on how the measurements were performed, and the analyses on them as well as results from them, are presented in *Paper 7*.

4.5.2.1 Measurement details

Timespan.

Changes can occur quite quickly in ventilation units, much quicker than in the entire building as a system. Since this measure (cleaning) impacts directly on the ventilation unit and indirectly on the building, the quickest way to measure the impact of the measure should be on the ventilation unit itself. Temporal variations in the unit(s) were considered, and therefore a considerable time was taken before the measured value was recorded. E.g. measurements before and after the measure in thermal wheels should keep the same rotational frequency and reach an equilibrium based on the circumstances at a given moment. Measurements were conducted for a minimum of 10 minutes before and after the cleaning of the heat exchangers, before instantaneous values were recorded. Furthermore, the study was limited to short-term measurements since the main purpose was to acquire statistical data for the impact of cleaning on heat exchangers, from as many heat exchangers as possible. Besides, contaminant deposition rates on heat exchangers, protected by a filter, are very low, and long-term measurements were not within the time span of the research project. Furthermore, measurements were conducted in connection with the cleaning procedure, which would not take more than an hour or two for each heat exchanger. It was only during this time that access was granted to the heat exchangers.

Accuracy.

Measurement guidelines were produced and collocated in a measurement protocol, see *Appendix A3*. According to this:

- information on the rotational frequency and time passed since the last cleaning of the unit were to be acquired from the operating technicians or the AHU interface.

Furthermore,

- measurements had to go on for at least 20 minutes before the readings were recorded, and:
- air flows, temperatures, RH, and heating/ cooling water temperatures, were to be measured according to the schematics in *Appendix A3*,

- and photography of the contaminated unit (J) were to be done in a specific manner in order for them to be comparable.

The determined values that describe the energy efficiency of heat exchangers, such as the sensible heat exchange efficiency, will fluctuate with variations in parameters D-H, as well as the relationship between these parameters. In order to detect relevant changes, measurement equipment was therefore to have low reading errors, and measurements were to be conducted in a specific manner.

Precision.

In order to achieve a good precision in the analysis, the aim was to measure in at least 30 AHUs. The number of units in which measurements were conducted were 87. This large number is assumed to have increased the precision of the assessment.

Since measurements in the AHUs were conducted instantaneously, the time interval for the measurements was irrelevant since it was not a logged time-series. However, fluctuations during measurements were considered, and values were not recorded until the ventilation system and thereby device readings had stabilized.

Induced reaction.

In order to determine the impact of accumulation, the contaminant either must be deposited on the heat exchanger or removed from it. In these field measurements, the contaminant was natural and accumulated over a long period of time (several decades), and therefore the most resource and time effective method was to remove the contaminant and measure over the units before and after cleaning. The change to the pressure-drop and parameters D-H was then to be used to determine the impact that the contaminant had on the heat exchanger.

Control object.

In this case no control object was needed. The measurements before and after were conducted within the same day and only separated by (at most) an hour or two, which meant that the measurements were conducted under the same circumstance and the before/after units could be directly compared to each other.

4.5.2.2 Supplementary measurements

Due to time and space restrictions in field, the protocol in *Appendix A3* could not always be fully followed. Measurements on airflows, RH and heating/cooling liquid temperatures were often far too time consuming for both the customer and those conducting the cleaning /measurements. It was reported that, in many AHUs, the space needed for the measurements was too restricted (low maneuverability), and that the AHU design was not appropriate for some of the measurements (too many bends). Therefore, only in six out of 87 units all parameters were measured, while in all units the pressure-drop was measured, which was prioritized.

Often, operating technicians were inexperienced with the equipment and had no records of events pertaining to the AHUs, e.g. data on time since last cleaning. Furthermore, it is unclear if airflows and rotational frequency were controlled in all measurements (except in six units, which further analyses were based upon). Finally, the mass and chemical compositions of the contaminants were not determined due to resource and time restrictions. In order to assess this parameter, an elaborate method would probably be required in order to collect the contaminants (which partially were in the form of small airborne particles) when cleaning the units. To this, chemical analyses would be required to determine the composition of the contaminant mass. Nevertheless, this type of analysis was not within the scope of the project.

Laboratory measurements and literature review.

In order to determine the relationship between the mass of contaminant deposited on the heat exchangers' surfaces and the decrease in thermal efficiency as well as an increase in the pressure drop, tests were made in a laboratory on a system best described in *Paper 7*. While all other parameters were controlled, the contamination on a heat exchanger was increased and the impact on the thermal efficiency and pressure drop determined.

In order to determine how the impact of contamination accrues over time, data was acquired through a literature study. In contrast to the field measurements, in the laboratory study the heat exchanger started out in a clean state and was contaminated gradually in order to determine the impact of contamination of the heat exchanger.

4.5.3 Conclusions from field measurements

The field measurements show that by removing the contaminant, the pressure drop is decreased, and the latent thermal exchange efficiency is increased. The field measurements thereby show that there is a significant increase in pressure drop over coils and heat recovery units due to the accumulation of contaminant, and that the latent thermal efficiency in heat recovery units (thermal wheels) is diminished significantly by this accumulation. Field measurements also show that there are differences in the results (pressure drop) pertaining to the geographical locations of the units that were included, as well as the types of units or the types of buildings. The field measurements alone therefore confirm the first two hypotheses stated. However, they do not answer if the accumulation of contaminant correlates with the runtime of the AHU, or how much contaminant must accumulate on a heat exchanger before it is profitable to clean it. These two questions are instead answered through the laboratory study, a literature study, as well as models based on the combination of these together with the field measurement results.

The aims of the study with the field measurements were achieved with measurements on the pressure drop and the relevant air temperatures (see *Appendix A3*). With information on the premises, measurements of the pressure drop could be related to the premises. The field measurements as well as data on some of the AHUs (specifically date of installation) was also used to validate results produced in the laboratory.

4.5.4 Conclusions from supplementary analyses

Laboratory experiment

The laboratory experiment together with a literature study determined how contaminants accumulate over time in a heat exchanger in AHUs, showing the impact this accumulation has on the energy efficiency of heat exchangers. The conclusion of the laboratory study was that increasing accumulation of a contaminant does diminish the thermal conductivity of a heat exchanger.

Modelling (calculations)

Data was acquired on contaminant deposition-rate through the literature study, while data on the relationship between deposited mass and reduced heat exchange was produced through the laboratory experiment. This resulted in models that exemplify the temporal impact of accumulating contaminants, which may serve as recommendations for property owners or managers.

4.5.5 Discussion

4.5.5.1 Causation

The impact on the parameters that are affected by the cleaning procedure was assessed through field measurements, however, in most units the precision of the assessments had the potential to be improved by extending the measurements that were conducted. This, since changes in these parameters (e.g. airflows, RH) could have affected the results, although it was unlikely since the measurements before and after the procedure were conducted within a short period of time and the systems were restored to run in the same manner after the procedure. Causation due to accumulation of contaminants could thereby be shown on the pressure drop on all units, and on the latent thermal exchange efficiency in a few (six) units. However, causation due to the amount of contaminant, and the accumulation of contaminant over time, could not be shown through field measurements since measurements were not conducted on the mass of contaminant and data on time since installation or last cleaning of the AHU was unavailable. Therefore, the impact of these two parameters (mass and time) were instead shown through a laboratory study (mass) and a literature review (time). As for the laboratory study, all parameters could be controlled and therefore causation shown. However, data acquired through the literature review were based on a modeling study that was fitted to experimental data [92]. This data might have been different if it was measured in field, and therefore also the temporal-causal relationship between contamination and deterioration.

In all field measurements, the only change that occurred was in the mass of contaminant that was deposited on the heat exchangers. No other known procedures were made that could have impacted on the measurement results. It is therefore most likely that the cleaning (and inversely the accumulated contaminant) was a necessary condition for the effect. If cleaning is conducted, and the unit is contaminated, the pressure drop is likely to decrease, and the heat exchange is likely to be improved.

In order to (more accurately) determine the temporal-causal relationship between the contamination and deterioration, long-time measurements can be conducted in a number of units in field after cleaning or installation. Furthermore, in order to further specify how the use and placement of different units affect the rate and impact of contamination, measurements including details on the rooms that the units serve are needed, as well as details on the use of (i.e. activities in) those rooms. The impact of other types of contaminants can be determined in a laboratory study.

4.5.5.2 Necessary measurements

In the table below, parameters that might impact on the results have been presented together with (from left to right) 1) their time intervals, 2) a qualitatively assessed degree of relevance within the study, 3) each parameter's dependency on other parameters, 4) the dependee parameters' time intervals, as well as 5) the limitation in the measurements of the dependent or the dependee parameters.

Table 4.9: Time intervals and limitations for parameters measured in field in the units that were included in the case study. [a] For determining latent thermal exchange efficiency.

Parameter	Pressure drop	Temperatures	Relative humidity	Air flows	Rotational frequency for heat recovery wheels	Time since cleaning
Time interval	1 sec	1 sec	1 sec	1 sec	1 sec (Hz)	
Importance (1-5)	5	5	1, (3[a])	2, (3[a])	4	2
Dependency (see section 4.5.1)	(D) (I)(K)	H[a] (D) (I) (K)	D	(A-2) (D) (I) (K)		
Time interval - dependee	-	1 sec	1 sec	1 sec		
Limitation		Time consuming, only conducted on a few units.	Time consuming, only conducted on a few units.	Difficult to conduct due to duct design, far too time consuming.	Only acquired for a few units. Often, staff lacked experience with the machines, and had no information on them.	No data.

Parameter	**Time interval**	**Importance (1-5)**	**Dependency (see section 4.5.1)**	**Time interval - dependee**	**Limitation**
Accumulation of contaminant and type		3	1		No data. No method to collect the dust appropriately. Much of the dust was presumed to be particles that were too small to catch during cleaning procedure. Besides, far too time consuming for the project.
Information about premises		3			Data on rooms served by unit not acquired.

Through field measurements, the impact of contamination on the energy used for heating the supply air, as well as on the pressure drop, could be determined. In order to do this, the most important measurements in this case were (in order of degree of importance):

1. Pressure drop over the heat exchanger
2. Temperatures within the unit (& Rotational frequency)
3. Airflows through the unit
4. Relative humidity within the unit
5. Information about the premises
6. Time since cleaning/ installation of the unit
7. Accumulation of contaminant and type of contaminant

With the first two parameters, the impact of the cleaning procedure on the energy efficiency of the AHU was determined. The energy use is primarily dependent on parameters 1-3, therefore if the settings for these parameters are changed in the AHU, the impact of the differences on the results would be significant. With data on 4, the impact of moisture recovery can be excluded, while data on 6 & 7 can give details needed for the specification of the results.

As for the time intervals, simultaneous values on all measured parameters were necessary, which has to do with the determination of the latent thermal efficiency. The conducted measurements were therefore made instantaneously. The time intervals are further discussed in section 4.7.3.2.

4.5.5.3 Necessary arrangements and prerequisites

In this study, the field measurements were primarily conducted by professionals in the cleaning industry, conducting cleaning for property owners. However, the field measurements would probably not have been possible if a need for applying the measure on the included AHUs didn't exist and the plan to implement it as well. Furthermore, the cleaning company (research partner) wanted to verify the impact of the measure on the units and was therefore quite invested in carrying out the measurements. Besides the cleaning company, property owners (i.e. customers) were also interested in the results. However, since the measuring procedure according to the protocol in *Appendix A3* was too extensive, complicated, and time consuming for the cleaning company to conduct on all units, measurements according to this protocol were conducted by me, on seven units. In order to be able to conduct these measurements, access to the premises was necessary.

4.6 Case study 5 – Ventilation measures for heritage buildings

Ventilation measures for heritage buildings need to consider the cultural and historical values of the buildings. A partial aim of *Paper 8* is to assess the impact of two ventilation measures that do so: A) a hidden mechanical ventilation system with heat recovery, and B) dampers for the reduction of the air change rates (ACR) out-of-hours. The impact of these measures on the: air flow, indoor air temperatures, relative humidity (RH), and the energy efficiency, is determined through field measurements. The focus of this study was the energy use of the building, since the impact on the energy use was not previously isolated through field measurements. Other aspects that were assessed were the impact on the indoor environmental quality (IEQ) as well as the moisture load on the building materials. The main study has been published in *Paper 8*.

This case study used an approach that was between the hypothetico-deductive and the inductive. What had previously been shown was that implementation of mechanical ventilation with heat recovery (MVHR) improves the IEQ and energy efficiency in comparison to natural ventilation (NV). Furthermore, the decrease of the ACR out-of-hours should, logically, decrease the energy use of the building. The hypotheses were therefore that:

- Installation of MVHR will improve the IEQ through the introduction of heated as well as filtered supply air in the buildings.
- Installation of A) MVHR or B) dampers out-of-hours system will improve the energy performance of the building through the A) introduction of heat recovery or B) the reduction of ACR out-of-hours.

At the same time, some questions were to be answered through an inductive approach, since previous studies have not determined the status of heritage buildings with NV in Sweden. Data on IEQ-conditions as well as common values for the ACR was scarce, but crucial for determining the impact that these measures might have on these buildings, and if these measures were relevant with regard to the IEQ as well as the energy performance of the buildings.

4.6.1 Derivation of parameters

For the MVHR, see section for a description on the parameters that might be affected by the measure. In the following, the parameters that might be affected by measure B) dampers are described. There are several main parameters that this measure can directly affect in the building as a system:

A. Energy use of a building, since the energy use for heating the supply air is reduced through reduction of the supply airflow out-of-hours when this is not necessary.
B. Indoor temperature, since the reduction of cold supply air out-of-hours reduces the cooling of the building materials and thereby preserves more heat through the heat capacity of the building materials.
C. Indoor relative humidity, since the reduction of supply air out-of-hours reduces the dry-out rate of the building materials and thereby preserves more moisture through the moisture capacity of the building materials.
D. Indoor emissions concentrations, since the reduction of supply air out-of-hours reduces the removal rate of emissions from the indoor air and thereby preserves more emissions in the indoor air through the emission sinks in the building materials.

Field measurements were primarily focused on the impact that the measure had on the energy use, but also on the IEQ. Control parameters for the MVHR are the same as those described in section 4.4.1. As for the dampers, control parameters that can directly or indirectly affect the energy use of the building, are surrounding environmental parameters as well as parameters depending on user behavior:

A. Temperatures outdoors.
B. Wind speed and Wind direction, which can impact on the air leakage through the building envelope and the natural ventilation rate.
C. Electromagnetic radiation outdoors, which can be expressed in:
    1. Global Radiation, which can be divided into:
        i. Direct Solar Radiation.
        ii. Diffuse Radiation.
D. Temperatures indoors, which are affected by:
    1. Temperatures outdoors.
    2. Electromagnetic radiation.
    3. Air leakage.
    4. Internal heat production (gains), from:
        i. Appliances.
        ii. Inhabitants.
        iii. Activities.
    5. Window opening.

Changes in the following parameters can impact changes in the indoor air quality (IAQ):

E. Emissions indoors, which are affected by:

1. Air change rates
2. Internal emission production (loads), from:
    i. Inhabitants
    ii. Activities
    iii. Building material
    iv. Furniture
    v. Equipment
3. Window opening

Changes in the following parameters can impact changes in the moisture loads:

F. Relative humidity outdoors, which can impact on internal moisture loads.
G. Precipitation.
H. Internal moisture loads expressed in either of the following:
    1. *Moisture supply* (difference between vapor content indoors and outdoors).
    2. Relative humidity indoors, which is affected by:
        - Air change rate indoors.
        - Moisture production indoors.
        - Temperatures indoors.
        - Vapor content outdoors.

4.6.2 Materials and field measurements

The study has determined the status of 12 different buildings across Sweden in order to form a general depiction of the IEQ in Swedish heritage buildings, with offices, in relation to the ventilation system that exists in them (i.e. natural ventilation). The included buildings were as follows:

1. Gamla Rådhuset in Ystad [93]
2. Kalmar Castle [94]
3. Karlskrona Residence [95]
4. Kastellet in Stockholm [96]
5. Krognoshuset in Lund [97]
6. Luleå Residence [98]
7. Skokloster Castle (Stockholm) [99]
8. The Royal Palace in Stockholm [100]
9. Stockholm's Banco [101]
10. Tjolöholm Castle [102]
11. Ulriksdal's Castle in Stockholm [103]
12. Ulriksdal's Castle Wing in Stockholm [103]

The study then determined the impact of two potential ventilation measures (MVHR and dampers) on the indoor climate and the energy performance in two (MVHR – building no. 8 and dampers - building no. 9) of the included buildings through two unit-studies. Measurements included: ACRs, temperatures, RH, carbon dioxide concentrations, as well as air flow measurements over supply and exhaust devices. For more details on these measurements, the reader is referred to *Paper 8*.

4.6.2.1 Measurement details

Timespan.

MVHR. In order to minimize the impact of seasonal variations, measurements were conducted during the same seasons before and after the implementation of the renovation measure, according to the same reasoning as in section 4.2.2.3. See details in *Paper 8*. This was done for at least 5 months before and after the measure.

Dampers. Simultaneous measurements were conducted in similar offices with and without dampers during the same time span. This in order to compare measurements in subunits with and without the dampers directly to each other and thereby eliminate the impact of seasonal variations. See details in *Paper 8*. This was done for at least one winter month.

Accuracy.

The expected impact that this type of measure has on the energy use is on the energy used for space heating. Measurements on this parameter might therefore be conducted on the supplied heat to the building, i.e. on the heat carriers. However, since the measures were applied to a few selected office rooms, and not the entire buildings, such measurements were irrelevant since the spatial resolution of the data would be too low. Nevertheless, such measurements might be possible to be conducted on the heat carriers to the parts of the building that are affected by the renovation measure. However, the installation of energy meters on the radiators in the rooms was not possible due to the time and resource restrictions of the project. Besides, installing equipment for such measurements in a building should be conducted by someone certified for such work. Furthermore, since the included buildings are culturally protected, installations of such sensors would require special permission. Therefore, supplementary analyses in the form of building performance simulations were required in order to determine the impact on the energy use. For these, data on the indoor climate and ACRs was acquired before/ after and with/ without implementation of the renovation measures, with focus on the cold season of the year. Measurements were also conducted during the warm season of the year in order to determine differences in ACR in a NV system over the year.

Since the IEQ can vary between rooms depending on the usage and occupancy of each room, a detailed approach would be to measure in at least one point of reference in every room. It was assumed that office workers mostly spend time by their desks at work, so most of sensors were placed nearby the desk in the office rooms. However, the placement of the sensors was not to be directly affected by changes in external parameters, such as solar radiation, since this would impact on the results. Neither was it to be too close to the office worker so that he/she wouldn't directly impact on the measurements through e.g. their breath. With this in mind, the sensors were placed on the office workers' desks, in a shaded location, but as far as possible from their breath. However, this was not always possible due to items placed on their desks, or due to the location of the desk, and therefore in some rooms the sensor was placed in another relevant location such as on a bookshelf within the room.

With regard to moisture loads, a preferred placement would be in the room with highest risk of moisture damage to the building materials or building envelope, due to internal moisture production. However, in an office environment there should not really be a meaningful difference between different rooms concerning this, i.e. considering the activities that take place. This assumes that there are no heavily moisture-producing activities, such as showering or cooking, in an office environment. The most moisture-producing source would therefore probably be the occupants themselves, and therefore the placement of the sensor nearby them or somewhere within their offices should be appropriate.

The ACR was measured during both the cold and the warm season since NV is highly dependent on the surrounding climatic conditions. Furthermore, it was important to measure during office hours as well as out-of-hours in order to determine the impact of the occupants on the ventilation rate with NV. This in order to make a proper comparison with other types of ventilation solutions.

Precision.

The time interval for the measurements of indoor air parameters (temperature, RH and CO_2) was set to 5 minutes. Following the reasoning in section 4.3.2.1, this time interval should be more than sufficient for the assessment of the IEQ. However, in order to compare values of indoor air parameters with changes in the outdoor climate (mainly outdoor temperatures), average hourly values were used, since hourly values is what SMHI [72] provides. Furthermore, 15-min averages were used in the assessment of the IEQ since a shorter time interval was assumed not to be representative of the IEQ. This assumes that a change to the indoor environment that lasts 5 minutes does not impact on the users' perception of the IEQ in general, but a change that lasts for at least 15 minutes might. Furthermore, data out-of-hours was not included in the IEQ assessment, since the building's might be operated differently then, and since it is assumed that there are not a significant number of workers present in the buildings.

Tracer gas decay measurements for the determination of the ACR were conducted with a maximum 5-min interval, but a minimum 1-min interval. This in order to achieve a detailed temporal resolution of the decay of NOX- and CO_2-concentrations, and a more accurate curve for use in the calculations of the average ACR during the measurements. The choice of time interval during the tracer gas decay measurements was dependent on the logger that was used, and the possibilities with that logger. Furthermore, one aim was to reach high enough concentrations during the measurements in order to minimize background levels, but not risk impacting on the occupants' health. Therefore, at least 3000 ppm was reached in the CO_2-measurements.

Induced reaction.

Since the buildings originally had NV, the air flow was most appropriately measured through tracer gas decay measurements. This entailed the exposure of the indoor climate to a high concentration of tracer gas, which enabled the calculation of the ACRs. More details on this can be found in *Paper 8*.

Control object.

For both measures, the assessment of the impact of changes in other parameters was considered in order to isolate the impact of the measures. Measurements on control objects were therefore conducted in similar rooms with similar loads and setups. In the assessment of the MVHR, control parameters were also analyzed before and after the implementation of the measure. Furthermore, the status was determined in ten other similar buildings across Sweden, in order to produce a general depiction of the IEQ in this type of building, as a basis for determining the need for ventilation measures.

4.6.2.2 Supplementary analyses

The inhabitants' perception of the indoor climate was acquired in order to determine the IEQ in heritage buildings. Surveys were therefore handed out in all buildings. Furthermore, since the energy use of the rooms that were affected by the measures could not be determined through measurements, energy performance simulations based on field measurements were conducted on the parts of the buildings that were affected by the measures. For more details on these analyses, the reader is referred to *Paper 8*.

The same surveys were handed out both before and after the installation of the ventilation measures, in order to assess the impact of the IEQ on the occupants affected in the units that received ventilation measures.

4.6.3 Conclusions from field measurements

Field measurements on the IEQ in the included buildings show that there is substantial room for improvement of the thermal comfort in this type of building. Furthermore, they show that care should be taken in order to not reduce the ACRs during office hours due to potential risk for a diminished IAQ. Determined ACRs for all buildings show differences between opened and closed office doors (higher – lower), between office hours and out-of-hours (higher – lower), as well as between winter and summer season (higher – lower). For more details on this, the reader is referred to *Paper 8*.

Field measurements on the units that got A) a hidden MVHR, and B) dampers for the reduction of the ACR out-of-hours, show that A) results in reduced CO_2 concentrations, and that measure B) does not have a negative impact on the moisture loads. ACRs were also changed by the measures. Measure A) increased the ACRs while providing heat recovery, as well as heated and filtered supply air, in comparison to the previous system (NV). Measure B) reduced the ACR out-of-hours during wintertime which should reduce the energy use of the affected offices.

Energy savings could not be measured for the units on which ventilation measures were applied since the measures only affected a part of the buildings that they were installed in, and energy data on building level was most likely not affected by a change of this size.

4.6.4 Conclusions from supplementary analyses

Building energy performance simulations in IDA ICE show that both measures reduce the energy use in the affected offices, but that the extent of the reduction depends on if other parameters are the same before and after the implementation of the measure, e.g. the ACR.

Surveys made in all included (12) buildings show that there is no direct need of ventilation measures due to a lacking IAQ, although it would be an improvement to install a system with a controlled ACR, especially during the summer. However, a substantial part of the rooms in these buildings can be improved due to issues with the thermal comfort (IEQ). One way to improve the thermal comfort might be by implementing a system with heated supply air during the winter and cooled supply air during the summer.

Surveys handed out before and after the ventilation measures were implemented did not have a high enough response rate in order to assess the impact on the IEQ and make deterministic conclusions.

4.6.5 Discussion

4.6.5.1 Causation

A large part of the research conducted in this case study was inductive, specifically the status determinations on the units (buildings) that remained untouched. Since indoor climate measurements were conducted simultaneously to surveys being handed out, the results from the analyses of these two were related and used for confirmation. Causality was shown by using this together with knowledge of the building as a system. The status determinations on each unit alone give descriptive knowledge and not really explanatory knowledge, but since this was a cross-unit analysis some of the knowledge gained was confirmatory and therefore causal (e.g. impact of NV on the thermal comfort). Differences between units with the same ventilation system (natural ventilation) show e.g. how different events (e.g. closed/ open door) affected ACRs. Similarities in structural design and ventilation show how these might impact on the indoor climate. For more details on this, the reader is referred to *Paper 8*.

The impact of the renovation measures on the ACRs, the temperature indoors, the RH and the CO_2 concentration, was shown through long-term indoor climate measurements, instantaneous tracer gas decay measurements (measure A, B) and/ or air flow measurements (measure A). This was done before and after the implementation of the measure (measure A) and/ or against control objects (measure A, B). Measurements with a control object (measure A and B) used rooms similar to rooms subjected to the change and were conducted simultaneously, therefore control of changes to other impacting factors (control parameters) was not necessary. Measurements made before and after (measure A) were separated by at least a year, and therefore control of changes in other parameters that might have impacted on the results was necessary. This control (measure A) was done through comparisons with control objects as well as through a global climate analysis comparing outdoor climate parameters that might have impacted on the results before and after the implementation of the measure. The conclusion was that no significant changes have occurred in these parameters that impacted on the results as much as the implementation of the MVHR-system. Causation due to the implementation of the ventilation measure was therefore shown and supported through these analyses.

Like case studies 2 and 3, window opening in this case study could not be tracked in order to assess its impact on the results.

4.6.5.2 Necessary measurements

The following analysis is made for parameters in the units in this case study that got ventilation measures, and not for the units on which only status determinations were made. In the table below, parameters that might impact on the results have been presented together with (from left to right) 1) their time intervals, 2) a qualitatively assessed degree of relevance within the study, 3) each parameter's dependency on other parameters, 4) the dependee parameters' time intervals, as well as 5) the limitation in the measurements of the dependent or the dependee parameters.

Table 4.10: Time intervals and limitations for parameters measured in field for the units that were included in the case study. Regional = from a station within the same city. Local = from the neighborhood.

Parameter	CO_2 concentrations	Air change rate/ Air flow through devices	$T_{outdoors}$	$T_{indoors}$	Wind speed (and Wind direction)
Time interval	5 min	1h (5 min)	10 min to 1h	5 min	1h
Relevance (1-5)	5	5	4	4	3
Dependency (see section 4.6.1)	E.1-3	A, B, D, D.5		D.1-5	-
Time interval dependee					-
Limitation	No information on worker details, e.g. schedules.	Wind measured regionally, not locally.	Data for measure A acquired locally, but regionally for measure B.	Not local, but regional. Not needed for the assessment of Measure B.	Not local, but regional.

Parameter	$RH_{outdoors}$	$RH_{indoors}$	Precipitation	Global radiation
Time interval	1h	5 min	1h	1h
Relevance (1-5)	3	4	3	3
Dependency (see section 4.6.1)				-
Time interval dependee	1h	5 min, 1h	-	-
Limitation	Not local, but regional.	.	Not local, but regional. Measure B) not needed.	Not vertical, but horizontal.

Measurements made in-field were sufficient for the analyses of the impact that the measures had on the IEQ and ACR, as well as for use in building performance simulations. This, despite the few limitations stated in the table above. These analyses relied on the following parameters (in order of degree of importance):

1. CO_2 concentrations (and thereby Air Change Rates)
2. Airflow measurements
3. Temperatures indoors (and in the MVHR system)
4. Relative humidity indoors
5. Temperature outdoors
6. Wind speed outdoors
7. Global radiation
8. Relative humidity outdoors
9. Precipitation

The energy use of the buildings in this case study is dependent on the ACR, and due to the NV the ACR is variable with the outdoor climate. Since energy used for space heating is relevant during the cold period of the year, ACR was determined when heating is needed for a building with such a system. With the first two parameters, the impact of the measures on the ACRs and thereby on the energy use could be determined. Assessing if changes to temperatures indoors (3) had occurred made it possible to exclude the impact that this had on the energy use in the building with measure A. Data on 5-7 was used for determining the impact of changes in outdoor parameters on the energy use, ACR and the IEQ. The fourth parameter was necessary to determine the impact of the measures on the moisture loads in the building. Data on 5 and 8-9 was used for determining if changes in outdoor humidity had an impact on the indoor humidity and was thereby considered in the assessment of the impact that measure A had on the moisture load. The differences in moisture loads for the system with dampers seem to be marginal and insignificant, and therefore the moisture safety risks due to implementing this measure out-of-hours should be low.

As for the time intervals, in order to determine the IEQ, 15-min average values on indoor temperature and CO_2 concentrations were used. However, measurements were made with 5-min intervals, which provided insight on the IEQ and increased the Precision of the determination of the ACR since this depended on the number of data points. The time intervals are further discussed in section 4.7.3.2.

4.6.5.3 Necessary arrangements and prerequisites

In order to conduct the status assessments, access was gained to the buildings through the property managers and the help of operating technicians. Since these buildings are rented, it was also necessary to receive the tenants' permission to enter the premises in order to install measurement equipment, to conduct tracer gas decay measurements, and to conduct a survey with the tenants (office workers). It was not easy to find buildings that fit the criteria for the study. Most of the heritage buildings that were considered, had transitioned to MVHR, if they had offices. Most of those that had NV did not have offices. At least 15 out of 48 buildings had both offices and NV. However, these buildings were not included, since the property manager of these buildings did not want the study to be conducted in them.

In order to conduct the field measurements in this study, help was needed from the operating technicians during the measurements. Access was needed to the buildings and the offices, during office hours and out-of-hours. In order to get the help of the operating technicians, appointments were made with them, which did not always work out as intended. Before each visit, contact was also made with the tenants, and information was handed out through letters (e-mails) before the visit, that detailed the measurement procedure and the reasons for the measurements.

In order to conduct the field measurements for assessment of the impact of the renovation measures, a property owner or a representative of a property owner (e.g. property manager), that was planning or willing to apply renovation measures to a building, was necessary. However, the field measurements would probably not have been possible if a need for applying the measures on the included offices didn't already exist and the plan to implement them as well. The property manager and operating technician, for the building on which renovation measure A was implemented, had stated that the office workers had complained about the IEQ, and wanted to try this measure's potential to remedy issues pertaining to the IEQ as well as reduce the energy. The property manager and operating technician for the building on which renovation measure B was implemented had stated that the building was unnecessarily requiring energy for space heating during cold evenings due to the NV and wanted to try a measure in order to reduce the energy losses due to this.

Besides the above, in order to acquire data, access was needed to the sensors and the possibility to control the measurements. For sensors that were reliant on batteries and were not possible to access remotely, access to the premises was granted at several occasions. Other sensors had a wired electricity supply and remote access was available wirelessly. However, when a sensor malfunctioned it was important to gain access in order to repair or replace it. Furthermore, in order to ensure that data was correctly logged, an analysis shortly after data logging was conducted on the acquired data. This enabled detection of faulty sensors and replacements of them.

4.7 Synoptic discussion

This section is a synoptic discussion on the combination of the case studies included in this thesis. It compares the studies with regard to specific aspects; the necessary arrangements and prerequisites, the study setups, and the measurement details. It then discusses parameters that could not be measured in the field studies due to limitations, and the consequences thereof.

4.7.1 Necessary arrangements and prerequisites

In general, across the case studies, the following arrangements and prerequisites were required for field measurements to be possible:

- Communication with property owners, managers or operating technicians.
- A need for renovation measure(s), or status assessment(s), e.g. due to tenant complaints, materials or services reaching the end of their lifespan, or the need for improvement of the building's energy efficiency.
- Interest in verification of the renovation measure's impact, by owners, managers, or technicians.
- In some cases, the consent of the inhabitants might be needed to install measuring equipment or to conduct measurements, depending on the measurements.
- Access to the building, the building's systems, offices, apartments or other rooms.

In summary, the following was conducted for data acquisition:

- For the measurements that required communication with or meeting the inhabitants or tenants of the building, information on the research project was handed out before the visits.
- The equipment was installed either by the involved researchers or by the research partner (property owner's representative).
- The measurements were controlled for errors as soon as possible after installation.
- In order to retrieve data, the researchers were either given access to the building to retrieve the data, or the possibility to connect the equipment to the internet so that remote access to the measurement devices was possible, or were handed data from the property managers.
- For parameters that were not possible to measure, data was acquired, if available, from other sources, e.g. property owners, or SMHI [72].

4.7.2 Comparisons of study setups

The table below clearly shows that before & after comparisons require control of parameters that might affect the status of the unit, while comparisons only conducted with & without the measure might not. However, with & without comparisons require a control object, which is not always available, as shown in case study 2. Either option, conducted properly, i.e. with a control object or control of parameters, should give causal relationships, and the lack of a control object or control parameters, should give descriptive knowledge instead.

Table 4.11: Summary of parameters measured in the case studies, as well as the comparisons made. Y = Yes, N = No, BA = Before & After, WW = With & Without.

Case study	**Main parameters**	**Control parameters**	**Control object? Y/ N**	**Comparison: Before & After or With & Without**
1. Interior added insulation on external SBM walls	T_{wall}, RH_{wall},	$T_{outdoors}$, $RH_{outdoors}$, $T_{indoors}$, $RH_{indoors}$, Global radiation, Precipitation, Wind speed & direction	Y	BA & WW
2. DCV for multifamily buildings	Emissions (VOC, CO_2), $RH_{indoors}$ & $T_{indoors}$, $RH_{outdoors}$ & $T_{outdoors}$, Airflows, Temperatures	(CO_2)	N	WW through calculations (BA not possible since measurements before were not sufficient)
3. MVHR for multifamily buildings	Energy supply, $T_{indoors}$, $RH_{indoors}$	$T_{outdoors}$, $RH_{outdoors}$, Global radiation, Airtightness, Precipitation, Electrical use, Wind speed & direction	Y	BA & WW through field measurements

Case study	Main parameters	Control parameters	Control object? Y/ N	Comparison: Before & After or With & Without
4. Air-side cleaning of heat exchangers in ventilation systems	P_{drop} Temperatures	Airflows Rotational frequency RH	N	BA
5. Ventilation measures for heritage buildings A) MVHR	CO_2 ACR $T_{indoors}$, $RH_{indoors}$	$T_{outdoors}$, $RH_{outdoors}$, Global radiation, Precipitation, Wind speed & direction	Y	BA & WW
5. Ventilation measures for heritage buildings B) Dampers	CO_2 ACR $T_{indoors}$, $RH_{indoors}$		Y	WW

4.7.3 Data resolutions

Choosing the spatial resolution and temporal resolution of the parameters in the case studies requires an understanding of how a building functions as a system. What is meant by *spatial resolution* is the spatial level, e.g. low to high: regional – local – city – town – building – room. Even if the highest temporal resolution with the highest spatial resolution might be desired, this is difficult to achieve. Based on the case studies in this thesis, what can limit the possibilities in the measurements and their extent is:

- The accessibility to and within the premises.
- The limitations of the measurement equipment, e.g. error in readings, maximum range, environments that it can be used in, memory space, electricity supply (e.g. battery life).
- Financial resources which can limit the extent of the study, the choice of equipment, traveling possibilities, and manpower.
- Consent of the inhabitants or users within the premises, or the property manager.

- The extent of the measure, e.g. if it affects the entire building or only a room in the building.
- Time available for the study.

Due to these limitations, the researcher can be presented with data that might not be ideal for the evaluation at hand. However, even if the possibility does exist for a higher temporal or spatial resolution it might not always be necessary to acquire this. What should determine these matters is the purpose of the measurement and what it is supposed to represent (see the following subsection).

4.7.3.1 Accuracy - spatial resolution & timespan

In a recent publication, Ahn and Park [37] show that the choice of spatial resolution is significant for the outcome of a study. The study shows that the occupancy of a small group, based on measurements on room-level, is unpredictable, while the occupancy of larger groups, based on measurements on building-level, is predictable [37]. The results of their study therefore strongly suggest that the variability of a smaller spatial resolution is higher than that of a larger spatial resolution.

With regards to the abovementioned results by Ahn and Park [37], some parameters that were measured in the included case studies in this thesis would be preferred at a higher spatial resolution in order to increase the precision of the assessment. These preferences are summarized in the following table; however, it should be noted that the impact of the difference between acquired and preferred temporal and spatial resolution has not been quantified. Nevertheless, in some case studies study 1, 2, and 3, the analysis mentioned in the table were not possible to do based on field measurements but required supplementary analyses. While in case study 3, the analysis was possible to do, however, measurements of CO_2 concentrations in the buildings would have supported the conclusions.

Table 4.12: Measured parameters within case studies that would have been preferred at a higher spatial resolution.

Case Study	**Parameter**	**Acquired spatial resolution**	**Preferred spatial resolution**	**Reason**
1. Interior added insulation on external SBM walls	Precipitation	Regional level	Local level	Determining correlation with RH in wall.
2. DCV for multifamily buildings	Indoor air parameters	**Before:** Inside two apartments + separated on building level for kitchen/ bathroom. **After:** In 24 apartments + united on building level for the entire apartment.	After implementation comparable to before implementation. I.e. 24 vs 24 apartments.	Determining the measure's impact on the IEQ.
	Energy use	Building level	Staircase	Determining the measure's impact on the energy used for space heating.
3. MVHR for multifamily buildings	Inhabitants' presence and habits	Electricity use on Building level + RH	Electricity use on apartment level + CO_2 + RH	More accurately determining the change in inhabitation and impact on energy use.
5. Ventilation measures for heritage buildings	Energy use	Building level	Offices	Determining the measure's impact on the energy used for space heating.

Besides spatial resolution, the time of year during which the measures had an impact was considered. In all case studies, an aim was to reduce the impact of seasonal variations, therefore comparisons were made during the same seasons of measurements before /without the implementation of the measure with the measurements after /with the measure, see the following table. Furthermore, measurements were conducted at least during the time of the year in which space heating was required in order to assess the impact of the measures on the energy use of the buildings, since one of the derived impacts of all included measures was the reduction of energy used for this purpose. However, in case study 1, 3 and 5 measurements were also conducted during other seasons (summer), which allowed the determination of the measures' impact on the hygrothermal status and the indoor climate during these seasons (1 – solar driven vapor, 3 – no impact, 5 – passive cooling). This shows the benefit of measuring with a timespan that includes all seasons of the year.

Table 4.13: Comparison of timespan in case studies.

Case Study	Timespan	Impact identified
1. Interior added insulation on external SBM walls	Lund – Jan-Sep, 2014 Örebro – July-July, 2015-2016	Cold season: - Heat transfer from interior to exterior. - Diffusion from interior to exterior. Warm season: - Heat transfer from exterior to interior. - Diffusion and capillary action from exterior to interior.
2. DCV for multifamily buildings	Approx. one year after measure. (Nov 2014 – Oct 2015).	Cold season: - Impact on heating determined.
3. MVHR for multifamily buildings	Approx. Jan- May 2016 vs. 2017.	Cold season: - Impact on space heating determined. - Impact on indoor climate determined. Warm season: - Impact on indoor climate determined.
4. Air-side cleaning of heat exchangers in ventilation systems	Instantaneous.	Cold season: Impact on heat exchange determined.

Case Study	Timespan	Impact identified
5. Ventilation measures for heritage buildings A) MVHR	Approx. five months before and after measure. Feb-Jun 2017 vs 2018.	Cold season: - Impact on supply-air temperature, ACR, heat recovery, and thereby space heating, determined. - Impact on indoor climate determined. Warm season: - Impact on supply-air temperature determined.
5. Ventilation measures for heritage buildings B) Dampers	Approx. five months Feb (3 weeks) + Apr-Sep 2017.	Cold season: - Impact on ACR and thereby space heating determined.

4.7.3.2 Precision - temporal resolution & data quantity

Data was sometimes acquired with higher temporal resolution (short time intervals – seconds, minutes) and sometimes with lower temporal resolution (long time intervals – hours), see Table 4.15. Sometimes data was acquired with greater or with minor spatial resolution, e.g. in case study 3 the measurements were conducted for entire apartments, while in case study 6 the measurements were conducted in offices. In some case studies, a higher temporal resolution on a specific parameter gave more information on events or occurrences that impacted on the results and could be used for further analyses of the measure. E.g. in case study 1, the measurements were conducted with a 2-min interval, which allowed for the visualization of the fluctuations in the different layers of the wall, see *Appendix A1*. Based on existing theory, some of these fluctuations can be estimated, however, some occurrences that might impact on the results cannot. Some of the shown fluctuations for the sensors placed close to the exterior surface might have occurred due to the sensor being placed in a cavity in the wall, or due to air seeping into the hole in which the sensor was installed, or some other unknown technological reason. These possibilities argue for measuring with a higher temporal resolution, as well as having reference sensors (greater detail). Furthermore, in some cases a too low temporal resolution might render the precision of an analysis too low for reliable conclusions, or not possible to conduct at all. The following table shows the acquired and preferred temporal resolution for some parameters that were measured in two of the case studies. In case study 1 the analysis would have too low temporal resolution in order to precisely determine the impact of precipitation on the RH in the wall, while in case study 2 the analysis was not even possible to perform.

Table 4.14: Measured parameters within case studies that would have been preferred at a higher temporal resolution.

Case Study	Parameter	Acquired temporal resolution	Preferred temporal resolution	Reason
1. Interior added insulation on external SBM walls	Precipitation Örebro	1d	1h	Determining correlation with RH in wall.
4. Air-side cleaning of heat exchangers	All parameters	Instantaneous measurements	Long-term measurements before and after cleaning.	Determining the impact of accruing contaminant over time, through field measurements.

In general, a higher temporal resolution (shorter time interval) might safeguard for possibilities that have not occurred to the researcher in the design of the field measurement. The following two tables summarize the acquired temporal resolutions for all parameters included in the case studies, and the used temporal resolution. These show that, for most parameters, the analyses required lower temporal resolution than measured. However, the data used in the analyses with lower resolution mostly consisted of average values based on measurements with higher temporal resolutions. The methods used for the analyses and the purposes of the analyses were what primarily limited the use of the parameters to a lower temporal resolution. It is possible that if other methods were used to conduct the analyses, the temporal resolutions might have needed to be higher. Thus, what this analysis primarily shows is the dependency of the used temporal resolution on the method chosen for analysis of the impact of the measure, or for risk assessment, and that the researcher should therefore choose a temporal resolution that depends on which method the researcher plans to use in the analysis.

This thesis has not assessed the impact of a lower temporal resolution on the analyses conducted in the case studies. However, recently Ahn and Park [37] conducted a comparison of temporal resolutions for predictability of building occupancy, which showed that the assessment was not significantly influenced by varying the temporal resolutions. In their paper they showed that differences in spatial resolution are much more significant. However, in order to safeguard for possibilities that have not occurred in the design of the field measurement, e.g. an alternate or upcoming method for analysis, a higher temporal resolution might be beneficial. Furthermore the chosen resolution might improve the precision of the assessment [104] itself. Also, a too low temporal resolution might impact on the assessment by diminishing impact of potential peaks of a parameter [38], [39].

Besides the temporal resolution, the timespan affected the quantity of data points acquired through the measurements, which inevitably affected the precision of the assessment. What was considered regarding the timespan in all case studies, was:

- the nature of the study (instantaneous – case study 3, long-term – other case studies),
- the time limits of the study itself,
- the accessibility of the premises,
- the location of the premises and thereby the possibilities of travels (which relied on itineraries and financial resources),
- if remote access to the chosen sensors was possible and thereby the choice of sensors (which depended on numerous factors).

Only in case studies 4 and 5 was the quantity of measurement points limited in order to make the workload manageable. How this has affected the precision of the analyses has not been quantified. However, all analyses aimed at acquiring a large quantity of data points in order to increase the precision of the analysis. In all analyses, the quantity of data points deemed to be sufficient with regard to the precision of the assessment.

*Table 4.15: Acquired and used temporal resolutions. Parameters measured indoors. Reason for used temporal resolutions in final analyses. *In wall, sensor closest to indoor climate.*

Parameter	Case study	Min. acquired res.	Analyses res.	Δ	Use
T	1* Interior ins.	5-10m	12h avg.	<	Mold growth risk analysis
	2 DCV	5m	12h avg.	<	Mold growth risk analysis
	3 MVHR	1h	1h	=	IEQ + change assessment
	4 Cleaning	1s	10m	<	Heat exchange calculation
	5 Heritage	5m	15m	<	IEQ assessment
RH	1* Interior ins.	5-10m	12h	<	Mold growth risk analysis
	2 DCV	5m	12h	<	Mold growth risk analysis
	3 MVHR	1h	1h	=	Indoor climate change
	4 Cleaning	1s	-		(Not enough data)
	5 Heritage	5m	1h	<	IEQ assessment
CO_2	2 DCV	7-15m	15m, 1h	<	IAQ + correlation assessment
	5 Heritage	5m	15m	<	IEQ assessment
VOC	2 DCV	5m	5m, 1h	<	IAQ + correlation assessment

*Table 4.16: Acquired vs. used temporal resolutions, parameters measured outdoors. *Normalized data from Meteonorm. Δ difference in res. after, < lower, > higher, = equal.*

Parameter	**Case study**	**Min. acquired**	**Analyses res.**	**Δ**	**Use**
T	1 Interior ins.	5m	12h avg.	<	Mold growth risk analysis
	2 DCV	5m	12h avg.	<	Mold growth risk analysis
	3 MVHR	1h avg.	Avg: 1h, 1d	=,<	Impact: Energy, Indoor climate
	4 Cleaning	1s	10m	<	Heat exchange calculation
	5 Heritage	30m, 1h	30m, 1 mon	=,<	Heat exchange, Climate change
RH	1 Interior ins.	5m	12h avg.	<	Mold growth risk analysis
	2 DCV	5m	12h avg.	<	Mold growth risk analysis
	3 MVHR	1h	1 mon avg.	<	Impact: indoor climate
	4 Cleaning	1s			Not enough data
	5 Heritage	1h	1h	=	Impact: indoor climate
Global radiation	1 Interior ins.	1h avg.	1h avg.	=	Validation of simulation model
	3 MVHR	15 min	1d sum	<	Impact: Energy, Indoor climate
	5 Heritage	1h avg.	1 mon avg.	<	Impact: indoor climate
Precipitation	1 Interior ins.	Sum: 1d, 1h	Sum: 1d, 1h	=	Impact on RH, Validation of model
	3 MVHR	1h sum	1 mon sum	<	Impact on indoor climate
	5 Heritage	1d sum	1 mon sum	<	Impact: indoor climate
Wind speed & direction	1 Interior ins.	1h avg.	1h avg.	=	Validation of simulation model
	3 MVHR	1d avg.	1d avg.	=	Impact: Energy, Indoor climate
	5 Heritage	1h avg.	Avg: 1d, 1 mon	<	Impact: ACR, indoor climate

4.7.4 Parameters that could not be measured

For most part, in all case studies, the parameters that were needed in order to determine the impact of the renovation and maintenance measures were possible to measure. However, due to varying circumstances and limitations, some important parameters were not possible to measure, and some data was not possible to acquire. The following table summarizes the limitations for such parameters in each case study, the reasons for those limitations, and how analyses besides the field measurements supplemented for the consequences due to these limitations.

The table shows that three case studies had some limitations in the study, or deviation in the field-measurement procedure due to circumstances out of the researchers' control, that resulted in the need for supplementary analyses. In case studies 1, analyses using measurements with lesser precision (Örebro: sensor in wall instead of indoors) were conducted instead, in order to determine the impact of the measure on the building. Furthermore, simulations were conducted in order to determine the impact of control parameters (moisture indoor, precipitation, material) on the measure. In case study 2, analyses using comparisons to guidelines (recommended CO_2) were conducted instead of comparisons with the case before the implementation of the measure. Causation could thereby not be shown, and descriptive knowledge was gained instead. In case study 4, laboratory experiments were deployed in order to answer a research question (temporal aspect) that concerned the impact of the measure, however, in comparison to the other studies, this was a chosen limitation due to the nature of the field measurements (predominately statistical).

Table 4.17: Analyses that could not be conducted due to parameters that could not be considered in field measurements; reasons, consequences, and necessary supplementary analyses.

Case Study	Parameter	Reason	Consequence	Supplementary analyses
1: Interior added insulation on external SBM walls	Indoor climate in Örebro	No access to apartments.	Could not determine impact of interior loads, through measurements.	Paper 5 – Sensor in wall closest to interior surface, as an indication. Paper 2 – comparison of external and internal loads, showing that external loads are far superior and thereby more important in the assessment.
	Insulation types	No possibility to test different insulation types due to sensor failure in Lund.	Could not determine impact of different types of insulations on the results due to the insulation type through measurements.	Paper 5 - comparison of the impact of different insulation types through simulations, based on validated model.
2: DCV for multifamily buildings	IAQ measurements before measure	Only permitted to access two apartments.	Could not determine the impact of the measure on the IEQ through measurements before and after.	Paper 4 – Determination of IAQ through correlation of MOS-sensors with CO_2-sensors and existing guidelines (field measurements).

Case Study	**Parameter**	**Reason**	**Consequence**	**Supplementary analyses**
4: Air-side cleaning of heat exchangers in ventilation systems	Time of accumulation.	No records.	Could not determine the accumulation rate of contaminant in field measurements.	Data was acquired on accumulation rates through literature study.
	Amount of contaminant	Resource and time limitations.	Could not determine the mass of contaminants in the field measurements and the impact that this mass had on the pressure drop and the heat exchange.	Laboratory tests were deployed in order to determine the impact of the amount of contaminant.

5 Field measurements for assessment of renovation and maintenance measures

This chapter illuminates the process of field measurements for acquiring data for the assessment of renovation and maintenance measures, based on the empirically acquired data from the combination of the five case studies, i.e. chapter 3.1.5.

If an impact that is dependent on multiple simultaneous factors is to be studied in a laboratory study, the study can be designed according to what is called factorial design. This type of design intends to vary a set of factors on a specific number of levels simultaneously and evaluate the effect of each of these factors and levels on a dependent parameter [35]. However, based on the included case studies, and the literature review [32], this seems to be difficult to conduct in a field study due to the lack of control of e.g. access to the premises, possibility to freely test different measures, and no control of the outdoor climate. These limitations seem to be common in field research, even in other research disciplines [34]. It seems therefore necessary to design the field measurements based on experience as well as knowledge of how the building functions as a system.

The following is based on the analyses of the included case studies:

1. Interior added insulation on external Solid Brick Masonry (SBM) walls
2. Demand Controlled Ventilation (DCV) for multifamily buildings
3. Mechanical Ventilation with Heat Recovery (MVHR) for multifamily buildings
4. Air-side cleaning of heat exchangers in ventilation systems
5. Ventilation measures for heritage buildings
    A. MVHR through a duct-in-duct solution installed in a chimney pot
    B. Dampers that restrict the buoyancy in a natural ventilation system out-of-hours in order to reduce energy use

The combination of case studies in this thesis show that, in order to conduct field measurements on the impact of renovation or maintenance measures, a set of prerequisites must exist, and the proper arrangements made (see section 4.7.1 for more on this). A need for a renovation or maintenance measure on a building should exist, the researchers need support, access, and help with communicating the research project to those affected by it, who also might need to give consent. The researchers also might need access to the premises to repair or replace faulty sensors, or support in doing so. An example of the impact of inaccessibility are the differences in measurements before and after implementation of the measure in case study 2. Inaccessibility to premises (apartments) before renovation caused large discrepancies between the measurements in the apartments before and after renovation, which made the data before renovation incomparable to the data after renovation.

For the research conducted in the case studies, hypotheses were formed, and parameters that were impacted on by the measure were derived, based on previous research on the measures and based on knowledge of the building as a system (see chapter 2). Field measurements were designed focusing on these parameters, and knowledge of the buildings' functionality (as well as knowledge of previous research) affected measurement details concerning the accuracy and precision of the measurements. In some case studies (1, 3, and 5) the field measurements were also designed to inductively answer questions that illuminate the extent of the impact of the measure. In case studies 2 and 4, this was also done through supplementary analyses. In one of the case studies (5), an induced reaction was needed in order to assess the system that was to be affected by the renovation measure.

In at least three case studies (1, 3, 5), comparisons with a control object were conducted in order to assess the impact of the measure on the affected object. In two of these studies (1, 3) the control object was not necessary for the analyses, but confirmed the conclusions based on analyses of measurements before and after the implementation of the renovation measure. In case study 2, no comparable control objects existed, while in case study 4 no control object was necessary since the measurements before and after the measure were instantaneous and conducted shortly after one another (within 1-2 hours). These comparisons enabled the definition of causal effects in each case study.

Three types of study setups can be identified from the analyses of the case studies, see the following three figures. These study setups were derived from the following.

- Case study 1 deployed setup 2 by comparing measurements in Lund (uninsulated) with those in Örebro (insulated), since setup 1 (Lund – before & after) could not be deployed due to deviations (sensor failure in Lund).
- Case study 2 deployed setup 2 through calculations on energy savings based on field measurements (DCV vs MVHR vs MEV), as well as comparisons of IEQ between apartments and comparisons with thresholds (CO_2, moisture supply). However, case study 2 also made use of control parameters (temperature and RH outdoors) for the calculation of the moisture supply.

- Case study 3 deployed setup 3 by comparing the renovated buildings as well as control buildings with themselves before renovation, and renovated buildings with control buildings after renovation.
- Case study 4 deployed setup 1 by comparing measurements on contaminated units with measurements on the same units shortly after cleaning. However, control parameters were not possible to measure in all units.
- Case study 5-A deployed setup 3 by comparing the renovated offices as well as control offices with themselves before renovation, and renovated offices with control offices after renovation.
- Case study 5-B deployed setup 2 by comparing renovated offices with control offices after implementation of the measure.

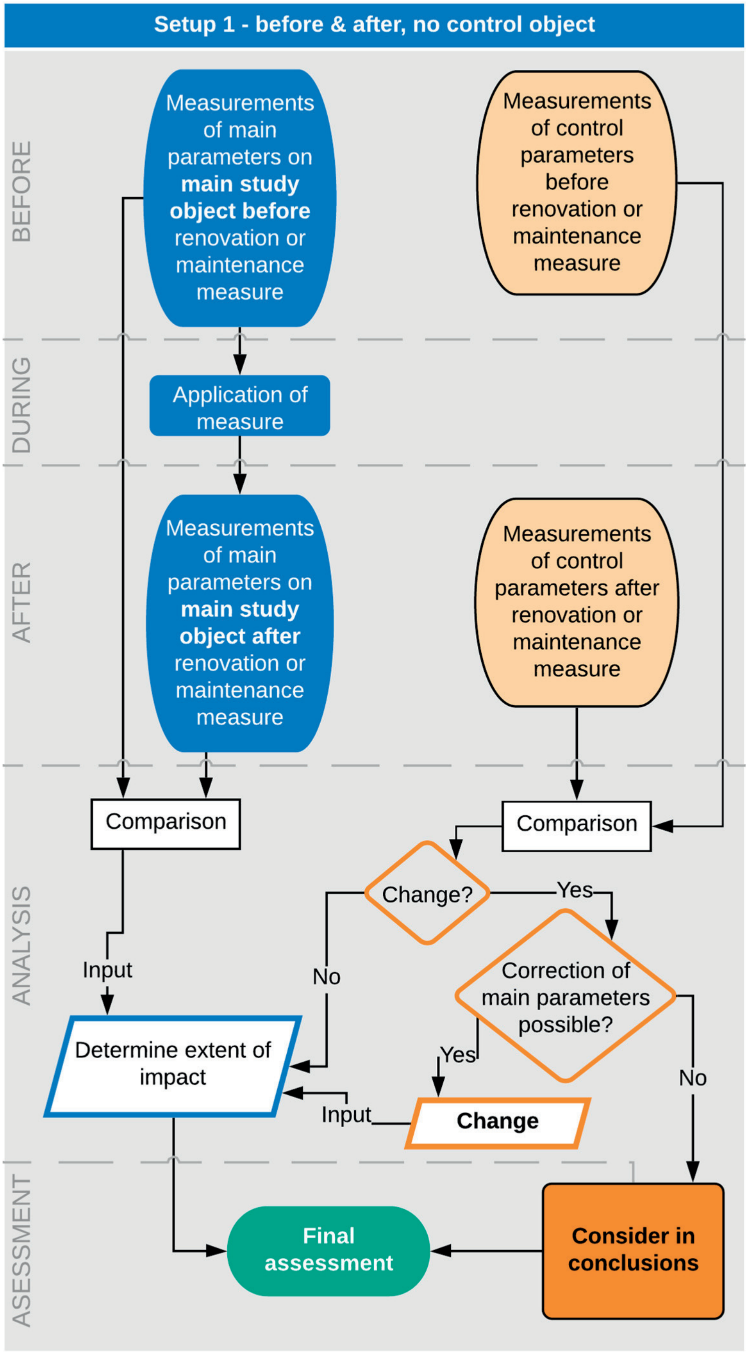

Figure 5.1: Study setup 1, used in case studies for determination of impact of renovation or maintenance measure.

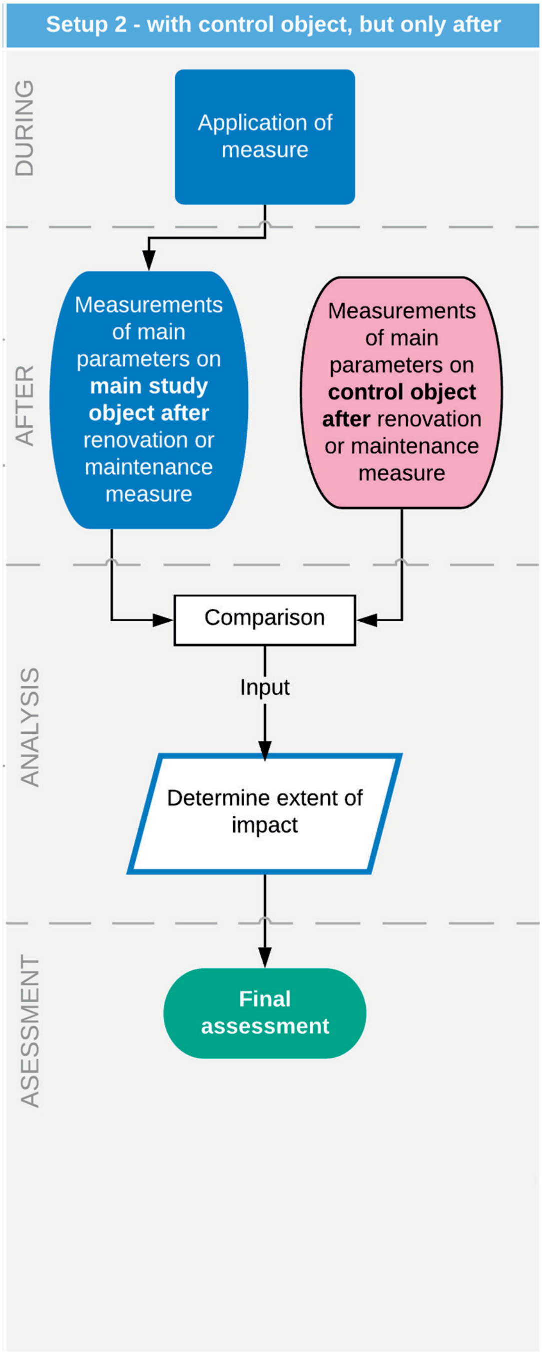

Figure 5.2: Study setup 2, used in case studies for determination of impact of renovation or maintenance measure.

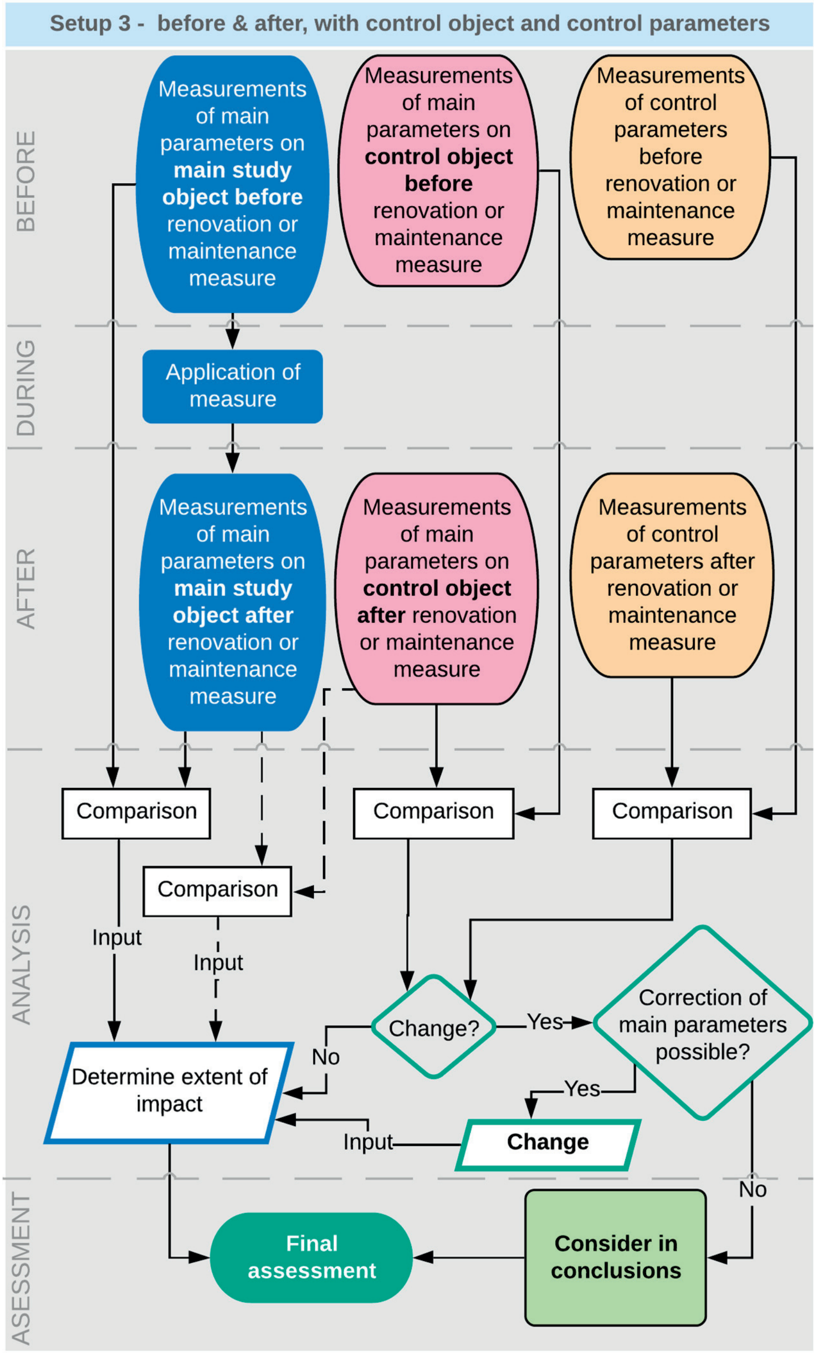

Figure 5.3: Study setup 3, used in case studies for determination of impact of renovation or maintenance measure.

Supplementary analyses were conducted in order to illuminate the impact of renovation measures but also to compensate for limitations, e.g. restricted access to the buildings. Furthermore, deviations out of the control of the researchers occurred in the field-measurement procedure, and measurement data, that were crucial for the determination of the impact that the measure had on the main parameters. These limitations and deviations were identified as:

1. Faulty sensors, and thereby lost data:
    a. Case study 1
        i. T & RH in the apartments, Örebro.
        ii. All sensors in Lund, after 9 months.
    b. Case study 2 – T & RH in outdoor air, caused the system to malfunction during the first months after installation.
2. Restricted access to the premises:
    a. Case study 1 – T & RH in the apartments, Örebro.
    b. Case study 2 – IAQ in apartments before renovation.
    c. Case study 3 – IAQ in apartments.
    d. Case study 4 – long-term measurements.
3. Limited impact (extent) of the measure:
    a. Case study 2 – on apartments connected through one staircase.
    b. Case study 5 – on the offices affected by the measures.
4. No available (relevant) control object:
    a. Case study 1 – for the assessment of different types of insulation.
    b. Case study 2 – due to ventilation (duct) design differences.
5. Disturbances or other interventions:
    a. Case study 3 – adjustment of the heating system between measurement periods.
6. Lack of information regarding events that might impact on the results:
    a. Case study 2 – events in the indoor climate.
    b. Case study 4 – type of activities in the buildings and the contaminant resulting thereof.
    c. Case study 4 – time since cleaning.

Some of these limitations and deviations were made redundant through the use of control objects (5-a) or other measurements (1-a-i, 1-b). However, in order to remedy most of the deviations and limitations, supplementary analyses were conducted in the form of calculations (3-a, 4-b), laboratory experiments (3-d, 6-a), literature reviews (3-d), simulations (1-a, 3-b, 4-a), and survey studies (2-c). Besides compensating for deviations, supplementary analyses were conducted in order to support field measurements, e.g. the IEQ-survey in case study 5.

Figure 5.4, illuminates the overall research process in the case studies with focus on field measurements. The figure is based on empirical data from the analysis of the procedures of the case studies included in this thesis. Besides illuminating the procedure for field measurements, and possibilities with the study setup, this thesis shows that it is important to consider the field measurement details. Following is a list of aspects to consider when planning a field measurement, including brief summaries of how they were considered:

- **Timespan.** In all case studies, an aim was to reduce seasonal variations by comparing measurement data acquired during the same season. Another aim in all case studies was to measure when space heating was required in order to achieve a comfortable indoor climate, since one of the derived impacts of all included measures was the reduction of energy use for this purpose. However, in three case studies measurements were also conducted during other seasons, which allowed the determination of other impacts that the measures had on the building. See section 4.7.3.1. This shows the benefit of measuring with a timespan that includes all seasons.
- **Accuracy.** The proximity to the true value of the main parameters that were assessed was considered in all the included studies, that aimed to conduct measurements as close to the point of impact of the measure as possible. In all case studies the proximity of the measurements to the true value were deemed sufficient to determine the true impact of the measure on a specific parameter through field measurements, except for case study 2 in which measurements before the implementation of the measure could not be conducted with a sufficient spatial resolution for a comparison with the measurements after. In the included case studies, the sensors were chosen depending on the limitations and premises of the study, the proximity to the true value, as well as with consideration of the financial resources of the study.
- **Precision.** In the included case studies, this depended largely on the choice of sensors, which relied on the possibility to access the premises, the possibility for remote access to the data, possible sources of electricity, and the financial resources. Nevertheless, considering these limitations, a priority in all case studies was to measure with as high interval as possible in order to increase the precision of the measurements and safeguard for unexpected events. Section 4.7.3.2 shows that the precision of the data logging (temporal resolution) should at least consider potential models that will be used for the analyses that are to be conducted, but also the risks (noise) with high temporal resolutions (short time intervals), as well as the risks (loss of peaks and valleys) with low temporal resolutions (long time intervals).

- **Induced reaction.** All but one case study, completely relied on naturally occurring events in the outdoor and indoor climate. In case study 5, the indoor climate was exposed to a high concentration of tracer gas, which enabled the calculation of the air change rates due to natural ventilation. This shows that it is likely that it is possible to measure the impact of a measure through naturally occurring events and activities – such as weather events or activities indoors.
- **Control object.** This was considered in all case studies, see p. 154-155.

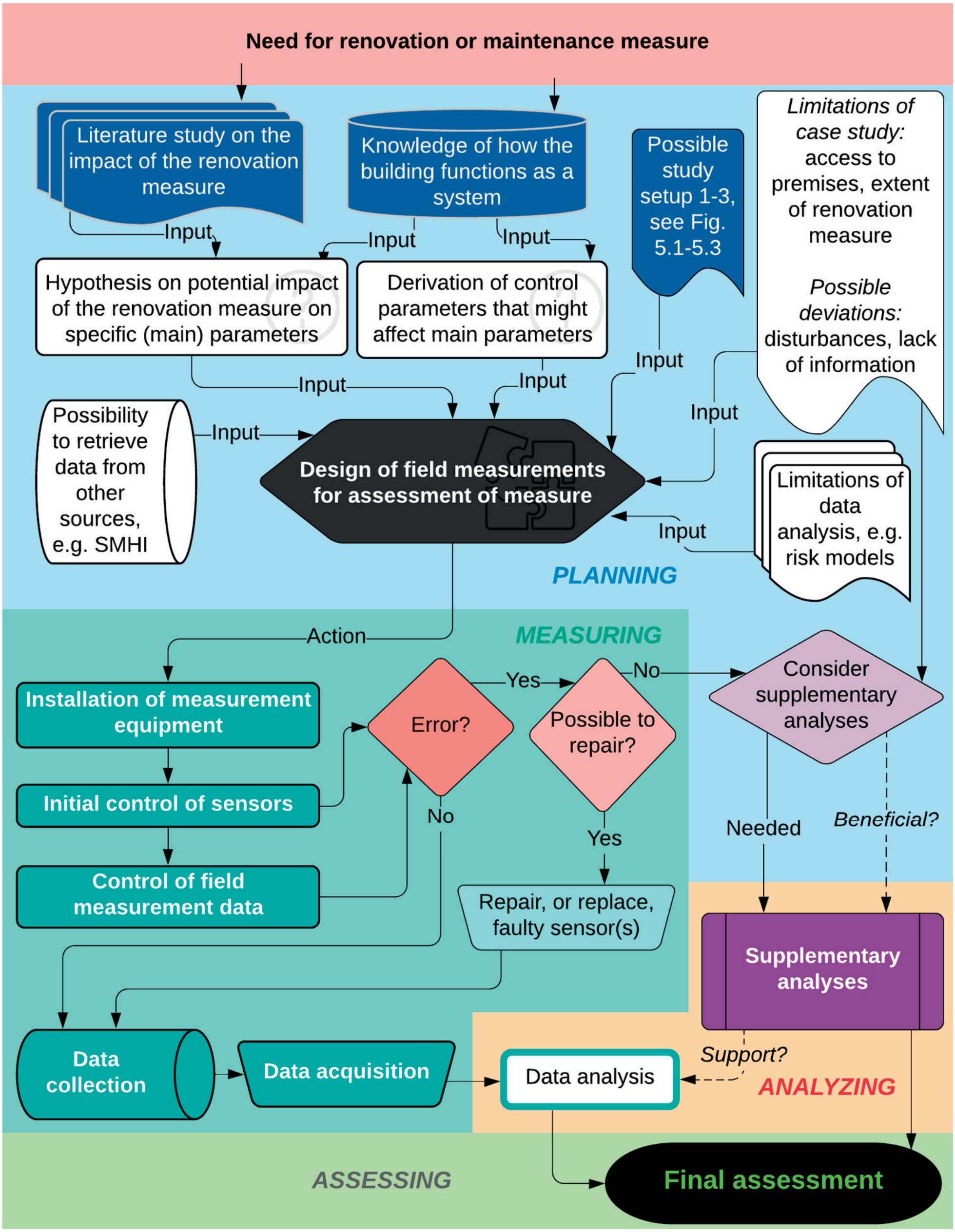

Figure 5.4: Process flow for the assessment of the impact that a renovation or maintenance measure has through field measurements.

6 Conclusions

This thesis presents the results and conclusions from the assessments of renovation and maintenance measures in five case studies, primarily through field measurements, in eight research articles. The case studies show that it is possible to assess the impact of a renovation or maintenance measure through field measurements, with accuracy. The renovation and maintenance measures that are included in this thesis are measures that are relevant for the renovation and maintenance of the Swedish building stock and are shown to have an impact on the energy use, indoor air quality and moisture safety in Swedish buildings.

- All measures reduce the energy used for space heating of the affected buildings (DCV>MVHR>dampers out-of-hours, reduction by other measures not determined).
- Three measures (DCV>MVHR>cleaning) are known or shown to achieve good, improve, or not diminish the indoor environmental quality (case studies 2-5).
- One of the measures (DCV) is also shown to reduce the moisture loads on the building materials (case study 2).
- Three measures (MVHR, cleaning, dampers) are shown to have no significant impact on the moisture loads (case study 3, 4 and 5).
- One of the measures (interior insulation, case study 1) is shown to entail increased risks of damage due to moisture (depending on the chosen solution).

The results and conclusions from the research conducted on the measures that are included in this thesis can be used:

- By property managers, when deciding which renovation measures to implement on their buildings.
- By property managers, for the preservation of the performance of the building service equipment through maintenance.
- By consultants when considering renovation measures for a specific building in the design process.
- By the partnering companies that allowed research to be conducted on their premises, or otherwise supported the research projects.
- By society in large, when making policy and regulations.

This thesis illuminates the overall process for assessments of renovation and maintenance measures through field measurements, the analyses that were made based on these measurements in order to show causation, the deviations that occurred throughout these procedures, the limitations that existed in the case studies, as well as the supplementary analyses that were made in order compensate for the deviations and limitations. This thesis shows that data acquisition through field measurements in buildings may require long timespans (four out of five studies) of weeks, months or maybe even years, in order to determine the impact of a measure. This thesis also shows that the internal validity of the results partially relies on the study setup, and that the "choice" (or possibility) of setup is highly dependent on the limitations of the premises. Experiences from the case studies show that research including field measurements require careful planning, and coordination with contacts at partnering actors. They further show that a number of impediments (deviations) are likely to occur in field research, e.g. faulty sensors, which require the researchers to stay alert and to regularly check up on the installed measurement equipment as well as keep updated with the property manager or owner on events regarding the buildings. However, the thesis shows that even then it is likely that supplementary analyses are required in order to deal with uncertainties due to limitations or deviations in a case study, or in order to answer questions regarding details relevant to the impact of the measure. Furthermore, in field measurements on measures that impact on the IEQ, the thesis shows that it should be beneficial to also conduct a survey with the inhabitants (or occupants), since survey responses can support conclusions made based on the field measurements. Other types of analyses can also be conducted for supportive reasons, i.e. laboratory experiments, calculations, or simulations.

The process of field measurements that is identified in this thesis should be possible to deploy as a road map in future studies with focus on field measurements. This since the process flow is based on empirical data from the analysis of the included case studies, and the limitations and deviations that affected them, as well as the remedies to the consequences of these. However, one should mind that the identification of this process is limited to the included case studies, and that every case study is unique. Due to this limitation, the identified process flow probably does not encompass all variations of case studies on renovation or maintenance measures based on field measurements. It is possible that the process flow would look different if it was based on other case studies and other measures, and even other researchers. Therefore, future research on this topic should include more case studies, and case studies conducted by other researchers, in order to develop and expand the extent and nuance of the identified process flow. However, an exhaustive method for the assessment of renovation and maintenance measures through field measurements, that covers all aspects and all details that need to be considered when designing and conducting field measurements, would probably require a detail level that would make it inefficient. The process flow that is identified in this thesis, partly relies on the researcher's expertise and competence to conduct field measurements. To some extent, the researcher must have knowledge of how the building functions as a system and what might affect the results in an assessment, in order to succeed in similar assessments.

The hope of the author is that future case studies of similar nature, i.e. with focus on assessments through field measurements, are aided in the design and execution through the identified process flow and the knowledge gained from the empirical data gained through the analysis of the combination of the included case studies. Thus, the author hopes to increase the reliability of data produced on the impact of renovation and maintenance measures.

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APPENDIX A – More on case studies

A1 Case study 1 – Insulation on SBM walls

Renovation of multifamily building, Örebro

Figure A1.1: Exterior masonry wall in an apartment during renovation.

Figure A1.2: Beneath floorboards in living room during renovation.

Figure A1.3: Mold growth in internal insulation layer of an exterior masonry wall.

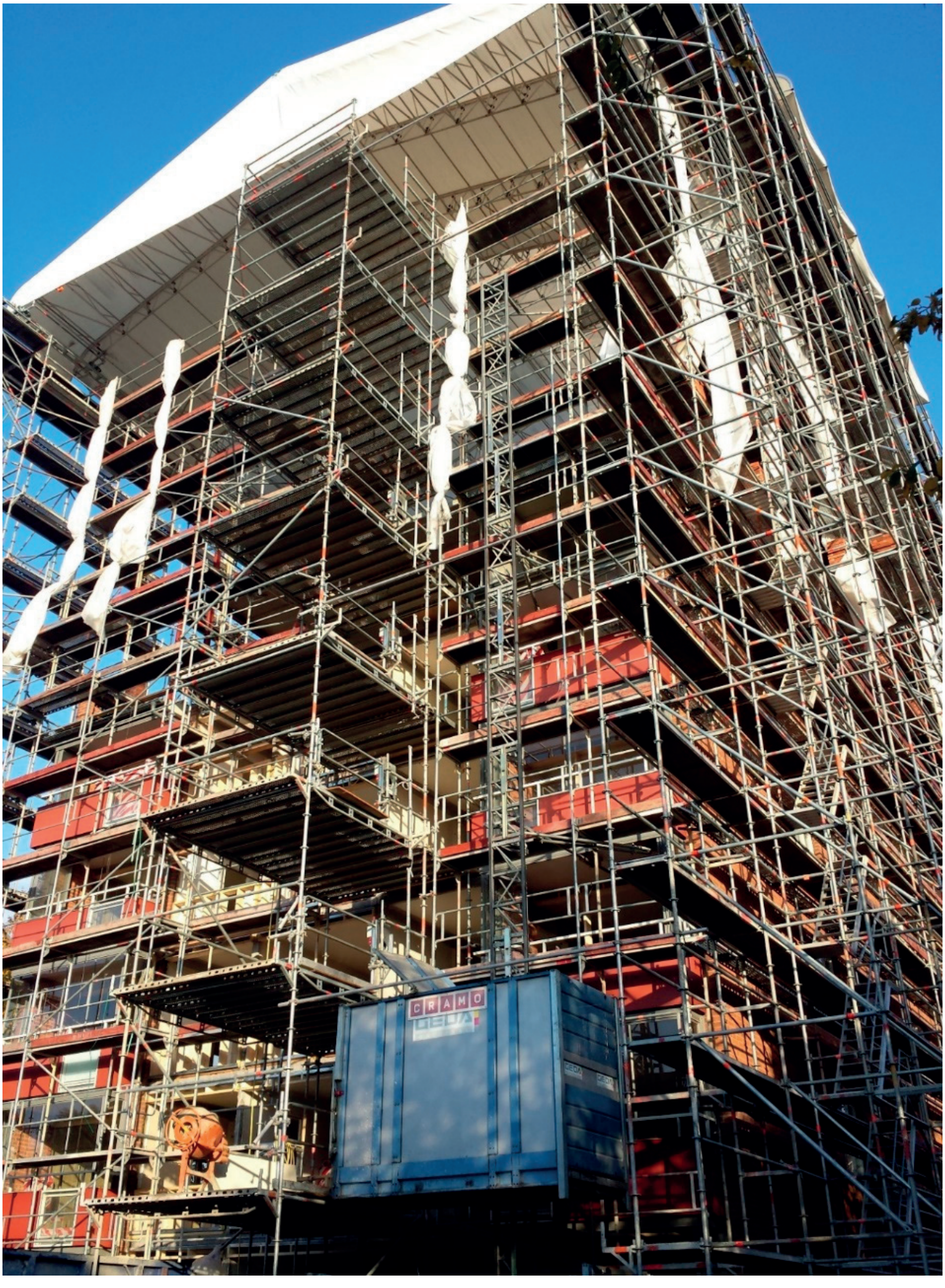

Figure A1.4: Example of weather protection during renovation.

Measurement equipment installation, Örebro

Figure A1.5: Sensor installation behind new internal insulation with steel studs.

Figure A1.6: Sensor installation on both sides of vapor barrier applied with new internal insulation with steel studs.

Figure A1.7: Taken from Melorose 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.

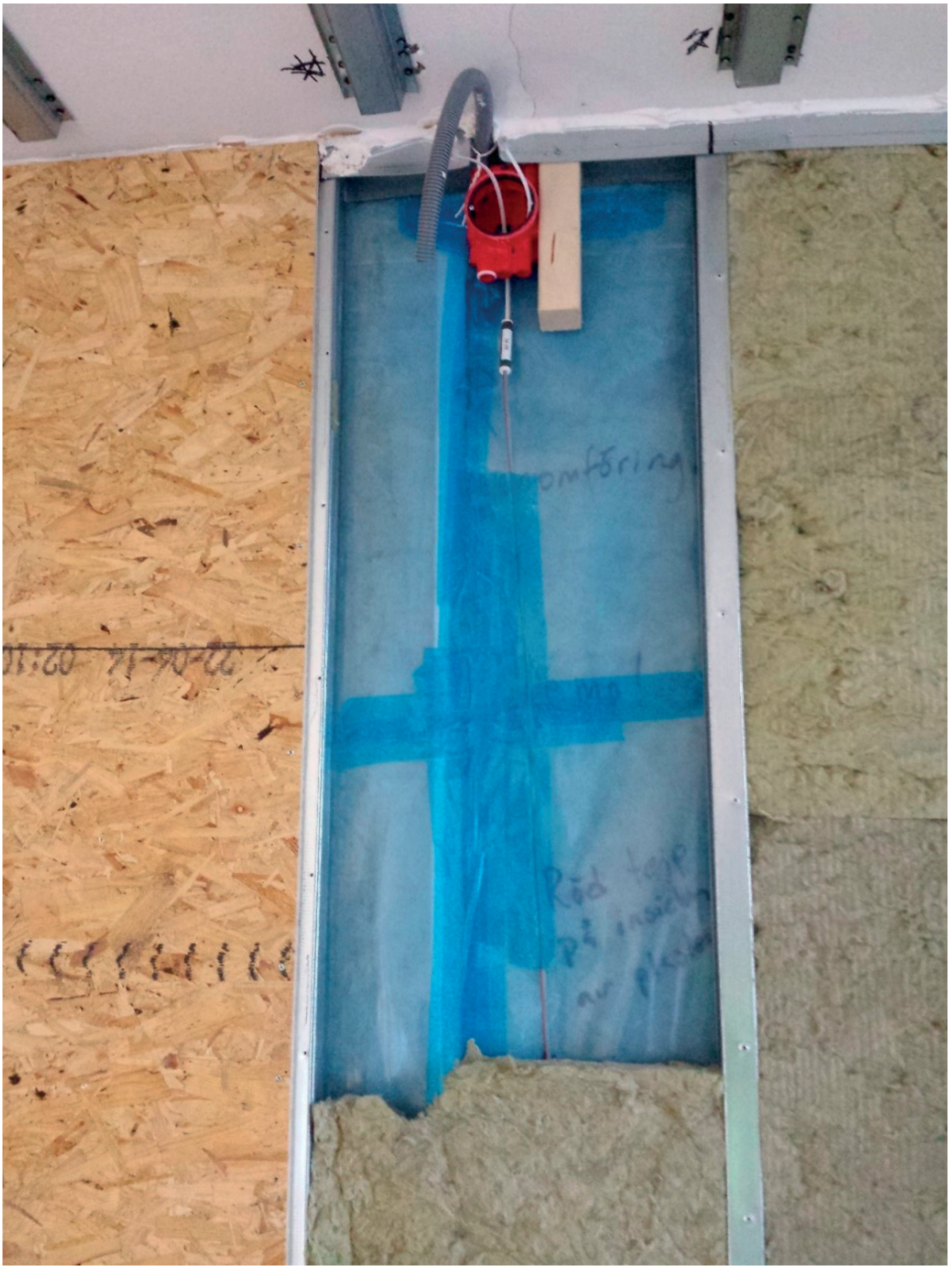

Figure A1.9: Sensor installation on both sides of vapor barrier applied with new internal insulation with steel studs.

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 A1.1: Monthly average climate data from METEONORM 7, showing typical weather in Lund for a normal year based on a 10-year period.

Month	Glo. Rad. Horiz., kWh/m^2	Dir. Nor. Rad. kWh/m^2	Air Temp /°C	Rel. Hum. /%	Wind Sp. /ms^{-1}	Wind Dir. /°	Prec. /mm
Jan	20	6.4	1.1	88	4.8	270	38
Feb	42	6.2	0.9	86	4.6	90	30
Mar	93	5.9	2.6	80	4.5	90	33
Apr	164	4.6	7.3	71	4.0	90	21
May	216	4.4	11.9	70	3.8	90	41
Jun	229	4.8	15.1	71	4.0	270	51
Jul	223	4.7	17.8	72	3.5	270	64
Aug	179	5.0	17.4	76	3.6	270	70
Sep	118	5.5	13.7	79	3.8	270	28
Oct	62	6.0	9.2	85	3.9	270	54
Nov	24	6.3	5.6	86	4.4	270	52
Dec	13	6.8	2.3	89	4.3	270	47
Year	115	5.5	8.7	79	4.1	270	529

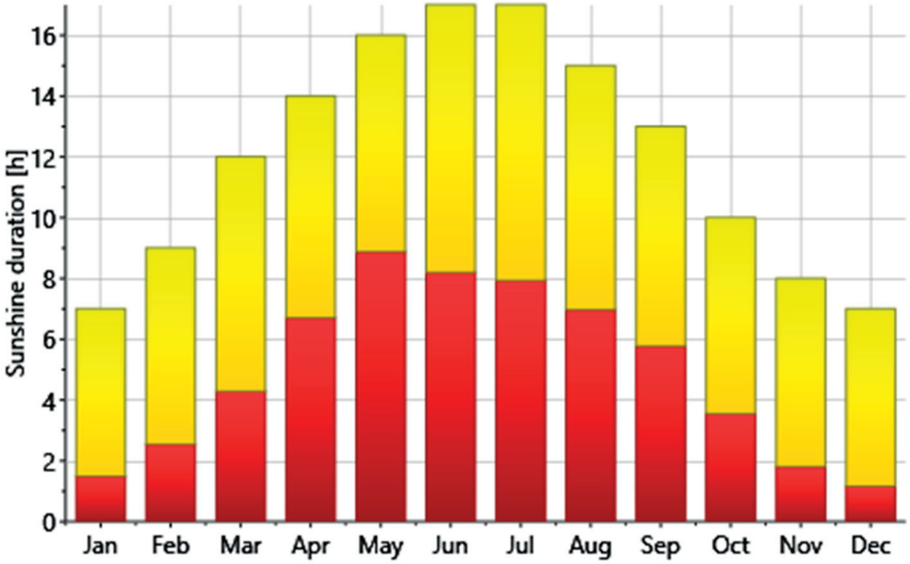

Figure A1.10: Sunshine duration from METEONORM 7, showing typical sunshine duration in Lund for a normal year based on a 10-year period.

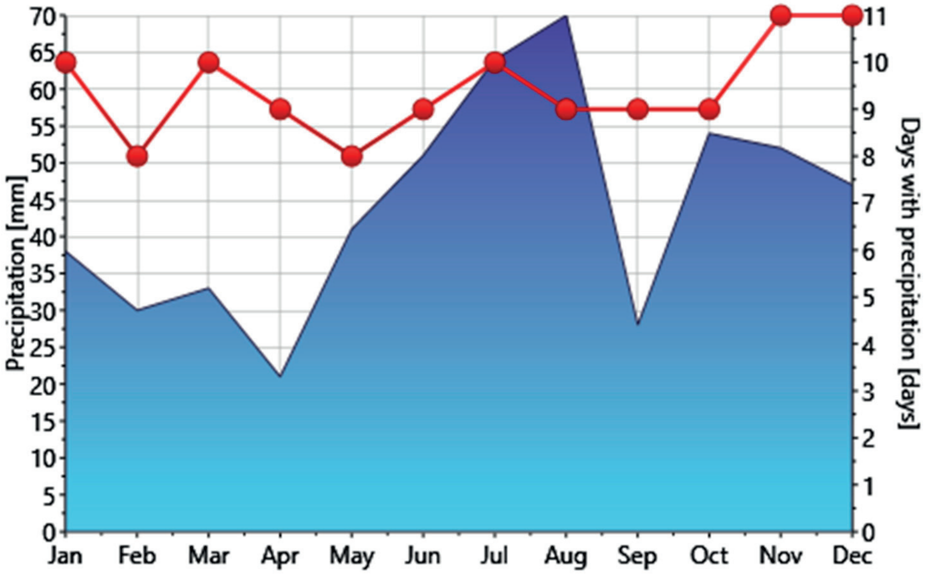

Figure A1.11: Precipitation from METEONORM 7, showing typical precipitation in Lund for a normal year based on a 10-year period.

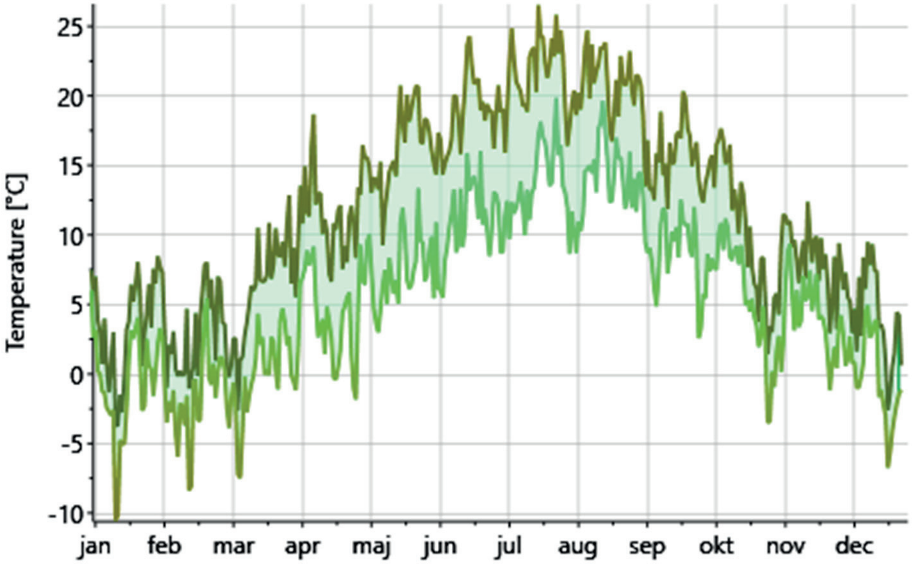

Figure A1.12: Temperature data from METEONORM 7, showing typical temperatures in Lund for a normal year based on a 10-year period.

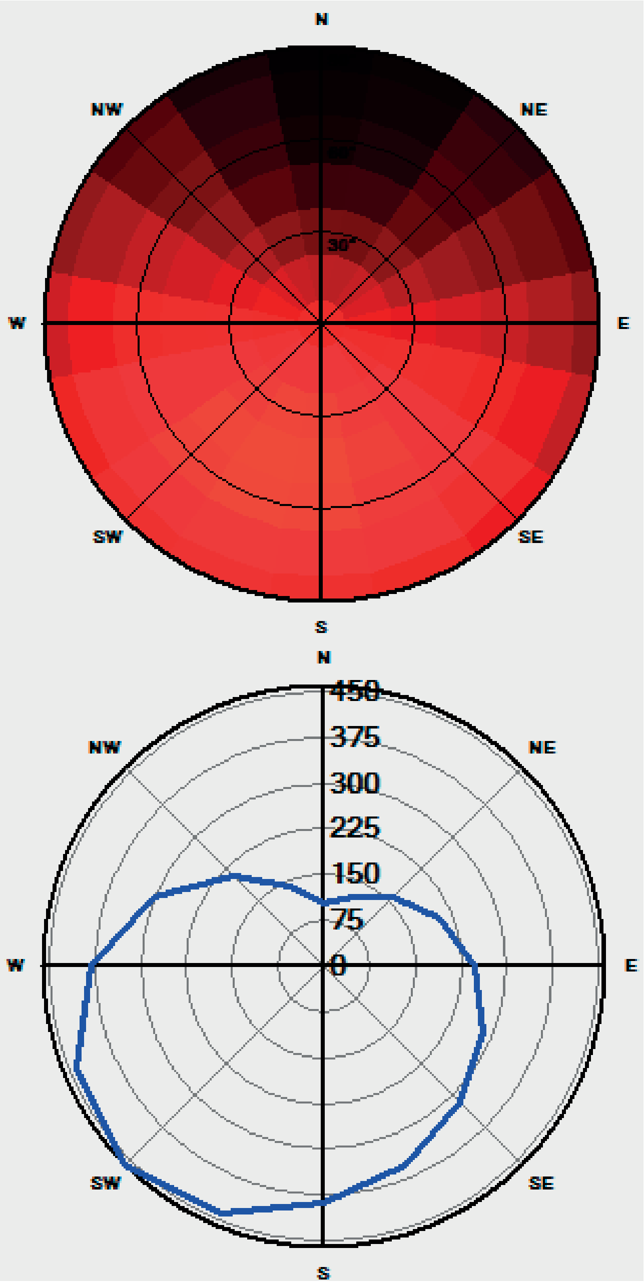

Figure A1.13: WUFI analysis of solar radiation and precipitation in Lund in 2014. The brighter color in the left figure indicates a larger annual solar radiaton sum, showing stronger intensities in the south than in the north or the west.

Örebro climate

Situated 35 m above sea level.

Table A1.2: Monthly average climate data from METEONORM 7, showing typical weather in Örebro for a normal year based on a 10-year period.

Month	Glo. Rad. Horiz., kWh/m²	Dir. Nor. Rad. kWh/m²	Air Temp /°C	Rel. Hum. /%	Wind Sp. /ms⁻¹	Wind Dir. /°	Prec. /mm
Jan	10	7.0	-1.6	80	3.5	71	29
Feb	31	6.6	-2.2	79	3.2	71	19
Mar	88	5.9	0.2	71	3.2	71	17
Apr	160	4.7	5.9	64	3.0	71	17
May	204	4.8	11.3	64	3.2	71	30
Jun	235	4.8	15.0	66	3.0	71	42
Jul	219	4.8	17.3	73	2.6	71	63
Aug	151	6.0	16.3	75	2.6	71	58
Sep	107	5.7	11.6	77	2.9	71	30
Oct	47	6.4	6.6	83	2.8	71	52
Nov	14	6.7	2.4	83	3.1	71	41
Dec	6	7.8	-0.1	82	3.4	71	32
Year	106	5.9	6.9	75	3.0	71	430

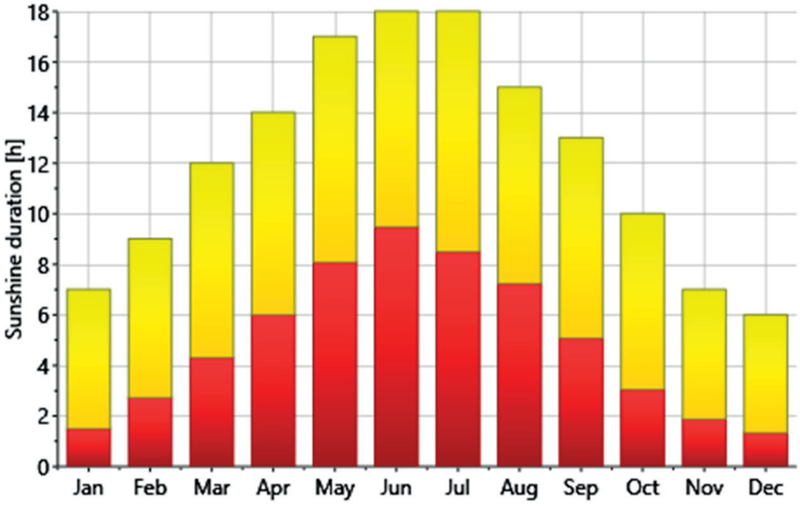

Figure A1.14: Sunshine duration from METEONORM 7, showing typical sunshine duration in Örebro for a normal year based on a 10-year period.

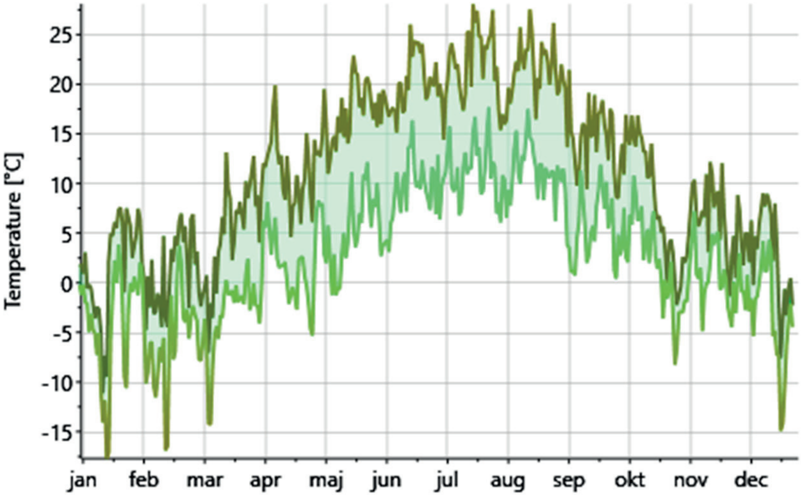

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Figure A1.15: Temperature from METEONORM 7, showing typical temperature in Örebro for a normal year based on a 10-year period.

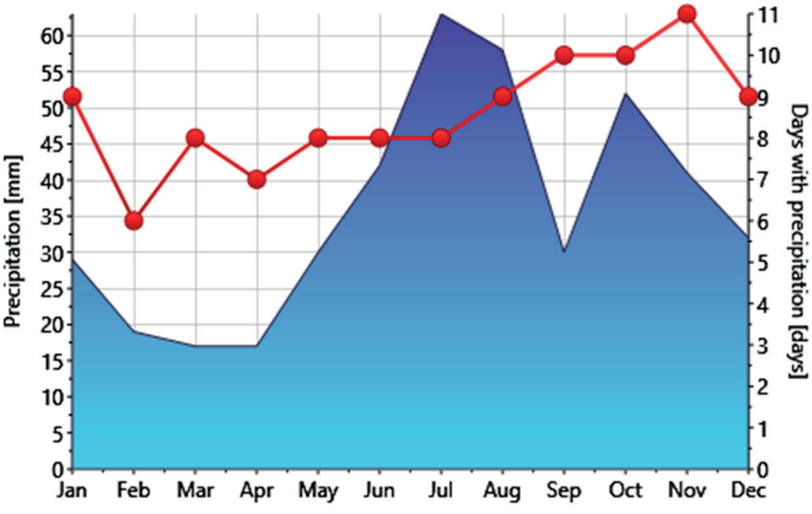


Figure A1.16: Precipitation from METEONORM 7, showing typical precipitation in Örebro for a normal year based on a 10-year period.

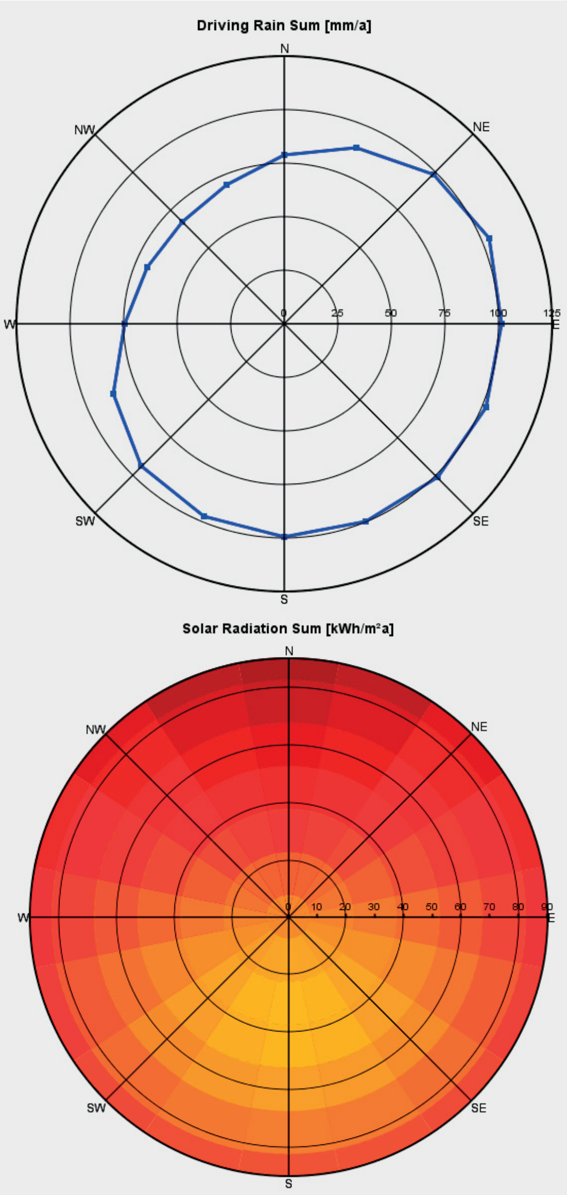


Figure A1.17: WUFI-analysis of typical wind driven rain in and solar radiation Örebro, based on statistically assembled data in METEONORM 7.

Additional results used for analyses in Paper 5

Lund

Table A1.3: Sensors placed in the southern and western attic walls of the V-building at the Faculty of Engineering, Lund University. Sensor name, climate surrounding the sensor, and depth in wall from the interior to the exterior.

Name	Climate	Depth (mm)
S-B1	Brick	197
S-B2	Brick	287
S-B3	Brick	331
S-M1	Mortar	202
S-M2	Mortar	295
S-M3	Mortar	325
W-B1	Brick	200
W-B2	Brick	277
W-B3	Brick	329
W-M1	Mortar	198
W-M2	Mortar	287
W-M3	Mortar	329
s	Indoor air	Not in wall

*Table A1.4: Sensors placed in the northern wall of the V-building at the Faculty of Engineering, Lund University. Sensor name, climate surrounding the sensor, and depth in wall from the interior to the exterior. *Note: the order of depth differs on these.*

Name	Climate	Depth (mm)
NL-B1	Brick	203
NL-B2	Brick	285
NL-B3	Brick	328
NL-M1	Mortar	*280**
NL-M2	Mortar	*325**
NL-M3	Mortar	*215**
NR-M1	Mortar	205
NR-M2	Mortar	280
NR-M3	Mortar	325
NR-B1	Brick	205
NR-B2	Brick	276
NR-B3	Brick	328
n	Indoor air	Not in wall

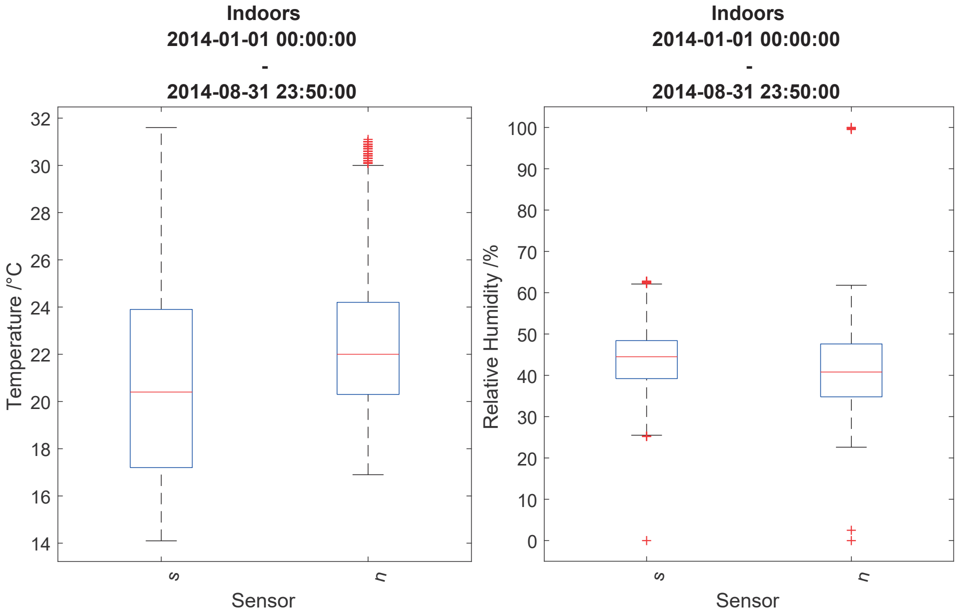
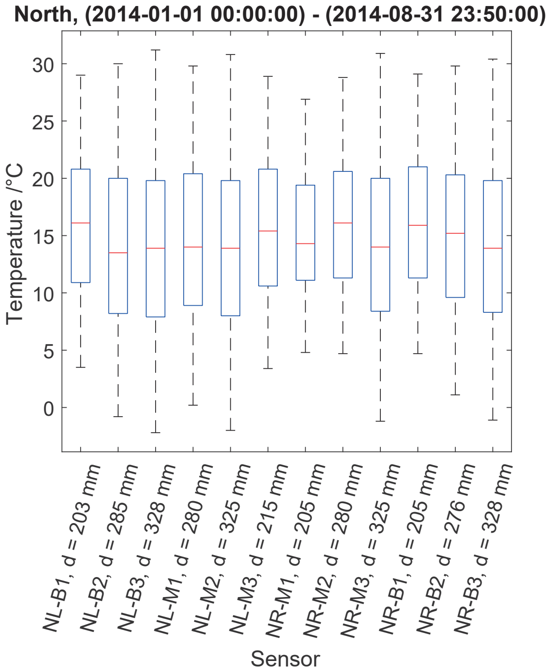


Figure A1.18: Boxplots on measured temperature and relative humidity for indoor sensors in the V-building's attic. Showing 25th percentile, median, 75th percentile, whiskers (1.5 x interquartile range) and outliers. Note that the southern indoor air sensor is also very close to the western wall setup, thus the indoor environmental conditions registered by this sensor also applied for the western wall.



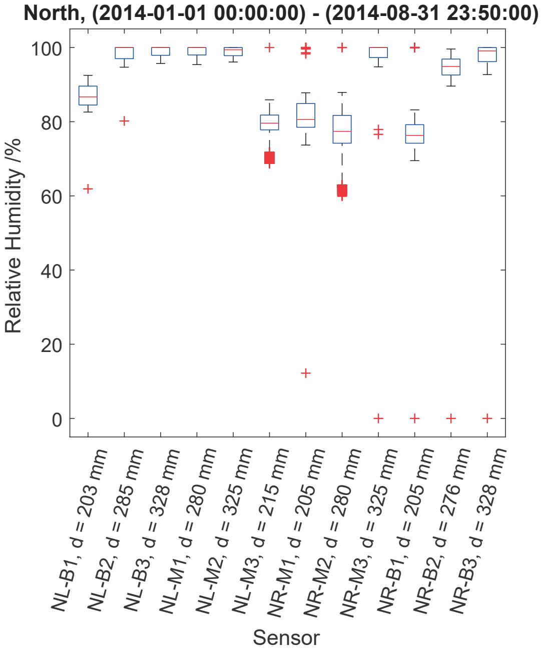


Figure A1.19: Boxplots on measured T and RH for northern sensors in the V-building's attic wall.

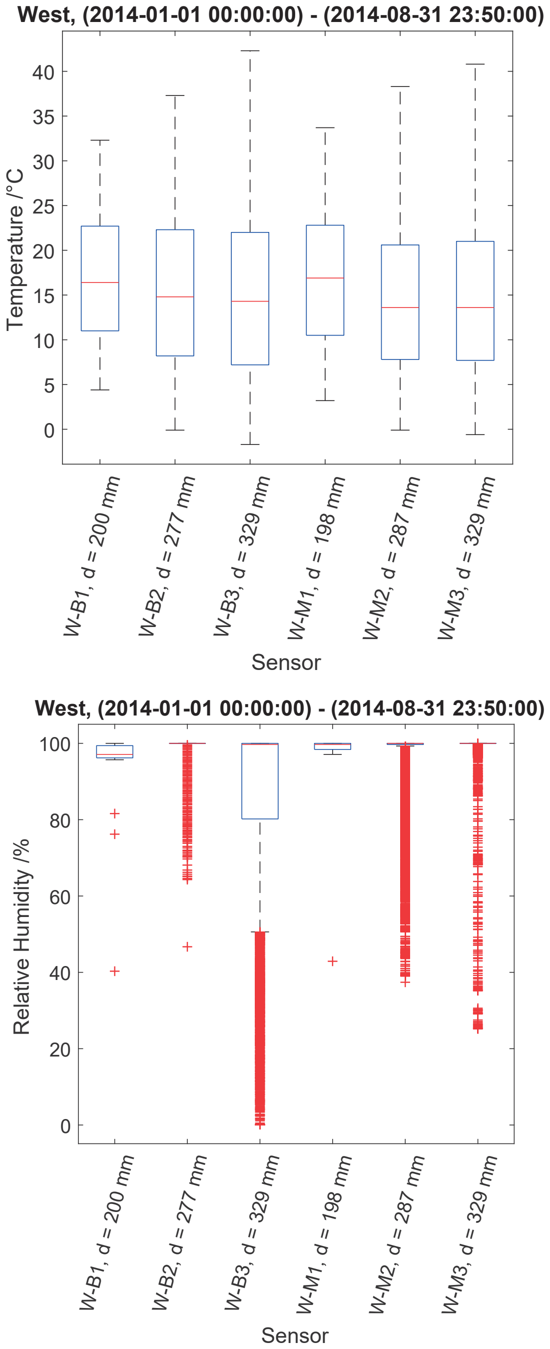


Figure A1.20: Boxplots on measured RH for western sensors in the V-building's attic wall.

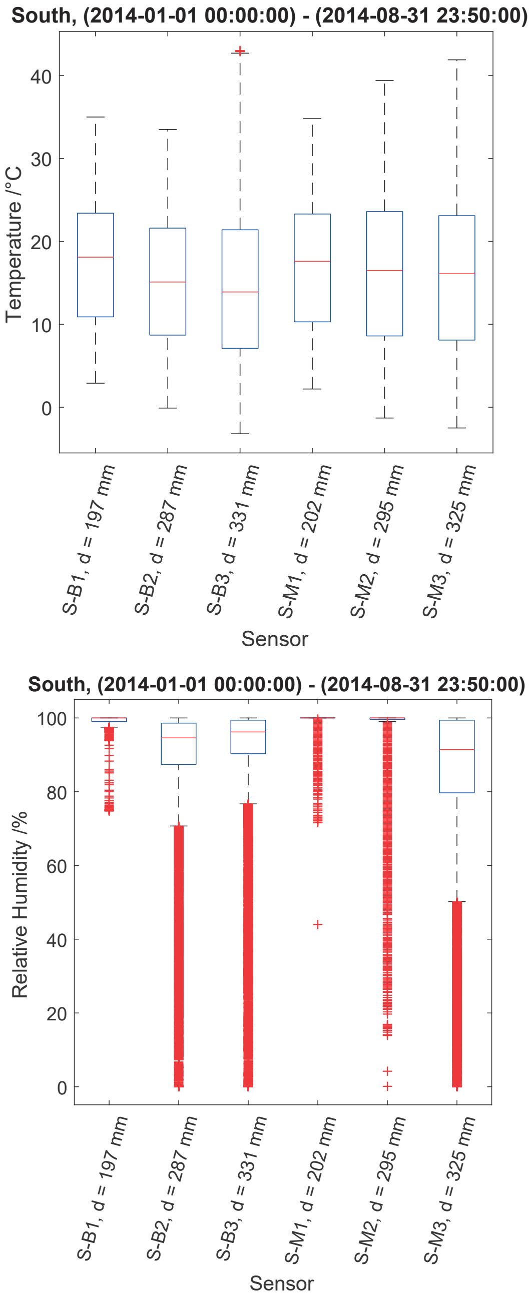


Figure A1.21: Boxplots on measured RH for southern sensors in the V-building's attic wall. Showing 25th percentile, median, 75th percentile, whiskers (1.5 interquartile range) and outliers. S=South, B=Brick, M=Mortar.

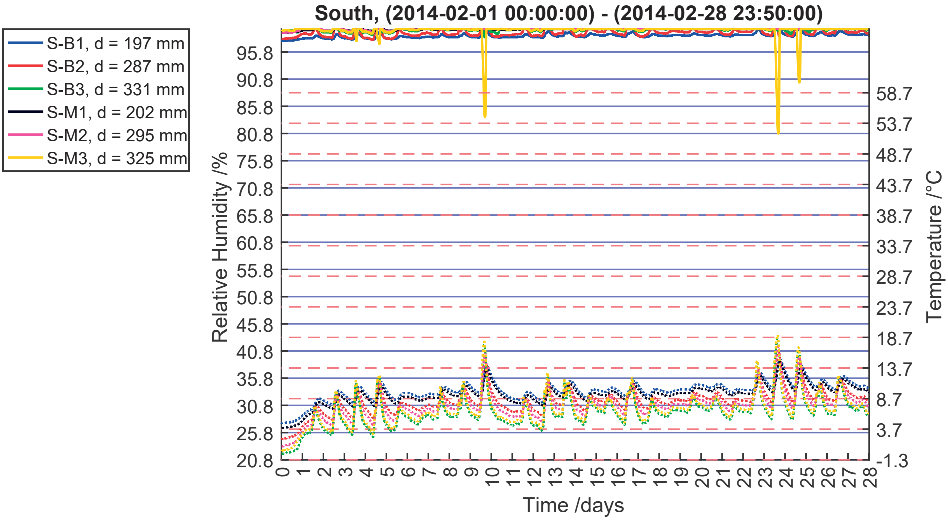


Figure A1.22: Temperature and relative humidity registered in the southern wall for a winter month. Dotted lines represent T. S='south', B='brick', M='mortar', number=order of placement from the interior surface.

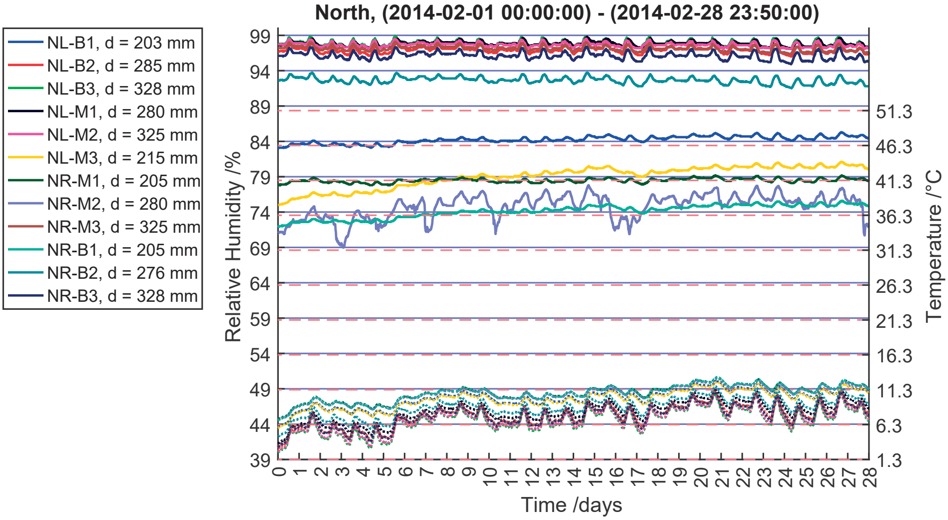


Figure A1.23: Temperature and relative humidity registered in the northern wall for a winter month. Dotted lines represent T. N='north', L='left placement', R='right placement', B='brick', M='mortar', number=order of placement from the interior surface.

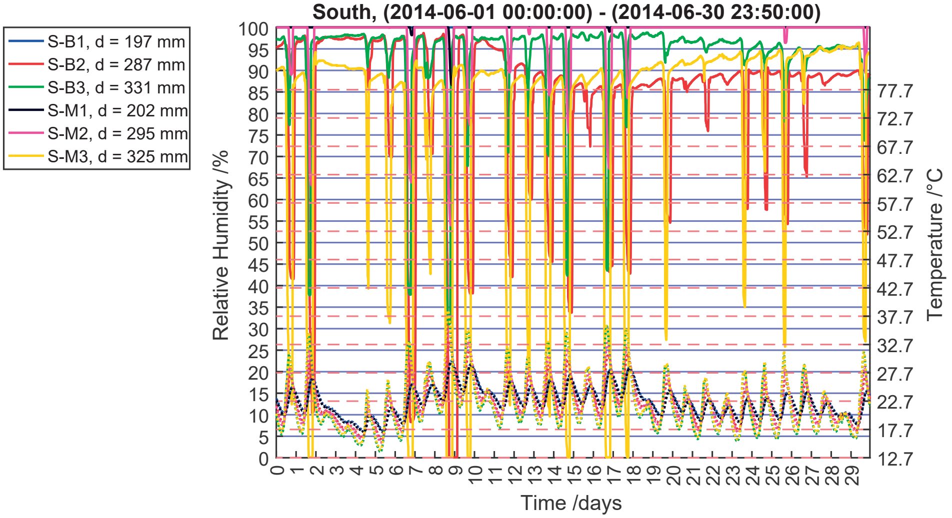


Figure A1.24: Temperature and relative humidity registered in the southern wall for a summer month. Dotted lines represent T. S='south', B='brick', M='mortar', number=order of placement from the interior surface.

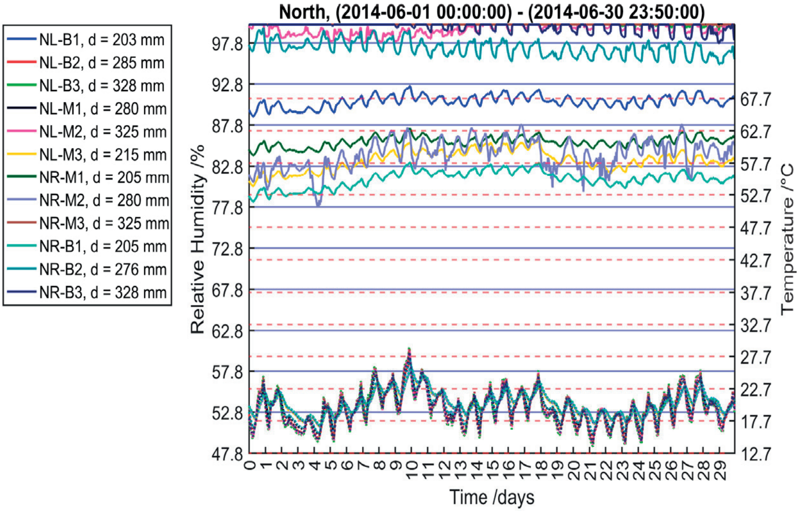


Figure A1.25: Temperature and relative humidity registered in the northern wall for a summer month. Dotted lines represent T. N='north', B='brick', M='mortar', number=order of placement from the interior surface.

Örebro

*Table A1.5: Sensors placed in Karmen 15, in the northern wall on the second floor. Sensor name, climate surrounding the sensor, and depth in wall. *Depth shown in mm into the material from the interior surface of the brick to the exterior.*

Name	Climate	Depth (mm)*
N2-B1	Brick	87
N2-B2	Brick	151
N2-B2	Brick	203
N2-Ca	Cavity air	In cavity
N2-FO	Outside air	On the facade
N2-M1	Mortar	83
N2-M2	Mortar	160
N2-M2	Mortar	212
N2-BI	Air/ Mineral Wool	Inside face of vapor barrier
N2-BO	Air/ Mineral Wool	Outside face of vapor barrier

*Table A1.6: Sensors placed in Karmen 15, in the northern wall on the second and fifth floor. Sensor name, climate surrounding the sensor, and depth in wall. *Depth shown in mm into the material from the interior surface of the brick to the exterior.*

Name	Climate	Depth (mm)*
N5-B1	Brick	85
N5-B2	Brick	153
N5-B2	Brick	205
N5-Ca	Cavity air	In cavity
N5-FO	Outside air	On the facade
N5-M1	Mortar	83
N5-M2	Mortar	160
N5-M2	Mortar	205
N5-BI	Air/ Mineral Wool	Inside face of vapor barrier
N5-BO	Air/ Mineral Wool	Outside face of vapor barrier

*Table A1.7: Sensors placed in Karmen 15, in the southern wall on the second floor. Sensor name, climate surrounding the sensor, and depth in wall. *Depth shown in mm into the material from the interior surface of the brick to the exterior.*

Name	Climate	Depth (mm)*
S2-B1	Brick	80
S2-B2	Brick	155
S2-B2	Brick	210
S2-Ca	Cavity air	In cavity
S2-FO	Outside air	On the facade
S2-M1	Mortar	80
S2-M2	Mortar	155
S2-M2	Mortar	210
S2-BI	Air/ Mineral Wool	FAILED
S2-BO	Air/ Mineral Wool	Outside face of vapor barrier

*Table A1.8: Sensors placed in Karmen 15, in the southern wall on the fifth floor. Sensor name, climate surrounding the sensor, and depth in wall. *Depth shown in mm into the material from the interior surface of the brick to the exterior.*

Name	Climate	Depth (mm)*
S5-B1	Brick	90
S5-B2	Brick	150
S5-B2	Brick	205
S5-Ca	Cavity air	In cavity
S5-FO	Outside air	On the facade
S5-M1	Mortar	80
S5-M2	Mortar	155
S5-M2	Mortar	210
S5-BI	Air/ Mineral Wool	Inside face of vapor barrier
S5-BO	Air/ Mineral Wool	Outside face of vapor barrier

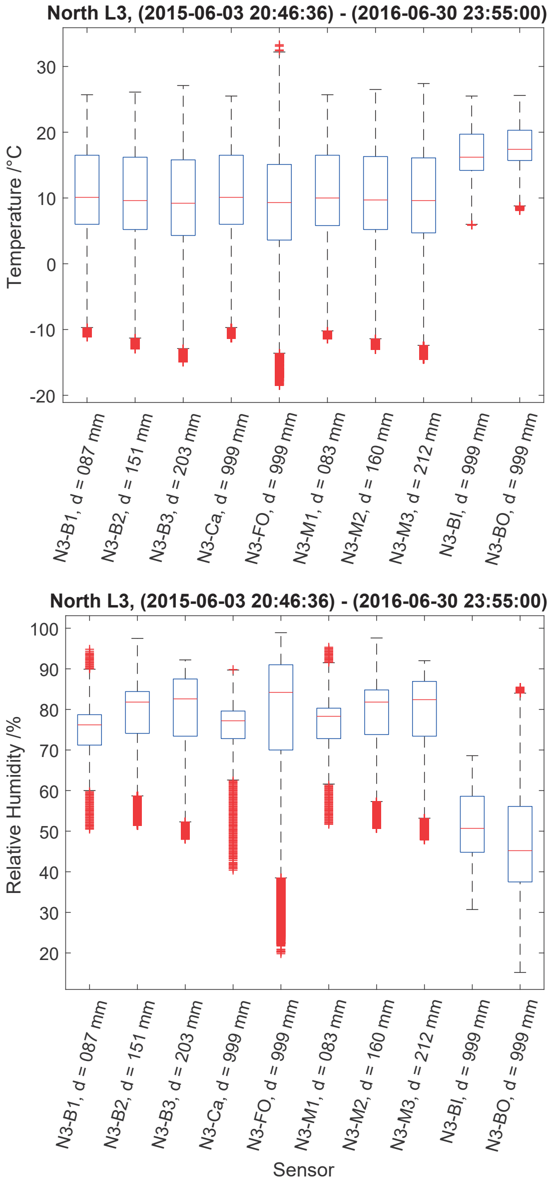


Figure A1.26: Boxplots on measured T and RH for sensors in the northern wall on level 3. Showing 25th percentile, median, 75th percentile, whiskers (1.5 × interquartile range) and outliers. N = North, FO= façade exterior surface, B = brick, M = mortar, Ca = cavity, BO = barrier exterior surface, BI = barrier interior surface.

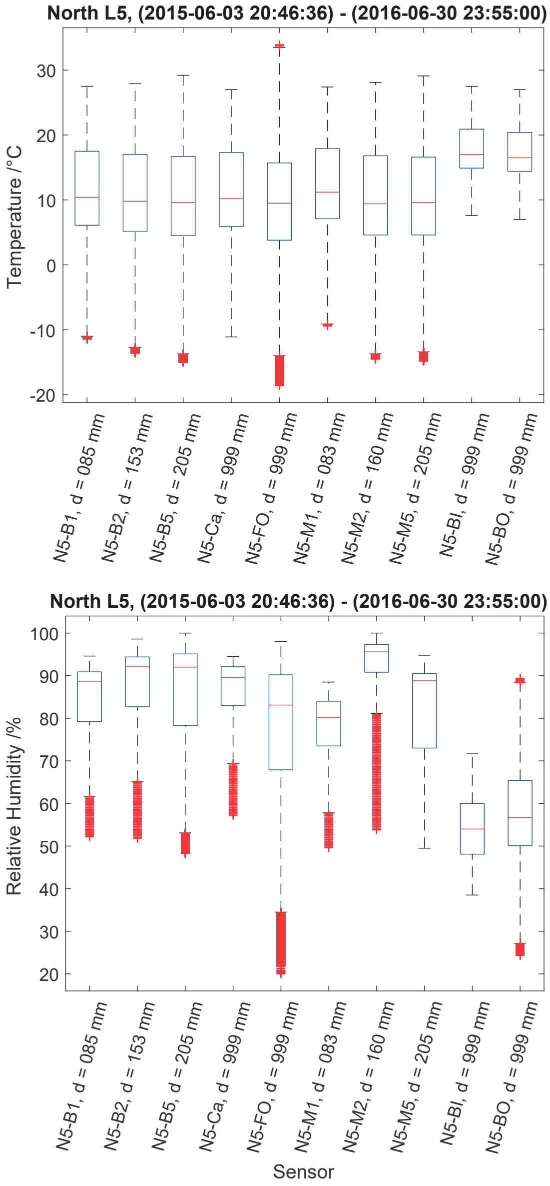


Figure A1.27: Boxplots on measured T for sensors in the northern wall on level 5 and southern wall on level 3. See Figure for details.

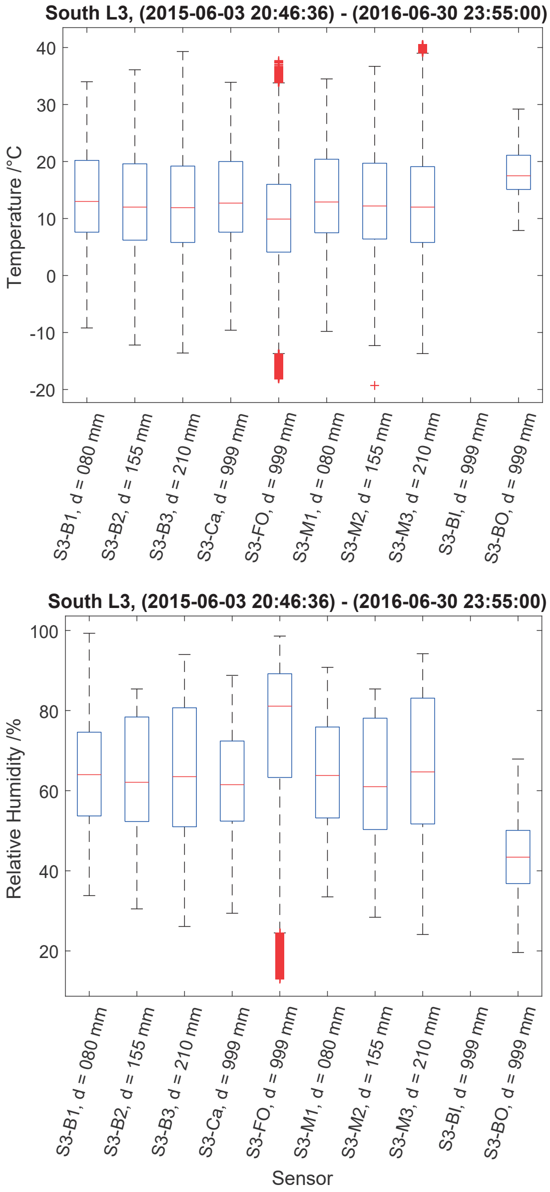


Figure A1.28: Boxplots on measured RH for sensors in the southern wall on level 3. See Figure for details.

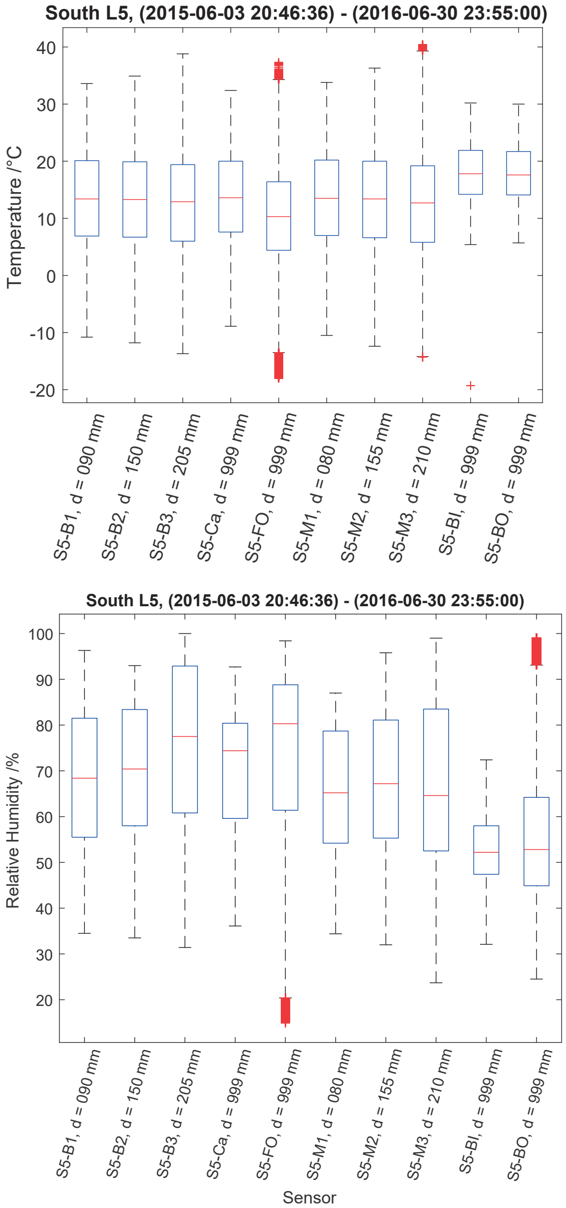


Figure A1.29: Boxplots on measured T for sensors in the southern wall on level 5. Showing 25th percentile, median, 75th percentile, whiskers (1.5 x interquartile range) and outliers. N = North, S = South, FO= façade exterior surface, B = brick, M = mortar, Ca = cavity, BO = barrier exterior surface, BI = barrier interior surface.

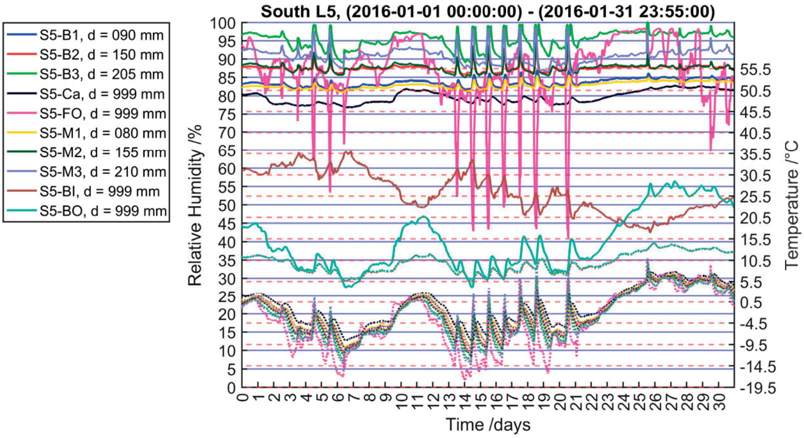


Figure A1.30: Temperature and relative humidity registered in the southern wall for a winter month. Dotted lines represent T. S='south', B='brick', M='mortar', 'Ca'=cavity, 'FO'=facade, 'BO'=barrier's exterior surface, 'BI'=barrier's interior surface, number=order of placement from the interior surface.

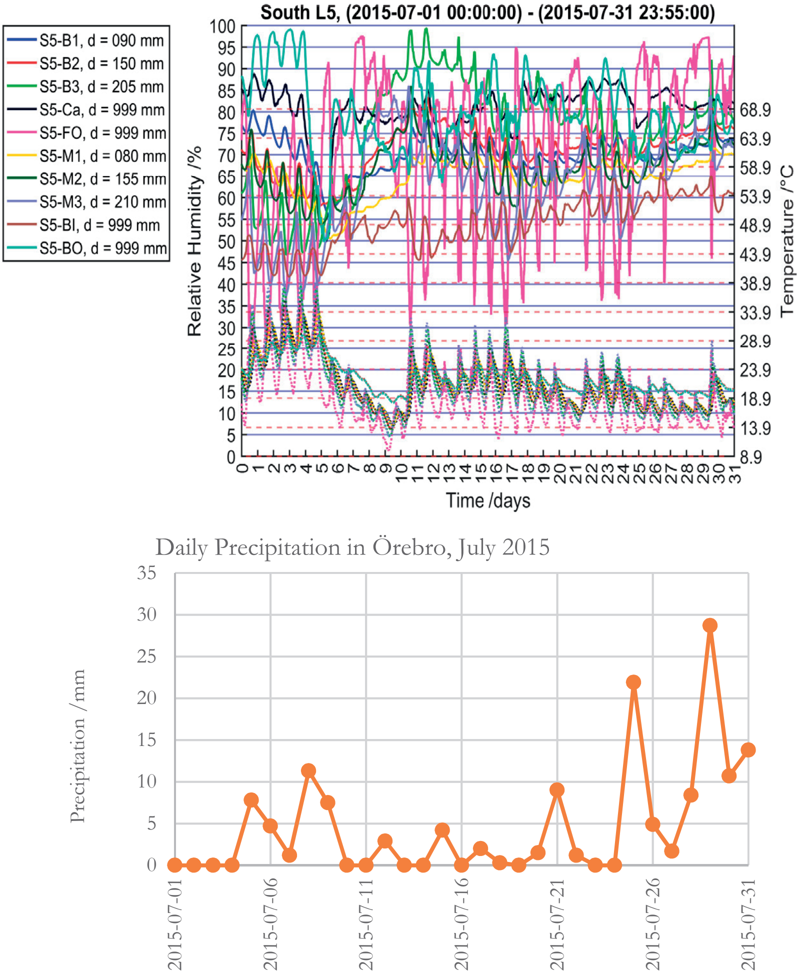


Figure A1.31: Temperature and relative humidity registered in the southern wall for a summer month. Dotted lines represent T. Daily precipitation for Örebro in July 2015.

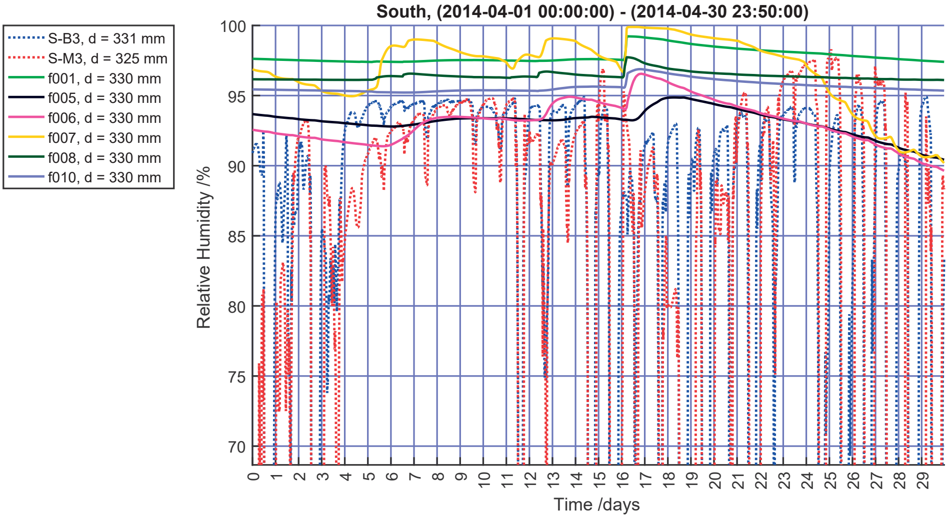


Figure A1.32: Measured vs simulated RH for April 2014, at approximately 330 mm depth.

A2 Case study 2 – DCV in multifamily buildings

Figure A2.1: Picture of distribution box in hallway during installation.

Figure A2.2: Picture of sensor and damper box in hallway during installation.

Figure A2.3: Picture of supply and exhaust air ducts in apartment during installation.

Figure A2.4: Picture of covered ducts inside apartments after installation.

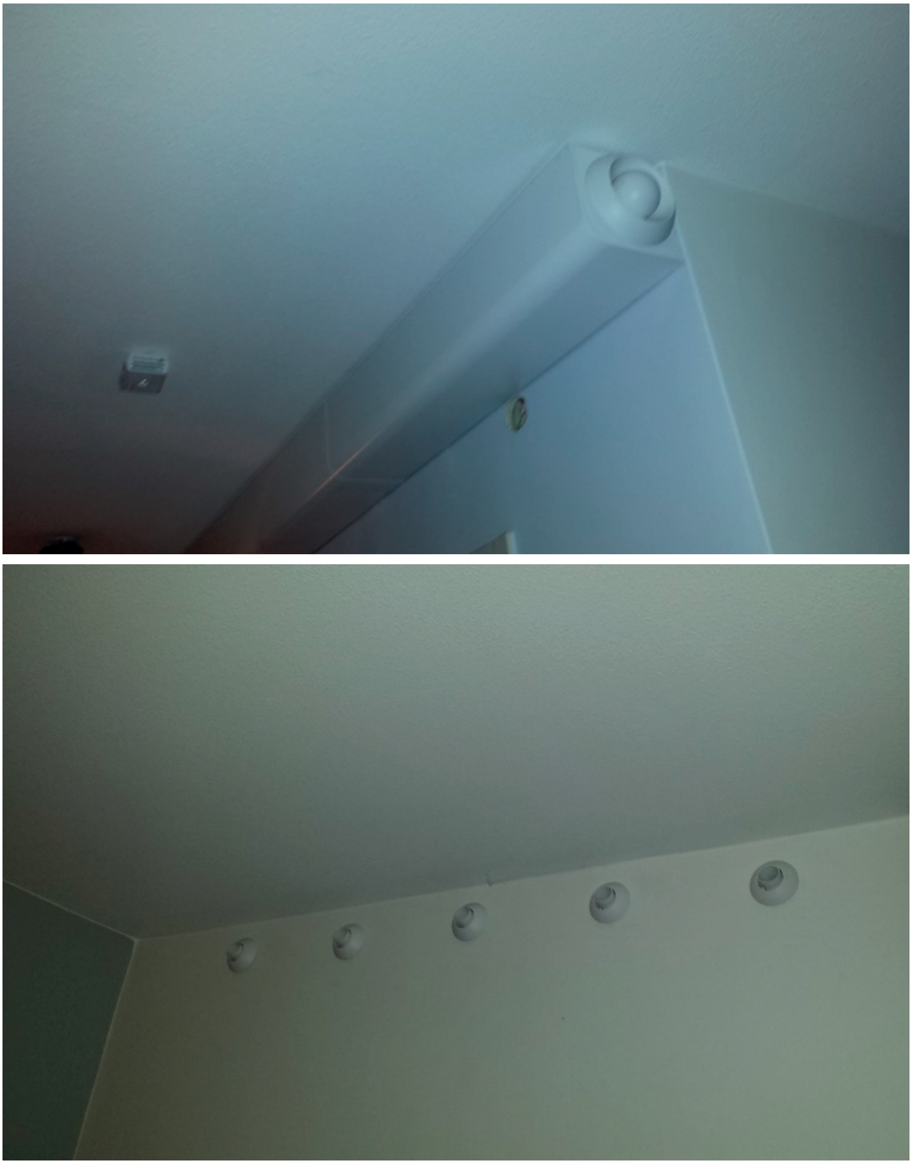


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Figure A2.5: Pictures of covered supply and exhaust air devices inside apartments after installation.

Figure A2.6: Picture of sensor placement in ventilation system before renovation.

Figure A2.7: Pictures of sensors placed in ventilation system after renovation.

Figure A2.8: Pictures of sensor placement in ventilation system after renovation.

Additional results

The following two figures show data on the temperatures in the AHU and the resulting thermal efficiency which is varying with the airflow.

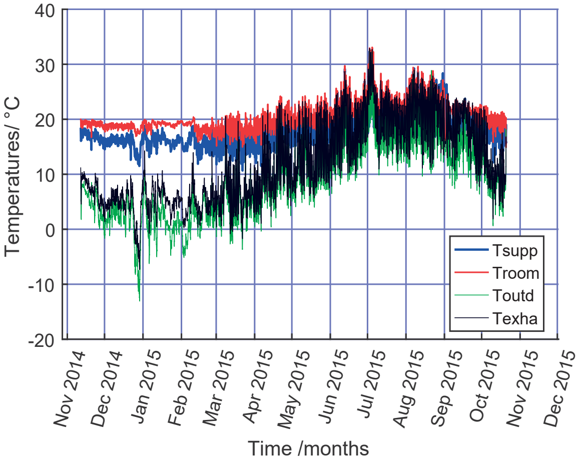


Figure A2.1: Measured temperatures for supply, indoor, outdoor and exhaust data. Data with 15 sec to 30 sec time intervals.

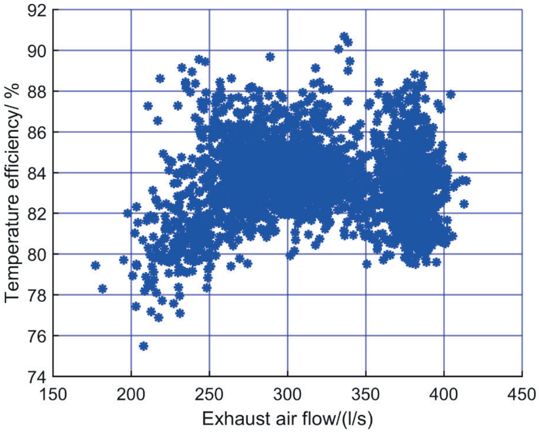


Figure A2.2: Calculated thermal efficiency of the AHU in the case study. Based on hourly averages of measurement data. 2014-11-12 until 2015-02-25.

A3 Case study 4 – Cleaning of heat exchangers

Measurement protocol (in Swedish)

Mätprotokoll

Nedan mätningar ska utföras när systemet är i drift. Detta innebär att både frånluft och tilluft ska vara igång. Om det finns en rotor i systemet ska denna <u>helst</u> vara igång under mätningens gång. Anteckningar om dessa förhållanden ska göras före mätningarna. Rengöringsluckor och andra luckor som finns på systemet bör dessutom vara stängda.

Tabell 1

	Driftfall						
Tidpunkt	**Frånluft** %/ *Hz/ RPM*	**Tilluft** %/ *Hz/ RPM*	**Styrning** Tryck/ Flöde/ Annat	**Växlartyp** *Rotor/ Platt/ Medium*	**Rotor** %	**Datum** *YYYYMMDD – HH:MM*	**Kommentarer/ Avvikelser**
Före rengöring							
Efter rengöring							

Maxkapacitet fläkt:

…………………………………………………………………………………
………………………………………………………..

Rengöringsobjektets adress:

…………………………………………………………………………

Aggregatnummer/ serienummer:

…………………………………………………………………………

Utfört av: ……………………………………………

Lufttemperatur, Relativ Luftfuktighet (605i)

Följande avläsningar bör utföras i kanalen som befinner sig i direkt anslutning till rengöringsobjektet. Finns ej möjlighet att mäta i denna kanal, kan mätvärden tas i de delar av aggregatet som är avsedda för frånluft, tilluft, avluft och uteluft. Se kolumn 1, tabell 1-2.

1. Placera mätgivaren för temperatur och relativ fuktighet mitt i kanalen på ett stativ. Det är viktigt att denna givare inte hamnar för nära några ytor. Finns det ej möjlighet för placering av ett stativ i kanalen, bör ett hål borras för att nå den sökta punkten. Hålet ska täppas till på ett hållbart sätt efteråt (åldersbeständig diffusionstejp bör räcka).
2. Vänta tills mätningen har stabiliserats (någon minut) innan ni antecknar mätvärdena.

Före rengöring

Tabell 2

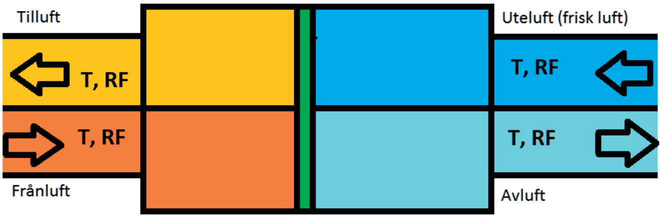
	Temperatur (°C)	Relativ Luftfuktighet (%)	Kommentarer/ Avvikelser
Uteluft			
Tilluft			
Frånluft			
Avluft			

OBS! Det bör gå ca 20 minuter efter rengöring, när systemet återigen har satts i drift, innan mätningar utförs på nytt.

EFTER rengöring

Tabell 3

	Temperatur (°C)	Relativ Luftfuktighet (%)	Kommentarer/ Avvikelser
Uteluft			
Tilluft			
Frånluft			
Avluft			

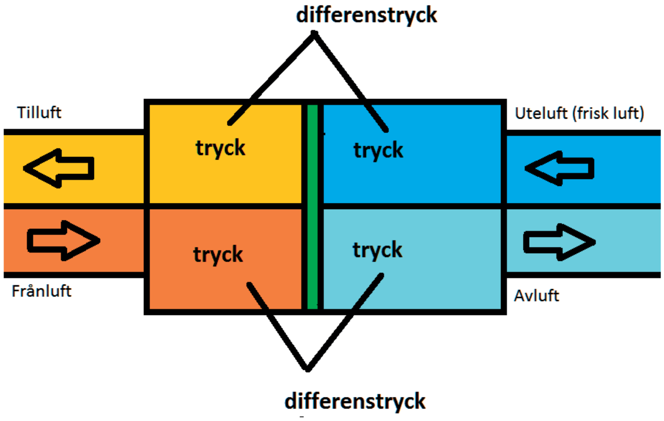


Differenstryck (510i)

Följande avläsningar bör utföras i de delar av aggregatet som är avsedda för frånluft, tilluft, avluft och uteluft.

1. Om systemet har uttag för mätning av differenstryck, ska dessa användas. Annars får hål borras för att mätvärdena ska kunna tas. Hålet ska täppas till på ett hållbart sätt efteråt (diffusionstejp bör räcka).
2. Vänta tills mätningen har stabiliserats (någon minut) innan ni antecknar mätvärdena.

	Frånluft-Avluft Differenstryck (Pa)	**Tilluft-Uteluft** Differenstryck (Pa)	**Kommentarer/ Avvikelser**
Före rengöring			
Efter rengöring			



Systemtryck (510i)

	Före rengöring (kPa)	Efter rengöring (kPa)
Uteluft		
Tilluft		
Frånluft		
Avluft		

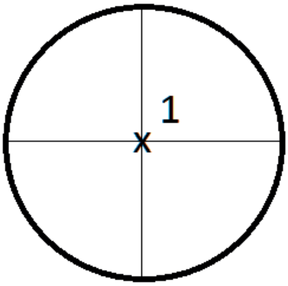
Avvikelser:

Lufthastighet (405i)/ Flöde (system)

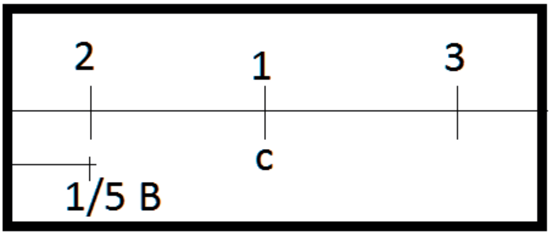
Följande avläsningar bör utföras i kanalen som befinner sig i direkt anslutning till rengöringsobjektet. Helst med en viss raksträcka före/ efter mätpunkten på ca 10x diametern. Finns ej möjlighet att mäta i denna kanal, kan mätvärden tas i de delar av aggregatet som är avsedda för frånluft, tilluft, avluft och uteluft.

Metod för mätning av lufthastighet beror på kanalens utformning/ gränssnitt. Referera till nedan figurer.

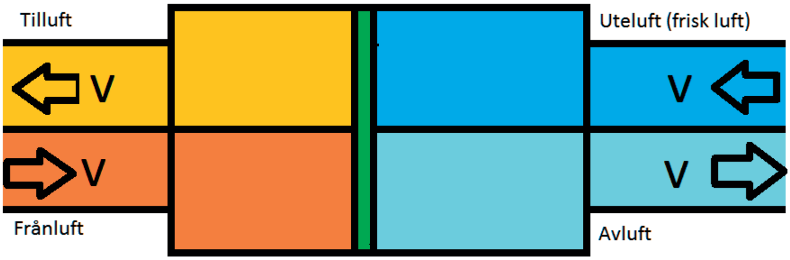
Vänta tills mätningen har stabiliserats (när siffrorna ej fluktuerar/ varierar kraftigt) innan ni antecknar mätvärdena.



Figur 2: Mätning i cirkulärt tvärsnitt



*Figur 3: Mätning i rektangulärt tvärsnitt. 2 och 3 mäts vid minst 1/5 * bredd.*



Före rengöring

Tabell 5

	Lufthastighet/(m/s)			Bredd (cm)	Höjd (cm)	Kommentarer/ avvikelser
	1	2	3			
Uteluft						
Tilluft						
Frånluft						
Avluft						

EFTER rengöring

Tabell 6

	Lufthastighet/(m/s)			Bredd (cm)	Höjd (cm)	Kommentarer/ Avvikelser
	1	2	3			
Uteluft						
Tilluft						
Frånluft						
Avluft						

Tabell 7

	Flöde (m^3/s) eller (l/s)	
Flödesriktning	Före rengöring	Efter rengöring
Avluft/ Tilluft		
Uteluft/Frånluft		

Vätsketemperaturer (830-T4)

Använd den IR-temperaturmätaren för att ta yttemperaturen på vätskeledningar anslutna till ventilationssystemet, om sådana ledningar finns. Det är dock viktigt att det tas på oisolerade delar av ledningarna.

1. Hitta en oisolerad del av vätskeledningarna, så nära värmebatteriet som möjligt.
2. Tejpa på vitfärgad eltejp. Vänta minst 10 minuter.
3. Använd IR-termometern för att avläsa yttemperatur.

OBS! Det bör gå ca 20 minuter efter rengöring, när systemet återigen har satts i drift, innan mätningar utförs på nytt.

Tabell 8

	Temperatur (°C) **Före rengöring**	Temperatur (°C) **Efter rengöring**	**Kommentarer/ Avvikelser**
Framledning			
Returledning			

Fotografier

Detta ska ske före och efter rengöring, med den kamera som finns för detta ändamål.

Syftet med fotografierna är både att ge en översiktlig bild av systemets uppsättning samt detaljerade bilder av försmutsningen i systemet.

Alla bilder bör tas med samma inställning på kameran.

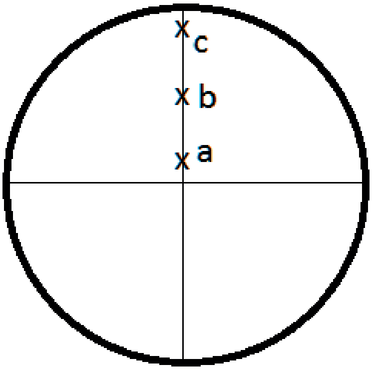
Anteckna på ramen med en White board-penna inför varje foto. Anteckna steg enligt tabell nedan.

Följande bilder vill vi ha in:

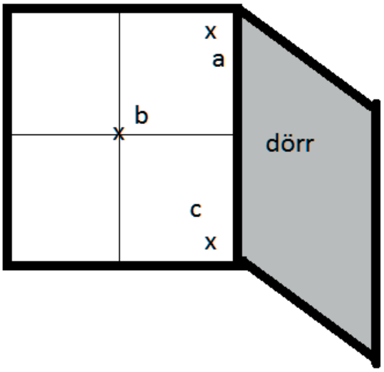
1. Större bild på hela aggregatet/ systemet.

2. Om möjligt, två bilder som täcker hela rengöringsobjektets båda sidor.

3. Närbilder med hjälp av ram och stativ byggt för ändamålet. För *rotoraggregat*: se Figur. **Om obalans finns på smutsfördelningen i rotorväxlare, ta då bilder på den smutsigaste sidan.** För *rektangulära batterier*: se Figur . Ta bilder *på rengöringsobjektets båda sidor* (ex. lameller på värmeväxlare).



Figur 4



Figur 5

	Bildnummer/ Filnamn/ Datum och tidpunkt		**Förklaring**
Punkt	**Före rengöring**	**Efter rengöring**	
Helhetsbild			*Hela aggregatet, översiktsbild*
Utifrån a-c			*Punkt a-c i diagram, ute-sidan, dvs. från avlufts- eller uteluftsutrymmet i aggregatet*
Inifrån a-c			*Punkt a-c i diagram, inne-sidan, dvs. från tillufts- eller frånluftsutrymmet i aggregatet*

Kommentarer/ Avvikelser:

Field measurements

Figure A3.1: Cleaning process of heat exchangers – abrasive blasting with frozen CO_2.

Figure A3.1: Laboratory rig setup.

Figure A3.2: Contamination of heat exchanger in lab.

Figure A3.3: Collection of contaminants not stuck on heat exchanger in laboratory tests.

A4 Case study 5 – Ventilation measures for heritage

Measurements – heritage buildings

Figure A4.1: Tracer-gas-decay measurement for ACR.