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THOR HANSEN

DISSERTATION SUBMITTED 2019

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Dissertation submitted: December 27, 2019

PhD supervisor: Research Director Ruut Peuhkuri, PhD
Aalborg University, Denmark

Assistant PhD supervisor: Professor Eva B. Møller,
Technical University of Denmark, Denmark

PhD committee: Professor Alireza Afshari (chairman)
Aalborg University

Professor Stig Geving
Norwegian University of Science and Technology

Post doc. Evy Vereecken
KU Leuven

PhD Series: Faculty of Engineering and Science, Aalborg University

Department: Danish Building Research Institute

ISSN (online): 2446-1636
ISBN (online): 978-87-7210-574-1

Published by:
Aalborg University Press
Langagervej 2
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Rosendahls, 2020

PREFACE

The present thesis, *"Vapour barrier in cold ventilated attics"*, is the result of a work which was started in April 2015 at Aalborg University in Copenhagen as a part-time employment at the section Danish Building Research Institute. I would like to thank the Landowners' Investment Foundation, the National Building Fund, the Association of Danish Insulation Manufacturers, the Danish Construction Association and Aalborg University for providing funding for the work and Team Mobbis for providing the equipment for measuring the temperature and relative humidity in the full-scale test building.

Above all, I would like to express my sincere gratitude to my former main PhD supervisor Eva B. Møller. Thank you so much for meetings characterised by both a great deal of knowledge sharing and a good many laughs; many of our previous collages were quite envious of these meetings. If it was not for you, I would never have started this journey! I am eternally grateful to you.

Many thanks also to Ruut Hannele Peuhkuri for being my main supervisor at the end of my PhD journey, and for support, fruitful comments and discussions on the way.

Thank you to all members of staff in the Department of Building Technology and Management, especially Martin Morelli for his positive attitude and supporting advice.

Thank you to Stine for looking after the farm and horses during the last part of the writing process. And finally, from the bottom of my heart, thank you to Christel for taking good care of our kids and everything else. I would not have made it if you had not been there.

Copenhagen, December 2019

Thor Hansen

ABSTRACT

Background: A simple way of reducing energy consumption in buildings with cold ventilated attics it to install additional insulation material above the ceiling. However, Danish recommendations on this include a vapour barrier if the total amount of insulation material exceeds 150 mm. Unfortunately, installation of a vapour barrier is in most cases difficult and therefore costly. In buildings with poor or no vapour barrier the building owner may therefore count out this energy saving measure. The reasoning behind the recommendation is that if the ceiling against the attic is substantially re-insulated, the temperature in the attic will decrease and the humidity increase compared to the condition prior to the re-insulation. This means that in many existing buildings with no mould growth problems although vapour and airtightness of the ceiling was unknown, problems may occur after re-insulation due to the higher relative humidity of the colder attic. Airtightness itself is not sufficient with high insulation amounts; vapour tightness is also needed. Nevertheless, some building owners have disregarded the recommendations without experiencing any mould growth problems in the attic. Therefore, it is relevant to investigate under which conditions a vapour barrier is needed.

Objective: The objective of this PhD thesis has been to obtain knowledge in order to answer the practical problem: **When is a vapour barrier needed in the ceiling under a cold ventilated attic?**

Hypotheses: For answering the practical problem, three hypotheses were formed concerning how the moisture level in cold ventilated attics would be affected by the presence of a vapour barrier, the insulation material's hygroscopic properties and the thickness of the insulation material. The hypotheses were tested by examining the hygrothermal performance in cold ventilated attics.

Methods: The present Ph.D. thesis is based on two published journal papers and one submitted journal paper; in the thesis they will be referred to as Paper I, II and III.

In **Paper I**, hygrothermal performance of cold ventilated attics in a full-scale test building was examined. The test building had controlled indoor climate and was built with high awareness on the workmanship, ensuring airtightness. The test building had six different attic constructions above three rooms with different indoor humidity classes. The attic constructions differed from each other by insulation material type and thickness and presence of vapour barrier. During the period of the Ph.D. work it was possible to obtain measurements of temperature and relative humidity for the two winter periods 2016/17 and 2017/18. The collected data was in each test attic obtained from eight temperature and relative humidity sensor locations. Furthermore, the wood moisture content was measured at twelve

positions. Based on the measured parameters a statistical analysis on hygrothermal differences was carried out.
In **Paper II**, the attic's hygrothermal performance was investigated in 34 different inhabited case buildings erected in the period from 1952 to 2015. The case buildings were categorised in different groups depending on the study's objective e.g. insulation type, thickness or vapour barrier type. The field measurements were conducted over three winter periods 2015/16, 2016/17 and 2017/18. Temperature and relative humidity in the attics were measured. Furthermore, the vapour pressure and the initiation of mould growth were calculated and compared. Unfortunately, it was not possible to perform measurements in all attics at the same time, however, the period of measurements was minimum one year.
In **Paper III**, a simulation model, which was based on the attic construction in the full-scale test building, was presented. The results of hygrothermal simulation was validated with the values measured in the full-scale test building. In addition, parameter variations of different types and thicknesses of insulation material and presence of vapour barrier were performed and the model was used for testing different combinations of air change rate and moisture leakage in cold attics. Furthermore, investigations of the attic performance with expected future climate conditions were carried out. The hygrothermal performance was mainly evaluated by calculation of the risk of mould growth using the MRD model.

Results and discussion: Based on the collected data, both in the full-scale test building, the field survey and simulations, no significant effect of the vapour barrier, insulation type and insulation thickness on the hygrothermal performance of cold ventilated attics was found. This leads to a rejection of all the hypotheses set up for the present work. Due to the rejection, the current guideline regarding use of a vapour barrier cannot be supported and should therefore by revised. As expected, the ventilation rate of the attic space is a crucial parameter influencing the hygrothermal performance of the attic. Nevertheless, based on the simulations it seems that the robustness of the traditional attic construction is likely to change within the next 25 years, even if the moisture leakage to the attic is low and the ventilation rate is high.

Conclusion: Concerning the practical problem related to reducing the energy consumption in existing houses the conclusion is: **If the existing attic construction is without moisture related problems, additional insulation can be added to the ceiling without installing a new vapour barrier as long as the attic ventilation rate and the ceiling air tightness is unchanged.** However, based on the findings from the simulations including a possible future climate change, it is strongly recommended that a vapour barrier is installed in new constructions as it contributes to the long-term airtightness of the construction. As stated for the simulations based on possible future climate conditions, new solutions for handling the moisture conditions in cold ventilated attics, or new construction designs might be needed in the future.

RESUMÉ (IN DANISH)

Baggrund: En enkel måde at reducere energiforbruget i bygninger med et koldt ventileret tagrum er at udlægge yderligere isoleringsmateriale ovenpå loftet. I de danske anvisninger anbefales det dog, at hvis den samlede mængde isolering overstiger 150 mm, bør der være en tæt dampspærre i loftet. Desværre vil etableringen af en tæt dampspærre i de fleste tilfælde være vanskelig og kostbar, hvilket vil få nogle bygningsejere til at fravælge energibesparelsen ved ekstra isolering på lofterne i bygninger, hvor dampspærren er i dårlig stand eller helt mangler. Baggrunden for anbefalingerne er, at hvis loftet mod et tagrum efterisoleres væsentligt, vil temperaturen i tagrummet falde og dermed vil luftfugtigheden stige. Dette betyder, at der i mange eksisterende huse med ukendt damp- og lufttæthed i tagrummet, hvor der ikke tidligere har været problemer med fx skimmelsvampevækst, potentielt kan opstå problemer som følge af at efterisoleringen gør tagrummet koldere og øger den relative luftfugtighed. Lufttæthed af lofter er i sig selv ikke tilstrækkeligt ved høje isolerings-tykkelser; her er en damptæthed også nødvendig. Ikke desto mindre har nogle bygningsejere set bort fra anbefalingerne uden at det har medført problemer med fx skimmelvækst på loftet. Derfor er det relevant at undersøge, under hvilke betingelser en dampspærre er påkrævet.

Formål: Formålet med denne ph.d.-afhandling har været at opnå viden relevant for at kunne besvare det praktiske problem: Hvornår er der brug for en dampspærre i lofter mod et koldt ventileret tagrum?

Hypoteser: For at besvare det praktiske problem blev der opstillet tre hypoteser med henblik på at vurdere, hvorvidt en dampspærre, isoleringsmaterialets hygroskopiske egenskaber samt tykkelsen på lofter mod kolde ventilerede tagrum har indvirkning på fugtniveauet. Hypoteserne blev testet ved at undersøge de hygrotermiske egenskaber i kolde, ventilerede tagrum.

Metode: Denne ph.d.-afhandling er baseret på to publicerede videnskabelige artikler og en indsendt videnskabelig artikel; disse vil blive omtalt som artikel I, II og III.

I **artikel I** blev hygrotermisk ydeevne af kolde ventilerede tagrum i en fuldskala testbygning undersøgt. Testbygningen havde kontrolleret indeklima og blev opført med stor opmærksomhed på udførelsen og sikret lufttæthed. Testbygningen havde seks forskellige loftskonstruktioner over hver af tre forskellige indendørs fugtigheds-klasser, de forskellige parametre i lofterne var typen og tykkelsen af isoleringen. Ydermere blev anvendelsen af dampspærre undersøgt. Der blev indsamlet data for temperatur og relativ luftfugtighed i to vinterperioder: 2016/17 og 2017/18. For hvert testloft blev temperatur og relativ luftfugtighed målt ved otte forskellige

sensor-positioner, endvidere blev træfugtighedsindholdet målt 12 forskellige steder. Der blev udført statistisk analyse af indsamlet data til vurdering af de hygrotermiske forskelle.
I **artikel II** blev tagrummets hygrotermiske ydeevne undersøgt ved feltmålinger i 34 forskellige beboede huse med opførelsesår fra 1952 til 2015. Husene blev kategoriseret i forskellige grupper afhængigt af undersøgelsens formål, fx isoleringstype, tykkelse eller dampspærren. Feltmålingerne blev udført over tre forskellige vinterperioder: 2015/16, 2016/17 og 2017/18. Desværre var det ikke muligt at måle i alle tagrummene på samme tid, men måleperioden var mindst et år. Temperatur og relativ fugtighed blev registreret. Desuden blev damptrykket og kriteriet for skimmelsvampevækst beregnet og sammenlignet.
I **artikel III** blev en simuleringsmodel præsenteret, der var baseret på tagrums-konstruktionen fra fuldskala-testbygningen. Resultaterne fra de hygrotermiske simuleringer blev valideret med de målte resultater fra testbygningen. Derudover blev der simuleret med parametervariation på forskellige typer og tykkelser af isoleringsmateriale og tilstedeværelse af dampspærre anvendt til at teste forskellige kombinationer af luftskifte og fugttilskud til tagrummet. Desuden blev der udført undersøgelser af tagrummets ydeevne under forventede fremtidige klimaforhold. Den hygrotermiske ydeevne blev hovedsageligt evalueret ved beregning af risikoen for skimmelsvampevækst ved hjælp af MRD-modellen.

Resultater og diskussion: Baseret på den indsamlede data, henholdsvis fra fuldskala-forsøgshuset, feltundersøgelserne og simuleringerne, kan der ikke ses nogen signifikant betydning af anvendelse af en dampspærre, en bestemt isoleringstype eller isoleringstykkelse på de hygrotermiske egenskaber for kolde, ventilerede tagrum. Samtlige opstillede hypoteser kan således forkastes. Dette betyder, at de nuværende anvisninger ikke bekræftes, hvormed disse bør revideres. Som forventet har tagrummets luftskifte en afgørende rolle for dets hygrotermiske egenskaber. Baseret på simuleringerne ser det imidlertid ud til, at robustheden i den traditionelle tagrumskonstruktion sandsynligvis vil ændre sig inden for de næste 25 år, selvom fugttilskuddet til tagrummet er lavet og luftskiftet er højt.

Konklusion: Vedrørende det praktiske problem i forbindelse med reduktion af energiforbruget i eksisterende huse er konklusionen: **Hvis det eksisterende tagrum er uden fugtrelaterede problemer, kan der tilføjes yderligere isolering på loftet uden behov for installering af en ny dampspærre, så længe ventilering af tagrummet og lufttætheden af loftet ikke ændres**. Baseret på resultaterne fra simuleringerne med fremtidigt klima, anbefales det dog stærkt, at der i nye konstruktioner anvendes en dampspærre, da den på lang sigt bidrager til konstruktionens lufttæthed. Som anført for simuleringerne med fremtidige klimaforhold, kan der opstå behov for nye løsninger til håndtering af fugtigheds-forholdene i kolde ventilerede tagrum eller helt andre konstruktionsløsninger i fremtiden.

LIST OF APPENDED PAPERS

In the thesis, three journal papers are appended and will be referred to in the text by their Roman numerals.

I. **Thor Hansen,** Eva B. Møller, Torben Tvedebrink. *Hygrothermal performance of cold ventilated attics above different horizontal ceiling constructions – Full-scale test building.* Journal of building physics, December 2019.
DOI: https://doi.org/10.1177/1744259119894028

II. **Thor Hansen,** Eva B. Møller. *Hygrothermal performance of cold ventilated attics above different horizontal ceiling constructions – Field survey.* Building and Environment, Vol. 165, November 2019.
DOI: https://doi.org/10.1016/j.buildenv.2019.106380

III. **Thor Hansen,** Eva B. Møller, Ruut Peuhkuri. *Hygrothermal performance of cold ventilated attics – Simulations with current and future conditions.* Submitted to Journal of building physics, December 2019.

LIST OF OTHER SCIENTIFIC WORK

The author has authored or contributed to the following peer-reviewed publications. These have been precursors of the journal papers or on related topics. These publications are not appended in the thesis.

A. **Thor Hansen,** Eva B. Møller. *Full scale laboratory test building for examining moisture penetration through different ceilings.* International RILEM Conference on Materials, Systems and Structures in Civil Engineering Conference segment on Moisture in Materials and Structures, Denmark, 2016.

B. **Thor Hansen,** Eva B. Møller. *Field measurements of moisture in cold ventilated attics with different types of insulation materials and vapor barrier.* Proceedings of Thermal Performance of the Exterior Envelopes of Whole Buildings XIII, Florida, USA, 2016

C. **Thor Hansen,** Eva B. Møller. *Field measurements of moisture variation in cold ventilated attics with different ceiling constructions.* Proceedings of 11th Nordic Symposium on Building Physics, Norway, 2017

D. Eva B. Møller, **Thor Hansen**. *Artificial aging of air-and-vapour barriers.* Proceedings of the 14th International Conference on Durability of Building Materials and Components, Belgium, 2017

E. **Thor Hansen,** Eva B. Møller. *Measurements of temperature dependency on thermal insulation thickness in ventilated attics.* Proceedings of 7th International Building Physics Conference, NY, USA, 2018

F. **Thor Hansen,** Petter Wallentén. *Validations of the MRD mould model by attic case studies in northern Sweden.* Conference: Forum Wood Building Baltic, Estonia, 2019

G. Eva B. Møller, Martin Morelli, **Thor Hansen**. *Air change rate in ventilated attics – reality and input for simulations.* Conference: 4th Central European Symposium on Building Physics, Czech Republic, 2019

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CHAPTER 1. INTRODUCTION

There is a need for clarification and validation of the current Danish guideline concerning the conditions under which a water vapour barrier is required in ceilings under naturally ventilated attics. This clarification is especially important when installing extra roof insulation in existing buildings where the airtightness and the vapour diffusion resistance of the ceilings are often unknown. However, a clarification is also needed for other factors such as hygroscopic properties, the amount of ventilation and the internal moisture load. The present project combines laboratory and field tests supported by hygrothermal simulations. The combination of theory (laboratory) and practice (field) makes it possible to estimate how sensitive the different solutions are to tolerances, material variations, execution errors etc.

1.1. OBJECTIVES

The point of departure for this Ph.D. study was a very *practical problem*: **When is a vapour barrier needed in the ceiling under a cold ventilated attic?** In the following chapter, this question is divided into more detailed questions which subsequently has led to the formulation of several hypotheses. Although the question seems simple, the problem is highly complex as it involves many different factors which have to be considered before an exact answer can be given.

1.2. OUTLINE OF THE THESIS

The present thesis is based on three papers and consists of six chapters. Chapter 1 gives an introduction to the thesis, and Chapter 1 describes the background. Chapter 3 refers to the methodology used. There is no chapter presenting the results of the work as these are given in the included Papers (I-III). In Chapter 4, the main findings presented in the three Papers (I-III) are discussed. In Chapter 5, the main findings are summed up and concluded, and a practical solution to the practical problem is suggested. Chapter 6 provides perspectives and further research questions based on the main findings and conclusion.

1.3. HYPOTHESES

In order to define the practical problem a *literature study* was undertaken. Based on this, the practical problem was seen from different angles and hypotheses were formed, and finally decisions were made on how to test the hypotheses. The three main hypotheses were tested by examination of the hygrothermal performance of cold ventilated attics. Is the moisture level in cold ventilated attics affected by:

H1 – The presence of a vapour barrier?
H2 – The hygroscopic properties of the insulation material?
H3 – The thickness of the insulation material?

Although, there had been ideas of how to test the hypotheses from the beginning, when the problem was raised, knowing what other researchers have found out and how they did it, was an inspiration for how to define new tests of hypotheses and make the initial ideas more concrete. The literature study showed different ways to handle the complex problem, from simplified models to complex set-ups, trying to cope with the complexity of real conditions.

The hypotheses were tested by three different set-ups as described in the three columns in Figure 1-1 below:

- A *test building* where most of the conditions were controlled, except the outdoor climate conditions. In the test building, special care was taken to avoid the many uncertainties of ordinary houses. The airtightness of the ceiling was for instance ensured in a more effective way than in an ordinary building. All dimensions were known, the indoor climate conditions were controlled and temperature, relative humidity and wood moisture content were measured at many points. The complexity was therefore reduced compared to investigations of inhabited houses built with normal care.
- A *field survey* where measurements were carried out in existing houses. Here no efforts were made to reduce the complexity of normal houses. Materials and dimensions were registered as far as possible, and temperature and relative humidity measured at several points. The idea was to use these measurements as a reality check on the outcome of the measurements in the test building and the simulations.
- *Simulations* are simplifications of the reality. Hygrothermal simulations involve mathematical modelling of physical phenomena, but as not every detail about a construction and boundary conditions is known, and models do not include all physical processes, a simulation will never be precise. As George Box put it “All models are wrong, but some models are useful” (Box, et al., 2009). In this case, hygrothermal simulation models are built and calibrated to reality by using measured results. When a useful model was obtained, parameters or boundary conditions were changed; hereby results could be obtained for cases that were not measured in reality. Main focus was twofold: 1) Testing single parameters that were not part of the experiments i.e. ventilation in the attic and leakage from below. 2)

Predicting how different constructions may perform under future weather conditions. These conditions are, however, based on assumptions of coming climate scenarios and will therefore only be educated guesses.

The three columns also represent the three Papers (I-III) which this thesis is based on. However, as the results of each of the columns are already presented in the papers, focus of the thesis is the interconnection between the three main themes.

Therefore, a general discussion includes the results of all three columns/papers and how they support each other, with the purpose of finding a way to cope with the practical problem: **When is a vapour barrier needed in the ceiling under a cold ventilated attic?**

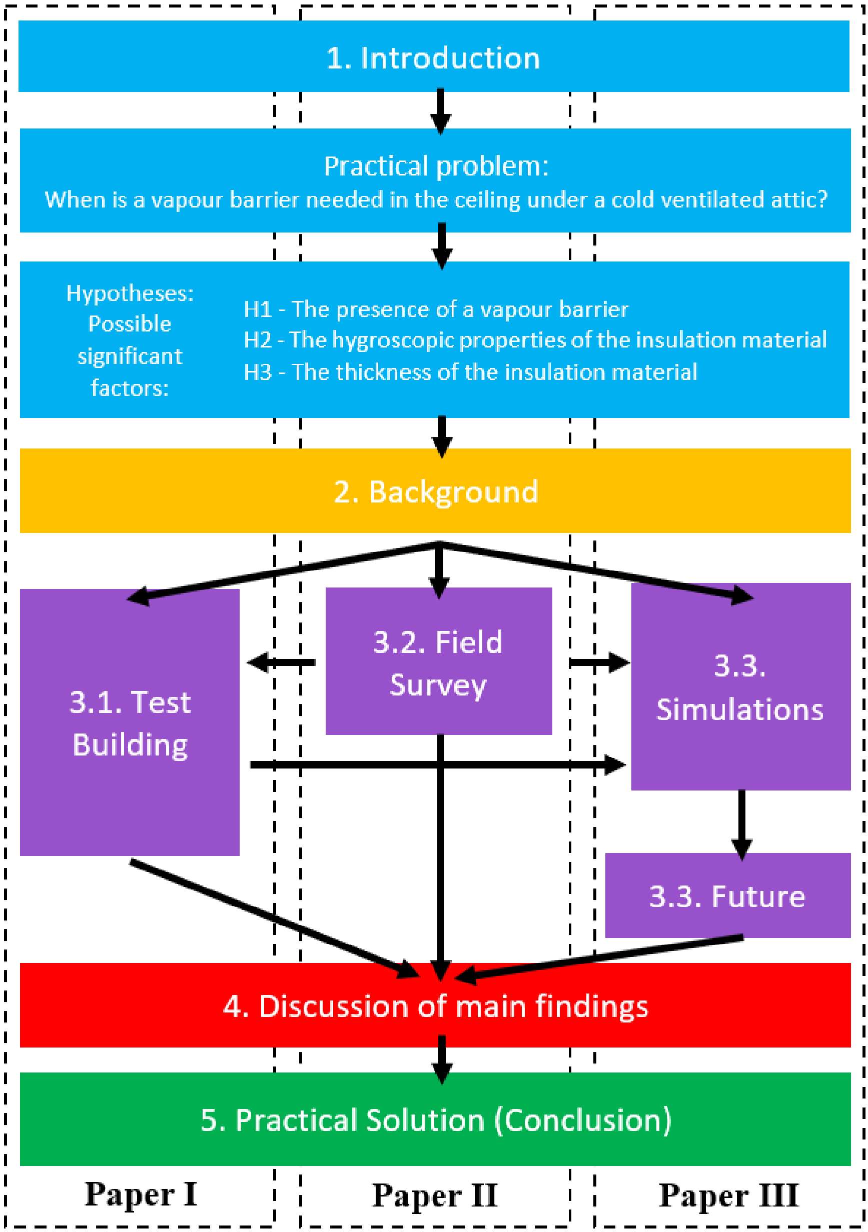


Figure 1-1. Structure of the present project and thesis. At the top, the introduction to the PhD-study which aims to answer a practical problem by testing three hypotheses. This leads to the background. Based on the background, three parts (methods) have been investigated, one in each paper. Paper I and II test the hypotheses for the test building and the field survey respectively, whereas paper III tests the impact of future climate conditions on the hypotheses.

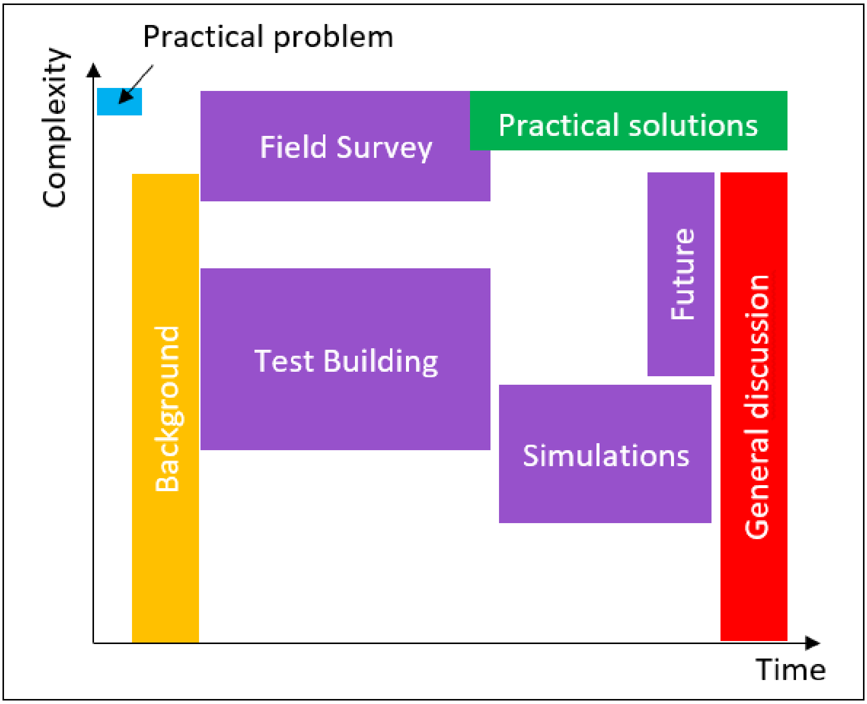


Figure 1-2. Timeline of the Ph.D. study for each part and its complexity.

In real houses (field survey), the complexity is high as there are many uncontrolled factors and therefore uncertainties; consequently, it can be difficult to determine if all factors are fulfilled. In a test building, on the other hand, these uncertainties are minimised due to monitoring and close attention to workmanship, which differ from the monitoring and attention to workmanship usually seen in connection with the construction of ordinary buildings. The complexity of the simulations is relatively low as the user controls all factors. However, the simulations are a high simplification of the reality, which makes simulation medium complex. Simulations are necessary when the robustness of a construction is to be tested for future climate changes. As predictions of future climate are associated with a very high degree of uncertainty, this makes the simulation of future conditions highly complex. In Figure 1-2 a timeline of the PhD study is presented for each part and its complexity.

CHAPTER 2. BACKGROUND

The objective for this PhD project is to identify conditions under which a vapour barrier is needed in ceilings under ventilated attics, when different parameters are taken into account:

- Airtightness and vapour diffusion resistance of the ceiling.
- Hygroscopic properties of different insulation materials.
- Thickness of the insulation.
- Amount of ventilation.
- Humidity class of the building.
- Impact of future climate changes.

The vapour and airtightness of a ceiling in an existing building is usually unknown. This may not be a problem as long as the humidity level in the attic above the ceiling is acceptable. However, if additional insulation is installed above the ceiling, the temperature in the attic will theoretically decrease and the relative humidity increase. Depending on the tightness of the combined vapour and air barrier, the relative humidity level may now become critical. At the same time, installing a new vapour and airtight barrier in an existing roof construction is very difficult, because of lack of space and the surfaces and shapes of the construction. Therefore, it is relevant to examine under which circumstances a vapour and air barrier may be needed.

2.1. FUNCTION OF AN ATTIC

In Denmark, building constructions with a ventilated attic space above the ceiling construction have been used for centuries. Figure 2-1 shows a principle sketch of a cold ventilated attic. The attic moisture level is a combination of the indoor and outdoor moisture entering the attic space and the removal to the outdoors, mainly by ventilation. The external air enters the attic through ventilation openings, most appropriate at the eaves and ridge. The ventilation openings provide an air exchange of the attic, which is crucial for the removal of the moisture which has penetrated into the attic.

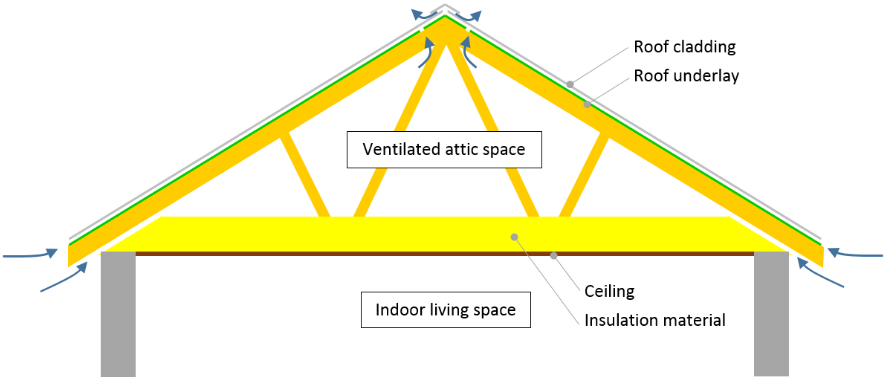


Figure 2-1. Principle sketch of a cold ventilated attic space.

Moisture penetrating to the attic from the indoor climate is caused either by convection or by diffusion. Convection will normally transport significant larger amount of moisture compared to diffusion, (DUTT, 1979). Moisture transport by convection appears through leakages in the ceiling with air movements, which occur when there is a difference in the air pressure over a given volume of air. This difference will appear e.g. when there is a difference in temperature, wind pressure or an air pressure difference caused by a ventilation system. Contrary to convection, moisture transport by diffusion occurs through the material and the driving potential is the difference in the water vapour pressure or water vapour content.

The risk of moisture-related problems (e.g. mould growth) in attics depends on the relative humidity and temperature. The moisture transport, both by convection and diffusion, can be reduced by a vapour barrier in the ceiling construction. Ceilings without a vapour barrier can be airtight but vapour open, the moisture transport caused by convection is in this case insignificant. This means that the vapour barrier in most cases has two effects. It is a barrier against vapour diffusion and makes the construction airtight. Furthermore, under some conditions moisture can also enter the attic space from the outdoor climate.

There will always be some moisture transport to the attic not only from the indoor climate but also from other sources. However, moisture can be removed by ventilating the attic with outdoor air. Ventilation with outdoor air will in most cases remove most of the excess moisture, especially if the outdoor air is heated after it enters the attic, simply because warm air can contain more moisture than cold air. In Denmark, the recommendation is that attics should have 200 cm^2/m openings at the ridge and a 15-30 mm air gap at the eaves (Brandt, et al., 2013).

2.2. CURRENT GUIDELINE

Until now, the Danish guideline (Brandt, et al., 2013), has recommended that if the ceiling is without cracks and the thickness of the insulation layer is 150 mm or below, there is no need of a vapour barrier. The ceiling itself is regarded as airtight, and the amount of moisture transported by diffusion through the ceiling can be removed by the ventilation of the attic. The guideline does not make any distinction between insulation materials with different moisture buffer properties.

Before reduction of energy consumption became a priority, it was considered sufficient for the prevention of moisture problems if the ceiling was airtight, as seen for example in a plastered ceiling. In older buildings (>50 years), there is normally no vapour barrier present in the construction, or if there is, its condition is usually rather bad, but in spite of this, not many moisture problems in the attics are reported. However, in order to reduce energy consumption, the thickness of the insulation material in attics has now been increased in both renovated and new buildings. Consequently, the heat loss to the ventilated attic is decreased and the temperature in the attic is lowered. Subsequently, the relative humidity in the attic rises, which means that there is a higher risk of mould growth in the attic (Brandt, et al., 2007).

This explanation of the development was supported by Swedish reports (Samuelson, 1998) and (Nik, et al., 2012) on the subject and unverified statements from some practitioners who indicated that the number of attics with mould problems had increased. Therefore, the Danish Building Research Institute (SBi) recommends in its SBi-guidelines 224 and 240 that uncracked plastered ceilings could no longer be considered to be sufficiently tight to ensure an acceptable humidity level in the attic if the insulation thickness is above 150 mm (Brandt, et al., 2013) and (Møller, 2012). If more insulation is needed, a water vapour barrier must be installed, irrespective of the type of vapour open insulation material used. The thickness of 150 mm is based on experience with insulation materials with a thermal conductivity of 0.036-0.040 W/mK.

The current guidelines have become especially relevant to buildings which are renovated to save energy. Extra insulation installed on top of the ceiling construction is effective and cheap if no vapour barrier has to be installed. However, it can be difficult to install a tight vapour barrier, e.g. to existing rafter. There is often a lack of space and the surfaces of the construction can be complicated because of fishplates and unevenness. As a result, the price of installing a tight vapour barrier may cause extra insulation to be non-profitable.

The recommendation to insulate with up to only 150 mm in ceiling constructions without a water vapour barrier is based on experience and is chosen to be on the safe side. However, it may be too restrictive, and the recommendation has been challenged from different actors:

- Some manufacturers state that they have not recived any complaints from customers, even when there is an insulation thickness of 400 mm without a vapour barrier.
- Some manufacturers state that a hygroscopic insulation material can absorb moisture, and when the temperature increases in the attic, the moisture will evaporate and be removed by ventilation. The humidity level in the attic will never become critical and cause mould growth or rot.

2.3. EVOLUTION OF CEILING DESIGN

In 1966, the Danish Building Regulation stated for the first time that there should be a vapour barrier between a wooden roof construction and a heated space, placed on the warm side of the insulation material. Before that time, it was recommended that all building constructions were erected in such way that condensation of moisture was prevented. The recommendation of a vapour barrier was changed with the regulation in 1998, which was less descriptive than previous versions; a vapour barrier was no longer mandatory. However, the risk of condensation was still to be avoided, e.g. by using a vapour barrier. Figure 2-2 illustrates the development of the overall thermal transmittance, the corresponding approximate thickness of insulation material and the different vapour barriers typically used in a ceiling construction. The description of the development is based on the Danish Transport Construction and Housing Authority (2019), where a description of the different regulations over time is available. Nowadays, there is a great deal of awareness of the importance of the airtightness of building constructions, while focus in the 1960s primarily was on diffusion tightness of the vapour barrier material. The 1970s saw the emergence of awareness of airtightness, and during this period sealing of joints in the vapour barrier started.

In the early 1960s, vapour barriers were introduced in Denmark. In the beginning, a vapour barrier consisted of thin paper coated with bitumen. Later, the bitumen was exchanged with a thin aluminium layer (Alu-foil). Today the most commonly used vapour barrier is a polyethylene-based foil (PE-foil). Both Alu-foil and PE-foil was used in the period from the mid-1970s to the 1990s, during which period approx. 30 % of the existing single-family and detached houses in Denmark were built.

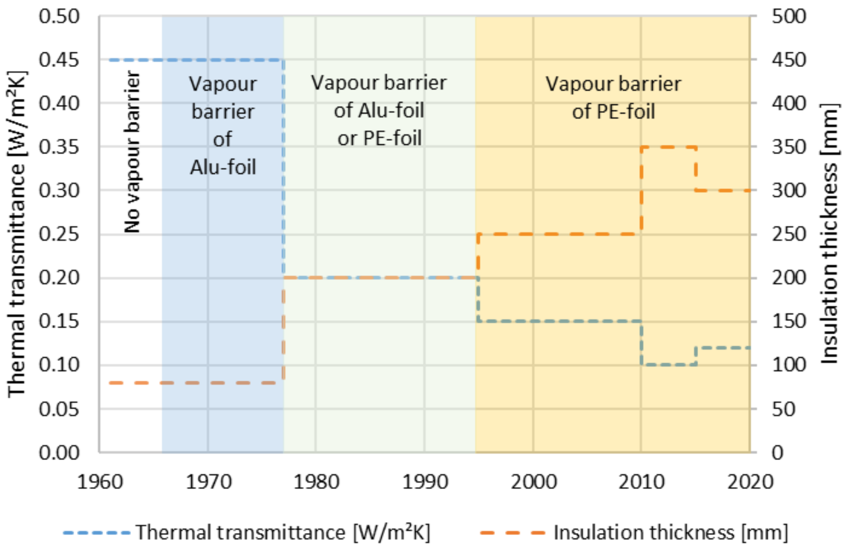


Figure 2-2. Development of the required thermal transmittance in the Danish building regulation over time and the approximated insulation material thickness of roof constructions and the most-used vapour barrier.

In some cold ventilated attics, moisture related problems such as mould growth occur. A Swedish survey (BETSI, (Boverket, 2009)), examined 1,800 buildings and found visible mould, smell of mould or high moisture load in the attics of 15% of the examined single-family houses. According to BETSI, a similar survey was conducted 15 years earlier, and at that point, the number of moisture related problems was lower. It was mentioned that increased thermal insulation was a probable cause. This theory that energy saving, in form of additional insulation on the ceiling against the attic, reduces the heat supply which causes a higher relative humidity level in the attic, and consequently mould problems, was also proposed by Samuelson (1998), Hagentoft and Kalagasidis (2010) and Nik et al. (2012). Another Swedish research project on single-family houses, (Hagentoft, et al., 2013), showed that 60 % of all traditionally ventilated attics in the area of Gothenburg (Västra Götalands Län) have massive mould growth problems. Simulations in that study show that:

- Climate is a significant factor. The problem is for instance bigger in the climate conditions around Gothenburg than in the climate conditions around Stockholm. The problem generally decreases when moving towards the north in Sweden.
- The expected climate changes will have a negative impact on mould problems.

- Insulation materials, which have a moisture buffer capacity, e.g. cellulose, have a positive impact, but not a sufficiently positive impact to avoid mould growth.
- As a solution the author of the present work has simulated an airtight attic with a mechanical ventilation system, controlled by the outdoor conditions to avoid ventilation during conditions which will not reduce the moisture level in the attic. The system was not tested in practice.

The argument that cellulose-based insulation material has a moisture buffering effect has been put forward by producers of this type of insulation material. Cellulose-based insulation material has become increasingly popular in Denmark, especially as additional insulation material on ceilings. Hagentoft et al. (2013) found that a cellulose-based insulation material has a minor effect on the moisture level; this was also stated by Samuelson (1998) and Kalagasidis (2004).

2.4. FUTURE DEMANDS

It can be foreseen that the climate will change, therefore, constructions and recommendations for renovation in general should be tested for their robustness under changed climate conditions. Simulations with predicted climate data (as described in section 2.6. Simulation) are often used to investigate the future performance of building constructions. There are different prediction models for world climate change. In the year 2000, the Special Report on Emissions Scenarios (SRES), which is reported by the Intergovernmental Panel on Climate Change (IPCC) in (Nakicenovic, et al., 2000) was published. The SRES operates with four different scenario families, A1, A2, B1, and B2. A1 has three subsets:

- A1FI: An emphasis on fossil-fuels (Fossil Intensive)
- A1B: A balance emphasis on all energy sources
- A1T: A emphasis on non-fossil energy sources

Based on the different scenarios, the global surface temperature, as estimated in Pachauri et al. (2007) is shown in Figure 2-3, which is a contribution to the IPCC's 4th Assessment Report.

For the IPCC's 5th Assessment Report, the SRES uses the Representative Concentration Pathways (RCP), which is the concentration of the greenhouse gas. The RCP model has four pathways, i.e. RCP2.6, RCP4.5, RCP6.0 and RCP8.5, depending on the amount of greenhouse gases emitted. The label on the RCP is related to the possible range of radiative forcing (the difference between sunlight absorbed by the Earth and energy radiated back to space in W/m^2) values in the year 2100. In Figure 2-4 the estimated global surface temperature according to the RCP model is shown, which is based on Stocker et al. (2013).

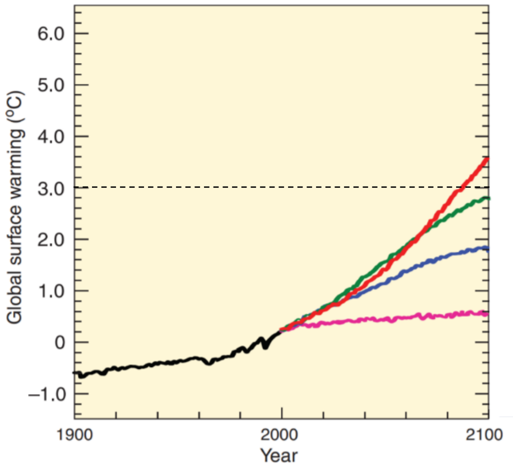


Figure 2-3. Time period of the global surface temperature change for SRES scenarios A2 (red), A1B (green) and B1 (blue), shown as continuations of the 20th century (black), and pink curve if the emissions are held constant at the year 2000 values. The figure is from (Pachauri, et al., 2007); added black dotted line is for comparison with Figure 2-4.

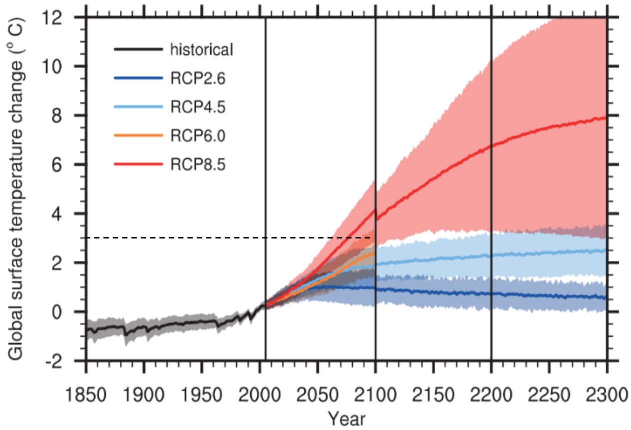


Figure 2-4. Time period of the global surface temperature change for projections from each RCP model. The figure is from (Stocker, et al., 2013); added black dotted line is for comparison with Figure 2-3.

The A1B scenario in Figure 2-3 and the RCP model in Figure 2-4 can be compared. The global surface temperature change in 2100 is approx. 3 °C for the A1B, corresponding to a level between RCP6.0 and RCP 8.5. The difference in the two scenarios is therefore small.

In the work by Nik (2012) hygrothermal simulations of buildings were performed with the use of future climate conditions corresponding to the SRES scenarios B2, A1B and A2. As the overall difference between the two models is small, and as it becomes easier to compare with Nik (2012), it was decided to use the SRES A1B scenario in the present thesis. Another reason for using the SRES A1B scenario is that the project CLIMATE FOR CULTURE (2009-2014) produced climate files, which are compatible with the chosen simulation program, described in section 2.6.

2.5. HUMIDITY CLASS

The indoor humidity level in buildings depend on the moisture production, ventilation rate and outdoor humidity. According to the European standard (ISO 13788, 2012), the indoor humidity load is categorised into five different humidity classes (HC), of which the excess moisture depends on the monthly mean outdoor temperature. According to Brandt et al. (2013), Danish single-family houses with normal occupancy are normally categorised in HC2, whereas apartments for social housing are normally with unknown occupancy and categorised in HC3.

In the work of Hansen and Møller (2017), the humidity classes in 500 Danish single-family houses were investigated. They span from HC1 to HC3. Furthermore, Geving et al. (2008) and Geving and Holme (2011) has made measurements in 117 houses in Trondheim, Norway. Their results were originally compared with a previous version of the European standard ISO 13788, where the humidity class boundaries were different. However, if the measurements are compared with the present European standard, the humidity class for bedrooms and living rooms is HC1 and HC2 whereas HC2 and HC3 are most likely for bathrooms. Arumägi et al. (2015) investigated and compared the indoor climates in 41 apartments in Estonia with the European standard. They found that the average for all apartments was at the high end of HC2. Vinha et al. (2018), on the other hand, found that the humidity class for Finish apartments was lower than single-family houses. However, the air change rates of the apartments were also higher. Similar to this Morelli and Møller (2019) found that the humidity class in apartments drops from HC3 to HC1 after installing a balanced mechanical ventilation system.

2.6. SIMULATION

There are several commercial computer simulation tools available, which can make estimations of hygrothermal performance of building constructions. Mundt-Petersen and Harderup (2013) found DELPHIN (Grunewald, 1997), WUFI (Künzel, 1995) and COMSOL Multiphysics (Multiphysics, u.d.) user-friendly. In Denmark DELPHIN and COMSOL are mostly used for academic purpose, whereas WUFI is more commonly used in the building sector. Furthermore, the Danish Building Simulation Tool, BSim, is another program used for energy consumption and indoor climate simulations. The program can also be used for simulating moisture transport in constructions and spaces with 3D models (Wittchen, et al., 2008). A comparison between BSim and WUFI was performed by Møller et al. (2019) for an attic construction as 1D simulation in WUFI and a 3D simulation in BSim. The comparison suggests that WUFI 1D simulations are sufficient for most purposes.

Even though WUFI 1D has limitations, it will be used in the present work. One of the main limitations is that moisture transport due to convection (vapour transport due to airflow) from the room below the ceiling is ignored. However, this can be handled by manually placing a moisture source in the construction. Another limitation is the simplification on the moisture storage effect of the building materials. Schafaczek et al. (2012) showed that simulations with widely accepted simulation programs cannot determine whether a construction with an insulation product with moisture buffer effect and no vapour barrier is more moisture safe than one with a traditional insulation product and a vapour retarder. It depends on which simulation program is used. Schafaczek et al. (2012) compared their own simulations of the two types of outer wall constructions made with WUFI (Künzel, 1995) to other simulations (Pfluger, 2005) made with DELPHIN (Grunewald, 1997). The result showed that the conclusions of the two simulations are exactly opposite: the moisture buffering effect in DELPHIN was high, whereas in WUFI simulations it was low. The WUFI results correspond to the experimental findings of Samuelson (1998).

2.7. MOULD GROWTH

In cold ventilated attics, there is a risk of mould growth if the relative humidity is too high and the temperature is favourable. There are a high number of mould fungi species with varying favourable growth conditions (Sedlbauer, 2001). In general, there is a mould growth potential at relative humidities above 75 % if the surface contains easily accessible nourishment e.g. organic materials, the higher humidity the better the growth condition and a larger amount of different species can grow. The stated relative humidity – or water activity – is at the surface of the material, or in the pores in the surface. When the humidity is low, the growth will stop, but the spores will survive and can start growing when moisture is available again.

Besides the relative humidity the mould growth is also dependent of the temperature, the optimal temperature being 20-30 °C for most of the species. However, several species also have good growth conditions at lower temperatures. When the temperature is around 0 °C, the mould is no longer active, however not dead but in a torpid state and will survive even if frozen. At temperatures above 25-30 °C, the growth potential is reduced, and at temperatures above 40-60 °C most of the spores die, (Viitanen, et al., 2010). The relative mould growth potential expresses a combination of the temperature and the relative humidity, which gives a certain mould growth rate and can be shown in a figure as given in Figure 2-5 for some ordinary species based on Byggforskserien (2005). Unfortunately, the substrate is not stated. However, in the work of Sedlbauer (2001), a similar combination is described based on the relative humidity, temperature, time and substrate.

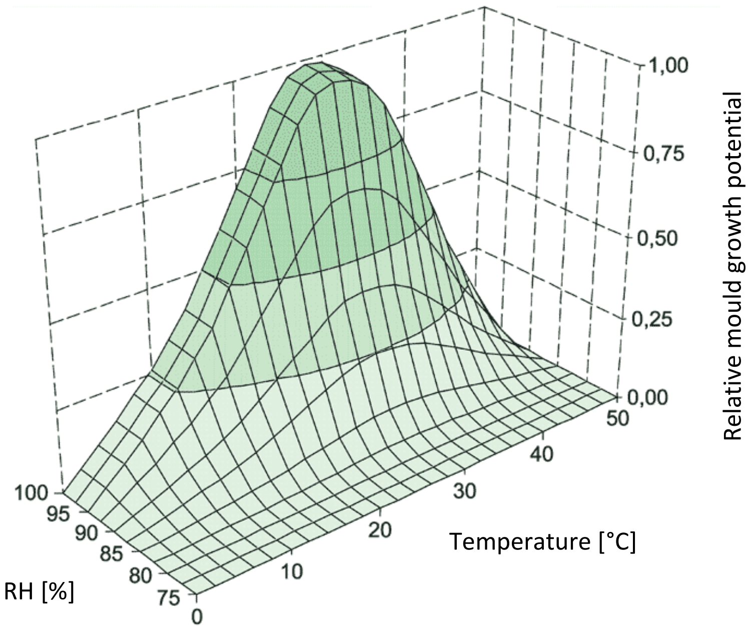


Figure 2-5. Relative mould growth potential for the most ordinary species as a function of temperature and relative humidity, (Byggforskserien, 2005).

For prediction of mould growth risk, a number of different models have been developed (Vereecken & Roels, 2012). Gradeci et al. (2017) performed a generic framework of nine different mould prediction models applicable to wood-based materials. In this present work two of these models have be presented, where the prediction is based on the measured relative humidity and temperature over time:

- VTT (Technical Research Centre of Finland) model, described by Hukka and Viitanen (1999) and Ojanen et al. (2010).
- MRD (mould resistance design) model, described by Isaksson et al. (2010) and Thelandersson and Isaksson (2013).

There are different graduations of mould growth for each model. Even though it is not possible to make a direct comparison between the models, a cautious attempt is given in Table 2-1. For each level a descriptive text is given, based on the description for the VTT model and by Johansson et al. (2012) where the MRD index is compared. The VTT model has six levels of mould growth graduation, whereas the MRD model has its focus on initiation of mould growth, which to some extend can be compared with the mould rating by Johansson et al. (2012). In the present work, evaluation has its focus on the initial growth; therefore, primarily the MRD model is used. The MRD model is described briefly here, whereas in Paper I both models are described in more detail.

Table 2-1. Graduation of mould growth, based on (Johansson, et al., 2012) (Mould rating), (Thelandersson & Isaksson, 2013) (MRD index) and (Viitanen, et al., 2010) (VTT index)

Mould rating (MRD index)	VTT index	Description of extent of growth
0 (0)	0	No mould growth
1 (0.5)	1	Initial growth detected with microscopy
2 (1)	2	Moderate but clear growth detected with microscopy
3	3 4	Visual mould growth detected. VTT index, 3: < 10% and 4: 10%-50% coverage
4	5 6	Visual heavy mould growth detected. VTT index, 5: > 50% and 6: about 100%

Beside the input data for temperature and relative humidity, mould growth models in general consider the availability of nourishment for mould fungi. E.g., mould growth starts at a lower relative humidity level on surfaces with easy susceptible organic material, e.g. wood than on inorganic surfaces where the only nourishment is organic dirt like e.g. on concrete surfaces. In the MRD model this material parameter is described by D_{crit} the critical dose, which describes the time, in days, required for mould growth to reach a MRD index of 1. An MRD index of 1, is related to "*Sparse but clearly established growth; often conidiophores are beginning to develop*" (Johansson, et al., 2012). This corresponds to mould rating 2 by Johansson et al. (2012). The critical dose is depended on the material surface or substrate on which the mould growth occurs under a constant temperature of 20 °C and 90 % relative humidity. Based on Thelandersson and Isaksson (2016) a critical dose of 17 days has been selected, which corresponds to sawmill planed Norwegian spruce. It is important to keep in mind that an MRD index above 1 is not in all cases linear to mould rating as described by Johansson et al. (2012), which is remarked by Thelandersson and Isaksson (2013), a translation from one scale to another should therefore be handled with care.

Due to ethical problems and costs, no mould growth tests were performed in the cases buildings, but visual inspections (mould level ≥ 3) were carried out. However, tape samples were used to test the presence of mould growth in the full-scale test building. Each sample was analysed by microscopical examination at 10-40x magnification. This test was also used by Arfvidsson et al. (2013) which examined mould growth in 19 different Swedish houses. Furthermore, Johansson et al. (2012) used it for analysing the prevalence of mould growth in laboratory tests.

CHAPTER 3. METHODOLOGY

This chapter presents the overall methodology of the work. The methodology is divided into three parts, which each describes different hygrothermal investigations and analyses of cold ventilated attics:

1. A full-scale test building with controlled boundary conditions used to investigate the influence of different parameters in the construction of the ceiling between inner lining and ventilated space.
2. A field survey of Danish dwellings with different erection years and building constructions, and consequently different hygrothermal performance.
3. Based on the experience of the first two parts, hygrothermal simulations were performed where different parameters and a predicted climate change impact were investigated.

3.1. TEST BUILDING

A full-scale test building was erected in order to investigate the moisture conditions in cold ventilated attics under a controlled indoor climate and under the same climate conditions (see Figure 3-1). The full-scale test building was constructed with a size of 7 x 22 m and a height of 2.8 m, with a 30° pitched roof and trussed rafters; the orientation of the roof was north/south facing. The depth, height and surroundings of the building influence the ventilation rate and air movements in the attic space. For this reason, no tall objects were located near the test building. In size and location, the test building represented a traditional Danish single-family house.

3.1.1. MAIN CONSTRUCTION OF THE BUILDING

The test building was a lightweight construction with 300 mm of insulation in the walls and floor and plasterboard and chipboard as interior finish. Inside the wall construction, 50 mm from the warm side, a 0.02 mm PE-foil was placed as a vapour barrier. The wall cladding was steel plates with a ventilated air gap behind, and the roofing was light grey steel plates above a diffusion tight roof underlay consisting of a membrane (s_d = 160 m). Between the roof underlay and roofing was a 25 mm ventilated air gap. The attic space was ventilated through openings at the eaves (30 mm air gaps in both sides) and at the ridge (two valves of 50 mm² per m in the roof underlay). This corresponded to the recommendations in the Danish guidelines (Brandt, et al., 2013) and to Danish tradition. The construction of the ceiling is described in section *3.1.2 Construction*.

Figure 3-1. Picture of the full-scale test building at its first location.

Figure 3-2 shows the timeline of the erection and measurements in the full-scale test building.

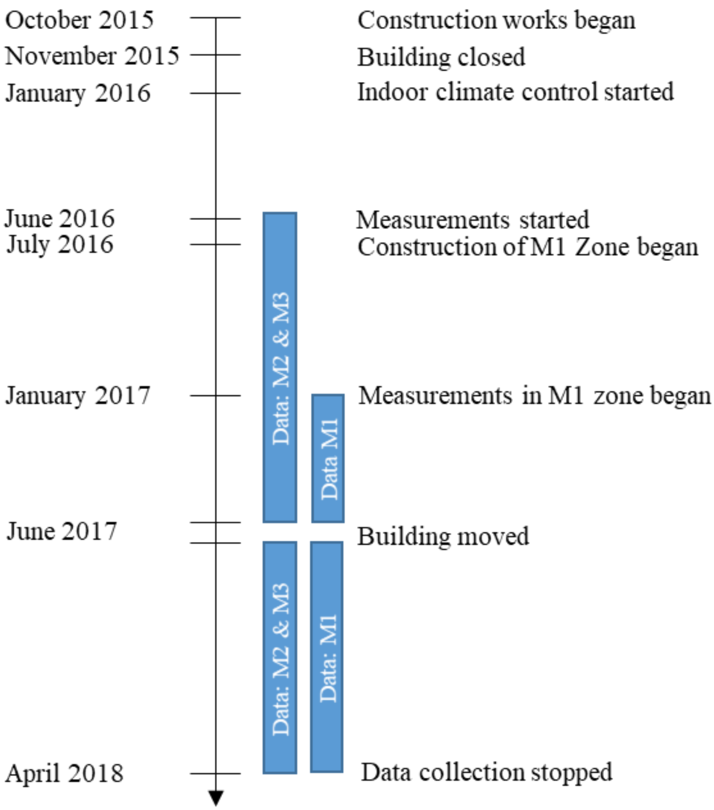


Figure 3-2. Timeline for erection and start of measurements in the full-scale test building. M1-M3 indicates the indoor humidity class 1-3.

The construction work started at the beginning of October 2015, and the building envelope was closed after three weeks. The interior finishing and construction of the test ceilings and indoor climate controls were established mid-January 2016. Due to complications with the acquisition of the right sensor system for measuring temperature and relative humidity, data collecting was delayed. The system was installed and functioning from 1 June 2016 for the first two zones of the test building. The third zone was erected during the summer 2016 and functioning from 1 January 2017. In 2017 the university established a new test location, and the test building was therefore moved and not functioning during the period from 1 June to 18 July 2017. The test building was split into six sections, as shown in Figure 3-3 and moved 30 km south to the new test site. The airtightness of the ceilings was tested after the move; the type of surroundings and the building orientation were kept as at the original test location.

Figure 3-3. Separation and moving of the test building.

3.1.2. CONSTRUCTION OF DIFFERENT ATTIC SECTIONS

The interior of the test building below the ceiling was divided into three zones. The humidity level in each zone could be controlled individually. In the attic above every zone, there were six test sections with different ceiling constructions, i.e. a total of 18 test sections (see Figure 3-4).

The six different test sections had an airtight ceiling construction consisting of one layer of plasterboard (λ = 0.2 W/m^2·K, s_d = 0.1) with spackled and taped joints.

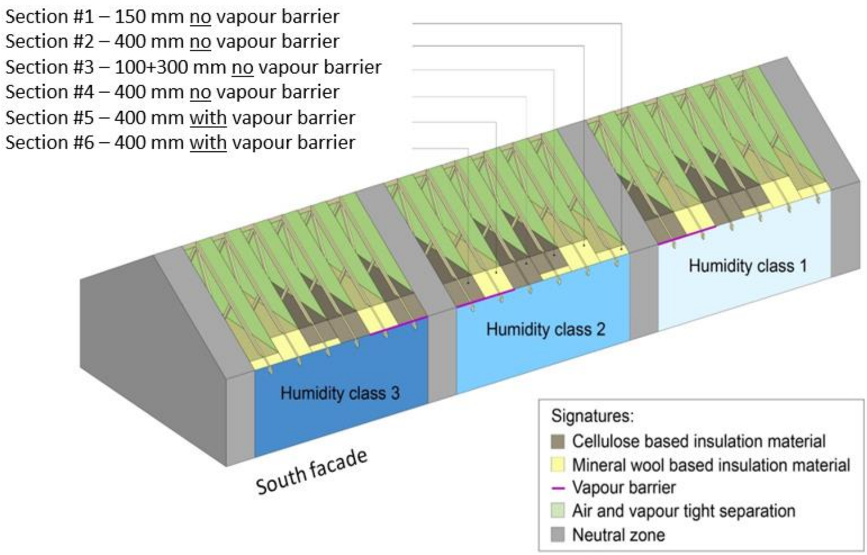


Figure 3-4. Sketch of the test building illustrating the six attic sections with different ceiling constructions above each of the three indoor zones with different humidity classes.

The constructions of the ceilings were linked to the different hypotheses:

- To test the influence of the vapour barrier; two sections had a polyethylene foil (PE-foil) as a vapour barrier (s_d = 140 m) (section 5 and 6); the other sections had no vapour barrier.
- To test the hygroscopic influence; two different insulation materials were tested either non-hygroscopic insulation (mineral wool based on stones, λ = 0.041 W/m^2·K) or hygroscopic insulation (cellulose fibres based on recycled newspaper, λ = 0.039 W/m^2·K).
- To test the insulation thickness; two sections had insulation material with a thickness of 150 mm and 400 mm, respectively. In both cases, non-hygroscopic mineral wool was used, and there was no vapour barrier. The 150 mm insulation material corresponded to the maximum thickness without vapour barrier as recommended by Brandt et al. (2013) and Brandt et al. (2007). Granulates were used for the 400 mm insulation material as it represented re-insulation.

The difference in the sorption isotherms of the material (e.g. in WUFI) (Künzel, 1995) or (Pedersen, et al., 2003) shown in Figure 3-5 illustrates that at a relative humidity of 90%, cellulose-based insulation material can contain 10 times more moisture than mineral wool. Furthermore, cellulose-based insulation material has a steep sorption curve from 50% to 90% relative humidity, contrary to mineral wool.

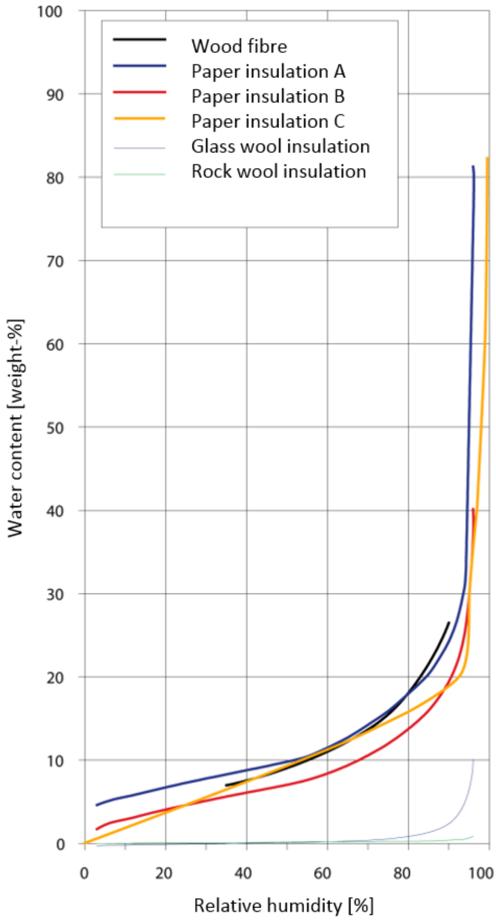


Figure 3-5. Sorption isotherm for different insulation material at 20 °C. (Pedersen, et al., 2003). Paper insulation A with 18 weight-% boron salt, Paper insulation B with 6 weight-% boron salt and 9 weight-% aluminium hydroxide, Paper insulation C with 3 weight-% boric acid and 9 weight-% magnesium sulphate.

To prevent moisture transport between each test sections, vertical plywood boards lined with PE-foil were installed between the sections. The separation boards were installed from the roof underlay through the ceiling and tightened to the ceiling. All joints were tightened with tape, and airtightness between attic sections and the indoor zone was tested by using negative pressure and smoke. The air change rate (ACH) of the attic space was measured with passive tracer gas (Heiselberg & Bergsøe, 1992) over three periods of 3-4 weeks during July/August 2016, March/April 2018, and January/February 2019. The results of these tests were also used to test the separation between the attic section and the ceiling tightness.

3.1.3. DATA COLLECTION

In each attic, data collection was performed for the wood moisture content, relative humidity and temperature. The sensor positions are shown in Figure 3-6. Sensors along the roof underlay were placed on the trusses approx. 3 cm from the underlay.

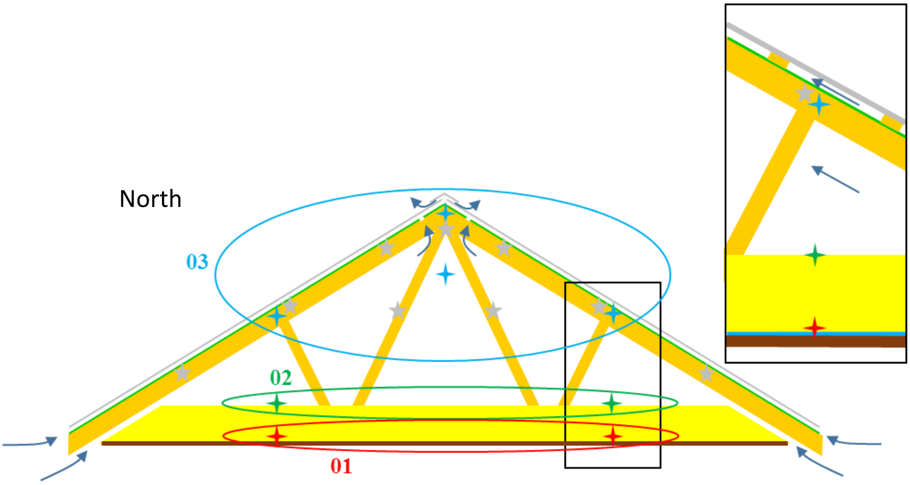


Figure 3-6. Sketch of the attic construction and sensor positions in the full-scale test building. Relative humidity and temperature sensor points are marked with four-point stars, while wood moisture content measuring points are marked with five-point stars. The relative humidity/temperature sensors are pooled into three groups from 01 to 03 above the ceiling and placed above the insulation material and in the attic space respectively. The close-up in the right corner illustrates the cross section of ceiling and roof; brown symbolizes plasterboard, light blue symbolizes vapour barrier, yellow insulation material, green roof underlay membrane and grey roofing steel plates.

The wood moisture content was measured at 12 different positions directly in the timber roof trusses by means of two 15 mm screws (Figure 3-7 A). The screws were connected to a cable which led to a connection box in the indoor zone (Figure 3-7 B), where a handheld pin-moisture meter was connected to a switch. From here the resistance between the two screws was measured for each sensor point. Every week or every other week the moisture content was manually recorded. Based on (Brandt, 1990), the inaccuracy of wood moisture content measured with a pin-moisture meter is to be less than 10 %. Before installation, the wiring and the pin-moisture meter were controlled with a calibration box with given values of wood moisture.

Beside sensors for wood moisture content, sensors to record temperature and relative humidity were installed in each attic (Figure 3-7 C). Based on the recorded temperature and relative humidity, the air moisture content by volume was calculated as given in ISO 13788, Annex E (ISO 13788, 2012). The sensors used were

HTemp-1 wires from HW group. According to the manufacturer (HW group, 2014), the temperature accuracy is ± 1.0°C (between -10°C and +70°C) and ± 2.5% relative humidity (between 20 and 80%). The system was set to record the temperature and relative humidity every hour. All sensors were tested before installation at three controlled climate levels of relative humidity at two different temperature levels. This test was performed in a controlled environment in the lab. After two years of measurements in the test building, all sensors were re-tested onsite in calibration boxes with three different saturated salt solutions (approx. 75, 85 and 95 %RH). All measured values during the two years of recording were adjusted assuming a linear drift of the sensors over the two-year period.

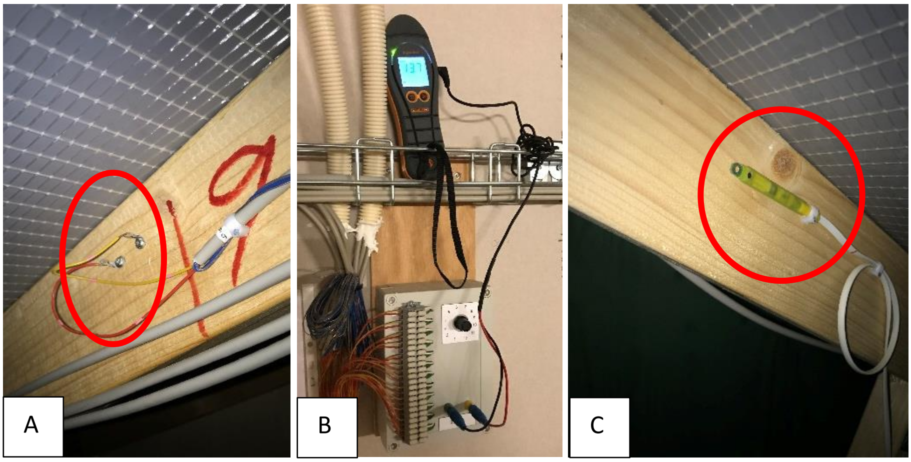


Figure 3-7. Pictures of sensors in the attics. A) Wood moisture content based on resistance between two screws, mounted directly in the wooden construction. B) The connection box where to the handheld pin-moisture meter was connected. C) Temperature and relative humidity sensors.

Due to the recording interval of one hour and the normal day variation in a ventilated attic, high fluctuation was expected in the data collected. For this reason, a moving average of one-week was used for all sensors. The recorded indoor and outdoor climate was likewise measured hourly and treated in the same way.

In the test building, 216 wood moisture points and 158 temperature and relative humidity sensors were installed. With this high number of data collection points, it was important to have an identifiable name for each sensor. An example of the name system used is *'M2_5_03'*. Here the first denomination corresponds to the indoor humidity class, the second denomination refers to the test section as given in Figure 3-4 (in this example, it is Attic 5 with mineral wool based insulation material and with vapour barrier), and the third denomination is the sensor position shown in Figure 3-6.

Measurements of relative humidity, temperature and air moisture content by volume were collected in each test section, and the differences were compared with the sensor accuracy. The results from the four temperature and relative humidity sensors were pooled and averaged in order to improve the accuracy of the measurements.

3.1.4. INDOOR MOISTURE LEVELS

The indoor climate is one of the key parameters when buildings are designed. The three selected zones used in the test building are based on the examination of the humidity class of 500 Danish single-family houses (Hansen & Møller, 2017). The examination showed that 32% were in humidity class 3 or above, and 40% were in humidity class 1. For this reason, humidity classes 1, 2 and 3 were selected for the test building, see Figure 3-4 below. The indoor moisture level is normally dependent on the outdoor moisture level and the internal moisture production and ventilation. According to ISO standard (ISO 13788, 2012), the internal humidity load is dependent on the average monthly outdoor temperature. Based on ISO standard (ISO 13788, 2012) and the Danish design reference year (Wang, et al., 2013), different monthly set points were chosen for the indoor climate, as shown in Figure 3-8.

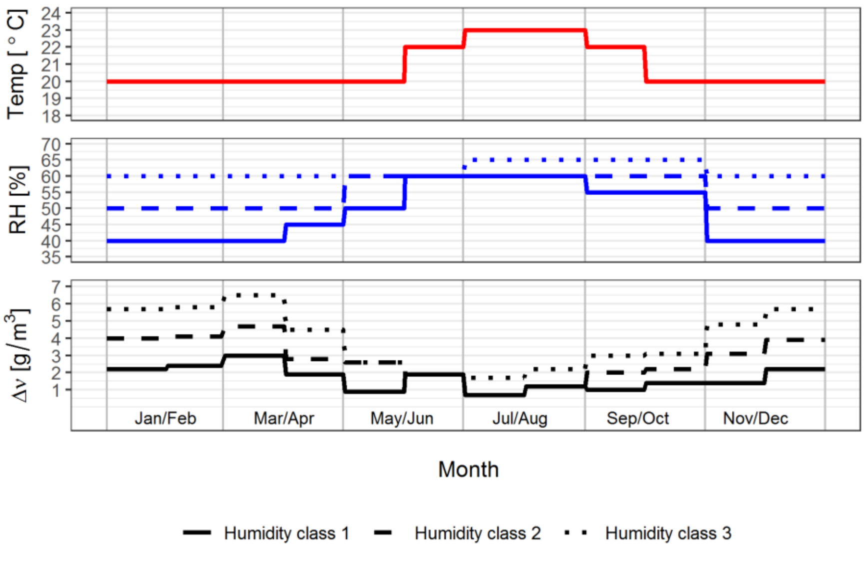


Figure 3-8. Monthly set point for the different humidity classes for temperature (Temp) and relative humidity (RH). Furthermore, the internal moisture excess (Δv), water vapour content calculated by the use of ISO 13788 (2012) is shown.

3.2. FIELD SURVEY

As a supplement to the full-scale test building, a field survey was needed for collection of knowledge about ceilings in buildings erected at different times and with common workmanship, i.e. not erected with the special care that was taken in the construction of the full-scale test building.

The selection of case buildings was conducted by searching the web for previously sold single-family houses with different erection years. Thereafter, letters were sent to the building owner, which were followed up by a telephone call for making an agreement for investigation. Families of more than 80 addresses were contacted where 35 were willing to participate. One of the case buildings was constructed differently from expected and was omitted from the survey. In all case buildings, the data collection was performed for at least one year in the period from July 2015 to April 2018. Unfortunately, it was not possible to collect measurements in all case buildings at the same time, due to difficulties in finding suitable buildings and getting access to these.

3.2.1. ATTIC DESIGN

A vapour barrier was one of the selection parameters for the case buildings. As indicated in Figure 2-2, the vapour barriers used 30-50 years ago in Denmark were usually PE-foil or Alu-foil. During this period, the insulation material used was normally mineral wool, and the thickness was 80-200 mm. However, since insulation thickness is a selection parameter, thicker layers of insulation (400-600 mm) were also considered as seen in modern ceilings, or when additional insulation has been applied. Furthermore, since the use of cellulose-based insulation material has increased during the past 10 years, the insulation material selection parameter included both mineral wool and cellulose based material. Conversely, ventilation rate in the attic was not a selection parameter. The recommendations regarding ventilation of attics have been more or less the same since the first Danish recommendation by Becher and Korsgaard (1951) on ventilated attics was published. Even before, the traditional way was similar to the later recommendation. No information on the effectiveness of attic ventilation was available in any of the case buildings. Therefore, the attic ventilation was not a selection parameter, but during the inspection of the case buildings, it was noted if the ventilation was visibly impaired.

*Table 3-1. Case buildings listed according to the type of vapour barrier. The measured winter period, total insulation material thickness and the corresponding thermal transmittance are given. *Insulation material type, i.e. CL = cellulose and MW = mineral wool. **Case buildings where the ventilation openings of the attic do not follow the Danish recommendation. The colours divide the case buildings according to the thickness of the insulation material: Yellow means: 150-200 mm, Green 300-400 mm and Orange: 450-600 mm.*

	Test_ID	Year of erection	Vapour barrier type	Measured winter period	Insulation Type*	Total insulation, mm	Thermal transmittance, W/m²K
A	01	2015	None	15/16	CL	600	0.07
	02	1964		15/16	MW/CL	350	0.11
	03	1935		Discard due to different roof construction			
	04	1956		16/17	MW	250	0.15
	32**	1956		17/18		175	0.22
	33**	1953		17/18		150	0.25
	34**	1952		17/18		250	0.16
B	05, 08**	2004, 1998	PE-foil	15/16	MW	250	0.16
	06	1979		15/16		200	0.19
	07	1996		15/16		150	0.25
	09**	1970		16/17		450	0.09
	31	1976		16/17		350	0.11
	35	1998		17/18		300	0.13
C	10, 12	1969, 1971	Alu-foil	15/16	MW/CL	300	0.13
	11	1969		15/16		450	0.09
	13 – 22	1980		15/16		500	0.08
D	23	1971	Alu-foil	15/16	MW	200	0.19
	24, 28	1968, 1964		16/17		400	0.10
	25	1970		16/17		300	0.13
	26	1976		16/17		250	0.16
	27, 29, 30	1976		16/17		350	0.11

3.2.2. DATA COLLECTION

In order to collect data concerning the relative humidity and temperature, numerous sensors were installed in each case building both in the cold attic and the heated space below. Data collection was performed with sensors from Lascar electronics (2019) for at least one year with hourly recordings. Positions of the sensors are shown in Figure 3-9. Furthermore, sensors were located indoor and outdoor to register the climate. Some case buildings were in the same area, and one sensor could therefore cover several case buildings for the outdoor climate. Before installation, all sensors were controlled for uncertainty. This was within 0.55°C and 2.25% relative humidity in the interval of 50-90% relative humidity. This corresponded to the information given by the manufacturer.

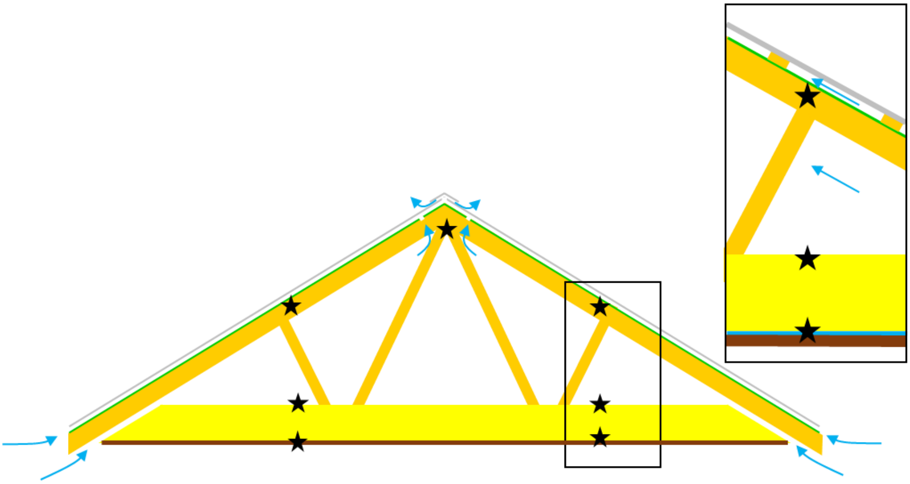


Figure 3-9. Sketch of a cold ventilated attic, with positions of sensors (black stars); blue arrows indicate ventilation. All case buildings had more or less the same attic construction, but only some of the case buildings had a roof underlay. Where roof underlay was present, it consisted of a membrane (except one where the roofing was wooden board with roofing felt, B31). In the close-up, the brown line is the ceiling covering, the blue line indicates the position of a possible vapour barrier, whereas the green line a possible roof underlay.

Beside measurements of temperature and relative humidity, permission to measure the air change rate (ACH) was granted in seven of the case buildings. Two different passive tracer gases were used Heiselberg and Bergsøe (1992); one was placed in the attic and the other in the living space. Samplers were also placed in the attic and the living space. By using two different gases, the ventilation rate of the attic and the living space and the air exchange between attic and living space could be calculated. The measurement of air change rate with passive tracer gases is highly dependent on the period measured; different wind conditions can for instance give different results. Therefore, the measurements were performed over a period of at least 14 days, which was considered sufficient to provide an indication of the ACH magnitude.

3.3. SIMULATIONS

Simulations were performed to investigate different parameters, which could not be tested in practice, due to economical or practical reasons. The different parameters are given in Table 3-2. For the simulation, different steps have been investigated:

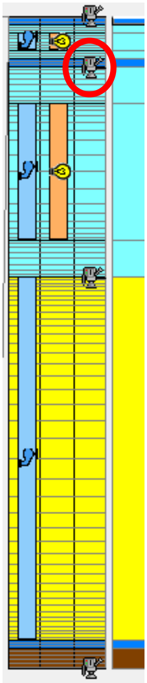
1. An attic construction as described in section 3.1. Test building was simulated and compared with measurements.
2. A parameter study with the parameters – vapour barrier, insulation material type, insulation material thickness, ACH and leakage – was performed with a standard climate based on the calibrated simulation model. Mould growth models were used based on the results of temperature and relative humidity, to evaluate the hygrothermal performance.
3. Models with acceptable levels of mould growth were simulated with a predicted future climate condition for the next 30 years (2020-2050).

Table 3-2: Investigated parameters in the simulations to investigate their impact on the hygrothermal performance of an attic.

Parameter variation	Vapour barrier	Insulation thickness	Type of insulation	ACH	Leakage CMML	Climate
Option	Yes/no	150/400 mm	Mineral wool / cellulose based	5 values	3 values	Present /future

3.3.1. SIMULATION MODEL

The WUFI simulation tool was used and the base model is shown in Figure 3-10. As described by Künzel (1995) and Mundt-Petersen (2015) a ventilated air gap in an attic model may consist of three layers. This makes it possible to handle free water and moisture capacity. The three layers are defined as a middle air layer without additional moisture capacity, between two thin air layers with moisture capacity. Furthermore, the air change of the model was placed in the middle air layer to ensure the capability to remove moisture. Simulation of a moisture source from the indoor climate to the attic, e.g. a moisture flow caused by an air leak, can be done in different ways in WUFI, and so can the placement of the source. In this work, the moisture supply to the attic was placed in the entire thickness of the insulation material. The different materials used in the model were all taken from the WUFI database. Another simplification, which is crucial, is the modelling of the attic space. In most cases, the attic is triangular, whereas the simulation model was 1D. Consequently, the air space of the attic can only have a single thickness. Furthermore, WUFI can only handle small air gaps (Mundt-Petersen & Harderup, 2015). Hence, the attic space was simulated as a small air gap (the middle air layer) where the ventilation was enhanced compared to the actual ACH. This is described in further detail in Paper III, and the method is also used by Mundt-Petersen and Harderup (2015).



Material description	Thickness [mm]
Roof membrane V13	1
Air layer	10
Air layer without additional moisture capacity	20
Air layer	10
Roof membrane V13, Correspond to vapour tight roof underlay	1
Air layer	40
Air layer without additional moisture capacity	150
Air layer	40
Insulation material, either mineral wool or cellulose fibre (0.04 W/mK)	150/400
Vapour barrier (sd = 1,500m)	1
Ceiling, Spruce tangential (430 kg/m^3)	22
Monitor position, where results are retrieved	
Moisture source, given in Table 3-3 as CMML	
Air change source, given in Table 3-3 as ACH	

Figure 3-10. Basic model used in the simulation. Description of each material layer which was found in WUFI material database.

As indicated in Table 3-2, the different parameters were varied. These were combined in groups with different values of air change rate (ACH) and estimated moisture flow through the ceiling (CMML). Further description of the design of the values for the ACH and CMML is given in Paper III. Consequently, all groups were simulated with mineral wool and cellulose, with 150 and 400mm insulation material, with or without a vapour barrier respectively. Table 3-3 shows the different combinations for each group of simulation.

Table 3-3. Case matrix for all performed simulations with mineral wool and cellulose, respectively with 150 and 400 mm of insulation and with or without a vapour barrier, i.e. eight simulation in each group. The given ACH (air change rate) is the used value in WUFI, where the value in brackets is the value for a real size attic. The given CMML (constant monthly moisture load) moisture leakages to the attic space.

Group	**A**	**B***	**C**	**D***	**E**	**F**	**G***	**H**	**I****
ACH [h^{-1}]	12 (2.0) Low	21 (3.5) Medium	12 (2.0) Low	21 (3.5) Medium	120 (20) Very high	3 (0.5) Very low	60 (10) High	21 (3.5) Medium	60 (10) High
CMML [$kg/(m^2 \cdot s)$]	6 Small	6 Small	20 Medium	20 Medium	20 Medium	6 Small	20 Medium	30 Big	6 Small

* Cases where simulation is performed for future climate.
** Case only simulated with future climate.

3.3.2. CLIMATE

For the indoor climate, the European standard (ISO 13788, 2012) for humidity class 2 was used (this was also one of the humidity classes used in the full-scale test building). Other humidity classes could also have been simulated, but it was decided not to do this because the moisture supply, defined as CMML, covered the situations with different moisture loads in the indoor climate. The outdoor climate was obtained from Meteonorm (2018) for Taastrup, Denmark. The annual variation of outdoor temperature and relative humidity is illustrated in Figure 3-11 together with a one week moving average (black line) and the measured values at the full-scale test building (grey line). It was decided to use a standard climate because only the relative humidity and temperature were measured at the test building. The aim of the simulation was not to validate how the model reflects changes in the weather, but to obtain results from the model that reflects the trend measured. It was decided not to gather data from a meteorological station.

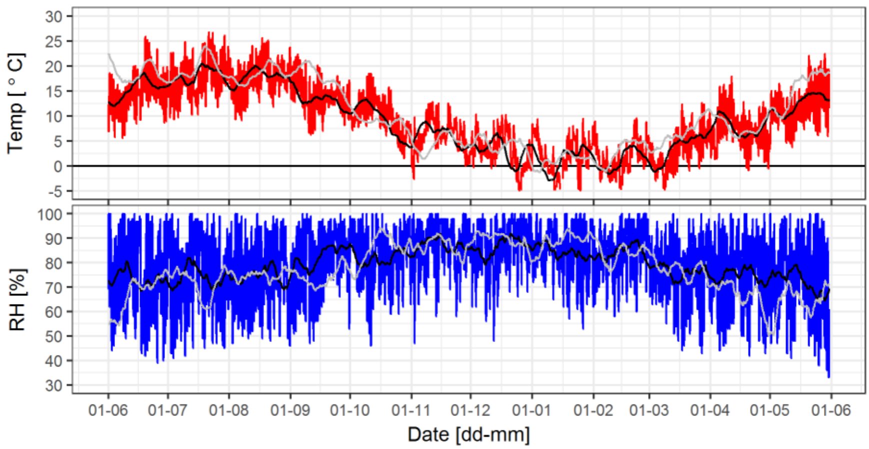


Figure 3-11. Standard current outdoor climate for one-year period, obtained from Meteonorm (2018), for Taastrup, Denmark. The moving average of one week is illustrated as a black curve. The grey curve is the measured one week running average outdoor climate at the test building.

Concerning future climate conditions, several prediction models are available. In this thesis, results from the project (CLIMATE FOR CULTURE, 2009-2014) was used. The model chosen was based on the IPCC 4th Assessment Report A1B scenario (Nakicenovic, et al., 2000). The Climate for Culture project includes several locations in Europe. In the files, all climate data for simulation in WUFI are given for the period 2020-2050. In Figure 3-12 temperature and relative humidity for the predicted climate is illustrated.

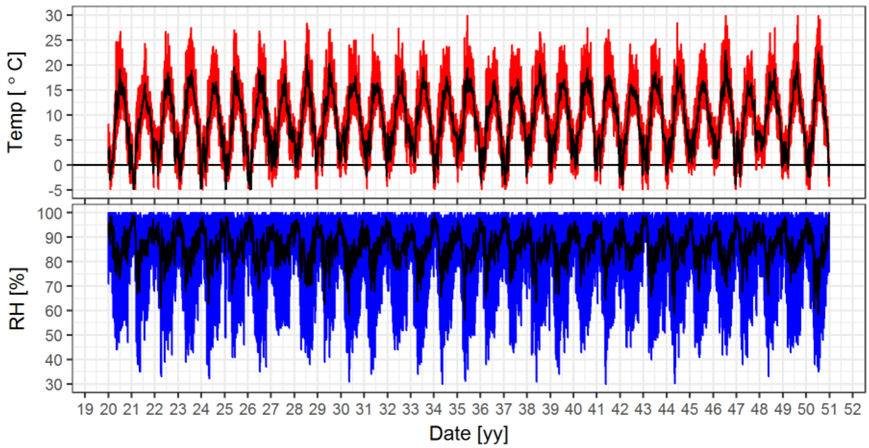


Figure 3-12. Future outdoor climate prediction for 2020-2050 based on (D. & L., 2013). Black curves indicate moving average of one week.

CHAPTER 4. DISCUSSION OF MAIN FINDINGS

The main findings from Paper I-III are summarised and discussed in the following chapter.

4.1. HYPOTHESES ANALYSES

Based on the recorded parameters in the full-scale test building and the case buildings in the field survey, three hypotheses have been tested for the effect on moisture level in the cold ventilated attic:

- H1 – The presence of a vapour barrier.
- H2 – The hygroscopic properties of the insulation material.
- H3 – The thickness of the insulation material.

Besides testing the hypotheses by measuring temperature and relative humidity the hypotheses are also tested by calculating the air moisture content by volume (in the full-scale test building) or water vapour pressure (in case buildings).

For the test building, a statistical analysis was performed, and the results are presented in section 4.1.1. The findings from the field survey are discussed in subsections for each hypothesis together with the findings from the test building, based on visual evaluation of the data recorded. Not all graphs are included, but the reader will be referred to the respective Papers.

4.1.1. GENERAL/INTRODUCTION

The measured data (temperature, relative humidity and calculated moisture content) from the attics of the test building can be compared graphically. In this simple way, the hypotheses can be tested. In Figure 4-1 and Figure 4-2 from Paper I, an example is shown for the vapour barrier hypotheses for mineral wool for humidity class 2 and humidity class 3, respectively; these were chosen to illustrate two extremes. For humidity class 2, the difference in the relative humidity for the two test sections are close to each other during most of the winter period. However, for humidity class 3, there is a noticeable difference for practically the whole winter period, and this corresponds to the statistical analysis given in Table 4-1.

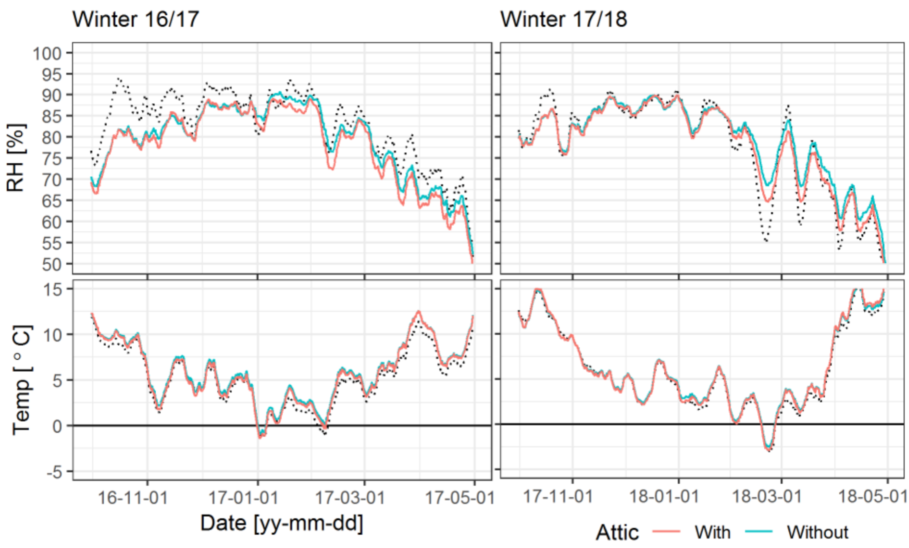


Figure 4-1. Vapour barrier hypothesis (H1) tested in the full-scale test building, for mineral wool, humidity class 2. The hygrothermal conditions between the two test section with or without a vapour barrier is insignificant. The black dotted curve is the outdoor climate at the full-scale test building.

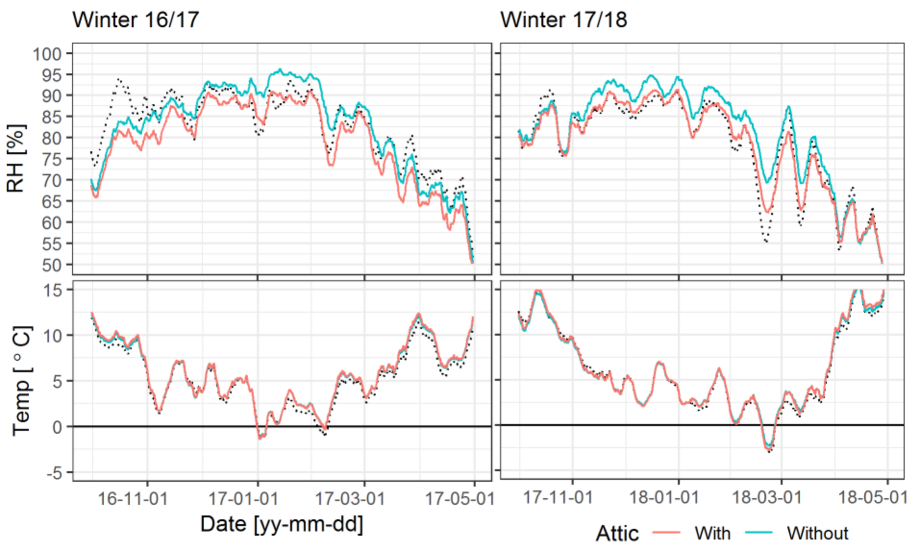


Figure 4-2. Vapour barrier hypothesis (H1) tested in the full-scale test building, for mineral wool, humidity class 3. The relative humidity is noticeable higher in the attic without a vapour barrier. The black dotted curve is the outdoor climate at the full-scale test building.

Besides making a simple graphic evaluation, a statistical analysis was performed for the test building based on the average margins. For each series of measurements, the data were aggregated to daily averages. The effect of vapour barrier, insulation material type and insulation material thickness were tested by pairwise comparisons. The margin at which the two series would yield a significant statistical difference was computed. A significance level of 0.05 was chosen, and a paired t-test was used to define the margin for the minimal mean difference needed for the measurements to be significantly different. The margin was compared with the tolerance of the sensors to judge whether this margin was within the practical limits and accuracy of the sensors. In this way, it was possible to separate the differences of constructional importance from those of merely statistical significance. The calculated margins are gathered in Table 4-1. A similar statistical analysis of the field survey was not performed because of the differences in outdoor climate and because the number of case buildings with the same conditions was too small to make a significant analysis.

*Table 4-1. Statistical analysis of the margins for each hypothesis, based on calibrated measured data in the full-scale test building for sensor point 03 above each humidity class. The * by the number indicates the level at which the margin is statistically significant. Significance: 0.05 level (*), 0.01 level (**), and 0.001 level (***) (highly significant).*

Hypotheses		**Sensor point: 03**		
		HC1	**HC2**	**HC3**
Relative Humidity [%]	H1 – Cellulose	1.1	2.3	2.5
	H1 – Mineral wool	0.0	0.8	4.0*
	H2 – With vapour barrier	1.3	3.2	0.8
	H2 – Without vapour barrier	0.0	1.8	2.2
	H3 – Without vapour barrier	1.0	1.2	3.2
Temperature [°C]	H1 – Cellulose	0.0	0.1	0.1
	H1 – Mineral wool	0.1	0.3	0.1
	H2 – With vapour barrier	0.0	0.4	0.1
	H2 – Without vapour barrier	0.1	0.1	0.1
	H3 – Without vapour barrier	0.1	0.2	0.5
Moisture content [g/m^3]	H1 – Cellulose	0.1	0.1	0.2**
	H1 – Mineral wool	0.1	0.2**	0.3***
	H2 – With vapour barrier	0.1	0.1	0.1
	H2 – Without vapour barrier	0.1	0.2*	0.2**
	H3 – Without vapour barrier	0.1	0.1	0.1

Due to the expectation that a minor temperature difference would have a high effect on relative humidity, the air moisture content by volume in the attic air was calculated. The conversion into moisture content compensated for the temperature variation and thereby gave a better description of the moisture level in the attic than relative humidity alone. Computing the standard error and thereby the margins for moisture content was more complicated than assessing the uncertainty of the direct measurements because of the non-linear relation between temperature, relative humidity and moisture content. The method is described in Paper I. The air moisture content by volume is included in the last part in Table 4-1, which indicates that there is a small tendency that the effect increases with the humidity class.

4.2. H1 – VAPOUR BARRIER

In the test building, the presence of a vapour barrier was tested against airtight but vapour open ceilings. In the field survey, the presence of a vapour barrier was compared to ceiling constructions of unknown tightness. Furthermore, in the test building, a PE-foil was the only vapour barrier tested, whereas in the field survey PE-foil and Alu-foil were tested.

The statistical analysis and the graphic evaluation showed that for all test set-ups in the test building, the highest relative humidity was found in the test ceiling without a vapour barrier. This was also expected. The statistical analysis of the margins for the test building is given in Table 4-2 (section of Table 4-1) between ceiling constructions with or without a vapour barrier. The relative humidity margin increases with humidity class. However, it is only for mineral wool at humidity class 3 that the margin is statistically significant. For moisture content, the difference is significant for mineral wool in humidity classes 2 and 3, while for cellulose it is only humidity class 3 which is significant. Due to the big difference in relative humidity in the attic between humidity classes 2 and 3, the results for all sensors were scrutinised. This is discussed thoroughly in Paper I. The difference could not be fully explained. However, the conclusion was that the measurements in attic section M3_2 are less trustworthy than in other sections, see also Section 4.7. Moisture leakage.

The same result was found in the field survey case buildings where there was no clear indication of the vapour barrier type having an impact on the moisture level (relative humidity or moisture content) in the attic. As shown in Figure 4-3 the relative humidity during the winter period is between 85% and 95%. Grey curves in the figure represent attics with insufficient ventilation where the relative humidity is at a high level >95% for long periods. The variations of temperature between the case buildings reflect only the uncertainty of the measurements.

*Table 4-2. Statistical analysis of the margins for each hypothesis, based on calibrated measured data in the full-scale test building for sensor point 03 above each humidity class. The * by the number indicates the level at which the margin is statistically significant. Significance: 0.05 level (*), 0.01 level (**), and 0.001 level (***) (highly significant).*

Hypothesis H1 – Vapour barrier		**Sensor point: 03**		
		HC1	**HC2**	**HC3**
Relative Humidity [%]	H1 – Cellulose	1.1	2.3	2.5
	H1 – Mineral wool	0.0	0.8	4.0*
Temperature [°C]	H1 – Cellulose	0.0	0.1	0.1
	H1 – Mineral wool	0.1	0.3	0.1
Moisture content [g/m^3]	H1 – Cellulose	0.1	0.1	0.2**
	H1 – Mineral wool	0.1	0.2**	0.3***

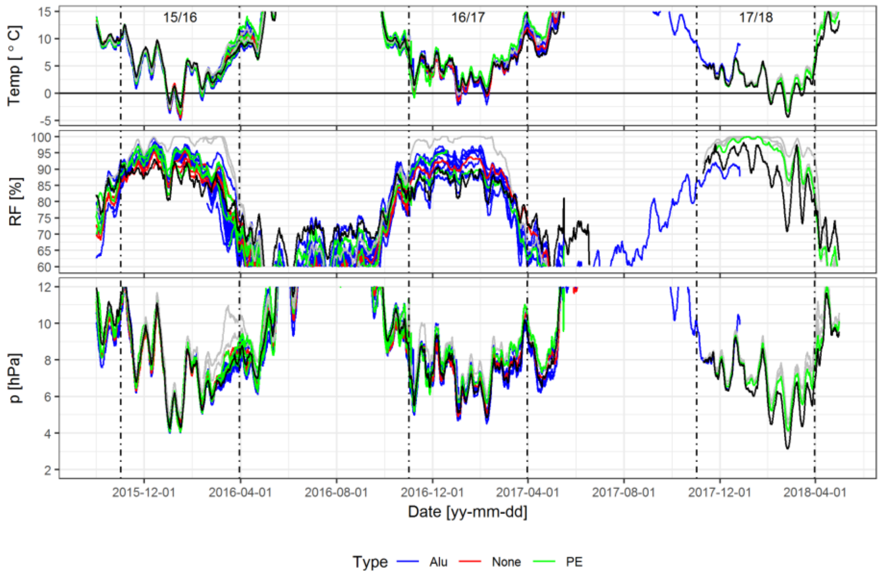


Figure 4-3. Measured attic data in case buildings grouped by the vapour barrier type. The colour of the curve represents the vapour barrier type. The number of case buildings in each group: Alu: 21, no vapour barrier: 3 and PE: 5. The grey curves are the five case buildings where attic ventilation did not meet the recommendations. The black curve illustrates the average outdoor values.

In general, for the simulated models, the results obtained for the same constructions with and without a vapour barrier coincided. Only for group B, with small moisture leakage and medium ventilation, there was a tendency towards a lower mould growth risk for the construction without a vapour barrier. The same picture was seen in group F, with small moisture leakage and very low ventilation, but only for insulation material thickness of 400 mm. For group H, with extensive moisture leakage and medium ventilation, it was only for 150 mm of insulation material. This negative effect of a vapour barrier in these groups is difficult to explain. However, the difference was small, and the simplest explanation was that the leakage, which was introduced as a moisture source above the vapour barrier, overruled any effect from the vapour barrier except in the simulation groups with small leakage.

Consequently, hypothesis H1 that a vapour barrier has an effect on the moisture level in cold ventilated attics was not collaborated with current climate when the ventilation of the attic fulfils the requirements for ventilation.

4.3. H2 – HYGROSCOPIC PROPERTIES

The graphic evaluation of the attic sections in the test building showed a tendency that attics with mineral wool have higher relative humidity than attics with cellulose. However, the statistical analysis in Table 4-3 (section of Table 4-1) does not show any significant difference between the relative humidity regarding insulation type irrespective of the presence of a vapour barrier or not. Likewise, the temperature was independent of the presence of a vapour barrier or of the insulation type. The moisture content was significantly higher in attic sections with mineral wool and no vapour barrier at humidity classes 2 and 3. However, with a vapour barrier there is no significant difference between the humidity classes.

*Table 4-3. Statistical analysis of the margins for each hypothesis, based on calibrated measured data in the full-scale test building for sensor point 03 above each humidity class. The * by the number indicates the level at which the margin is statistically significant. Significance: 0.05 level (*), 0.01 level (**), and 0.001 level (***) (highly significant).*

Hypothesis H2 – Hygroscopic properties		**Sensor point: 03**		
		HC1	**HC2**	**HC3**
Relative Humidity [%]	H2 – With vapour barrier	1.3	3.2	0.8
	H2 – Without vapour barrier	0.0	1.8	2.2
Temperature [°C]	H2 – With vapour barrier	0.0	0.4	0.1
	H2 – Without vapour barrier	0.1	0.1	0.1
Moisture content [g/m^3]	H2 – With vapour barrier	0.1	0.1	0.1
	H2 – Without vapour barrier	0.1	0.2*	0.2**

Due to difficulties in collecting case buildings, only during the winter period 2015/16 measurements in case buildings with both types of insulation material were carried out. Nevertheless, when examining the curves in Figure 4-4 for the winter period, there are minor differences in the relative humidity measured, but the temperature is almost the same. However, the differences in insulation material types do not seem to be the cause, since the highest and lowest measured relative humidity is case buildings with the same type of insulation material, cellulose-based, and the individual differences in vapour pressure are minor. In the winter, 2015/16 the vapour pressure difference is approximately 50 Pa and 100 Pa in the following winter period, with no difference in the insulation material type.

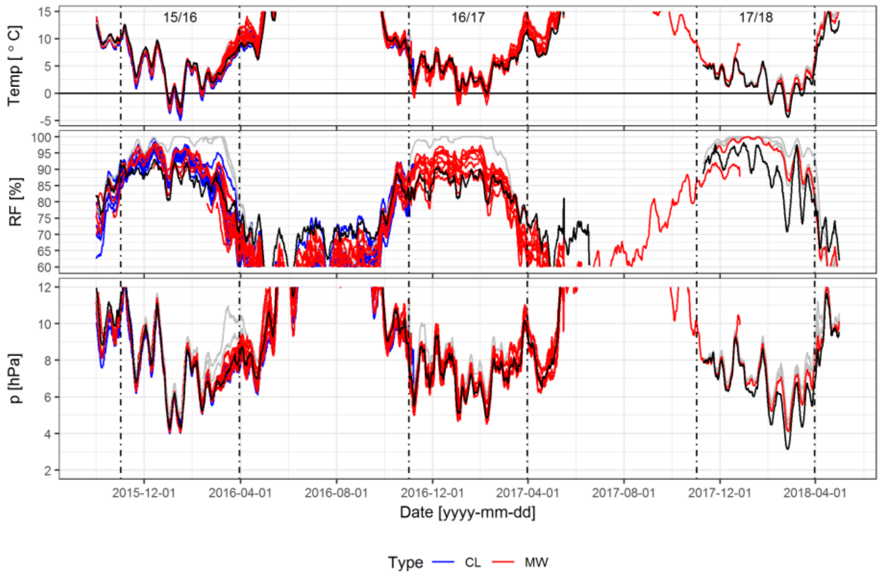


Figure 4-4. Measured attic data in case buildings grouped by insulation material type, 15 case building with cellulose and 14 with mineral wool insulation material. The grey curves are the five case buildings where the attic ventilation does not meet the recommendations. The black curve illustrates the average outdoor values.

The main reason for comparing different types of insulation material, cellulose and mineral wool, was their different sorption curves, hence their moisture buffering capacity. A possible effect of using an insulation material with a higher moisture buffering capacity could be that peaks in the moisture level in the attic space are levelled out, but this effect was not observed, neither in the test building nor in case buildings. However, for the simulations there was a minor tendency that mineral wool had a higher risk of mould growth compared to cellulose-based material. The minor difference is only noticeable in groups where the ventilation rate of the attic is low (groups C and F). This could mean that the moisture buffer effect is more pronounced in cases where the ventilation is below the normally recommended guidelines.

In the test building and case buildings, the effect of the moisture buffering capacity may have been levelled out due to the use of a one-week running mean. Running mean results were used to make it easier to distinguish between the curves in the graphical presentation of the measured hourly values. Furthermore, the main concern was the overall performance of the cold ventilated attic.

Consequently, hypothesis H2 that the hygroscopic properties of the insulation material have an effect on the moisture level in cold ventilated attics was not collaborated with current climate when the ventilation of the attic fulfils the requirements for attic ventilation.

4.4. H3 – INSULATION THICKNESS

For a number of reasons (see Section 2.3. Evolution of ceiling design) it was expected that the temperature in a cold ventilated attic would decrease with a higher thickness of insulation material, and that the relative humidity consequently would increase. However, when looking at the graphical results measured in both the case buildings and in the test building, there is only a minor difference. For the test building, a statistical analysis was performed. Table 4-4 (section of Table 4-1) shows no significant difference for the three parameters measured for the different humidity classes. In the test building, the insulation thickness was only varied for test attics without vapour barrier and with mineral wool because this was expected to be the worst combination, i.e. the case where the difference would be most pronounced.

Table 4-4. Statistical analysis of the margins for each hypothesis, based on calibrated measured data in the full-scale test building for sensor point 03 above each humidity class. None for the margin is statistically significant.

Hypothesis H3 – Insulation thickness		**Sensor point: 03**		
		HC1	**HC2**	**HC3**
Relative Humidity [%]	H3 – Without vapour barrier	1.0	1.2	3.2
Temperature [°C]	H3 – Without vapour barrier	0.1	0.2	0.5
Moisture content [g/m^3]	H3 – Without vapour barrier	0.1	0.1	0.1

Concerning higher relative humidity in cold ventilated attics caused by increased insulation material thickness, the measurements in the case buildings showed no clear difference for the different groups of total insulation thickness, see Figure 4-5. In the simulations, the same result was found in the groups with high ventilation (groups E and G), and also in group B, where the ventilation is normal, and the leakage is low. However, if the leakage is high and ventilation low, there is a reduced risk of mould growth with high insulation material thickness. This is contrary to the Danish guideline (Brandt, et al., 2013).

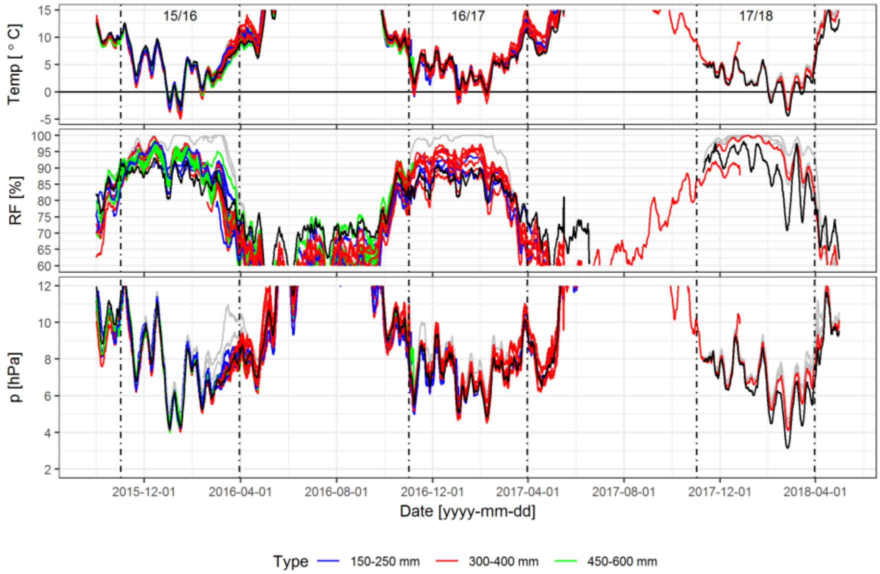


Figure 4-5. Measured attic data from case buildings, grouped on the basis of the total thickness of the insulation material. Six case building in group 15-250 mm (blue curves), 11 in group 300-400 mm (red curves) and 12 in group 450-600 m (green curves). Five case buildings with attic ventilation that does not meet the recommendation are represented by the grey curves; the black curves reflect the average outdoor values.

A decrease of the heat flux through the ceiling occurs when the total thickness of the insulation material is increased, and thereby it would be logical to expect that the attic temperature decreases. However, there is no noticeable temperature difference for the different insulation material thicknesses neither in the test building nor in the case buildings. The most likely explanation is that the noticeable temperature decrease appears with insulation material with a thickness of 50-100 mm. Furthermore, the indoor temperature is expected to have an influence on the attic temperature. However, this was not found in the ten case buildings (C13-C22) which were terraced houses in the same settlement, and where only the indoor climate varied. As shown in Figure 4-6, the indoor temperature was between 18 °C and 24 °C on average, whereas the temperature in the attics was at the same level.

A thorough analysis of these temperature measurements is presented in Hansen and Møller (2018).

Consequently, hypothesis H3 that the thickness of the insulation material has an effect on the moisture level in cold ventilated attics was not collaborated.

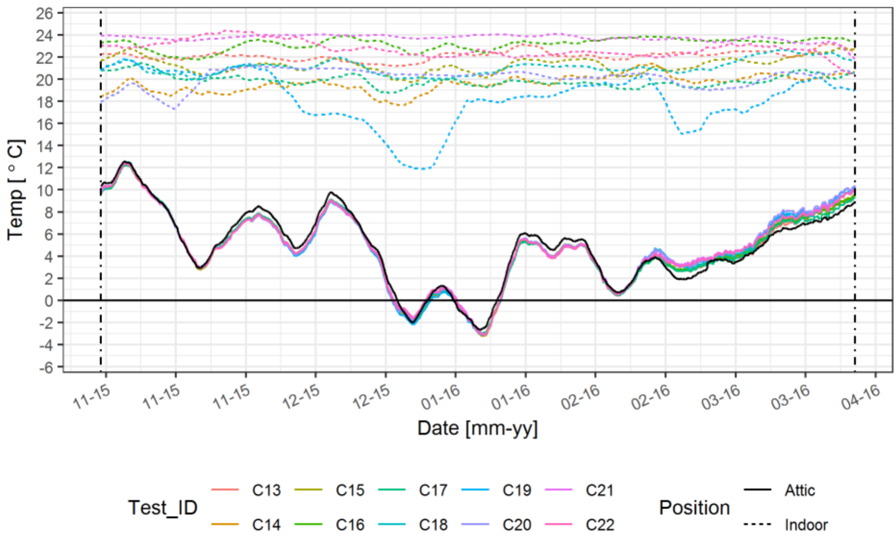


Figure 4-6. The measured indoor temperature in selected case buildings (dotted curve) compared with the attic temperature (solid curve), together with the measured outdoor temperature (black curve).

4.5. HUMIDITY CLASS

In general, it was expected that a high indoor humidity class would result in a higher moisture level in the attic. Graphically, the difference in the test house is very small, and the lowest relative humidity is measured above humidity class 2, which is difficult to explain. Nevertheless, when looking at the statistical analysis of the margins in Table 4-2 to Table 4-4 for relative humidity and temperature, there is no significant difference except for the vapour barrier hypothesis in humidity class 3. However, when looking at Figure 4-7, which illustrates (a simplification with linear connections) the evolution of the margin compared to the humidity class (based on values in Table 4-2 to Table 4-4), it is clear that the humidity class has an effect on the margins. It may not be correct to connect the dots linearly, but the lines make the tendency more visible. The effect is more noticeable for moisture content compared with relative humidity, where the difference becomes significant with an increased humidity class.

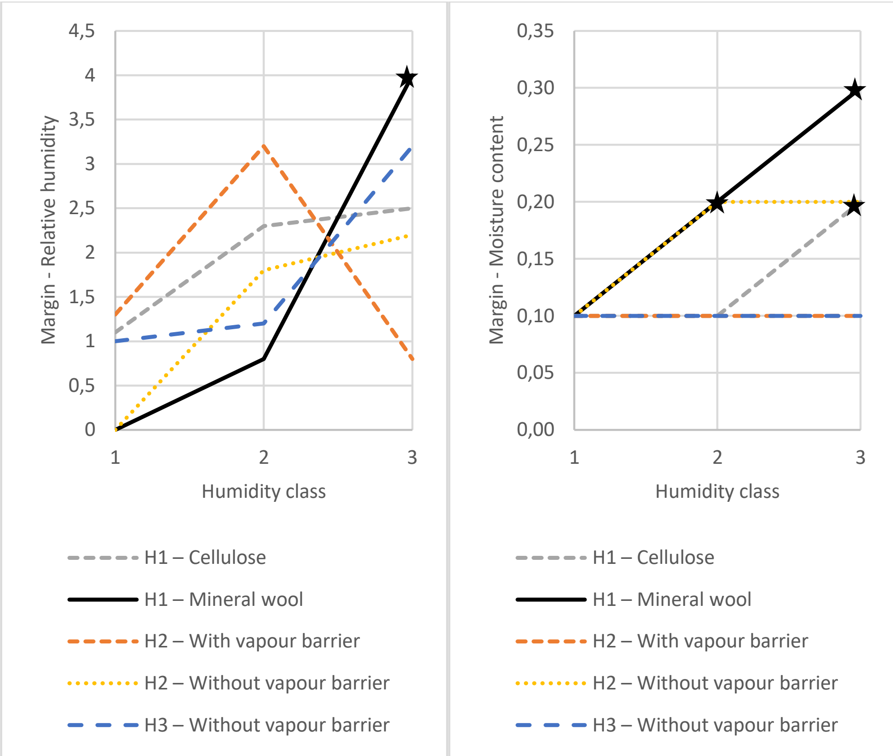


Figure 4-7. Margins for each hypothesis (H1-H3) compared with the humidity class for relative humidity and moisture content for the full-scale test building. Stars illustrate margins, which are statistically significant.

In order to evaluate the humidity class impact on the moisture level in the case building, it was necessary to calculate the monthly internal vapour pressure for each building and compare it with the outdoor mean temperature; this is shown in Figure 15 in Paper II. The humidity class varied from 1 to 3. Seven buildings were in humidity class 1, sixteen in humidity class 2 and six in humidity class 3. In Figure 4-8, the measured data are grouped for each humidity class. Five case buildings were with insufficient ventilation of the attic, and they were present in all three humidity classes. Therefore, the high relative humidity in the attic may not correlate to the indoor vapour pressure. Furthermore, as seen in Figure 4-8, if the ventilation of the attic meets the recommendation, the humidity classes do not have an influence on the moisture level in the attic.

Consequently, there was no evidence of the humidity class having an influence on the moisture level in the attic if the ventilation of the attic followed the recommendations.

Figure 4-8. Measured attic data for the case buildings grouped by indoor humidity class (HC). For HC1, there were seven case buildings, 16 in HC2 and six in HC3. Five cases with attic ventilation that does not meet the recommendations are reflected in the grey curves; the black curve is the average outdoor values.

4.6. ATTIC VENTILATION

Ventilation of the attic space was not one of the parameters to be investigated in the project due to the expectation that the current guidelines were correct and not to be refuted. However, during the project, the air change rate (ACH) was examined in a series of case buildings to be able to assess the "usual" magnitude. The tracer gas measurement performed provided information about the air change rate of the attic, and the air volume flow between the indoor climate and attic was measured. These measurements could be used to estimate the moisture leakage to the attic. In Table 4-5, the results from the tracer gas measurements are given together with the estimated leakage from the indoor climate to the attic. For the case buildings, the average attic air change rate was 10 h^{-1}, with the highest and lowest value of 24 h^{-1} and 1.9 h^{-1} respectively. Unfortunately, it was not possible to perform the measurements in all case buildings. In the full-scale test building, measurements of the air change were performed three times during the project period for 3-4 weeks during July/August 2016, March/April 2018, and January/February 2019. The air change rate was measured to be 4-10 h^{-1}. Due to moving of the tracer gas laboratory, the measured values from 2018 are not calibration, however the magnitude is correct, but the values not exact. The leakage to the attic from the living space is discussed further in Section 4.7. Moisture leakage.

Table 4-5. Measured air change rate (ACH) and air volume flow in some case buildings. The last column illustrates an estimate of the air leakage from living space to attics. For case buildings, it is calculated on the basis of a building of 150 m² with a circumference of 54 m; for the test building, the actual size is used (circumference of 16 m).

	Test_ID	Measured period	Attic ACH (in total) [h^{-1}]	Living space ACH [h^{-1}]	From living space to attic [m^3/h]	From attic to living space [m^3/h]	Leakage from living space to attic [$l/(s \cdot m^2)$]
Case buildings	A02	04-2016	24	0.31	30	46	0.15
	A02	03-2019	18	0.16	18	33	0.09
	A04	05-2016	1.9	0.25	13	125	0.07
	A32	02-2019	3.6	0.04	9	37	0.05
	B06	05-2016	3.8	0.20	38	18	0.20
	B35	02-2019	4.4	0.07	10	10	0.05
	C11	04-2016	22	0.32	25	59	0.13
	C10	05-2016	21	0.33	22	31	0.11
	C12	05-2016	2.7	0.38	56	19	0.29
	D24	04-2016	8.2	0.44	37	76	0.19
Full-scale test building	With vapour barrier	07-2016	4.1	0.19	0.0	0.7	0.00
		01-2019	3.9	0.28	0.1	3.8	0.00
	Without vapour barrier	07-2016	3.6	0.19	2.5	0.7	0.04
		01-2019	3.7	0.28	0.4	3.7	0.01

The air change rates measured in the test building and the case buildings are similar to the measured values in other studies. Walker and Forest (1995), found an air change rate in field measurements of approx. 2-10 h^{-1}. Harderup and Arfvidsson (2013) used 2 h^{-1}, which is based on (Larsson, 1995). Larsson (1995), distinguished between different attic ventilation solutions; 0.5 h^{-1} if the attic is more or less closed (only with grills in the gables), 2 h^{-1} if the ventilation openings were along the eaves (2-5 cm) only and 4-8 h^{-1} with both ventilation openings in the attic (both eaves and gables). Iffa and Tariku (2015) designed a 2-dimensional CFD model to simulate temperature distribution and air change rate in attics with variation in the baffle size and position of the upper ventilation opening. They found a simulated air change rate between 10-16 h^{-1} with ridge ventilation openings, which also provide the best air mixture in the attic. Compared with their measured air change rate, there is a notable difference.

When looking at the simulation illustrated in Figure 4-9, it is clear that the air change rate in the attic has an effect on the risk of mould growth, and low ventilation is only acceptable with a small leakage. Attics with very low air change rate are not acceptable, which can explain why mould related problems can occur in some inhabited houses after additional insulation has been installed on ceilings. These mould problems may occur if sufficient attention was not paid to preventing blocking of the ventilation openings when additional insulation was installed. Increasing the air change rate from 10 h^{-1} to 20 h^{-1} does not have an effect on the hygrothermal condition of the attic as long the leakage is normal (groups G and E). If the ventilation rate is high, the risk of mould growth is at the same level as in outdoor conditions.

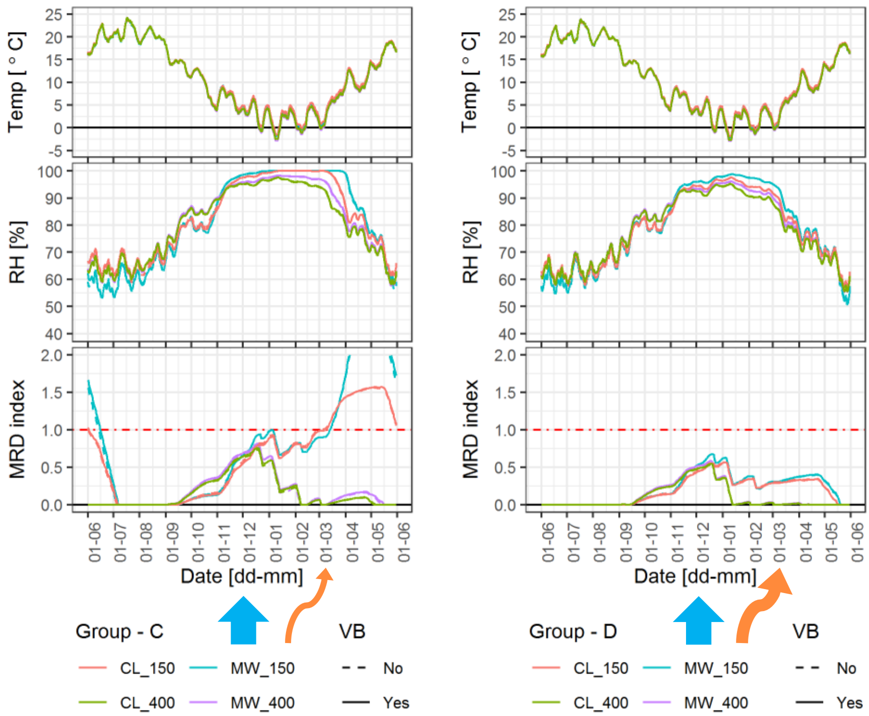


Figure 4-9. WUFI simulations of Group C and D – Results with CMML of 20 kg/(m²·s) and ACH 12 (2.0) and 21 (3.5) h⁻¹ respectively. The red dotted line indicates the initial value for mould growth based on the MRD model. Mould growth is more pronounced when the ventilation rate is low.

Consequently, the ventilation rate in the attic has a high effect on the moisture level in the attic, but only until a certain level, e.g. the difference in attics with the same moisture leakage is very little when the ACH is 10 or 20 h^{-1}.

4.7. MOISTURE LEAKAGE

A vapour barrier does not ensure a vapour and airtight construction if the joints are not tight. Likewise, an attic construction can be airtight without a vapour barrier. At the same time, convection compared to diffusion can move much larger amounts of moisture. Therefore, the airtightness is essential factor to ensure in building constructions.

The air change between the attic and living space could be determined from the passive tracer gas measurements. However, no correlation could be found when comparing the values of the moisture leakage in Table 4-5 and the measured moisture levels in the attics. When comparing moisture leakage in the case buildings with the test building, there was approx. a factor 10 times higher moisture leakage in the case buildings. This was also to be expected due to the high awareness of workmanship in the test building. The used moisture leakage in the simulation models corresponds to the measured leakage found in the case buildings. The used moisture leakage in the simulation model of 6 and 20 kg/(m^2·s) (see Table 3-3), corresponds to the measured leakage from living space to attic of 0.09 and 0.30 l/(m^2·s) (see Table 4-5) respectively.

In the test building the awareness of moisture leakage was not only concentrated on the ceiling construction, also the air exchange between each test section was important to ensure no moist transfer. The performed tracer gas measurements in the test building showed, that the transfer between the test sections was negligible. Even though, the measurements were only performed in attics above humidity class 2 they were considered representative.

As mentioned in Section 4.2. *H1* – Vapour barrier, the measurements in attic section M3_2 are less trustworthy compared to other sections due to higher moisture level. This could be explained by minor moisture leakage. Therefore, the airtightness was tested with tracer gas and compared with other ceilings. The results showed that the airtightness of the ceiling construction in attic section M3_2 was lower compared to other test sections.

In order to investigate the impact on the moisture level as a combination of the leakage and ventilation rate, simulations were performed. It was found that if the leakage is low, the mould growth risk is low unless the attic ventilation is very low (group F, simulations). A low leakage is acceptable. However, installing a vapour barrier is recommended and it requires high awareness of workmanship on airtightness. Installing a very airtight vapour barrier in existing houses may be considered a challenging job. It is therefore more realistic to expect medium moisture leakage in older houses. With a medium moisture leakage to the attic, the ventilation rate must be at least medium as described in the current guidelines. If the ventilation rate is reduced to low, an unacceptable risk of mould growth occurs, group C.

Consequently, awareness of airtightness is important to ensure acceptable moisture levels in attics. In many cases, installation of a membrane, e.g. a vapour barrier, is the most effective way to ensure airtightness although it can be difficult to obtain high airtightness in existing buildings due to practical issues.

4.8. MOULD GROWTH

In Paper I, which focuses on the full-scale test building, a comparison of the mould growth models VTT and MRD is carried out even though it is difficult to compare the two models due to their difference in the mould growth scale. Gradeci, et al. (2017) made a comparison of three mould models including VTT and MRD. They stated that there are disagreements between the models. This can also be observed when the two models are used for calculating mould growth predictions in the full-scale test building.

As the present PhD work looks at whether there are favourable conditions for mould growth, the MRD model is used since it focuses on initiation of mould growth (Isaksson, et al., 2010) and returns a response only if conditions are favourable for mould growth. In Figure 4-10, the calculated mould growth prediction is given for the full-scale test building. Tape samples were extracted from the test building, but no mould growth was detected, and this corresponds to the MRD prediction. It should be noticed that the test building had only been in use for a two-year period. There may have been a higher risk if it had been used for a longer period of time. However, the results from the MRD model do not indicate any initiation of mould growth.

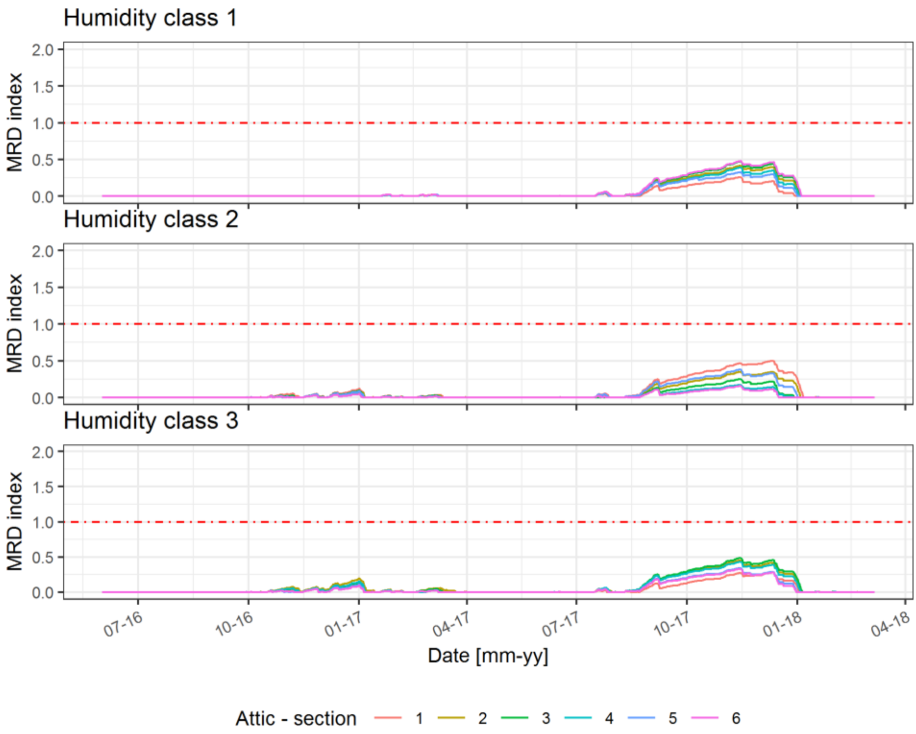


Figure 4-10. MRD model predictions of mould growth in each attic section in the full-scale test building.

A mould growth prediction was made for each case building using the MRD model. As shown in Figure 4-11, eleven case buildings had an MRD index of 0, whereas 17 case buildings had an MRD index below 0.5. Three case buildings were just below an MRD index of 1. Most of the case buildings had the same MRD curves, whereas two case buildings (B08 and B09) which may have a risk of mould growth showed different curves. The MRD index for both case buildings were above 1 for a long period during winter and early spring. The visual inspection of mould and moisture problems in B09 found clear signs of mould growth and condensation, whereas B08 had only initial visual growth. It was to be expected that the MRD index was higher for these two case buildings, and this could be an indication that the critical dose used $D_{crit} = 17$ should have been lower. However, this would have increased the MRD index for all case buildings, which might have been correct in some cases. Though, there is no other justification for changing D_{crit} given by Thelandersson and Isaksson (2013).

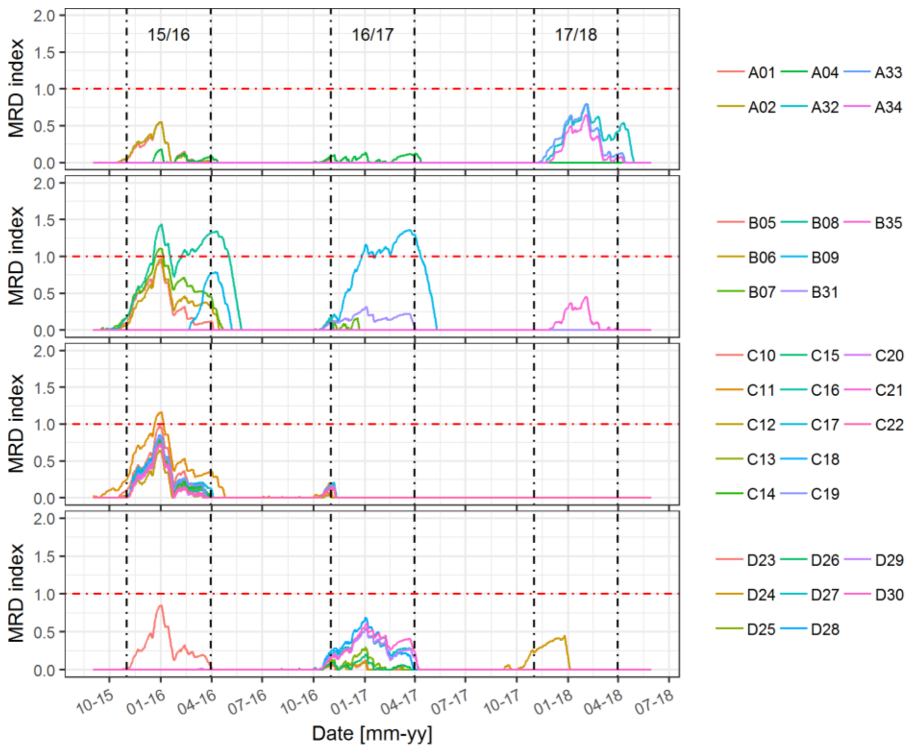


Figure 4-11. Predicted mould growth in each case building by the use of the MRD model.

When examining the case buildings five attics (A32, A33, A34, B08 and B09) did not fulfil the Danish recommendation concerning attic ventilation. The MRD index in A32-34 buildings is not at the same level as in B08-B09. The reason could be that the measurements in A32-A34 were started in the beginning of a winter period, where the temperature was lower, and this inhibited mould growth. A period with possible favourable conditions for mould growth prior to the measurements were therefore not captured. Comparing the vapour pressure in the attic with the outdoor vapour pressure shows considerably higher vapour pressure in these attics compared to attics with recommended ventilation rate.

On the other hand, mould growth at MRD index 1 could be a to low threshold considering the mould growth in a ventilated attic, where there is no occupancy and the air movement from attic to living space is limited.

4.9. FUTURE CLIMATE

As described in the previous sections, the ventilation rate of the attic and the moisture leakage from the indoor spaces are the most decisive factors for the moisture level in the attic. Based on the series of simulations with a standard year, further simulations with predicted future climate conditions were performed.

When it comes to temperature and relative humidity, there were only minor differences for the different cases, whereas mould growth predictions were more distinct. For all groups, the MRD index was above 1 after a few years. For the two groups D and G with a medium leakage (a bit higher than normal leakage in existing old houses, as shown in Table 4-5), there may be no problems today, but there is a high risk of mould growth in the near future. Even if the ventilation rate is raised as in group G, the MRD index will be above 1 after 10 years, and after 25 years it will be unacceptably high shown in Figure 4-13. However, if the moisture leakage is low, and ventilation is medium as expected in new houses, see Figure 4-12 (group B), the mould growth risk will initially be low, but at the end of the simulated period the risk will be more distinct. If the leakage is kept constant, and the ventilation rate is raised, as shown in Figure 4-14 (group I) the number of years where the MRD index exceed 1 is reduced. However, after 25 years the current guideline may not be useful any more as the MRD index no longer declines to 0 each year.

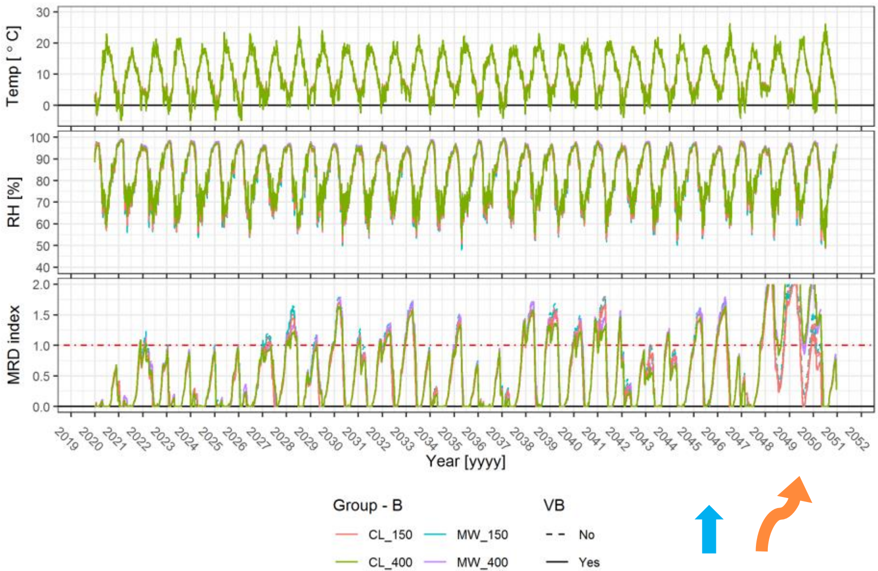


Figure 4-12. WUFI simulations of Group B – Future climate with CMML of 6 kg/(m²·s) and ACH 21 (3.5) h⁻¹.

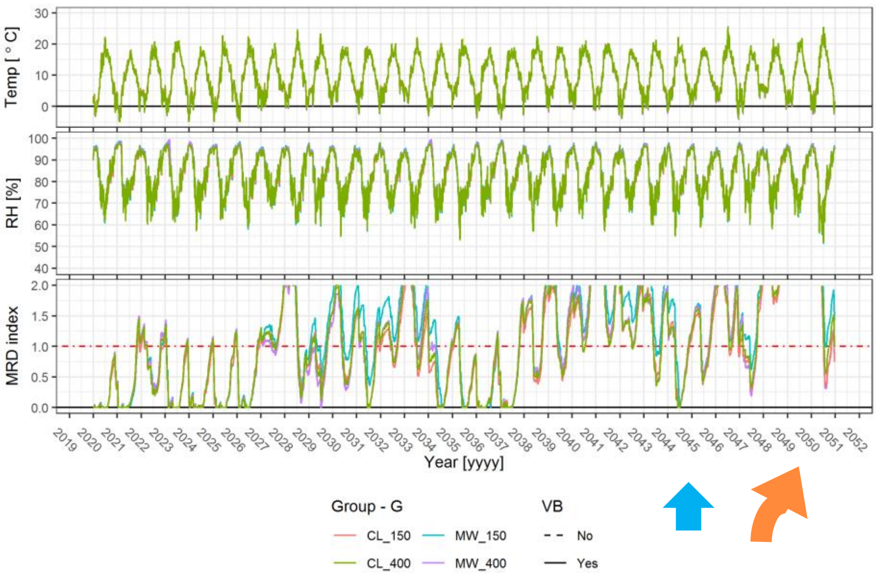


Figure 4-13. WUFI simulations of Group G – Future climate with CMML of 20 kg/(m²·s) and ACH 60 (10) h⁻¹.

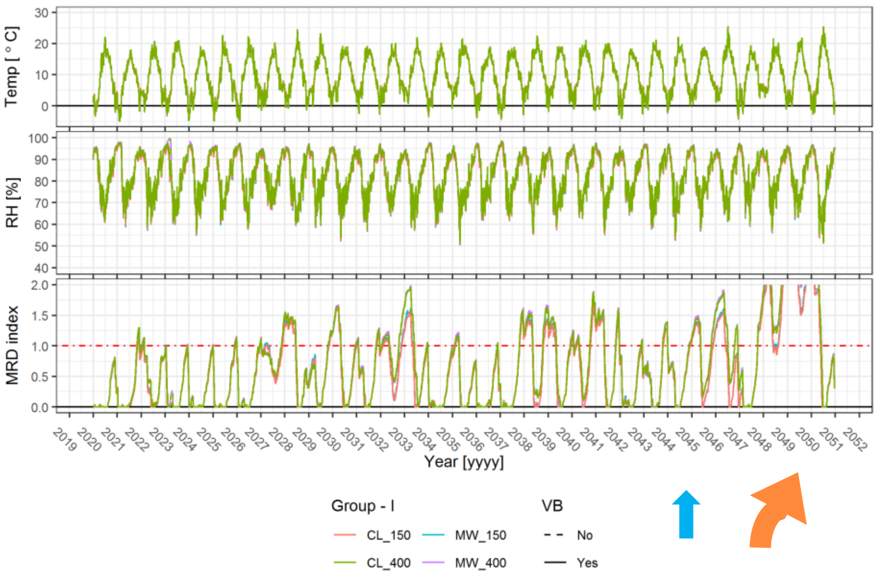


Figure 4-14. WUFI simulations of Group I – Future climate with CMML of 6 kg/(m²·s) and ACH 60 (10) h⁻¹.

Therefore, new solutions are needed in the future, and it does not seem that higher ventilation rates of the attic could be one of them as the MRD index for group I is slightly worse than for group B. However, if the temperature in the attic could be raised e.g. by insulating the roof underlay, the relative humidity will decrease and the capability to remove moisture will increase.

Another method was suggested by Nik et al. (2012), who studied the effect of climate change on typical Swedish attics; they studied the effect of controlled mechanical ventilation as a possibility to lower the risk of mould growth in cold attics; a method that might be needed in the future.

CHAPTER 5. CONCLUSION

There is a need to answer the practical problem: **When is a vapour barrier needed in the ceiling under a cold ventilated attic?**

Based on the measurements in the full-scale test building and the 34 case buildings, the following conclusions can be drawn for three hypotheses:

- *The presences of a vapour barrier*
  The presence of a vapour barrier has a minor effect if the air change rate of the attic is sufficient, and the ceiling construction has a reasonable air tightness.
- *The hygroscopic properties of the insulation material*
  Using hygroscopic compared with non-hygroscopic insulation material was not found to have a significant effect on the moisture level in the attic with sufficient air change rate.
- *The thickness of the insulation material*
  The total thickness of the insulation material did not have an effect on the temperature or the relative humidity in the attic. However, the investigation only looked at an insulation thickness above 150 mm.

Besides the three hypotheses, the effect on the moisture level in the attic of the humidity class below the attic was investigated. Especially for the case buildings, the internal moisture excess seems to have a minor effect on the moisture level in the attic if the ventilation rate is sufficient. Furthermore, in inhabited houses the differences of the indoor temperature had no effect on the attic temperature. However, the air change rate of the attic was a very important factor for the functionality of a cold ventilated attic, and small changes could have a major impact on the hygrothermal performance.

A solution to the practical problem is therefore: **If the existing attic construction is without moisture related problems, additional insulation can be added to the ceiling without installing a new vapour barrier as long as the attic ventilation rate and the ceiling air tightness is unchanged.** However, based on the findings from the simulations with future climate, it is strongly recommended that a vapour barrier is established in new constructions as it contributes to the airtightness of the construction in the long term. Concerning the simulations with future climate conditions, it seems that cold ventilated attics may be risky in the future, and that some older attics may become mouldy due to their high air leakage. Therefore, an investigation of possible new solutions such as controlled mechanical ventilation systems of the attic space or new construction types such as warm attics may be required.

CHAPTER 6. PERSPECTIVE

Although there are clear indications of which parameters are most crucial when installing additional insulation material on ceilings against cold ventilated attics, there are still some research questions to be answered in future research:

- To what degree can insulated roof underlays change the hygrothermal performance of the attic with current and future Danish climate conditions?

- Although the presence of a vapour barrier in the test and case buildings seems to have a minor impact, there was a tendency in the simulations of different scenarios that it enhanced the risk of mould growth. For this reason, further investigation should be made, e.g. by performing whole-building simulations and comparing these to field measurements to test if the simulations are trustworthy.

- In the simulations, the difference in the risk of mould growth between attics with 150 mm and 400 mm insulation material was insignificant. There was, however, a tendency that the risk was lower with high amounts of insulation material, irrespective of the hygroscopic performance of the material. This contradicts the original reason for limiting the amount of insulation material and should therefore be investigated further.

- It has been decided to use an MRD index of 1 as the threshold for mould growth. This may be considered conservative, depending on the air exchange from the attic to the indoor climate. As the exchange is likely to vary with a series of factors such as season, surroundings etc., this air exchange should be explored further.

- As no samples for mould growth were extracted from the case buildings, there are some uncertainties concerning the predictions from the mould growth model. Therefore, it would be useful to investigate the “normal” background for mould growth in attics and compare the results with prediction model.

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ISSN (online): 2446-1636
ISBN (online): 978-87-7210-574-1

AALBORG UNIVERSITY PRESS