NTNU
Norwegian University of Science and Technology

Moisture Safety in Highly Insulated Wood-Frame Wall Constructions

Thale Berg Nelson

Master of Science in Civil and Environmental Engineering
Submission date: June 2017
Supervisor: Stig Geving, IBM

Norwegian University of Science and Technology
Department of Civil and Environmental Engineering

NORGES TEKNISK-
NATURVITENSKAPELIGE UNIVERSITET
INSTITUTT FOR BYGG, ANLEGG OG TRANSPORT

Title: Moisture Safety in Highly Insulated Wood-Frame Wall Constructions	Dato: 11.06.2017 Antall sider (inkl. bilag): 150			
	Masteroppgave	X	Prosjektoppgave	
Name: Thale Berg Nelson				
Faglærer/veileder: Professor Stig Geving				

Ekstract:
This report addresses moisture safety in highly insulated wood-frame walls. Research shows that the risk of moisture damages may increase with the thickness of the insulation layer. One of the major threats may be the risk of mould growth.

The purpose of this study is to examine the effect on the moisture conditions in highly insulated wood-frame walls, when using thermal insulating materials as a weather barrier. The first part of the study is a literature search and is a study of existing literature and research on moisture issues related to highly insulated walls, weather barriers and external insulation.

The second part of the study are three parametric studies, using the hygrothermal simulation program WUFI. The results of the studies are used to evaluate the moisture conditions in highly insulated wall constructions, when using weather barriers with higher thermal resistance, compared to traditional weather barriers. The risk of mould growth is one of the critical factors.

The three parametric studies investigate the use of wood fibre boards and rigid foam products as weather barriers.

Key words:

1. Highly insulated wood-frame walls
2. Moisture safety
3. Weather barriers
4. Wood fibre boards

Thale Berg Nelson

Thale Berg Nelson

FORORD

Denne masteroppgaven er det avsluttende arbeidet for det 2-årige masterstudiet i bygg- og miljøteknikk ved Norges teknisk-naturvitenskapelige universitet, innenfor hovedprofilen bygnings- og materialteknikk. Oppgaven tilsvarer 30 studiepoeng og har et hovedfokus på bygningsfysiske problemer. Rapporten er utarbeidet våren 2017.

Oppgaven tar for seg fuktproblematikk i høyisolerte bindingsverkvegger, med hovedfokus på løsninger med utvendig isolering for å redusere risikoen for fuktskader, spesielt i forhold til mugg. Prosjektet startet med et litteraturstudie, der aktuell forskning og litteratur ble gjennomgått, og produkter ble undersøkt. Videre ble det foretatt tre parameterstudier med hygrotermiske simuleringer av mulige løsninger og vurdering mot tradisjonelle løsninger. Beregningene ble utført ved bruk av simuleringsprogrammet WUFI.

Jeg er svært takknemlig for gode råd og veiledning fra Professor Stig Geving ved NTNU, som var hovedveileder for denne oppgaven.

Trondheim, 11. juni 2017

Thale Berg Nelson

Thale Berg Nelson

SUMMARY

This report addresses moisture safety in highly insulated wood-frame walls. Research shows that the risk of moisture damages may increase with the thickness of the insulation layer. The possible consequences of increased insulation layers are reduced temperatures in the exterior part, more built-in moisture in the construction, reduced drying capacity and increased internal natural convection, which may lead to moisture damages. One of the major threats of elevated moisture levels in wood-frame constructions may be the risk of fungal growth, such as mould.

The purpose of this study is to examine the effect on the moisture conditions in highly insulated wood-frame walls, when using thermal insulating materials as a weather barrier. One of the main question of interest, is whether this solution will improve the moisture safety compared to using traditional types of weather barriers. In addition, there is a question of which materials may be suitable.

The first part of the study is a literature search and is a study of existing literature and research on moisture issues related to highly insulated walls, weather barriers and external insulation. In addition, different products from manufacturers have been researched in order to find interesting products, mainly rigid foam, wood fibre and mineral wool products, to be used in the moisture simulation.

A summary of the literatures search shows there may be a somewhat elevated risk of high moisture levels and mould growth in highly insulated walls compared to walls with less insulation. This negative effect of the insulation thickness on moisture levels can be influenced by many factors, such as the choice of materials, climate, moisture gains from the indoor air and air flow rate in the air gap. Laboratory investigations indicate that the choice of weather barrier may be of great importance for the moisture level in wall constructions. Weather barrier materials with higher thermal resistance and vapour permeability, may reduce the risk of moisture issues.

The second part of the thesis are the three parametric studies of hygrothermal simulations in WUFI. The calculations assess the use of exterior insulation as a measure to improve the moisture conditions in highly insulated wood-frame walls in a Norwegian climate. The wall construction in the parametric studies is limited to a common type of wood-frame wall. The influence of different insulating weather barrier products and the thickness of the material layers are the main parameters that are variated, in addition to different climates an initiation time of the calculations.

The results from the simulations are used to evaluate the moisture conditions in highly insulated walls when using weather barriers of materials with high thermal resistance versus a traditional weather barrier, in addition to assessments of the moisture safety based on quantitative criteria for moisture damages, such as mould growth.

The first study investigates the use of wood fibre boards as weather barriers. The results indicate that wood fibre boards may function well as weather barrier, and may even be more safe than conventional weather barriers. However, in the initial phases of the simulation periods, mould growth on an unacceptable level occurred. It may be desirable to achieve an acceptable level of growth in the initial stages.

Therefore, the second study further investigates the use of wood fibre boards as weather barriers. In this study, most of the simulations starts in May, as opposed to in the first study, when the starting point is in January. This seems improve the results, as the mould growth is at an acceptable level in many simulation cases. The conventional weather barrier also has an improvement, but the RH levels in the dynamic cycles are still at a concerning level.

The third study investigates the use of rigid foam boards used as weather barriers. When the simulations start in January, the product give very high initial levels of mould growth and very high RH levels, which may result in condensation. Starting in May, the initial mould growth is somewhat reduced, but the risk of condensation seems to be eliminated. The product does however result in low RH values after the initial moisture dries when thicker boards are used.

SAMMENDRAG

Denne rapporten omhandler fuktsikkerhet i høyisolerte trekonstruksjoner. Forskning viser at risikoen for fuktskader kan bli større ved økt tykkelse av isolasjonslaget. Mulig konsekvenser av økt isolasjonstykkelse er lavere temperaturer i ytterdelene av konstruksjonen, mer byggfukt i konstruksjonen, redusert tørkekapasitet og naturlig konveksjon, som kan føre til fuktskader. En risikoene med høye fuktnivåer i trekonstruksjoner kan være faren for muggvekst.

Hensikten med denne rapporten er å undersøke om fuktforholdene i høyisolerte trevegger kan forbedres ved bruk av vindsperrer av termisk isolerende materialer, fremfor tradisjonelle typer vindsperrer. Et av hovedspørsmålene er hvorvidt denne løsningen vil forbedre fuktsikkerhet sammenlignet med bruk av tradisjonelle vindsperrer. I tillegg er det av interesse å finne ut hvilke materialer som kan være aktuelle å benytte som termisk isolerende vindsperre.

Første del av rapporten er et litteraturstudie og tar for seg eksisterende litteratur og forskning på områdene fuktsikkerhet i høyisolerte trekonstruksjoner, vindsperrer og utvendig isolasjon. I tillegg har forskjellige produkter fra ulike produsenter blitt undersøkt, for å finne materialer som kan være aktuelle å bruke i fuktsimuleringene. Produktene som er undersøkt i litteraturstudiet er plastisolasjon, trefiber og mineralull.

Blant funnene i litteraturstudiet er forskning som viser at det kan være noe økt risiko for høye fuktnivåer og muggvekst i høyisolerte trekonstruksjoner sammenlignet med vegger med mindre isolasjon. Det viser seg også at fuktforholdene i høyisolerte konstruksjoner kan påvirkes av andre faktorer enn kun isolasjonstykkelsen, som materialvalg, klima, fukttilskudd fra inneluft og ventilasjonsmengden i luftespalten bak kledningen. Laboratorieeksperimenter indikerer at valg av vindsperre kan være av stor betydning for fuktnivået i veggkonstruksjoner, og at vindsperrer med høyere termisk motstand og lavere vanndamppermeabilitet kan redusere risikoen for fuktproblemer.

Den andre delen av oppgaven består av tre parameterstudier, utført ved hygrotermiske simuleringer i WUFI. Simuleringene viser effekten av å bruke utvendig isolasjon for å forbedre fuktforholdene i høyisolerte trevegger i et norsk klima. Veggkonstruksjonen i parameterstudiene er begrenset til en tradisjonell trevegg. Påvirkningen av forskjellige typer vindsperrer og tykkelsen på disse materialene blant de viktigste parameterne, i tillegg til klima og starttid for simuleringene.

Resultatene fra simuleringene blir brukt til å evaluere fuktforholdene i høyisolerte vegger ved bruk av vindsperrer av materialer med høy termisk motstand mot en tradisjonell vindsperre, i tillegg til evaluering av fuktsikkerhet basert på kvantitative kriteria for fuktskader, slik som risikoen for muggvekst.

Det første studiet ser på bruk av trefiberplater som vindsperre. Resultatene indikerer at trefiberplater kan være et bra alternative som vindsperre, i forhold til en tradisjonell vindsperre, med unntak av de første periodene. Produktet undersøkes videre i studie 2, og viser at problemene i den først fasen kan forbedres ved å starte simuleringer i mai, fremfor i januar. Det siste studiet undersøker plastisolasjon som vindsperre, og dette produktet oppnår ikke helt ideelle resultater, og behøver videre undersøkelser for å avgjøre om dette produktet er trygt.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

In this introductory chapter, the background for the report is presented. The goals, scope and limitations that create boundaries and restrictions for the work are explained, and finally a description of the structure of the report is given.

1.1. Background

The Norwegian regulations for energy efficiency in buildings have become stricter in recent years, due to a high focus on environmental issues. The aim is to limit the amount of energy required for building operation and reduce greenhouse gas emissions (Kommunal- og moderniseringsdepartementet, 2015). Anthropogenic emissions have been rising rapidly since the pre-industrial era, causing an elevated concentration of greenhouse gases in the atmosphere, which is contributing to global warming (IPCC, 2014). This is creating devastating consequences for the environment and life on earth. In the future, the climate in Norway is expected to become more extreme, with wetter and warmer weather due to global warming (Almås et al., 2011).

A huge potential exists for reducing the emissions from buildings (Kavgic et al., 2010), as most of the energy consumption in buildings usually goes to space heating, and poorly insulated buildings are a major contributor to waste of energy. To reduce thermal heat loss and the amount of energy required for heating, there is a need for more energy-efficient building envelopes. Therefore, the regulations for energy efficiency in the Norwegian building code requires an increasing amount of thermal insulation in construction parts.

Research shows that a greater thickness of the thermal insulation layer may have consequences related to the hygrothermal conditions in wood-frame walls (Geving and Holme, 2010, Mundt-Petersen et al., 2013). A possible adverse effect is the temperature in the exterior parts of a wall being reduced due to increased thermal resistance. The lower temperature may cause the relative humidity (RH) to increase. High RH values may cause serious problems, such as fungal growth, which poses a risk for both the health of the inhabitants and the structural integrity of the building. The critical point in a wall construction, in regard to moisture issues, is normally on the inside of the weather barrier, due to a lower temperature in this part (Geving and Holme, 2010, Mundt-Petersen et al., 2013).

Possible solutions to the problem is placing an exterior insulation layer on the outside of the weather barrier or using exterior insulation that can function as a weather barrier on its own. This may increase the temperature in the exterior part and reduce the RH. Wood fibre is an interesting option because of its high hygroscopic nature.

This issue of moisture safety in highly-insulated buildings is important to address. Especially considering the expectations of even stricter requirements for energy efficiency in the future, which may require even more thermal insulation in the building parts. This may possibly intensify the negative effects of the increased insulation thickness. It could become an even greater problem if the climate in Norway becomes more extreme due to global warming. The anticipated climate changes will most likely lead to higher moisture levels, more precipitation and higher temperatures, which may increase the risk of moisture damages and fungal growth (Almås et al., 2011). Buildings have to be made more robust to handle the potential increased strains.

1.2. The Purpose and Main Issues of the Report

This master thesis addresses moisture safety in highly insulated wood-frame walls. Research shows that the risk of moisture damages may increase with the thickness of the insulation layer. There are multiple factors that may contribute to an increased risk, one of the reasons may be because the thermal transmission through the wall is reduced, resulting in lower temperatures and higher relative humidity in the exterior parts of the construction. This may increase the risk of condensation and mould growth. A possible solution to this problem is using a thicker weather barrier product with insulating properties. i.e. exterior insulation materials. This may increase the temperature in the exterior parts and reduce the relative humidity. However, there may be adverse effects of using this solution.

The purpose of this study is to examine the effect on the moisture conditions in highly insulated walls, when using thermal insulating materials as a weather barrier. One of the main question of interest, is whether this solution will improve the moisture safety compared to using traditional types of weather barriers. In addition, there is a question of which materials may be suitable.

The first part of the work will be a literature study, with the purpose of finding information and previous research on the subject and finding products that may be of interest. Wood fibre insulation is chosen in advance as one of the materials to be investigated based on recommendations. Furthermore, hygrothermal calculations will be performed, using the simulation program WUFI Pro, to examine the moisture conditions in highly insulated walls when using thermal insulating weather barriers compared to conventional weather barriers. Different parameters and scenarios will be tested to investigate the impact on the moisture conditions.

Mould growth is considered to be one of the critical factors, as mould is one of the first indications of elevated moisture levels in a building. Therefore, one of the main methods for evaluating the results of the parametric studies will be based on the risk of mould growth.

1.3. Scope and Limitations

The master thesis is written during the spring semester of 2017, and represents 30 credits. Hence, there are limitations considering the time at disposal, which will confine the extent of the study.

The main parts of this project are the literature study and the three parametric studies. The calculations will be limited to assessing the use of exterior insulation as a measure to improve the moisture conditions in highly insulated wood-frame walls in a Norwegian climate. However, research on constructions in other climates is of interest in the literature study, and products that may not be available in Norway will be examined as there are more options in the international market.

The wall construction that will be simulated in the parametric studies is limited to a common type of wood-frame wall, with a ventilated wooden cladding, weather barrier/exterior insulation, cavity insulation, vapour barrier and an internal lining. This is the predominant principle of constructing wood frame-walls in residential buildings in Norway, therefore other solutions are not evaluated. Most of the construction parts will be identical in all studies, because these construction parts and their influence are not of interest in this work due to a limited time frame.

The parametric studies are confined to the variation of a few parameters and a certain amount of simulation cases. The exterior insulation products will be tested to give an indication of which materials and properties are suitable for reducing the risk of moisture issues in highly insulated wood-frame walls. One of the main focuses in the parametric studies is the thickness of the exterior insulation layer. The investigation will not focus on finding which exact thickness of a certain product is ideal, but how the thickness influences the moisture conditions, as the exact thickness may depend on many factors such as the climate and the other materials in the construction. Thus, one exact thickness will most likely not apply in all situations. The influence of other factors, such as the climate and a higher initial moisture contend, will be investigated as well.

The results from the simulations will be used to evaluate the moisture conditions in highly insulated walls when using exterior insulation as a weather barrier versus a traditional weather barrier, in addition to quantitative criteria for moisture damages, such as mould growth.

The results from the simulations are used to evaluate the moisture conditions in highly insulated walls when using weather barriers of materials with high thermal resistance versus a traditional weather barrier, in addition to assessments of the moisture safety based on quantitative criteria for moisture damages, such as mould growth.

The study will be based on simulations and will not be verified with laboratory tests.

1.4. Structure of the Report

The first part is the introduction, which provides the background for conducting this study and defines the main problems and purpose, in addition to the scope and limitations that confine the work. The methodology chapter describes how the study was conducted and which tools and methods were used to gather information and perform calculations and evaluations. The next chapter gives an insight into the theory related to the subjects of the report; moisture mechanics, wood-frame constructions and problems related to highly insulated walls. This information gives a basis for understanding the report.

Further on is the literature study, where research and literature on the subject and different external insulation materials on the market have been examined. The purpose of this chapter is to present previous information on the subject, in addition to finding materials that are suitable as exterior insulating weather barriers and to be used in the moisture calculations, as this part of the study is conducted before the calculations.

Chapter 5 explains the data input, the construction type and the materials used in the calculations. The three parametric studies are divided into chapter 6, 7 and 8, which contain descriptions and discussions of results. The main findings of the parametric studies are summarised in the conclusion in Chapter 9.

Additionally, is the Appendix, which mainly consists of information in connection with the moisture calculations.

2 METHODS

The first part of this chapter explains how the literature searches were performed and the quality control of the process. Furthermore, the methods used for the moisture calculations and the evaluation methods for assessing the results of the simulations are presented.

2.1. Literature Search

Retrieving information has been a big part of the work, both for the literature study and for the other parts of the report. The method for gathering information is mainly based on internet searches.

The literature search was conducted using well-acknowledged search engines and academic databases, such as Oria, Google Scholar and Scopus. Some literature was provided by Stig Geving, including reports, conference proceedings and dissertations. The search was done in both Norwegian, English and Swedish, using search words relevant to the topic. Literature was also found by checking the reference lists in previously found sources.

Evaluation of sources is highly important to secure the quality of the information and to rule out non-credible information. Sources like SINTEF and scientific journal publications are highly credible and reliable, and was therefore preferred over others. The year of publishing was evaluated to be of less importance, because older literature can still be relevant. Some of the information was acquired from manufacturers. This is the least credible source of information, as it may be prone to bias, therefore information containing certifications or documentation from third parties was preferred.

2.2. Moisture Calculations

Moisture and thermal transport are closely linked mechanisms and influence each other. Traditionally, the Glaser method has been used for this type of calculation (Thue et al., 2007). However, this method is limited to steady-state assessment method, and does not include the necessary factors required for a realistic result. The method is limited to water vapour diffusion as the only transport mechanism. The effect of radiation, precipitation and the thermal and moisture storage capacity of the materials is not included. This method has its limitations, thus the calculations in this report are performed using more advanced tools, which secures a more realistic result.

2.2.1. Simulation Program

WUFI Pro 6.0, developed by Fraunhofer Institute for Building Physics, is a program for transient non-steady simulations of hygrothermal conditions (Thue et al., 2007). The program includes the parameters that the stationary Glaser method does not account for. One of the great advantages is the databases with a wide range of material and climate data that are included in the program. Results from WUFI simulations have been verified and showed good compliance with experimental studies, but there are still some risks of error, mainly related to user error.

WUFI is suitable for evaluation of drying time, condensation risk, influence of driving rain, hygrothermal conditions with variating climate or extreme climate and effect of rebuilding or rehabilitation.

WUFI Pro 6.0 can be used for one-dimensional simulations and therefore has its limitations in terms of the complexity of the building components (Thue et al., 2007). The wooden parts of the construction cannot be modelled in a one-dimensional program; therefore, the results may deviate somewhat from real-life because the additional moisture from the wood is left out.

The calculations are performed in three parametric studies. The results from the simulations were used to evaluate the risk of mould growth, drying capability and condensation risk.

2.2.2. Parametric Study

The moisture calculations were conducted in three parametric studies with 21 to 25 simulation cases in each study. Different parameters, such as the weather barrier material, cavity insulation material, climate and starting point of the simulations, were changed to examine the influence of the moisture conditions in a highly insulated wood-frame wall. The choice of simulation cases often resolved in trying and failing, as possible calculation sets resulted in too many convergence errors or gave results that did not seem correct. Therefore, some of the parameters and effects, such as increased rain loads, were not simulated, even though it was desired.

2.3. Evaluation Methods

The assessment of the results is based on quantitative criteria for moisture damage. In this study, the risk of condensation, mould growth and the drying rate is evaluated. Mould growth is considered to be one of the most critical factors in this study, as this is one of the first indicators of elevated moisture levels in a building (Ojanen et al., 2011).

2.3.1. Evaluation of Drying Capacity and Condensation Risk

One of the important factors for mould growth to commence is the time in which the moisture level is elevated (Byggforskserien, 2005b). Building materials contain excess amounts of water in the initial stages after the construction has been built (Byggforskserien, 2006). It may be of great importance that the initial moisture dries quickly to reduce the risk of mould growth. Therefore, the drying capacity will be evaluated by the time it takes for the construction to dry below 80 % (RH_{min}) (Byggforskserien, 2005b), as this is considered the be minimum RH required for mould growth. For wood materials, this is equal to 16-18 weight % (Byggforskserien, 2005a).

The condensation risk will be evaluated in terms of the RH level in the construction. Values close to 100 % is of concern.

2.3.2. Evaluation of Mould Growth

There are a variety of factors affecting mould growth, and it is therefore a comprehensive task to determine the level of growth that may occur. Therefore, the VTT model was chosen as tool to evaluate the mould growth risk.

The VTT model is a mathematical model for simulating the level of mould growth on the surface of wooden materials (Hukka and Viitanen, 1999a, Ojanen et al., 2011). The model is based on previous regression models for mould growth on pine and spruce and validated experiments. The model was later improved to include more materials (Ojanen et al., 2011). In Appendix E.1., the model's main parameters and equations are explained.

The Mould Index (M) represents the growth level that is detectable on a surface of a specimen, either with a microscope or visually. The growth rate is described on a scale from 0 to 6 (Hukka and Viitanen, 1999a):

M	**Description**
0	*No growth*
1	*Some growth detected only with microscope*
2	*Moderate growth detected with microscope (coverage more than 10 %)*
3	*Some growth detected visually*
4	*Visually detected coverage more than 10 %*
5	*Visually detected coverage more than 50 %*
6	*Visually detected coverage 100 %*

The parameters A, B and C, in the equations in Appendix E.1, are material dependent (Ojanen et al., 2011). Materials have different levels of resistance against mould. Organic materials, such as wood, can be very sensitive, while inorganic materials have better robustness against mould. A classification of the sensitivity of a few materials has been developed based on experimental studies.

Table 1: Mould growth sensitivity classes (Ojanen et al., 2011, Fraunhofer Institute for Building Physics, 2017)

Sensitivity class	**Materials**
Very sensitive	Pine sapwood, untreated wood
Sensitive	Glued wooden boards, PUR with paper surface, spruce, planed wood, paper coated products, wood based boards
Medium resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool
Resistant	PUR polished surface, glass and metal products, materials with efficient protective compound treatments

The sensitivity classification of the material governs the parameters in

Table 2: Parameters for the different sensitivity classes (Ojanen et al., 2011)

Sensitivity class	**k_1**		**k_2 (M_{max})**			**RH_{min}**
	M<1	**M>1**	**A**	**B**	**C**	**%**
Very sensitive (vs)	1	2	1	7	2	80
Sensitive (s)	0,578	0,386	0,3	6	1	80
Medium resistant (mr)	0,072	0,097	0	5	1,5	85
Resistant (r)	0,033	0,014	0	3	1	85

Choosing the correct sensitivity class can be one of the major sources of error when using the VTT-model (Ojanen et al., 2011, Fraunhofer Institute for Building Physics, 2017). Table 1 is mainly an indication of which class to choose, as there may be variations within the same products. In addition, other factors may affect the sensitivity of a material. Dust, mould spores and nutrients may accumulate on the surface of materials if they are stored for a long time or in poor conditions, which increases the risk of mould growth (Fraunhofer Institute for Building Physics, 2017). Hence, there are some considerations to be taken in terms of the validity of the results from this model, as there may be many additional factors to consider. Still, the model is a good tool for assessments as it gives an indication of the risk level. It may be recommended to choose a higher level of sensitivity to secure a conservative result.

The calculations of the Mould Growth Index are conducted by inserting the results from the WUFI simulations into an Excel sheet with a template for the calculation of the VTT model. Appendix E.2. shows the parameters chosen for the calculations.

Traffic Light Classification of the Mould Growth Index

As a tool for evaluating the Mould Growth Index, a traffic light classification was developed to give a simpler indication of the risk level (Viitanen et al., 2015). The classification system divides mould growth into 3 risk levels; green, yellow and red, depending on the position of the material.

For materials that are not in direct contact with the indoor air, the classification is as follows: Green for values up to a Mould Index of 2 indicates no risk of relevant mould growth. Mould Index values between 2 and 3 are classified as yellow and represent a possible risk that should be further evaluated. Red, for values above 3 indicates an unacceptable risk. Materials that are in direct contact with the indoor air follow a stricter scale, and the boundaries for the risk levels are reduced by 1 (Viitanen et al., 2015).

This classification system is used in the interpretation and evaluation of the results from the VTT-model.

3 THEORETICAL FRAMEWORK

This chapter consist of the theory related to the main subjects of this report. The first section explains the mechanisms of moisture transport, air humidity and moisture in materials. The next parts give an insight into measures for achieving sufficient moisture safety in wood-frame wall constructions and weather barriers. The last subchapter presents the consequences of increased insulation thickness in wood-frame walls, which is the background for the work.

3.1. Moisture Mechanics

Moisture Transport

Moisture can be transported in gas or liquid state (Byggforskserien, 1998). Water vapour is transported either by air leakages or diffusion, with pressure equalization as a driving force. Moisture transport by air leaks, also called moisture convection, is caused by vapour travelling with air flows from areas with high air pressure to areas with lower air pressure. Diffusion is caused by vapour moving from areas with a higher water vapour pressure towards areas with lower pressure. The indoor air pressure is often higher than the exterior pressure because of temperature differences. Therefore, moisture is prone to move outwards through building parts. Transport of water in liquid state is caused by capillary suction in the materials' pores, water pressure, gravitation or wind pressure.

Air Humidity

Air usually contains some amount of water in the form of vapour (Byggforskserien, 2005a). The amount of vapour in the air is often expressed as the relative humidity (RH) or as the absolute moisture content in g/m^3. The maximum amount of water vapour that air can contain depends on the temperature. Warm air has the ability to contain more moisture than cold air. An RH of 100 % equals saturation and at this point, condensation may occur. The RH is the water vapour content of air at a certain temperature, as a percentage of the maximum vapour content that air at this temperature can contain, i.e. the saturation point.

The humidity of the outdoor air varies during the year, and the RH is usually lowest in the spring and highest during winter and fall, while the water vapour content is higher in the summer (Byggforskserien, 2005a). Great variations of the air humidity can occur within a day. The moisture content in the indoor air is dependent on the air added from the ventilation system, indoor moisture gains and the air exchange.

Moisture in Materials

Most materials contain a certain amount of water (Geving and Thue, 2002). Water can be bound either chemically or physically. Chemically bound water is usually not included in the moisture content of a material, because this water is strongly bound as a part of the material. Physically bound water is usually considered as the water content in a material. This is free water that may vaporize. The moisture content of a material is dependent on many factors, such as the type of material, the pore system and previous moisture history. Free water or vapour that comes in contact with materials with open pores can be bound to the material. Materials with this ability are called hygroscopic materials. The moisture content in a material can be given as the RH of the air in the pores of the material or as the absolute moisture content. For wooden materials, the moisture content is usually expressed in weight percentage (Byggforskserien, 2005a).

Moisture Equilibrium – Sorption Curves

Hygroscopic materials will at a given RH in the ambient air gradually adjust to a certain moisture content (Byggforskserien, 2005a). The adaptation is usually quick in the beginning, and later it slows down. After some time, the water content will be at a balance if the RH in the air stays constant. This balanced state is the material's moisture equilibrium for a specific RH. The value is more or less unaffected by temperatures within the range of temperature normally encountered in building physics (Geving and Thue, 2002). If the RH increases, the material will start adapting to a new value. This phenomenon can be described by sorption curves. The curves show the link between absolute moisture content in a material and RH in the air, which may be useful in conjunction with the critical moisture condition of materials.

Building materials often have a higher moisture content when they are built into constructions than the moisture equilibrium at normal conditions (Byggforskserien, 2006). The water content may become elevated if the materials are not properly stored and protected during the construction phase. The term "built-in-moisture" is often used as an expression of this.

3.2. Moisture Safety in Wood-Frame Walls

Moisture is always present in or around a building (Byggforskserien, 2005a). Common sources for water and moisture is precipitation, air humidity, built-in moisture, moisture in the ground and free water from technical installations.

To prevent moisture-related issues in a wall construction, important principles are to inhibit moisture from entering the wall and to give the construction a good ability to dry out excess moisture (Geving and Thue, 2002). In addition, high levels of built-in moisture should be prevented (Byggforskserien, 1998).

The materials should be arranged in an order that gives the wall a good drying capacity towards the outside; with a high vapour resistance on the internal side and descending value towards the outside (Geving and Thue, 2002). Both sides of the construction should be air tight. See Figure 1.

Conventional wood-frame walls in residential buildings often have a ventilated wooden cladding as the exterior finish, which consists of the cladding, an air gap and a weather barrier (Byggforskserien, 2013). The cladding protects the construction from rain, while the air gap allows moisture to be drained and dried, due to buoyance or wind, which creates ventilation in the gap. The weather barrier is explained in the nest subchapter, as this is the building part of interest in this study.

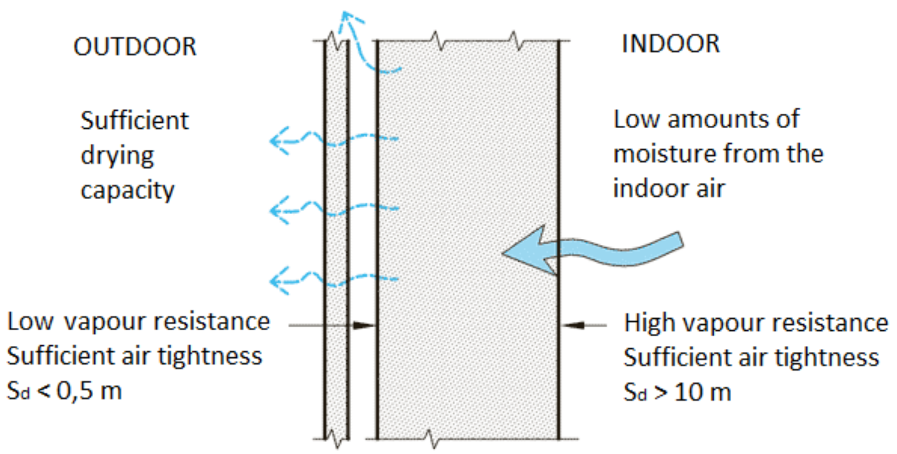

Figure 1: Principles for reducing moisture transport in wall constructions (Byggforskserien, 2008)

The cavities in the wood-frame construction is filled with insulating materials to prevent thermal heat loss and secure adequate indoor conditions. On the internal side of the construction is an air-tight vapour barrier with a high vapour resistance (Byggforskserien, 2003b). This layer prevents moisture transport by air leaks and diffusion, which is critical as the warm indoor air may condensate in the external parts of the wall. In addition, the vapour barrier prevents draught and heat loss due to air leaks.

Weather Barriers

The main purposes of the weather barrier is to protect the construction from precipitation that might enter through the external cladding and prevent heat loss due to air leaks, in addition to allowing moisture inside the wall to dry outwards (Byggforskserien, 2003b). Some weather barriers have mechanical strength and therefore function as wind bracing. The weather barrier can also contribute to protecting an unfinished building from wind and rain in the construction phase.

Common weather barrier products in Norway are boards or foil, usually made of paper, wood fibre, gypsum or plastic, se Figure 2. Some are treated with different coatings or other methods to ensure certain qualities, such as being water repellent. The water vapour resistance of the typical materials ranges from S_d values of 0,008 to 1,7 m (Byggforskserien, 2003b).

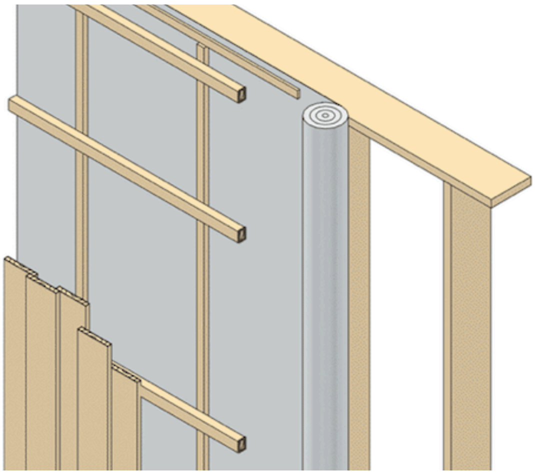

Figure 2: A conventional plastic foil weather barrier (Byggforskserien, 2007)

The weather barrier must have sufficient airtightness to prevent cold air from entering the construction. Recommended air tightness is a maximum value of 0,050 $m^3/(m^2hPa)$ for fully assembled product including seams (Byggforskserien, 2003b). Preferably, the weather barrier's vapour resistance should be as low as possible, because a low value reduces the risk of accumulation of moisture and ensures a good drying capacity outwards. The recommended value is an S_d value of maximum 0,5 m (Byggforskserien, 2003b). A higher value may be acceptable if the weather barrier material has the ability to store moisture in periods with heavy loads and release the excess moisture during dryer periods. The water vapour resistance of weather barriers of wood materials, and some plastic materials, decreases with increasing moisture content and RH level. This may be an advantage because it may allow more moisture transport through the materiel at the point when drying is desired.

The internal surface of the weather barrier is often considered to be the most critical point in a construction, in regard to the risk of elevated moisture levels, condensation and mould growth (Geving and Holme, 2010, Mundt-Petersen et al., 2013).

It should be noted, many different terminologies are used for this building component; air barrier, weather resistive barrier, wind barrier, sheathing, membrane, house wrap and so on. Some of the terms may be linked to the type of material. In this report, the term weather barrier was chosen consistently, to avoid confusion.

3.3. Consequences of Increased Insulation Thickness in Wood-Frame Walls

Thicker insulation layers may be beneficial with regards to lowering the energy consumption for space heating, as the increase of thermal resistance in the construction may reduce the thermal heat loss through the construction. However, an increased insulation thickness may result in adverse effects, related to the hygrothermal conditions of the wall, as research shows that there is a link between insulation thickness and RH levels in construction parts (Mundt-Petersen et al., 2013, Geving and Holme, 2010).

The possible consequences of increased insulation layers are reduced temperatures in the exterior part, more built-in moisture in the construction, reduced drying capacity and increased internal natural convection, which may lead to moisture damages.

One of the major threats of elevated moisture levels in wood-frame constructions may be the risk of fungal growth, such as mould and rot. Fungi is a threat to the health of the inhabitants, the material and the structural integrity of the building (Byggforskserien, 2005b). High moisture levels may in addition cause poor indoor air quality, health-related issues and damage to materials (Byggforskserien, 1997).

Lower Temperature in the Exterior Parts of the Wall

Thermal insulation reduces the amount of heat transmission through building parts. The thicker the insulation layer is, the less heat passes through the wall, because the thermal resistance of the wall is increased. Therefore, the temperature in the exterior parts of the construction may be reduced in highly insulated walls compared to thinner walls, depending on the outdoor temperature (Geving and Holme, 2010). A decrease in temperature may cause the RH to increase, as the vapour concentration in the external parts of the construction may still be the same. A higher RH value may increase the risk of moisture damages, such as condensation and biological activity. Concurrently, the temperature decrease may counteract the risk of mould growth to some extent, as the initiation of mould growth is dependent of a sufficient temperature level (Byggforskserien, 2005b).

Increased Drying-Time

An increase in the drying time in highly insulated wood-frame construction may be a result of two factors; the increased thickness of the insulation layer may require larger dimensions of the wood-frame construction, and thicker insulation gives a higher resistance against drying (Geving and Holme, 2010). An increased amount of wood may result in higher levels of built-in moisture to be dried out initially, and the increased thickness of the insulation layer may give the construction a higher vapour resistance, hence a lower drying capacity.

Increased Natural Internal Convection

Natural convection is circulation of air, due to buoyancy, because of the difference in the density of air at different temperatures (Gullbrekken, 2012). The air near the internal parts of the wall may be warmer than in the exterior parts, and because warm air has a lower density than cold air, the warm air rises, resulting in circulation within the wall. Natural convection is more likely to occur in the winter, because of a higher temperature difference between the outside and inside.

This phenomenon may result in an increased heat loss and unfavourable internal moisture redistribution in construction parts (Geving and Holme, 2010). There is an elevated risk of natural convection in highly insulated walls, because air circulation increases in insulation layers above 200 mm (Byggforskserien, 2008).

A measure to prevent the problem is using an airtight and vapour-open convection barrier of paper in the middle of the insulation layer (Byggforskserien, 2008). In addition, the insulation has to be properly placed, eliminating all air gaps as this will give a lower flow resistance, which increases convection.

Moisture Damages

About 60-80 % of building damages in Norway are related to water and moisture (Byggforskserien, 2005a). Moisture can cause biological activity, corrosion, swelling, harmful emission from materials, poor indoor air quality and so on (Byggforskserien, 1997). In conjunction with increased moisture levels in wall constructions due to thicker insulation layer, biological activity may be one of the major concerns.

In addition to causing damages to materials and health-related risks, moisture may reduce the thermal conductivity of insulation materials as this property is moisture dependent (Byggforskserien, 2004a). Therefore, high moisture levels in the insulation layer may counteract the higher insulating effect from increasing the insulation thickness.

Fungal Growth

Fungi are organisms that are dependent on other organisms for nutrition, and may exploit any type of organic material (Eduard, 2006). There are multiple factors that are necessary for fungal growth; moisture, nutrition (organic materials), temperature, oxygen and time. Oxygen and organic materials are present in most environments. Therefore, moisture and temperature are the crucial factors. Fungal growth may arise at any time when the conditions are right as spores are usually always present outdoor or indoor (Byggforskserien, 2005b). Figure 3 shows a correlation between the RH, temperature and time required for mould growth.

The two main types of fungi of concern in buildings are mould and wood-rot fungi (Byggforskserien, 2005b). Mould has the ability to grow quickly and spread large amounts of spores, which contain allergens. The fungi may produce other harmful substances that can be toxic, and mould is therefore a risk for the indoor environment. Rot grows slower than mould, but can causes decay of wood materials and is therefore a risk for the structural integrity of a construction.

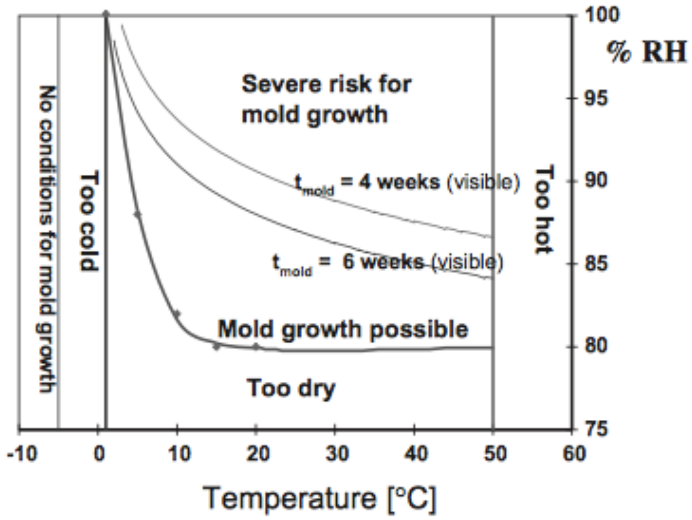

Figure 3: Conditions necessary for mould growth (Simonson et al., 2005)

The optimal temperature for mould growth is 25-30°C (Byggforskserien, 2005b), but mould can grow at other temperatures if there is enough moisture. Below 0°C and above 40-50°C there is usually no growth (Byggforskserien, 2005b). Fungi die in too high temperature, but the spores can still survive. At temperatures below 0°C, the mould growth seizes and the fungi go into hibernation.

For wooden materials, the minimum RH required for mould growth, RH_{min}, is 80 % RH or 16-18 weight % (Byggforskserien, 2005a). The RH_{min} increases with decreasing temperature, and opposite. The length of exposure is of importance, as mould can grow in lower temperatures if the conditions last for an extended period. In favourable conditions, the growth may be rapid (Byggforskserien, 2005b). Lower moisture levels can stop the growth, but if the moisture levels rise again, the growth may continue. Condensation or water leaks may be a trigger for fungal growth, and some types of fungi can grow almost instantly after water leaks.

4 LITERATURE STUDY

This chapter is a study of existing literature and research on moisture issues related to highly insulated walls, weather barriers and external insulation. In addition, different products from manufacturers have been researched, mainly in the Norwegian, European and the US market to get an idea of the options available. The aim of the literature study is to give an overview of current knowledge, to find advantages and disadvantages of various solutions and to find interesting products to be used in the moisture simulation.

4.1. Studies on Highly Insulated Wood-Frame Walls

Two studies, which were found to be interesting and relevant for this report, dealing with the issues of highly insulated wood-frame walls, are presented in this subchapter. Both studies were carried out as parametric studies, using WUFI to calculate the moisture conditions of traditional wood-frame walls in Scandinavian climates.

4.1.1. The Consequences of Thicker Insulation Layers

Geving and Holme (2010) analysed the consequences of increased insulation thickness in construction parts, due to stricter regulations in Norway in 2007. They address two main issues in conjunction with thicker insulation layers; lower temperature in the outer parts of the wall and prolonged time for drying out moisture, which is explained previously in the Theoretical Framework. The aim of the study was to investigate if these effects increase with the thickness of the insulation layers and contribute to a higher risk of moisture damages and mould growth.

First, a study on the effect of lower temperature in the exterior part was conducted, by performing simulations in WUFI. The construction was a conventional wood-frame wall, with an internal gypsum cladding, a vapour barrier (Sd=10), mineral wool insulation, a 12 mm asphalt impregnated wood fibre weather board and a ventilated cladding, simulated in a Norwegian climate. Three different insulation thicknesses, 150 mm, 250 mm and 400 mm, were simulated. The inner surface of the weather barrier, which is considered the most critical point in the construction, was the monitor position for measuring temperature and RH.

The results showed that the RH increases with the thickness of the insulation layer. The RH stayed above 90 % twice as long for an insulation layer of 400 mm than 150 mm. In this case, the temperature in the winter was too low for mould growth, and in the summer the RH was too low. The RH increased in the winter because the temperature in the exterior part of the wall became lower with the increased insulation thickness, but coincidently the lower temperature gives a slight reduction of the risk for mould growth. However, in short periods in the spring and fall, there was a somewhat elevated risk.

The second study was on the effect of drying time. The construction consisted of 12 mm gypsum board as interior lining, a vapour barrier (S_d=70), 20 mm mineral wool, 20 mm spruce, mineral wool of 130, 230 or 370 mm, a weather barrier (S_d=0,1 m) and a ventilated cladding. The 20 mm spruce was added as a fictitious stud, as the wood elements cannot be modelled correctly in one-dimensional simulations. The element was giving a higher initial moisture content at 98 % RH, which simulates the effect of wetting in the construction phase. This is an extreme case, but not necessarily unrealistic, as this may occur in real-life. The purpose was to examine the time it would take to dry to 80 % depending on the insulation's thickness.

In this case the monitor position was moved further into the wall, about 30 mm from the moisture barrier, as the temperature in this section may be high enough for mould growth, compared to the exterior part. The results showed that it takes about 20-40 % longer for a construction with 400 mm insulation to dry down to 80 % RH than a wall with 150 mm insulation. The results from the one-dimensional simulations may be somewhat underestimated, as the amount of wood is not realistic, due to the limitations of the one-dimensional program.

Two-dimensional calculations were performed for the same wall as above, which included both the effect of higher levels of built-in moisture from additional wood and the increased resistance from the insulation. The drying time to 80 % RH with 400 mm insulation was twice as long as for 150 mm. This shows, as expected, an increase from the one-dimensional test, and the indication that highly insulated constructions are at higher risk for moisture issues.

In addition to variating the insulation thickness in the previous simulations, other parameters were variated as well, to accentuate the significance of other factors that may affect the risk of mould growth.

The last part of this study, was laboratory test on the effect of the drying time. The test configuration was a conventional wall with two identical segments except for the insulation thickness. One segment had 400 mm insulation and the other 150 mm insulation. The results indicated that the wall with 400 mm insulation dried slower than the thinner wall in compliance with the two-dimensional calculations.

The adverse effects of increased insulation thickness are affirmed by the results of the calculations and laboratory experiments by Geving and Holme (2010); the exterior part becomes colder, which rises the RH, and it takes longer time for the construction to dry.

The conclusion of the paper, was that the risk of moisture damages and mould growth may be somewhat elevated, but not necessarily unacceptably high. The temperature and RH were rarely at critical levels at the same time in these specific cases, in regard to the risk of mould growth. The parameter study indicates that other factors than the insulation thickness may be of the same or greater importance for the risk of high moisture levels, and that thicker insulation layers are not necessarily a problem in itself.

This report indicates that highly insulated constructions may be secure against mould growth considering the effect of a colder outer part, and that there might not be any need for measures to counteract the issue if normal recommendations are followed. The effect of the lower drying capacity is evaluated to be more concerning in regards to increased risk of mould growth, and measures should be taken to prevent this effect.

4.1.2. Factors Affecting the Risk of Mould Growth in Highly-Insulated Walls

Another paper addresses factors influencing the risk of mould growth in well-insulated wood-frame walls (Mundt-Petersen et al., 2013). This paper investigates the use of exterior insulation as a measure to reduce the risk of mould growth. The study was conducted as a parametric study with one-dimensional simulations, and therefore the wooden elements of the wall were excluded.

The reference wall with material specifications is displayed in Figure 4. The work initiated with finding the most moisture-critical part in the wall, which was towards the exterior part of the wall, near the inside of the weather barrier. Simulations indicated that there is a risk of mould growth in this part of the reference construction, as the RH was above the minimum RH required for mould growth during winter and fall.

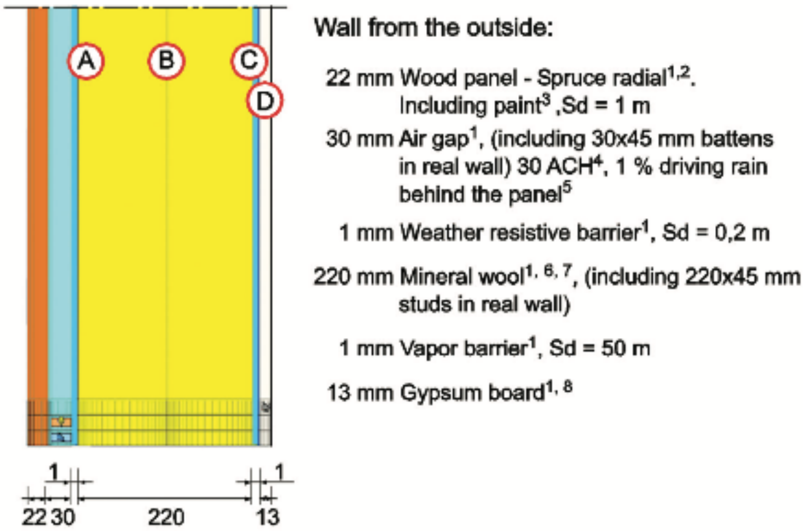

Figure 4: The reference wall (Mundt-Petersen et al., 2013)

Mundt-Petersen et al. (2013) recommend two measures that can limit critical conditions and RH; increasing the temperature or reducing the amount of moisture. The temperature in the outer part of the construction may be raised by using exterior vapour-permeable insulation boards, placed on the studs with a weather resistive barrier on the outside. This may lower the RH and the risk of mould growth.

To avoid critical conditions in the outer part of the reference wall, the minimum thickness of the exterior insulation board was found to be 33 mm for the reference wall, using an exterior insulation material with the same thermal conductivity as the cavity insulation. A wall with thicker insulation consequently required a thicker exterior insulating board. With 420 mm cavity insulation board of at least 52 mm was required to reduce the risk of critical conditions.

The drying capacity of four walls with variation in insulation thickness and exterior insulation materials were studied. The first wall had 220 mm insulation and 33 mm exterior mould-resistant insulation board of vapour-permeable mineral wool. The second wall had the same design, but thicker layers, respectively 420 and 52 mm. The third and fourth wall constructions had the same thicknesses as respectively the first and second wall, but with a relatively vapour-tight EPS as an exterior insulation board instead of mineral wool boards.

The RH level was calculated in two positions, on the inside of the exterior weather barrier and between the exterior insulation and the cavity insulation. Simulating leaks caused a higher RH level in both positions compared to a situation without leaks, as expected. The walls with thicker insulation showed higher RH levels than the thinner walls, likely due to the effect of reduced drying capacity with a greater volume of materials. The walls with EPS had a significantly higher RH level in the position between the exterior insulation and cavity insulation, because the moisture was inhibited from drying outwards because of the low vapour permeability of the EPS.

Other factors that may influence the risk of mould growth was examined. The ventilation level in the air gap behind the exterior cladding was found to be of great importance for the moisture level in the wall. A high airflow may keep the wall dryer, because moisture that enters through the exterior cladding is removed rapidly. Low airflow in the air gap was identified as a negative effect and caused critical conditions to occur more often. The negative effect was amplified with increased insulation thickness.

This study shows that the use of exterior insulation may reduce the risk of mould growth. The paper draws the same general conclusion as Geving and Holme (2010); that there is a somewhat elevated risk of higher moisture levels and moisture damages in highly insulated wood-frame walls, but there are factors that may influence the risk, other than the thickness of the insulation.

4.2. Studies on Different Types of Weather Barrier Materials

The previous study shows evidence of the inside of the weather barrier being the critical part of a wall construction, and that exterior insulation may reduce the critical conditions in this position (Mundt-Petersen et al., 2013). The research in the following subchapters investigates different types of materials used as weather barriers and their effect on moisture conditions.

4.2.1. A Study of Four Different Weather Barriers

As a part of the Swedish WoodBuild, a study with the aim to increase knowledge about the durability of wood as a part of the climate screen, a laboratory test of the effect of different weather barriers was conducted (Olsson, 2011). The aim was to investigate the moisture safety of different types of weather barriers. Four different types were tested on a wood-frame wall in a climate-controlled room for four months. The experiment was verified with calculations.

The weather barrier materials that were tested were; a conventional weather barrier membrane, 30 mm hard mineral wool, 70 mm hard mineral wool and 50 mm EPS. A test wall was divided into five segments, see Figure 5. The first section had cavity insulation of cellulose insulation and a conventional weather barrier. The four other segments had mineral wool as cavity insulation and respectively the four different types of weather barriers. All the sections had one wooden stud in the middle, and an internal moisture barrier of plastic foil, but the sections with cavity insulation of mineral wool with a conventional weather barrier had an additional stud of massive wood.

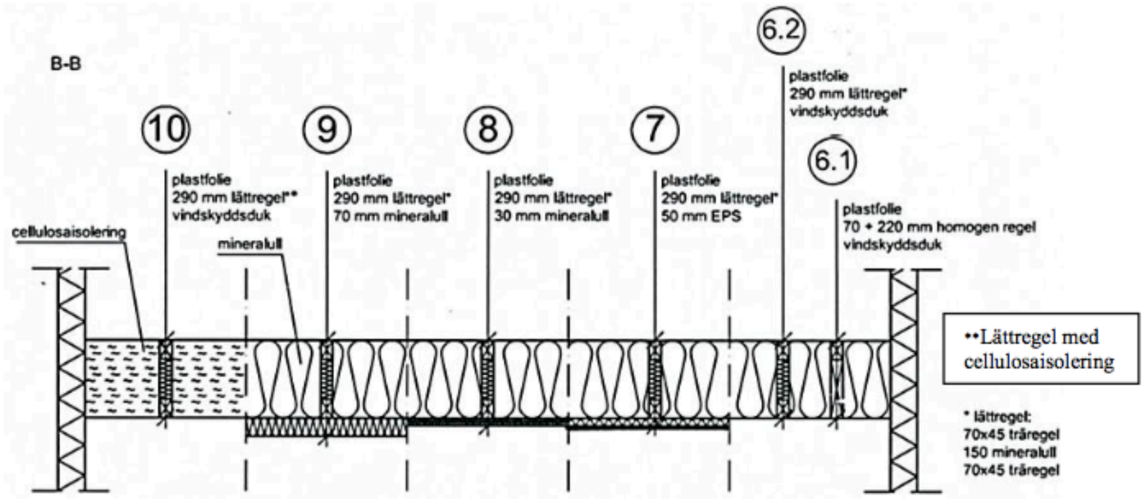

Figure 5: The test setup (Olsson, 2011)

The outdoor temperature was constant at 10°C, and the RH varied every other week between 70 % and 90 % RH for the first three months. The last month the RH was kept constant at 90 %. The indoor temperature was 20°C and the RH level varied naturally.

The moisture content was measured with electrodes placed in different locations, both in the insulation layer and on the studs. Measurements from the inside of the weather barriers, in the insulation layer, show that the segments with mineral wool as an exterior weather barrier had the lowest RH. The section with 70 mm mineral wool had an RH at about 75 %, and 30 mm mineral wool gave about 80 %. This indicates that the thickness of the layer is of importance, and a thicker layer may be favourable.

The two sections with a conventional weather barrier and cavity insulation of mineral wool or cellulose, resulted in RH values that were respectively right above 85 % and just below 90 %. According to Olsson (2011), the section with cellulose insulation seemed to have been influenced by air leaks through the vapour barrier, because the RH levels increased during the first few weeks. This may have resulted in higher values. The section with 50 mm ESP acted somewhat differently than the other sections. It had the highest RH, sometimes over 90 %, but it decreased during the last half of the test. There was some uncertainty whether this construction may have been influenced by air leaks. During the periods with the driest ambient conditions, the two segments with exterior mineral wool insulation dried down to about 65 %, while the rest of the segments had RH values above 77 %.

Measurements taken on the surface of the studs facing the inside of weather barrier, show mainly the same trend as the measurements above, from the insulation layer, but with a slightly lower RH. The values were about 1-6 % lower. This is most likely due to the heat transmission being greater through the studs than the insulation, resulting in a higher temperature in this position, hence a lower RH.

Only two segments showed indications of mould growth; the segment with cellulose cavity insulation and the section with 70 mm mineral wool as a weather barrier. There were only small traces in both cases, rated at level 1, which indicates a slight degree of growth. According to (Olsson, 2011), the mould growth in the section with mineral wool most likely occurred before the test started, because the RH was rarely at a critical level in the duration of the test. The mould growth in the other section most likely happened during the test, as the RH was high in this section.

From the results, it may be clear that the choice of weather barrier is of great importance. A weather barrier with a high thermal resistance and high vapour permeability seems to reduce the risk of elevated moisture levels, as the temperature in the exterior part of the wall becomes higher. Materials with low vapour permeability, such as the EPS, seems to cause high moisture accumulation if there are air leaks or if the initial moisture content in the wood is high. The conventional weather barrier seems to inhibit drying, because the RH level in the stud stayed elevated during dry periods, and calculations indicate that there is a risk of condensation on the inner surface of the conventional weather barrier.

4.2.2. A study of Wood Fibre Insulation

The use of wood fibre insulation was examined in a laboratory study on moisture conditions in wood-frame walls (Geving et al., 2015). The main focus was on wood fibre as cavity insulation compared to mineral wool, but the effect of various types of weather barriers was tested, including asphalt impregnated wood fibre boards.

There were 15 wall configurations with different combinations of the materials. In addition to 12 or 50 mm asphalt impregnated wood fibre boards, a conventional PE-foil was tested as a weather barrier. The cavity insulation was 300 mm mineral wool or wood fibre insulation of either batt of loose fill. Three types of vapour barrier were used; a PE-foil, a vapour barrier (S_d=2 m) and a smart vapour barrier. In addition, the wall was tested without a vapour barrier. A gypsum fibreboard was used as an interior lining.

The 15 wall configurations were built as cells in a wall between two climatic chambers, and sensors were placed in two positions of every cell; between the vapour barrier and the insulation and between the weather barrier and the insulation. Some of the cells had an additional sensor 50 mm from the weather barrier.

The conditions in the climatic chamber was set to simulate three different periods over a total of 195 days. Winter conditions were simulated during the first period, followed by a warmer spring/autumn period, and finally, another winter period. The indoor conditions were supposed to be constant with a moderate RH in the beginning, a lower humidity in the middle and then a high humidity at the end, but there were some issues during the test, which resulted in a less stable indoor climate.

Before the test started, the wood fibre batt insulation was conditioned, because of its high hygroscopic capacity, to ensure a good result as initial moisture content in the wood fibre may have a great influence on the measurements.

The weather barrier of 12 mm wood fibre board was tested with the three different cavity insulation materials in combination with a vapour barrier (S_d=2). Cavity insulation of wood fibre batt resulted in the highest RH in the monitor position on the inside of the weather barrier, which was near 80 % during the entire test, see Figure 6. Slightly lower RH values were achieved with the loose-fill insulation. The mineral wool generally had a lower RH, and the difference between the two materials was especially large in the first period. This is most likely due to the high initial moisture content of the wood fibre insulation. The difference during the last two phases were smaller.

When using a PE-foil as a weather barrier in combination with the same vapour barrier and wood fibre batt insulation as in the previous section, the two weather barrier products achieved approximately the same results, see Figure 6. This is probably because the PE-foil is more vapour open than the wood-fibre board, and the positive effect of the increased thermal resistance of the 12 mm wood fibre board is not enough to counteract this effect, according to Geving et al. (2015). However, this does indicate that the wood fibre board may perform on the same level as a conventional weather barrier.

In a similar configuration, but with a 50 mm wood fibre board instead of the PE-foil, the effect of the increased thickness, i.e. higher thermal resistance, seems to improve the RH levels, and the RH is reduced to values below approximately 75 % throughout the entire test. Thus, the wood fibre board achieves a better result than the PE-foil. See Figure 6.

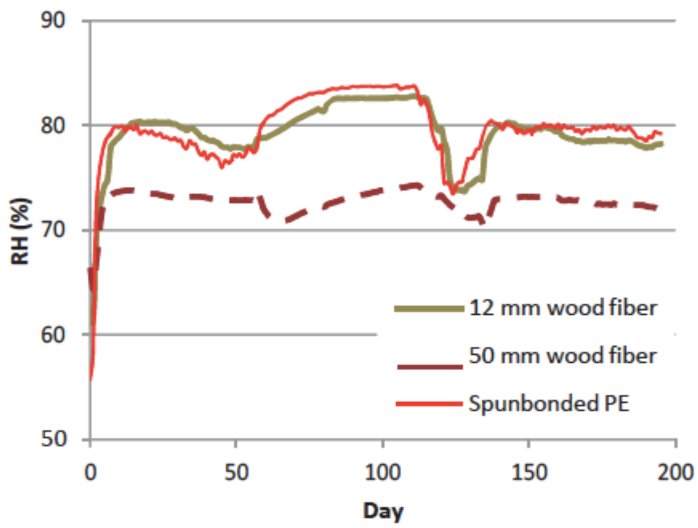

Figure 6: The results from the configurations with the three different types of weather barrier, in combination with wood fibre batt cavity insulation and a vapour barrier Sd=2 (Geving et al., 2015)

One interesting finding in this study, was that when a wood fibre board of 50 mm was used as a weather barrier in a construction without a vapour barrier, the RH at the weather barrier was still below 90 %, even in the third period with a high moisture supply from indoor. Geving et al. (2015) claims that a weather barrier with a low thermal resistance would most likely result in higher RH values.

These results indicate that the increased thermal effect of the wood fibre insulation reduces the risk of elevated moisture levels. As Geving et al. (2015) expresses, there is a general positive effect of using a weather barrier with a high thermal resistance, such as wood fibre boards.

4.2.3. A Study on Rigid Foam Exterior Insulating

Tsongas addresses the effect of rigid foam exterior insulation in wood-frame walls in the USA in the 80's (Tsongas, 1991). This method became more common in this period, and there was uncertainty of its effect on moisture levels in the wood elements within the walls.

There were two main hypotheses. The first was that it could increase the amount of moisture inside the walls, due to the exterior insulation acting as an external vapour barrier, resulting in moisture being trapped during colder periods. The second hypothesis was that it could lower the moisture levels, as it would result in higher temperatures in the wall.

Tsongas refers to "The Northwest Wall Moisture Study" (Tsongas, 1990), which was a field study in the late 1980's, with the purpose of investigating if newer buildings, with higher energy-efficiency standards, that were heavily insulation and relatively air tight, were prone to higher moisture levels in the exterior walls. The study included 86 newer buildings from three regions with different characteristic climates in the Northwest of the USA. About one third of the buildings had exterior insulation of various types of rigid foam; extruded polystyrene (EPS), isocyanurate with foil facing or moulded polystyrene. The rest had different weather barrier products of plywood or fibre board, common plastic wrap or other materials.

The study was executed by cutting open the walls of the buildings in the winter, when the conditions were expected to be at their worst, and measuring the moisture content of the wood members in the cavities of the walls. The results of the measurements showed that many of the buildings had wood members with a moisture content above 20 %, which was considered unacceptably high. New measurements were conducted in the summer one year later of the buildings that showed the highest amount of moisture in the first test. The outcome of the reopening was that many of the walls still had a wood members with a moisture content above 20 % in the summer. Then again, the wettest walls were reopened in the following spring, and there were still walls that had wood members with a moisture content above 20 %.

The statistical data analysis indicated that walls with rigid foam exterior insulation had a significantly lower moisture level than the buildings with other weather barrier products. Only 17 % of the homes with rigid foam exterior insulation had wooden elements with a moisture content above 20 %, and the highest recorded value was measured to 28,5 %. Of the houses with other weather barrier products, 86 % had a moisture content above 20 %, with a highest reading of 55 %. The data also showed a correlation between the thickness of the rigid foam exterior insulation and the moisture content in the wood; the thicker the insulation layer, the lower the moisture content.

Investigations in this study indicated that the more cavity insulation, the greater is the risk of inadequately high moisture levels. A greater insulation thickness may result in lower temperature on the exterior side of the wall, which may increase the risk of condensation and other moisture-related issues, as established in the previously mentioned studies (Geving and Holme, 2010, Mundt-Petersen et al., 2013).

The hypothesis that the exterior insulation of rigid foam might behave as a vapour barrier, was not proved (or disproved) in this study. The conclusion of this study, is that the increased thermal resistance in the exterior parts of the wall, when using exterior insulation of rigid foam, is likely the reason why the walls with exterior insulation gave a more satisfying result, as the moisture levels may be reduced because of the increased temperature, as was expected in the second hypotheses.

4.2.4. Laboratory Test of Exterior Rigid Foam Insulation

A full-scale field test of external insulation products was conducted at The Norwegian Building and Research Institute in the mid 80's (Norges Byggforskningsinstitutt, 1986). The products subject for testing were panels of rigid foam; Wallmate and Styrofoam SM-TG by Dow Chemical Europe. The purpose was to investigate the moisture content in the wood-frame wall during a test performed under realistic climatic conditions, when using the products mentioned as weather barriers. A moisture content in the wood members below 20 % was considered to be adequate, as moisture levels above increases the risk for fungal growth.

A wood-frame construction consisting of four sections with different characteristics was made. The first section had 30 mm Wallmate externally, cavity insulation of 100 mm mineral wool, a moisture membrane foil and plasterboard on the interior side. The second segment had no cavity insulation or moisture membrane, a weather barrier was 50 mm Styrofoam SM-TG and a plasterboard as an internal cladding. The third is the same as the first, but with a higher initial moisture content of the wooden elements, at 15-35 %. The fourth section would function as a reference. It had an asphalt impregnated paper as weather barrier, 100 mineral wool insulation in the cavity and 50 mm insulation in horizontal battens. There was also a moisture barrier of foil and plasterboard on the internal side.

The test was performed from October 1985 to August 1986, during conditions that were usually around 20°C and 50 % RH, but there were some problems with the evaporator, which caused 90 % RH levels during parts of the test. Multiple sensors monitored on the studs and sills in each section. When the testing period was over, the wall was dismounted and the studs, sills and test panels were examined.

During periods, the moisture content rose above 20 % in section 2, 3, and 4. At the end, all the sections had moisture content below 13 %. The first section had a variation between 12-20 % in the position of the sensor that recorded the highest moisture content, but in the end, it dried to about 6-9 %. Section 2 had a very high peak, about 38 %, but this is likely caused by the malfunction of the evaporation system, but the segment showed good ability to dry, and ended at about 10-12 %. Section 3 had a starting point at 15-35 % moisture content, but ended up between 10-13 %. The reference section had a variation of 13-28 %, and ended up at 8-13 %. Section 1, 2 and 4 showed signs of fungal growth.

There were small amounts of fungi detected in section 1, but the moisture content in this section did not rise above approximately 20 %, and therefore this solution may be considered acceptable. Section two had mould growth, probably because of the malfunction in the evaporation system, and the moisture content was below 20 % during the rest of the test. In section three, no fungi were detected even though the initial moisture content was higher. This could have been because the temperature was too low. This wall showed a good ability of drying the excess moisture, as the moisture levels were lower during the end of the test. The fungi in section 4 most likely occurred because the moisture content rose to 28 % in periods. From these results, it appears that the two products may function well as weather barriers. The reference wall indicates some mould growth and had the highest readings of the moisture content in this test, if the section with a possible malfunction is disregarded, and indicates that a traditional solution may not be secure.

4.2.5. Risks Related to Exterior Insulation of Rigid Foam

The results of previous research indicate that exterior insulating of rigid foam may give a lower risk of moisture damage (Tsongas, 1991). Results from laboratory investigations of using exterior rigid foam insulation as a weather barrier gives a somewhat uncertain outcome, as there is some mould growth, but still the moisture levels are mainly kept at a low level (Norges Byggforskningsinstitutt, 1986).

DuPont, a manufacturer of construction materials such as Tyvek (a common type of weather barrier foil), claims that when using exterior insulation of rigid foam, it should be combined with a conventional weather barrier foil (DuPont, 2011). Their argument is that exterior insulating rigid foam may be a good insulator, but it does not have adequate protection when it comes to water resistance and air tightness. They claim to have confirmed that issues arise when using exterior insulation of rigid foam as a weather barrier, with laboratory tests and field observations.

The following information in this chapter is from a report made by DuPont (DuPont, 2011). It should be noted that this report is made by the manufacturer of conventional types of weather barrier products, and may therefore be subjected to bias, as their products compete with products of rigid foam exterior insulation, but they have backed up their findings with laboratory results and third party statements.

Their research uncovered the following issues. Common foam insulation materials, such as EPS and XPS, may be dimensionally unstable when exposed to high or low temperatures. The seams between the rigid foam exterior insulation panels should preferably be taped to achieve water protection and air tightness. If the panels shrink or expand, due to high or low temperatures, the taped joints may be at risk of being damaged, allowing water and air to pass through the wall, which increases the risk of moisture damages. Another problem, may be the reversed shingling of the seams, see Figure 7. The joints cannot be lapped in a way that provides optimal security. There is a risk that water can pass through at the top edge of the tape and into the wall, because there is nothing covering the edge. Laboratory test supposedly verified this phenomenon.

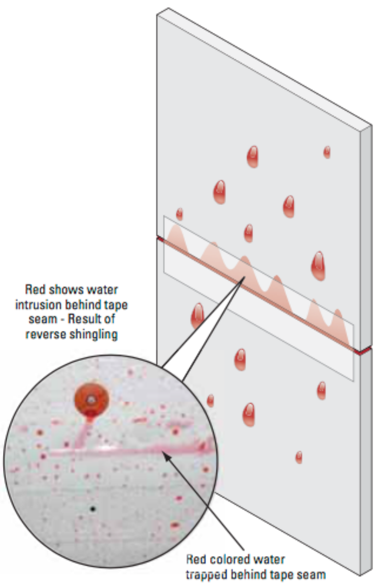

Figure 7: Laboratory test of taped exterior insulation of rigid foam (DuPont, 2011)

DuPont recommends using a conventional weather barrier plastic foil on either side of the exterior insulation, and that the seams between the foam panels should not be taped, because taping does not have a great impact on the insulating effect, and that not taping the seams may the wall a better ability to ventilate. Using a conventional weather barrier foil in addition will allegedly result in a moisture safe and air tight solution.

4.3. Exterior Insulation Products

A focus of this literature study, is finding specific products and solutions that are available on the market. Both systems without a separate weather barrier, and systems with a weather barrier placed behind the exterior insulating layer have been researched. Most of the information in this section came from the manufacturers, and should therefore be met with a bit of scepticism as they may have exaggerated the abilities of their products, but some products have certifications and third-party evaluations, which make the information more reliable. The purpose of investigating products was to find options to use in the simulations.

More products were researched than is presented, but were excluded from this chapter, due unclear or a lack of information about properties and characteristics, because they were evaluated to not be suitable, and in regard to limiting the extent of this chapter.

4.3.1. Rigid Foam Exterior Insulation

One of the benefits of rigid foam insulation is that many of the products have a low thermal conductivity (Byggforskserien, 2003a). However, foam insulation products may be disadvantageous in terms of fire safety and the environment. The products are highly combustible, and can burn rapidly and contribute to large amounts of smoke and toxic gases (Kallaos et al., 2014). Additives can be used to increase its resilience against combustion, but these often reduce other properties of the materials. Foam insulation may also be dimensionally unstable (Byggforskserien, 2004a). The products mainly consist of plastic and are usually made with blowing agents that may be harmful to the environment. However, amongst the rigid foam products researched, there were a few products that were found to be interesting.

Kingspan Insulation AS offers rigid foam insulation products for the Norwegian market. Kingspan Koolther K12 is a product that may be used as an external insulation in wood-frame constructions. (Kingspan Insulation AS, 2017). The product is a rigid thermoset phenolic insulation board, with aluminium laminate on both sides (Kingspan Insulation Ltd, 2017). The product is displayed in Figure 8.

According to the producer, the product is moisture proof, wind and air tight. The supplier claims that there is no risk of condensation because the product reduces the temperature difference in the wall. This insulation product is more diffusion open (μ=0,38) than other similar materials, which could make it safer in case of leaks in the moisture barrier (Kingspan Insulation AS, 2017). In addition, it has a low thermal conductivity, of 0,020 W/mK (Kingspan Insulation Ltd, 2016).

There is some uncertainty whether this product may be adequate to use without an additional weather barrier, as the producer recommends using a membrane on the outside if the ventilated airgap is large (Kingspan Insulation AS, 2017). This was not further elaborated in the product description, but according to the Sales Director in Norway, a membrane is required if the ventilated air gap is larger than 20 mm. Additionally, he recommended using Kooltherm K8C, instead of Kooltherm K12, if the product is to be used without a weather barrier in a wood-frame construction. The two products seem to be nearly identical as they are made of the same materials and have the same thermal conductivity and vapour resistance, in addition to other qualities mentioned below. (Kingspan Insulation AS, Kingspan Insulation AS, 2017).

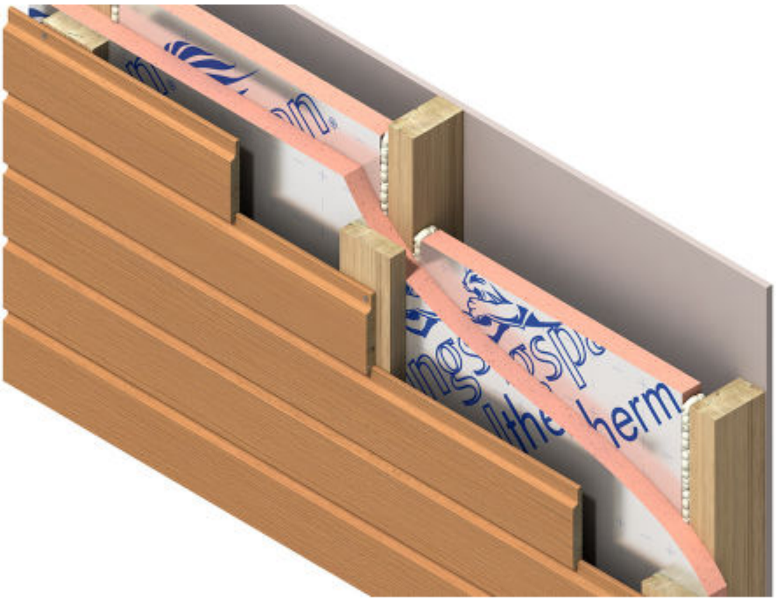

Figure 8: Kingspan Kooltherm K12 (Kingspan Insulation AS)

Advantages of these products, according to the producer (Kingspan Insulation AS, Kingspan Insulation AS, 2017):

- Air and water tight
- Toxin free
- Environmentally classified (Basta, BREEAM)
- Resistant against moisture and fungi
- Show good results in fire test
- Manufactured with blowing agents with zero Ozon Deplition Potential (ODP), and low Global Warming Potential (GWP)

4.3.2. Exterior Insulation of Mineral Wool

Mineral wool is the common name for glass and rock wool. The products are usually batt of different densities. The normal range of thermal conductivity for mineral wool is 0,032-0,040 W/mK (Byggforskserien, 2003a). The insulation materials are incombustible and dimensionally stable, unlike many rigid foam products (Byggforskserien, 2004a).

One of the well-known manufacturers of insulation in Norway, GLAVA, has two interesting systems for external insulation of glass wool for wood-frame walls which are shown in Figure 9. The systems do require an exterior weather barrier, but the two systems seem to have some advantages.

GLAVA Pluss is a system where the studs are made of rigid glass wool with wood parts glued on (GLAVA, 2017a). The glued-on wooden parts are not continuous through the construction. The studs are fastened to the wood-frame construction with screws, and the cavities are filled with mineral wool batts with a thermal conductivity of 0,032 or 0,0035 W/mK (GLAVA, 2015). The other solution, GLAVA Veggplate 31, is batt insulation of glass wool that is mounted on the outside of wood-frame walls. The glass wool insulation is fastened with brackets, therefore the amount of wood in the exterior parts is very low (GLAVA, 2017b). GLAVA Veggpate 31, has a thermal conductivity of 0,031W/mK (GLAVA, 2016). The products are displayed in the figure below.

a b

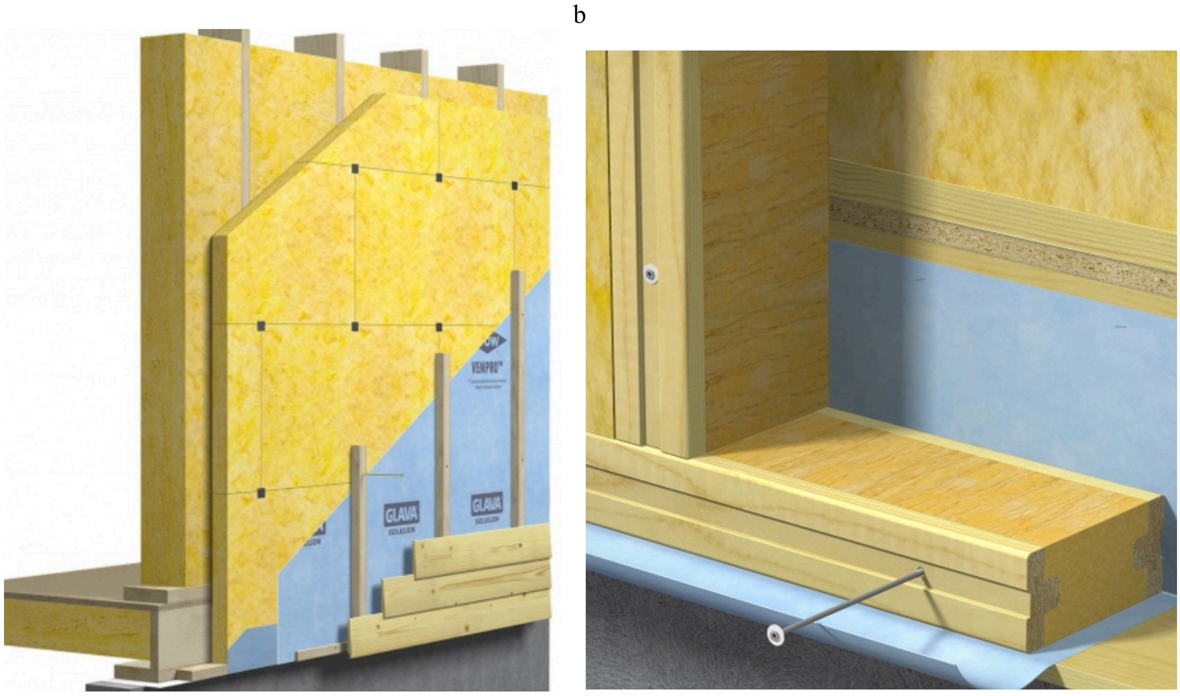

Figure 9: (a) Glava Veggplate 31(GLAVA, 2017b), (b)Glava Pluss (GLAVA, 2017a)

Both solutions supposedly give a continuous insulation layer and a reduction of the amount of wood in the exterior part of the construction, and therefore may reduce thermal bridges (GLAVA, 2017b, GLAVA, 2017a). The risk of mould growth may be reduced with both systems, because the wood studs are placed further inside the construction, where the temperature is higher. In addition, there are few wooden parts in the exterior insulation layer.

Isover in Sweden offers a system for exterior insulation of rigid glass wool called Isover Fasadsiva 30. This system is quite similar to GLAVA Veggplate 31, but the product is recommended to be mounted on the outside the weather barrier, as opposed to GLAVA's system.

The producer claims that placing the weather barrier directly on to the stud, behind the exterior insulation, provides better security. Their explanation is that water that might enter through the exterior cladding is drained off the surface, because the insulation is silicone impregnated, which makes it water repellent (Isover Saint Gobain SE, 2013). In addition, installing the weather barrier before the exterior insulation may be an advantage, as the wall is closed earlier during the construction phase, and protects the wood elements from rain and moisture. The product has a low thermal resistance of 0,030 W/mK (SP Sveriges Tekniska Forskningsinstitut, 2016).

4.3.3. Exterior Insulation of Wood Fibre

Wood fibre may be a more sustainable and environmentally-friendly solution, as it is made of wood, which is a natural material of a renewable resource. The hygroscopic nature of the wood fibre may be beneficial, as may contribute to regulating the humidity and improving the moisture transport. Wood fibre may be treated with additives such as fire retardants and mould growth inhibitors (Lopez Hurtado et al., 2016).

Figure 10: Hunton Windproof (Hunton, «n.d»)

Hunton is one of the major producers of wood fibre products in Norway. Hunton Windproof, see Figure 10, is a weather barrier products approved by SINTEF Certification. The boards are asphalt impregnated on one side to ensure air tightness (Hunton, «n.d»). The thickness of the boards is from 12-25 mm. The thermal conductivity is approximately 0,05 W/mK depending on the thickness of the board, and the S_d value is 0,2 m for the thinnest board (SINTEF Certification, 2015).

Steico offers a wide variety of sustainable and certified wood fibre products to the European market (Steico, «n.d»). Wood fibre boards that may be used as exterior insulation of wood-frame walls are Steico Special, Special dry, Universal, Universal dry, Therm and Therm dry. The products are claimed to be wind tight and weather proof. The products have a vapour resistance of μ=3-5, and thermal conductivity between 0,037 and 0,046 W/mK, according to the datasheets and declarations of performance. Steico Therm Dry has the combination of the lowest thermal conductivity and lowest vapour resistance (Steico, 2017a).

Figure 11: Agepan UDP N+F (Sonae Arauco, «n.d»)

Agepan UDP N+F, displayed in Figure 11, is another insulating wood fibre product, made by the multinational company Sonae Arauco. It is claimed to be moisture resistant and has a particularly robust surface. It is hydrophobic, vapour-permeable and hygroscopic (Sonae Arauco, «n.d»). This product is found in the WUFI material database.

5 MOISTURE CALCULATIONS

Three parametric studies have been conducted using WUFI Pro. The studies focus on the use of exterior insulation materials as a weather barrier in highly insulated wood-frame walls. The first section of this chapter explains the background of the investigation. Next is a description of the construction that was used in the three studies. Furthermore, is information about the material and climate data used in the simulations. In the last subchapter is an explanation of some of the input in the program.

Further information about input and parameters is found in Appendix C.

5.1. Background for the Studies

Weather barrier of plastic products such as PE-foil is commonly acknowledged as safe, but as research in the literature study indicates, this may not be the case, as there are indications of an increased risk of mould growth and condensation on the inner surface of the material (Olsson, 2011, Mundt-Petersen et al., 2013). Conventional weather barriers usually have high vapour permeability, which gives a good drying capacity, but poor thermal insulation properties may result in unstable conditions and a risk high moisture levels.

In highly insulated walls, the problem may become more pronounced, as the thermal heat transmission through the wall is reduced, resulting in lower temperatures and higher RH in the exterior part of a wall. The lower temperature may reduce the risk of mould growth to some extent, as certain temperatures are required for growth, but there may be an increased risk during parts of the year compared to thinner constructions. In addition, the increased amount of insulation and wood materials gives a higher initial moisture content and may reduce the drying capacity because of increased vapour resistance. Therefore the initial moisture levels, or additional moisture loads such as water leaks, may require more time to dry, which increases the risk of moisture damages Geving and Holme (2010).

Weather barriers with high thermal insulation properties and a low water vapour resistance seem to improve the moisture conditions within the wall (Olsson, 2011). Therefore, different types of insulating weather barriers are investigated in three parametric studies, to examine the effect on the moisture conditions in a highly insulated wood-frame wall. The purpose was to evaluate if other weather barrier materials can improve the moisture conditions, compared to a conventional weather barrier. Two of the studies examines the use of wood fibre insulation as a weather barrier, and the last has a focus on rigid foam insulation.

5.2. The Construction

The construction type is a traditional Norwegian wood-frame wall, as displayed in Figure 12. The same type of construction will be used in all three parametric studies, as this is one of the most common principle for constructing wood-frame walls in residential buildings.

From the exterior towards the interior side, the wall consists of:

19 mm wooden cladding
20 mm ventilated airgap
Weather barrier/Exterior insulation
Cavity insulation with wooden studs
0,15 mm PE-membrane
12,5 mm gypsum board

The total thickness of the insulation layer is 350 mm in all simulation cases. This includes both the exterior insulation and cavity insulation.

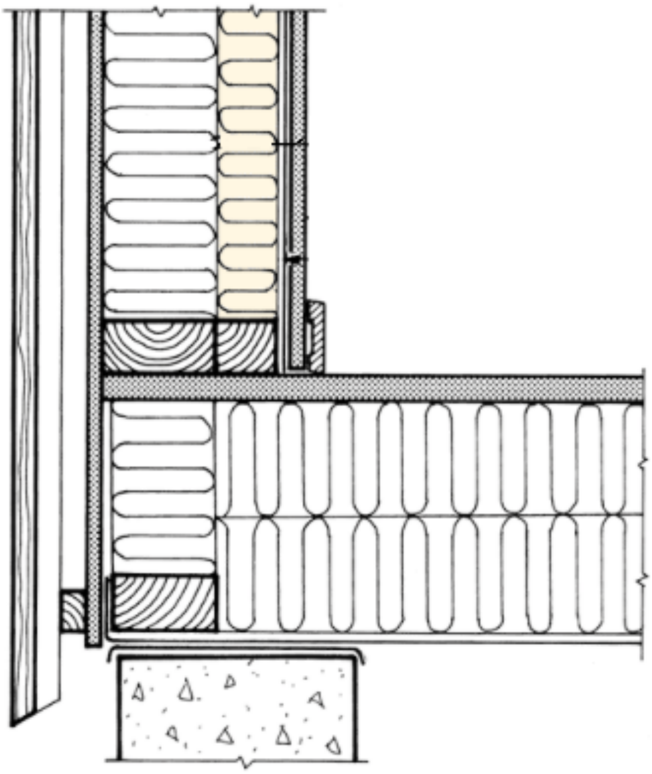

Figure 12: A traditional Norwegian wood-frame wall, as used in the constructions (Byggforskserien, 2004b)

5.3. Material Data

The external wooden cladding, air layer, vapour barrier and interior lining were the same in all studies, because these construction parts and the influence of their characteristics was not of interest in this work due to limitations. Basic products were chosen for these construction parts, using materials from the WUFI material database.

As cavity insulation, either a conventional type of mineral wool or wood fibre insulation was used. Three types of exterior wood fibre insulation, one type of rigid foam insulation and two types of conventional weather barrier were used in the studies. Some of these materials are not found in the WUFI database, and were added to the program by using similar products from the database as a basis, and editing the properties based on information from the manufacturer. Not all material data was available and was therefore left unchanged, as the materials used as a basis were similar types of products, and may have similar properties.

Descriptions of the materials are found in Appendix B.1, and an overview of which materials were used in each study is found in Appendix B.2

5.4. Climate Data

Outdoor Climate

A building component is influenced by the heat and moisture exchange with its surroundings, with the climate as a driving force, and therefore choice of climate may have a great impact on the construction. To simulate the hygrothermal conditions in a building, one should use climate data from a chosen location (Geving and Torgersen, 1997).

The Norwegian climate data in the WUFI climate database is based on the Moisture Design Reference Year (MDRY) from a study by Geving and Torgersen (1997). The choice of MDRY is based on evaluation of observed climate data from one geographic location over many years. A reference year may be constructed of datasets from months from different years put together to a complete year, but in regard to the design reference year for moisture calculations, it is preferred to choose a dataset from one complete year. However, it may be difficult to choose a year that is critical in terms of moisture calculations, as this may vary depending on the construction. Therefore, the MDRY is a referential year that is relatively critical for most types of constructions (Geving and Torgersen, 1997).

Table 3: Climate Data from the climate analysis in WUFI (Fraunhofer Institute for Building Physics, 2016a)

Location	Mean Temp. [°C]	Max temp. [°C]	Min temp. [°C]	Mean RH [%]	Max RH [%]	Min RH [%]	Normal rain sum [mm/a]
Trondheim	5,36	24,2	-13,8	88,06	100,0	46,0	1233.6
Bergen	8,11	28,0	-9,7	79,24	99,0	9,0	2421,0
Oslo	6,85	29,3	-14,8	73,1	100,0	15,0	604,7

The locations chosen for the moisture simulations are Trondheim, Bergen and Oslo, which each represents a different type of climate, see Table 3. Trondheim is colder with a high humidity. Bergen has a coastal climate and has a high mean temperature and a medium high mean RH. Oslo has the most ideal climate of the three, with a mean temperature approximately in the middle of the two other locations and the lowest RH. Bergen is well known for its heavy rain loads, and has about four times the amount of rain compared to Oslo.

The analysis of the outdoor climate from each location is in Appendix A.1

Indoor Climate

The indoor temperature is set to a constant level at 23°C. The internal moisture excess values chosen for the moisture simulations in WUFI are based on a study of indoor air humidity in Norwegian dwellings (Geving and Holme, 2012), as this may represent the typical internal moisture gains in the climates that are used. The data is manually added to the program. A medium internal moisture excess was chosen in all studies. See Figure 13.

The indoor RH for each location is in Appendix A.2

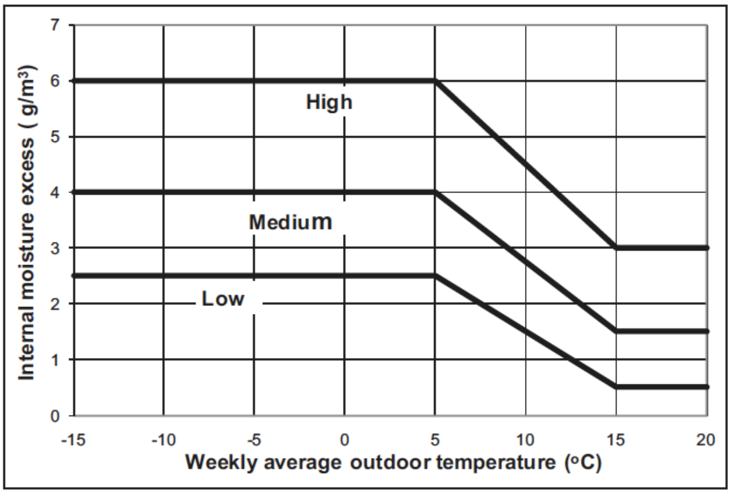

Figure 13: Internal moisture excess design curves for houses (Geving and Holme, 2012)

5.5. Data Input in WUFI

Calculation Period

The specific year of the calculation is not of importance, because most climate files represent the typical climate of the location and not a specific year (Fraunhofer Institute for Building Physics, 2016c). However, the length and start of the simulations may be of great importance. The starting point may affect factors such as drying of the initial moisture content in the materials. The WUFI manual recommends a calculation period of at least two years, because it takes a certain amount of time for the construction to reach a dynamic state where the water content does not vary from year to year (Thue et al., 2007). The exception is for cases investigating damages, where a shorter period may be used, and cases investigating drying or moisture accumulation, which may require more time.

The simulation period is set to three years for all cases, to allow the components to reach a dynamic state. Two starting points were used, January 1st and May 1st, to examine the influence of the initial moisture levels during different conditions.

Initial Conditions

The temperature is set to 23°C constant across the construction. The initial moisture in the materials were in most cases set to 0,8, which corresponds to the moisture equilibrium at 80 % RH for the specific materials. This is the default setting in WUFI, and may represent a typical level of built-in moisture. A few cases are simulated with a higher initial moisture content of 0,9 in certain materials. This is specified in the cases in which this applies.

Orientation

The size of the climatic loads may depend of the orientation of the building part. The orientation affects the amount of sun, wind and rain that the component is exposed to. An orientation to the north gives the lowest exposure to sunlight. The most critical orientation for wind and rain can variate depending on the location, and can be found from the climate analysis in WUFI.

The orientation is set to the North, as this orientation usually may result in a lower rate for drying, due the low sun exposure. Considering the high initial moisture content of wood fibre insulation, the importance of drying the excess moisture quickly is crucial, and this choice of orientating gives a conservative result.

Monitor Position

The three studies focus on the same main problem, the risk of elevated moisture levels in the exterior part of the construction, which may cause mould growth on the surface of the studs or result in condensation if the RH becomes too high. Therefore, the monitor position is the same for all simulation cases in the three studies. The position of interest is between the cavity insulation layer and the internal surface of the weather barrier, as this may be where the most critical conditions occur. The position variates with the thickness of the exterior insulation, and will therefore be in different locations dependent on the thickness of the weather barrier.

6 STUDY 1 –WOOD FIBRE BOARDS

6.1. Background

Wood fibre insulation has a high hygroscopic and thermal capacity, which may give the material the ability to regulate humidity and temperature, which could result in more stable conditions when used in constructions. In addition, the material has a good thermal conductivity, unlike a weather barrier of plastic products. Laboratory investigations, where asphalt impregnated wood fibre boards were used as a weather barrier, indicated that a wood fibre board of 12 mm can perform at the same level as a PE-foil with an S_d=0,023 m, as the two products achieved approximately the same RH levels (Geving et al., 2015). A wood fibre board of 50 mm resulted in lower RH values than with a PE-foil.

The use of wood fibre boards as a weather barrier shows promising results and the material is highly interesting because of its hygroscopic nature, and was therefore chosen to be examined in this study. The purpose was to investigate if weather barriers of wood fibre insulation is a robust solution in highly insulated wood-frame walls, and whether the moisture conditions were improved compared to using a conventional weather barrier.

An overview of the data input is in Appendix C.2. The materials are presented in Appendix B.1 and B.2.

6.2. Simulation Cases and Parameter Variations

The parametric study consists of 25 simulation cases of a wood-frame wall with different parameter variations, see Table 4

Cases with a conventional weather barrier are used as a reference for evaluating the performance of the wood fibre boards, and the effect of increased thermal resistance and a difference in vapour resistance in the exterior part of the construction. In cases 1 to 17, constructions with either a conventional weather barrier or variating thickness of the wood fibre boards are tested in three different climates. The thickness of the material may have an impact of conditions because of the difference in the vapour permeability and thermal resistance in the exterior part of the construction.

The 12 mm wood fibre board is a different type than those of greater thickness, and is indicated with WFB1 (Wood Fibre Board 1) in

Table 4. This product is based on “Hunton Windproof”, a product that is commonly used as a weather barrier in Norway. The other product is from the material data base in WUFI; Agepan UDP N+F, and has a lower vapour resistance than the first product, which may be beneficial, as it may increase the drying capacity of the wall. This product is indicated with WFB2 (Wood Fibre Board 2) in

Table 4. The conventional weather barrier is indicated with WB1 (Weather Barrier 1).

Table 4: Simulation cases in Study 1

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Weather Barrier: WB1	x						x						x					x				x			
WFB1 12 mm		x						x						x					x				x		
WFB2 25 mm			x						x						x										
WFB2 50 mm				x						x						x				x				x	
WFB2 80 mm					x						x														
WFB2 100 mm						x						x					x				x				x
Cavity insulation: Wood fibre	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x					x	x	x	x
Mineral wool																		x	x	x	x				
Climate: Trondheim	x	x	x	x	x	x												x	x	x	x	x	x	x	x
Bergen							x	x	x	x	x	x													
Oslo													x	x	x	x	x								
Moisture content: 80 %	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				
90 %																						x	x	x	x

In cases 18-21, the cavity insulation is changed from wood fibre insulation to mineral wool. The study by Geving et al. (2015) indicates that using wood fibre cavity insulation results in higher moisture levels than using mineral wool. This may be due to the high initial moisture content of the wood fibre insulation, and therefore, the material may require more time to dry and achieve stability than the mineral wool. The study was conducted during a period of 195 days, where the first and last periods simulated winter conditions. Because of the two winter periods in a short time frame, the excess moisture may not have dried properly, resulting in high RH values. A longer simulation period may result in lower values. Both mineral wool and wood fibre are used in this study, to further investigate the influence of the cavity insulation.

In the four final cases, the wood fibre cavity insulation has a higher initial moisture content than in the other cases. A normal initial moisture content may usually be 80 %. The value was increased to 90 % to simulate the effect of the material having been exposed to high moisture levels during the construction phase. The initial moisture content in the materials is of great importance, as the excess moisture in the materials may cause moisture damages if not dried quickly to an adequate level. Therefore, a few cases with a higher moisture content are simulated, to investigate the impact on the moisture levels and the drying rate.

Table 5: Parameter variations in Study 1

Weather Barrier material and thickness	The conventional weather barrier is used as a reference for evaluating the performance of the wood fibre boards. The thickness and characteristics of the material may have an impact on the hygrothermal conditions because of the difference in the vapour permeability and thermal resistance in the exterior part of the construction.
Cavity insulation	Two types of cavity insulation are chosen, the most commonly used product; mineral insulation, and wood fibre insulation. Some of their characteristics are different and may influence the moisture levels
Climate	The climate is the main influence of the temperature and moisture conditions for a building. The robustness in different climates is of interest, as the risk level may change during different conditions. Trondheim, Bergen and Oslo is chosen, as they represent different types of climates.
Initial moisture content	The initial moisture content will mainly be at a normal level; 80 % RH. Some cases include higher moisture in the wood fibre insulation, to simulate the effect of materials becoming wet or not being dried properly in the construction phase. This may indicate if the construction has a sufficient drying capacity. The value is increased to 90 % RH

6.3. Results and Discussion

The results are divided into subchapters, explaining the influence of different parameters. An overview of the results from the mould growth calculations is in the table below, and displays the results of both very sensitive and sensitive material classification. The material classification “very sensitive” was chosen, but the results of using classification “sensitive” is included, as there is some uncertainty to which class is adequate. The further discussion of the results is based on the results of “very sensitive”, but a comparison of the results is commented briefly. The time to RH_{min} is included in the table.

The complete results of this study are found in Appendix F.

Table 6: Results of Study 1. The colours indicate the risk level based on the Traffic Light Classification

Case	Very Sensitive		Sensitive		Time to RH_{min}
	Maximum Mould Growth Index M	Maximum Reoccurring growth	Maximum Mould Growth Index M	Maximum Reoccurring Growth	[Date]
1.1	3,729	2,815	1,438	0,939	02.04.17
1.2	4,099	0,650	1,953	0,081	11.04.17
1.3	4,002	0,121	1,971	0,035	09.04.17
1.4	3,494	0,000	1,828	0,000	13.04.17
1.5	3,028	0,000	1,507	0,000	02.04.17
1.6	2,602	0,000	1,347	0,000	18.03.17
1.7	2,593	0,000	1,030	0,000	27.02.17
1.8	2,770	0,000	1,284	0,000	26.03.17
1.9	2,597	0,000	1,218	0,000	22.03.17
1.10	2,876	0,000	1,511	0,000	22.03.17
1.11	2,792	0,000	1,555	0,000	15.03.17
1.12	2,719	0,000	1,498	0,000	07.03.17
1.13	1,593	0,000	0,394	0,000	25.03.17
1.14	3,482	0,000	1,163	0,000	31.03.17
1.15	3,353	0,000	1,210	0,000	20.06.17
1.16	3,238	0,000	1,305	0,000	03.04.17
1.17	2,204	0,000	0,811	0,000	13.03.17
1.18	4,117	2,186	1,404	0,793	13.02.17
1.19	3,358	0,895	1,172	0,009	21.02.17
1.20	2,632	0,000	0,829	0,000	04.02.17
1.21	2,113	0,000	0,648	0,000	20.01.17
1.22	5,023	2,814	3,802	0,938	08.05.17
1.23	5,386	0,646	4,414	0,081	27.05.17
1.24	5,383	0,000	4,474	0,000	20.06.17
1.25	5,167	0,000	4,263	0,000	28.06.17

6.3.1. The Effect of Increased Thermal Resistance

The results in each location are discussed first, before an evaluation of the impact of thermal resistance is further discussed.

Trondheim

These cases all result in an initial peak of mould growth, with a value between 2,6 and 4,1. The case with the thickest layer of exterior insulation, achieves the best risk classification of these configurations, "yellow", which indicates that further evaluations should be performed. The rest are classified as red – not acceptable.

The first three cases show repeated growth in the following years. Case 1.1, which is the reference case with a conventional plastic weather barrier, reaches a dynamic state where the mould growth index peaks at 2,8 during the winter and was reduced to 0 in a short period in the summer. The case with the thinnest wood fibre board gives a slightly higher initial M value, but shows an improvement in the repeated cycles of growth compared to the reference case. The reoccurring growth is at a much lower level, classified as green, as opposed to the reference case, which is classified with yellow. In addition, the periods with zero growth last longer in this case. In Case 1.3, the reoccurring growth is barely noticeable, and is classified as green.

The last three cases, with respectively 50, 80 and 100 mm exterior insulation, do not have any reoccurring growth cycles, and indicate a decrease in the M value with increasing thickness of the external insulation. In regard to the yellow classification of Case 1.6, there is uncertainty whether this solution can be considered safe.

Figure 14 shows the difference between the results from the VTT model when changing the material sensitivity class. The outcome is quite different when reducing the sensitivity. All of the cases are classified as green, and the order of which cases have the highest to lowest M value is somewhat changed.

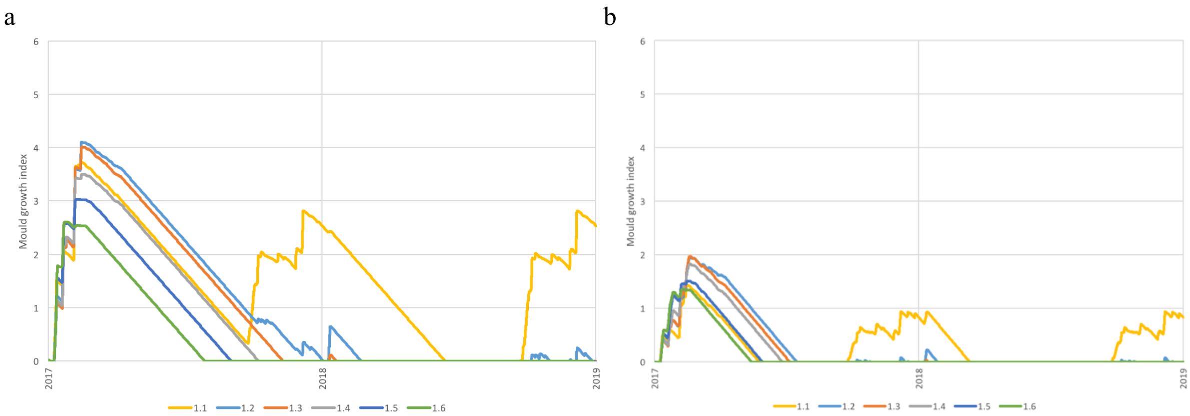

Figure 14: Mould Growth Index when variating the sensitivity classification of the material in cases 1.1-1.6, (a) very sensitive (b) sensitive

Figure 15 shows a decrease in the RH values with increased external thermal insulation thickness, most likely because the temperatures in the monitor positions become higher due to the increased amount of thermal resistance, see Figure 17 for the temperatures. The RH values rise to high levels in the beginning because of the excess moisture in the materials. The high initial RH values, in combination with temperatures just above zero degrees cause the initial peaks of mould growth. Case 1.6 with the thickest insulation layer had the lowest RH peak, and a quicker reduction to a RH_{min} than the rest.

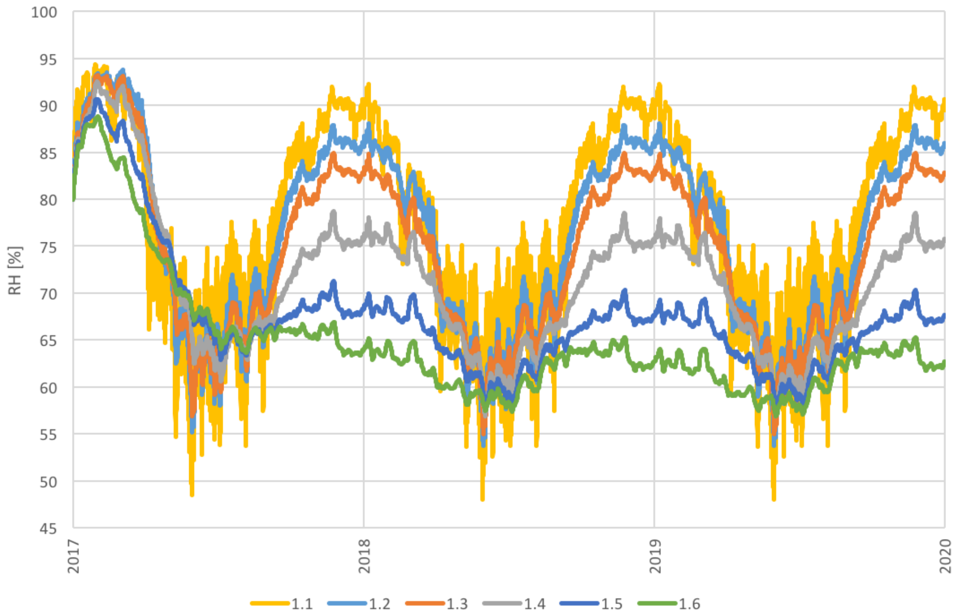

Figure 15: RH in cases 1.1-1.6

In most of the cases, the RH values stabilise into dynamic cycles within a year when the excess moisture dries out. Case 1.5 and 1.6 have a very slight reduction in the RH levels in 2019 compared to the year before, which indicate that these walls are still drying. This is probably because the moisture resistance of these wall becomes higher due to the increased thickness of the wood fibre boards, consequently reducing the drying capacity of the construction. However, in this situation, it does not pose a risk as the RH is at a very low level, but this accentuates that there are adverse effects of increasing the thickness.

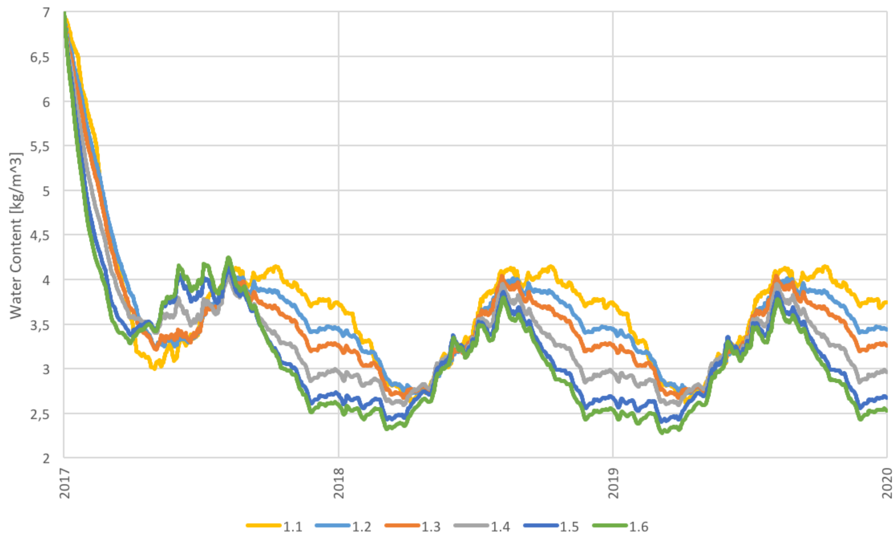

Figure 16: Moisture content in case 1.1-1.6

In Figure 16, the moisture content at the monitor position ais displayed, which also indicates that the excess moisture in the cases with the thickest wood fibre boards is still drying while the rest has stabilised. The moisture content in the cavity insulation stabilises at a lower level with increasing exterior insulation thickness. This may be related to the fact that materials will adapt to the moisture equilibrium as the RH at the monitor position is reduced with increased thickness of the insulation layer.

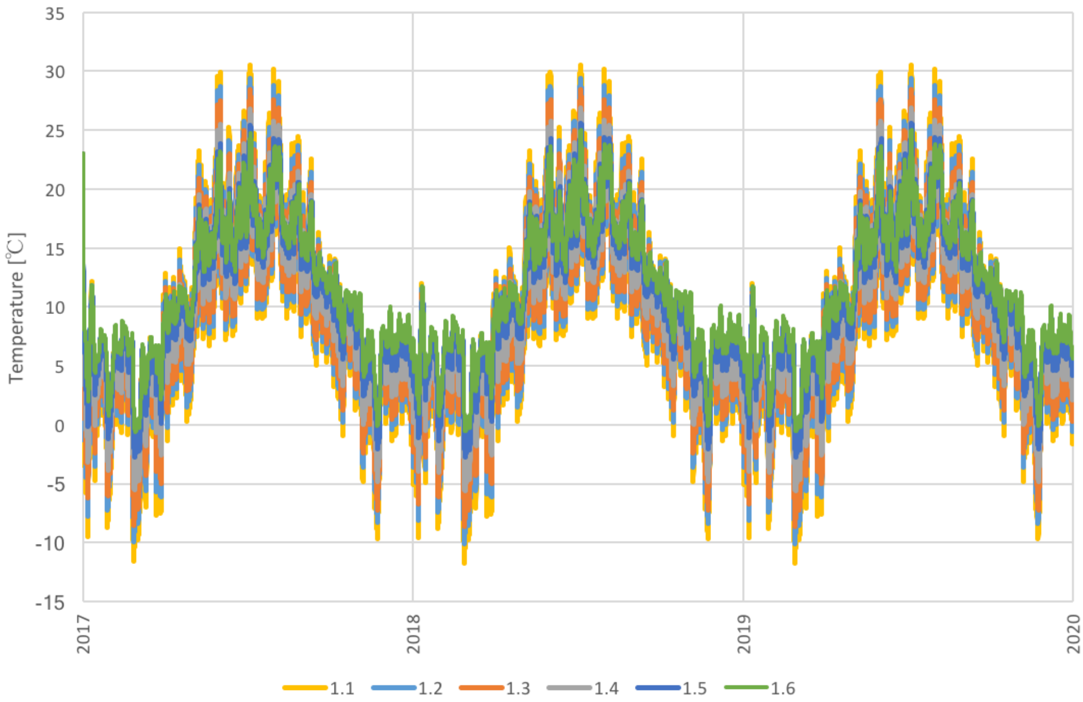

Figure 17: Temperature in cases 1.1-1.6

Figure 17 shows the temperature becoming more stable and the average temperature increasing, with the increase in thermal resistance. The conventional weather barrier results in the least stable temperatures, which can be observed by the great span in the RH values.

The reference cases result in the highest RH values, and is the only configuration with an RH above 90 % after the initial moisture dries. Due to a lack of thermal insulation, the conditions at the monitor position are highly influenced by the outdoor conditions.

The first three cases achieve values above 80 % in the winters after the built-in moisture had dried, and at times the temperature was high enough for mould growth to occur, hence the repeated cycles of growth. Better results are achieved when the exterior insulation is increased to a minimum of 50 mm; the cases with 50-100 mm wood fibre insulation had RH values achieved low values after the initial phase, and therefore the risk of mould is eliminated.

The wood fibre board of 100 mm gives the best result in these simulations, due to the increased amount of insulation on the outside giving a higher temperature, reducing the RH in the monitor position. In this climate, the conventional weather barrier is not a good option because the periods without mould growth are very short and the level of the reoccurring growth is classified as yellow. In addition, this solution resulted in the highest RH values. Even though the vapour permeability of this product is very low, and gives the construction a good ability to dry, it does not counteract the effect of the low temperatures.

Bergen

There is initial growth in all of the simulation cases in Bergen, but no signs later on. The results from these six simulations are quite similar to each other, and the range of the initial peaks are within 0,5 M. All cases are classified as yellow, therefore there is uncertainty whether these solutions can be considered safe merely based on the M value.

The reference case and the case with 25 mm wood fibre board result in approximately the same M value, and the lowest result of these cases. The wood fibre board of 50 mm, gave the highest M value. Changing the sensitivity class to "sensitive" resulted in green classification for all cases.

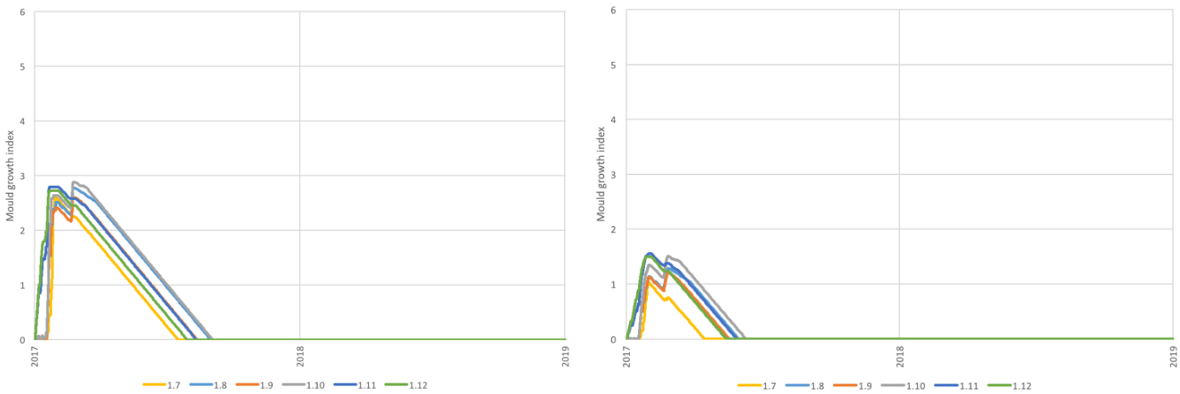

Figure 18: Mould Growth Index when variating the sensitivity classification of the material in cases 1.7-1.12, (a) very sensitive (b) sensitive

There is however a greater difference in the RH results. The values increase initially because of the built-in moisture, and stabilises below 85 % in all cases, see Figure 19. The RH follows the same trend as in Trondheim; the values decrease with increasing thickness of the wood fibre boards. The reference case and the 12 mm wood fibre board have RH values above 80 % after the initial phase, but the temperature is not sufficient to result in reoccurrence of mould after the initial growth period. However, the RH in the reference case is very close to the critical RH, se Appendix F Figure 19, which is concerning as it makes this construction less robust. The constructions with 50, 80 and 100 mm wood fibre boards achieve very low RH values.

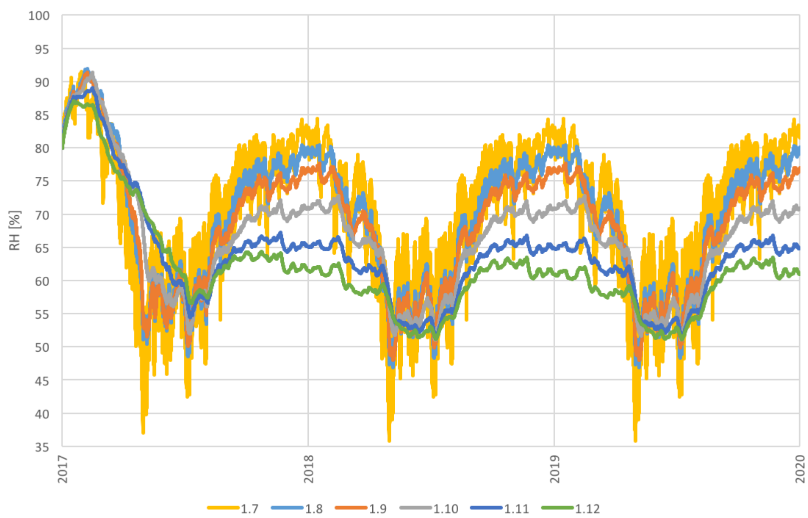

Figure 19: RH in cases 1.7-1.12

Oslo

The construction with a conventional weather barrier has the lowest mould growth index with a peak of approximately 1,5, which is relatively quickly reduced to zero. This is the only case that achieves a green classification. The rest of the cases are classified as red, except for the case with the thickest wood fibre board, which achieves an M value resulting in yellow.

Case 14, 15 and 16 result in the highest M values, which is quite close to each other, and it seems like the effect of increased thermal resistance does not have much impact on the initial M value until increasing to 100 mm of exterior insulation. The results of the mould growth index with a material classification of "sensitive" result in all of the cases being rated as acceptable.

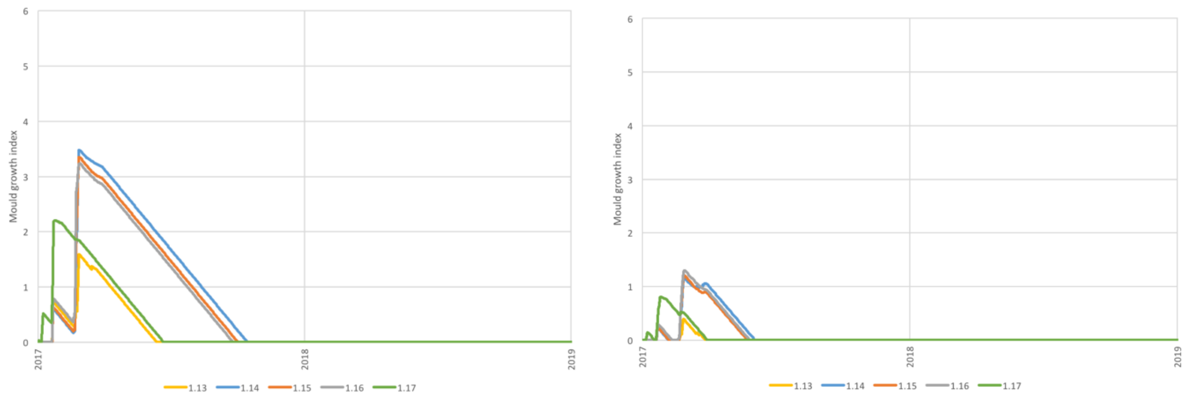

Figure 20: Mould Growth Index when variating the sensitivity classification of the material in cases 1.13-1.17, (a) very sensitive (b) sensitive

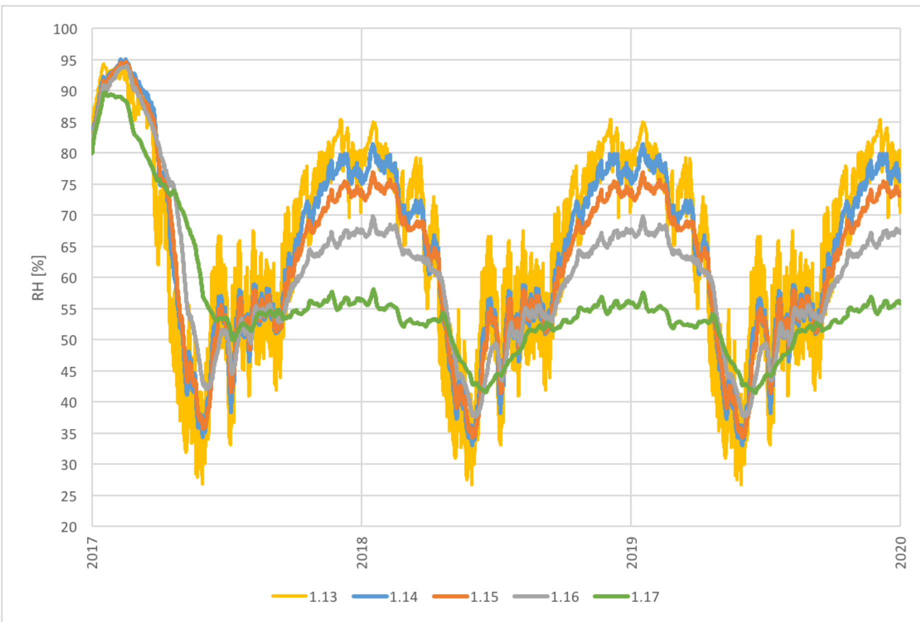

Figure 21: RH in cases 1.13-1.17

Again, the same trend as in the other climates appears in Figure 21. The reference case and 12 mm wood fibre board result in values above 80 %. The RH in the reference cases is close to the RH_{crit}, but there is a greater difference with 12 mm wood fibre board, see Appendix F.

The Effect of Increased Thermal Resistance

The results of the simulations in different locations illustrate the impact of the different hygrothermal conditions in each climate has on the construction, and indicate that the increased thermal resistance in the exterior part of the construction is beneficial in terms of the RH levels. This become apparent in the phase where the materials reach dynamic stability, as there is a clear tendency of decreasing RH with increased thermal resistance in the exterior part of the construction. In regard to mould growth, the results show variating levels of occurrence in the different locations.

With increased insulation, the temperature becomes more stable and less extreme values are achieved, because the exterior parts of the construction are less affected by the outdoor conditions. The increased temperature seems to generally be a positive influence in the dynamic cycles, but in the initial phase, in combination with the high initial moisture levels in the materials, the increased temperature may be the cause of mould growth. The results from this phase are somewhat different in the respective climates, but there is a general trend of the two thickest wood fibre boards resulting in the lowest RH values, while there is less difference between the other cases.

The cases with a conventional weather barrier result in initial RH values at about the same level as the thinner wood fibre boards in each climate, even though the temperature in the monitor positions of the reference cases is slightly lower, due to a lack of thermal resistance. This is probably a result of the high vapour permeability of the conventional weather barrier allowing more moisture to dry, and therefore achieves approximately the same RH values as the thinner wood fibre boards. In Oslo, the lack of thermal resistance seems to be an advantage in the initial phases, as the temperature in the monitor position becomes less favourable than in the other cases with increased thermal resistance, due to the low temperatures in this climate, resulting in the lowest M value and the only case with a green risk level.

All the constructions with wood fibre boards stabilise in dynamic cycles resulting in values below RH_{min} irrespective of climate, except for the 12 and 25 mm boards, while the reference cases reach values above 80 % in all climates.

In regard to the 12 mm wood fibre board, which is based on a weather barrier product commonly used in Norway, this solution is considered to present more risk than the other products, as it has a higher vapour resistance. These cases result in amongst the highest initial M values in their respective climates, in addition to values above or very near the RH_{min} in the dynamic phase. Values above 80 % do not necessarily represent a higher risk, as the corresponding temperature has to be of a certain level to result in mould growth. Because of the thickness of the board, it has a lower thermal resistance, resulting in colder temperature in the monitor position than with thicker boards. Hence, a higher RH_{crit} as this value is dependent on the temperature. The risk of mould growth may therefore be somewhat reduced even though the RH is high. See Appendix F. In Oslo and Bergen, the product seems to be adequate in the dynamic phases, but in Trondheim, the RH is very close to the RH_{crit}. This may be related to the high outdoor RH levels in Trondheim, and the temperatures just above zero degrees, see Appendix A.

The 25 mm boards achieve good results in the dynamic phases in Oslo and Bergen, but in Trondheim, the RH is above 80 % and close to the critical RH, and may therefore not be a robust solution. Se Appendix F, Figure 3, 8 and 14. The same is to say about the robustness of the conventional weather barrier, as it achieves the highest RH values in its respective climates, in some cases very close or above the critical RH, see Appendix F. The conventional weather barrier does not seem suitable in the conditions in Trondheim, as it results in the high RH values and reoccurring growth at a concerning risk level.

Based merely on the RH and M values after the excess moisture dries, the wood fibre boards of 50-100 mm are considered safe in all the climates, as the RH values are below 80 % and there is no mould growth in this phase for any of these cases. However, there is some uncertainty whether the mould growth in the initial phase can simply be disregarded. There is a question whether the initial mould growth classified as yellow or red may pose a risk, or if this could be acceptable because there is no growth later on. It would most likely be desirable to achieve mould growth at a green risk level initially, to eliminate any possible risk of

6.3.2. The Influence of the Cavity Insulation Material

The first two cases with mineral wool as cavity insulation have initial peaks of mould growth resulting in a red classification and shows reoccurring mould growth after the built-in moisture dries. The reoccurring growth in the reference case is classified as yellow, while for the wood fibre board of 12 mm, the classification is green.

The first case has the highest M-value, and does not reach a period with zero growth until more than a year later because it takes to long for the growth to decrease, and by the time it reaches a low level, the ambient conditions cause the growth to restart. The growth starts up towards the end of each year and reaches a level of just above 2. In the summer the growth seizes.

These cases all achieve a green classification when the robustness of the material is increased. The reoccurring growth in case 1.19 becomes negligible, and in the reference case the risk level of the growth cycles is reduced to a green risk level.

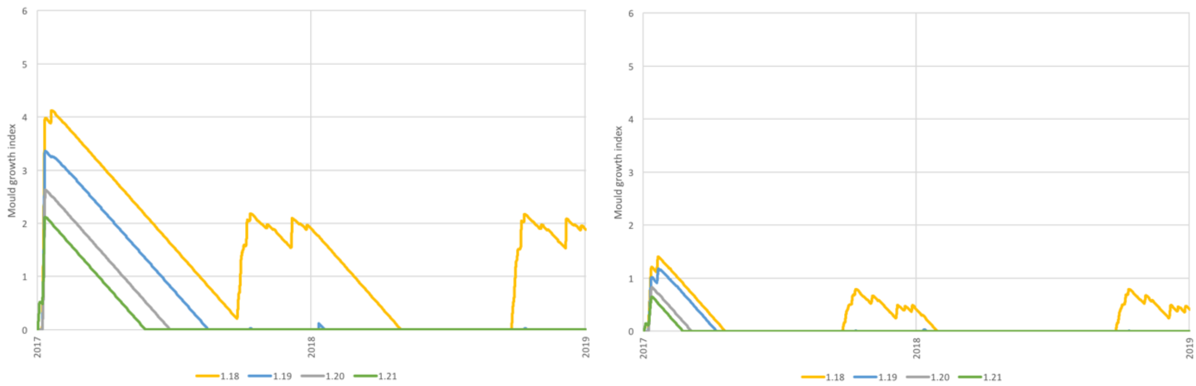

Figure 22: Mould Growth Index when variating the sensitivity classification of the material in cases 1.18-1.21, (a) very sensitive (b) sensitive

When comparing these results to the corresponding cases with wood fibre insulation as cavity insulation, see Figure 14, the initial M values are lower with the mineral wool except for in the reference case. The risk classification of the 50 mm wood fibre board is reduced from red to yellow, while the classification of the other cases stays the same. The mineral wool seems provide better conditions in the initial phase, except for in the reference case.

The RH values in the reference case becomes very high initially, above 95 %, and is approximately 90 % in the winter, see Figure 23. The RH with the 12 mm wood fibre board follows the same trend as the reference case, but the level is about 5 % lower. The RH is very close to or above the critical RH values in both cases, se Appendix F, which causes the reoccurring growth. The growth level is however much lower in the second case, most likely due to the increased thermal insulation. The wood fibre board of 50 and 100 mm does not exceed 80 % after the initial phase.

When using wood fibre versus mineral wool cavity insulation, see Figure 23 and Figure 24, the RH values are slightly lower during the winter and a little bit higher in the summer with mineral wool, after the materials reach a stabile dynamic state. In addition, the cycles have a somewhat different development through the year.

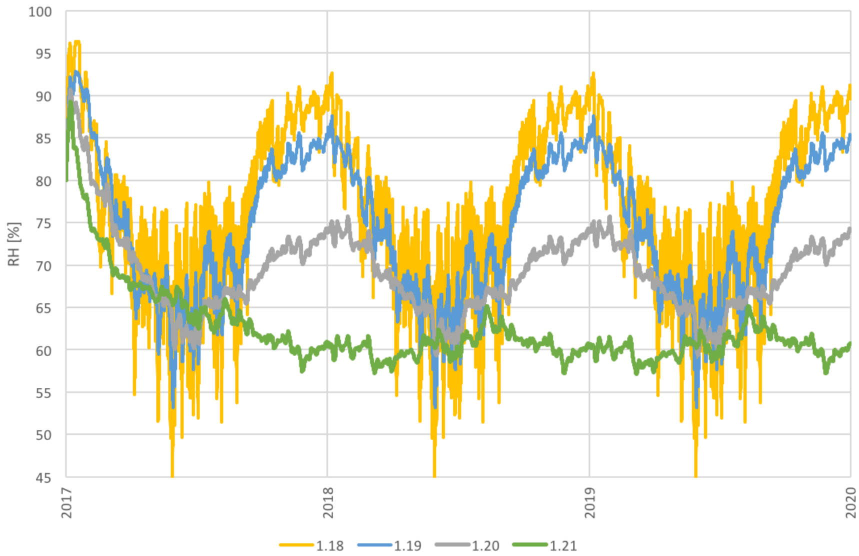

Figure 23: RH in cases 1.18-1.21

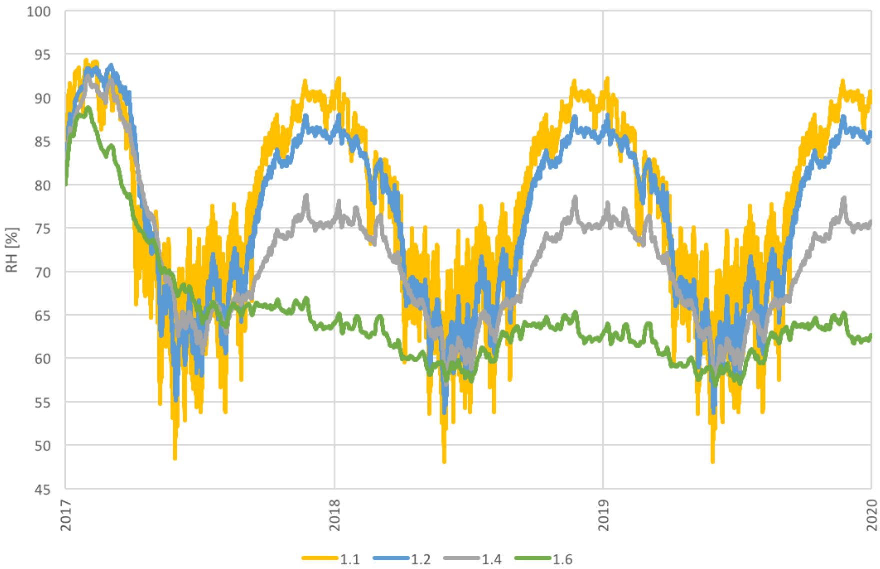

Figure 24: RH in cases 1.1, 1.2, 1.4 and 1.6

The different characteristics of the two cavity insulation materials become apparent in the initial phase of the simulation period. With mineral wool, the values increase rapidly and is quickly reduced, as opposed to the using wood fibre which has a slower development and RH values staying elevated longer. Wood fibre insulation has a much higher initial moisture content at about 7 kg/m^3, while mineral wool has 1,79 kg/m^3 at 80 % RH, see Appendix B.3, in addition to a high hygroscopic capacity. This is most likely the reason why the initial RH values have a different development.

The constructions with mineral wool is reduced to RH_{min} in 20-61 days and with wood fibre in 78-103 days, where the thickest wood fibre boards have the quickest reduction for each type of cavity insulation. Most likely due to the higher initial moisture content of the wood fibre insulation.

The conventional weather barrier results in a higher initial RH level compared to the construction with the wood fibre insulation, even though the moisture content is lower in the construction with mineral wool. This may be a result of the mineral wool having a low hygroscopic capacity, resulting in a more rapid moisture transport initially, while the wood fibre cavity insulation contributes to a more evenly distributed moisture transport because of its high hygroscopic capacity.

The wood fibre boards of 12 and 80 mm result in slightly higher RH levels during the winter periods in the dynamic stages with wood fibre insulation compared to mineral wool, while the thickest wood fibre board achieves about the same maximum RH values. The reference cases achieve approximately the same RH values in the winter, but the mineral wool contributes to a higher maximum RH value. The average RH values in the reference case with wood fibre cavity insulation are stable on a slightly higher level, causing a higher level of reoccurring mould growth for the case with wood fibre.

The development of the water content is displayed in Figure 25. The mineral wool reaches stability within the first year, unlike the wood fibre insulation. The materials most likely stabilise at different levels because of their different moisture equilibriums.

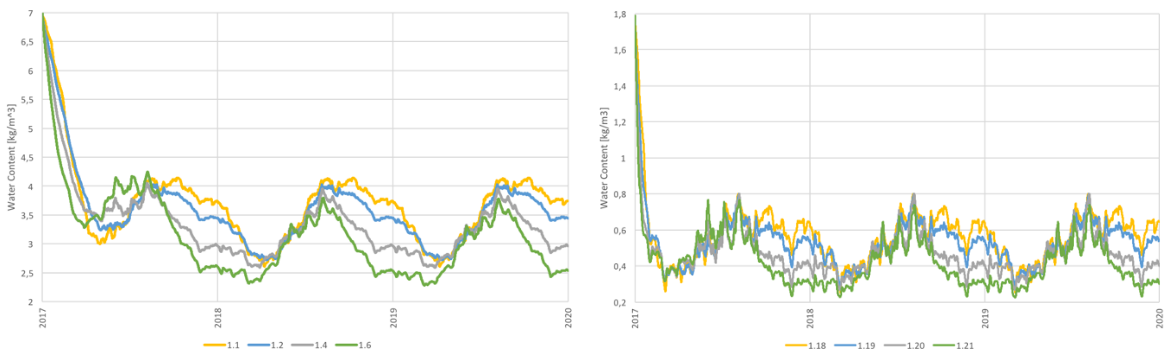

Figure 25: Moisture Content in (a) cases 1.1, 1.2, 1.4 and 1.6, (b) cases 1.18-1.21

6.3.3. Effect of a High Initial Moisture Content

In these cases, the moisture content of the wood fibre cavity insulation is set to 90 %, which is 14.92 kg/m^3 according to the sorption curve from the material database in WUFI, see Appendix B.3. This is more than double the value at 80 %. A moisture content of 14,92 % in the wood fibre insulation is equal to 28 weight percent, which is above the critical value for mould growth in wooden materials. The thermal insulating properties of the insulation is reduced with a higher moisture content, leading to more heat loss through the wall, which increases the temperature in the external parts, and may result in more favourable conditions for mould. Therefore, it is essential that the moisture is quickly reduced.

These cases result in the highest readings of the mould growth index and the high initial RH values. All of the cases have an initial mould growth index above 5, and are classified with a high risk level. The first two cases have reoccurring growth after the initial peak, which are respectively classified as yellow and green. It takes more than a year for the growth to seize in all cases.

When the classification of the material is changed to “sensitive”, the risk level is still red in all cases, but the reoccurring growth in the reference case is reduced to green.

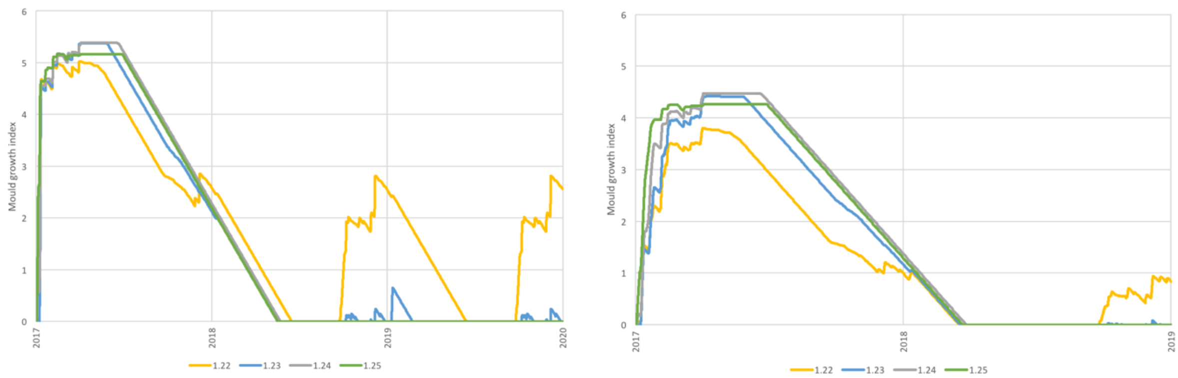

Figure 26: Mould Growth Index when variating the sensitivity classification of the material in cases 1.22-1.25, (a) very sensitive (b) sensitive

Compared to the corresponding cases (1.1, 1.2, 1.4 and 1.6), the initial M values are much higher in the cases with a higher initial moisture content, but the mould growth during the reoccurring cycles are approximately equal to the values in the corresponding cases. This indicates that the high moisture content in the beginning dries and does not impact the constructions later on.

Initially, the RH is above 95 % in all cases, and the further development is similar for all of the cases with exterior wood fibre insulation. The thickness of the exterior insulation does not seem to be of importance to the RH values in the beginning, but further on, it seems like the construction with the thinnest wood fibre board has a quicker stabilisation than the constructions with thicker boards. This may be because the vapour resistance in the exterior part increases with the thickness of the boards, and therefore the drying capacity is reduced, resulting in the excess moisture drying slower.

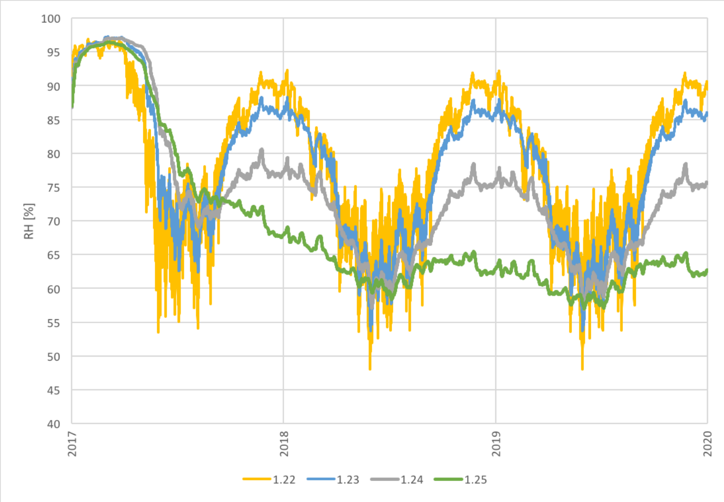

Figure 27: RH in cases 1.22-1.25

Finally, as the excess moisture dries, the effect of the increased thermal insulation results in lower RH levels and the cases reach the same dynamic state as in the corresponding cases with a lower initial moisture content.

The time for reduction to below 80 % RH is between 128-178 days. The drying time increases with the thickness of the exterior insulation, see Table 6. The reference case has the quickest reduction of the initial RH values. This is probably a result of the lower vapour resistance of the conventional weather barrier, which gives this construction a better ability to dry.

Figure 28: Temperature in cases 1.22-1.25

There is a very slight difference in the temperature in the initial phase of the simulations compared to the following years. This may be because the thermal resistance of the wood fibre insulation is reduced, because of the high initial moisture content. This could result in a higher heat transmission through the wall, hence a higher temperature.

These simulations show the importance of drying and keeping materials dry during the construction phase. This may be especially critical to materials with a high hygroscopic capacity such as wood fibre insulation.

7 STUDY 2 – FURTHER INVESTIGATIONS OF WOOD FIBRE BOARDS

7.1. Background

The results from the first Study 1 indicate that wood fibre boards may function well as a weather barrier, as it reduces the RH levels to a lower level compared to the conventional weather barrier. However, the main issue with the results from the first study is in the initial phase, when there are high amounts of excess moisture in the materials. The RH values become very high, which consequently results in an initial mould growth in all cases. The mould growth in the first phase is classified at a yellow or red risk level in all simulation cases with wood fibre boards, but after the RH stabilises into dynamic cycles, there is no reoccurring growth at a concerning level. Using mineral wool as a cavity insulation does not improve the initial mould growth levels much, even though this gives the construction a lower level of built-in moisture than with the wood fibre cavity insulation. It would be interesting to examine if the high initial mould growth and RH levels can be reduced. Further investigations will therefore be performed, as to see if the initial mould growth may be reduced or eliminated.

7.2. Simulation Cases and Parameter Variations

The same basic construction was used in this study, as this is a standard type of wall construction that is common in Norway. The study consists of 21 simulation cases.

Starting the simulations in the winter may be the reason for the high values in the initial phase in the results from Study 1. The pressure difference between the outdoor and indoor is large in January because of the temperature difference inside and outside, which may result in higher levels of moisture transport. However, the outdoor temperatures are low, and may therefore result in high RH levels. Starting in a different period with higher temperatures may improve the initial phase. The temperature should not be too high in the starting period, as this may reduce the drying capacity because the temperature difference between the exterior and interior side of the wall may be too small, or the higher temperatures may cause high levels of mould growth if the excess moisture does not dry quickly.

From the climate analysis in Appendix A, it is observed that the outdoor temperature in May is still at a moderate level and the RH values are amongst the lowest values during the year. Therefore, this may be a suitable starting point. Most cases will start in May, when the conditions for drying may be more favourable, to investigate if this results in lower initial RH values and level of mould growth. In cases 2-7 and 12-17, a wood fibre board is tested in two different climates, Trondheim and Bergen, both in the summer and winter climates to investigate the robustness of the wood fibre board, and to evaluate the importance of the outdoor conditions during initiation.

In most cases, Wood Fibre Board 3, indicated with WFB3 in Table 7, is simulated, as this product is assumed to have the most beneficial properties of those found in the product research, and may therefore reduce or eliminate the initial mould growth.

In cases 8-10, a different wood fibre boards are simulated. WFB3, which is tested in most cases, has the combination of the lowest lambda value and lowest water vapour resistance factor of the products found in the product research. Therefore, the product that had the combination of the highest lambda value and water vapour resistance factor was chosen to be simulated, because it would be interesting to test two wood fibre boards that had properties at each end of the scale, to investigate the different impact two wood fibre boards with a great difference in their properties have on the conditions in the wall. The second wood fibre board, is the same product as was used as the 12 mm thick boards in Study 1. This product is indicated with WFB1 (Wood Fibre Board1) in Table 7. The same conventional weather barrier as in Study 1 is used, indicated with WB1, and is only simulated in some cases, as the main focus of this study is the wood fibre boards.

A few cases with higher moisture levels are tested as well, to investigate if the construction can handle the high initial moisture content in spring conditions.

Table 7: Simulation Cases in Study 2

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Weather barrier: WB1	x										x							x			
WFB3 12 mm		x			x			x				x			x				x		
WFB3 50 mm			x			x			x				x			x				x	
WFB3 100 mm				x			x			x				x			x				x
WFB1 12 mm								x				x	x	x	x	x	x	x	x	x	x
WFB1 50 mm									x												
WFB1 100 mm										x											
Climate: Trondheim	x	x	x	x	x	x	x	x	x	x								x	x	x	x
Bergen											x	x	x	x	x	x	x				
Start: May 1.	x	x	x	x				x	x	x	x	x	x	x				x	x	x	x
January 1.					x	x	x								x	x	x				
Moisture content: 80 % RH	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				
90 % RH																		x	x	x	x

Table 8: Parameter variations Study 2

Weather Barrier Material and Thickness	In this study, the main interest is on the wood fibre board. The conventional weather barrier is used as a reference for evaluation in a few cases. The material and thickness of the weather barriers may have an impact on the hygrothermal conditions.
Climate	The climate is the main influence of the temperature and moisture conditions for a building. The robustness in different climates is of interest, as the risk level may change during different conditions. Trondheim and Bergen are chosen
Start of Simulation	The simulations are started in two different times of year, to examine if the high initial RH levels and mould growth can be reduced. The starting dates are January 1st and May 1st. The conditions are quite different in these periods and may possibly influence the initial results
Initial moisture content	The initial moisture content will mainly be at a normal level, 80 % RH. Some cases include higher moisture in the wood fibre insulation, to simulate the effect of materials becoming wet or not being dried properly in the construction phase. This may indicate if the construction has a sufficient drying capacity. The value is increased to 90 % RH

7.3. Results and Discussion of the Study

The results from the calculation of the Mould Growth Index is shown in Table 9. The results of both "very sensitive" and "sensitive" material classification are included in the table, but the further discussion is based on the results from the material classification of "very sensitive". The difference is not commented in this study other than being displayed in the table.

The results are divided into subchapters, explaining the influence of the different parameter variations.

The complete results of this study are found in Appendix G.

Table 9: Results of Study 2. The colours indicate the risk level based on the Traffic Light Classification

Case	Very Sensitive		Sensitive		Time to RH_{min}
	Maximum Mould Growth Index M	Maximum Reoccurring growth	Maximum Mould Growth Index M	Maximum Reoccurring Growth	[Date]
2.1	2,845	2,854	1,178	1,178	05.01
2.2	0,941	0,151	0,394	0,205	08.01
2.3	1,831	0,000	0,988	0,000	29.01
2.4	1,860	0,000	1,005	0,000	31.01
2.5	3.750	0,157	1,801	0,065	06.04
2.6	2,822	0,000	1,395	0,000	08.04
2.7	2,345	0,000	1,250	0,000	08.03
2.8	1,307	0,636	0,530	0,304	09.01
1.9	2,312	0,000	1,416	0,000	01.02
2.10	2,279	0,000	1,376	0,000	23.02
2.11	0,000	0,000	0,000	0,000	01.01
2.12	0,000	0,000	0,000	0,000	01.01
2.13	1,558	0,000	0,725	0,000	28.01
2.14	1,951	0,000	1,071	0,000	03.02
2.15	2,113	0,000	0,951	0,000	19.03
2.16	2,471	0,000	1,308	0,000	18.03
2.17	2,410	0,000	1,335	0,000	25.02
2.18	3,503	2,814	1,672	1,143	08.01
2.19	3,518	0,457	2,003	0,204	29.01
2.20	4,009	0,000	3,032	0,000	27.08
2.21	4,105	0,000	3,139	0,000	16.06

7.3.1. The Influence of the Starting Time

In this subchapter, the results of simulating the constructions with different initiation time is discussed, and is divided into the results from each location. The discussion mainly focus on the initial phase, as the corresponding cases are expected to result in the same dynamic stages as the moisture content in the materials stabilise, as the results from Study 1 indicate that the initial phase does not affect the further development of the mould growth.

Trondheim

The results of the simulations of Weather Barrier Type 3 with a starting point in January versus May in location Trondheim, show a reduction in the initial M values when the simulations are started in May, see Figure 29. This is not unexpected, as the outdoor temperatures are at a higher level at this time of year and the outdoor RH is slightly lower, see Appendix A. The higher temperature may have reduced the RH level in the monitor position.

The mould growth index in the spring is all classified at a green risk level, while in the winter, the first case is classified as red and the two other are classified as yellow. After the initial moisture dries, all cases are reduced to zero growth, except for the two cases with the thinnest wood fibre boards, which result in the same dynamic growth cycle, as is to be expected. This indicates that the starting point does not affect the mould growth after the initial moisture has dried.

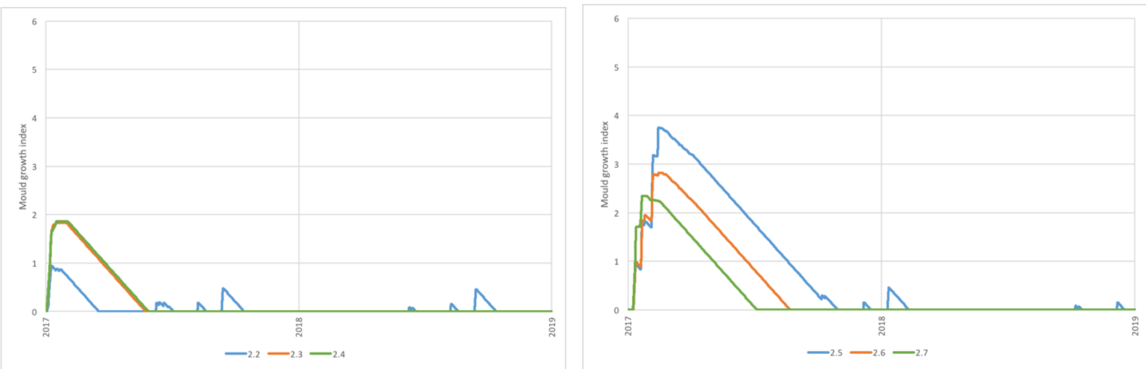

Figure 29: Mould Growth Index, note that the graphs start in their respective months, (a) Starting in May cases 2.2-2.4 (b) Starting in January cases 2.5-2.7

The 12 mm wood fibre board does not seem to function well initially when starting in the winter, as it has the highest M value and a red classification. The thermal resistance of the board is probably not sufficient to achieve high enough temperature to reduce the RH, and even though it has a fairly low vapour resistance, it does not seem to be sufficient. However, when starting in May, the thinnest board results in the lowest M value. This is probably because the outdoor temperatures are higher, and the exterior part of the wall has a low vapour permeability due to the thickness of the board, allowing the moisture to dry quickly.

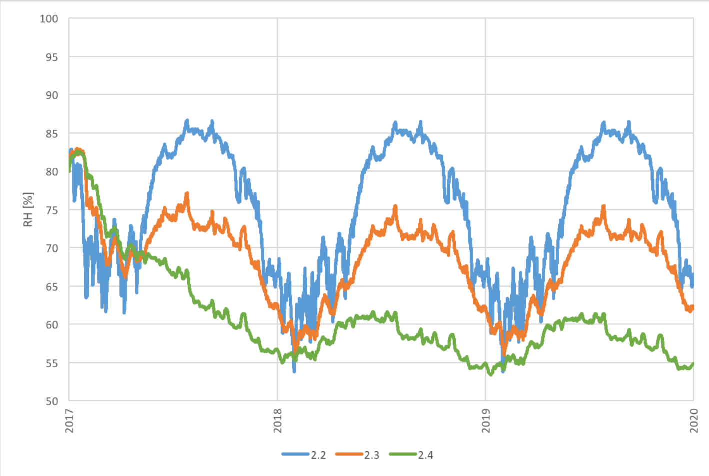

Figure 30: RH in cases 2.2-2.4 (The year on the x-axis indicates May for each year)

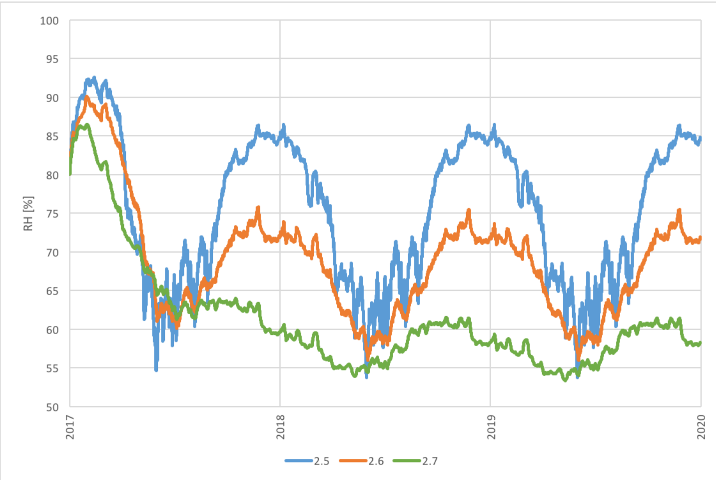

Figure 31: RH in cases 2.5-2.7 (The year on the x-axis indicates January for each year)

From the results of the RH values, there is a clear difference in the initial values. In the spring, the values rise slightly above 80 % RH, and are quickly reduced, while in the winter, the RH values rise above 90 % and require a longer time to dry below 80 %. The RH values in the cases with boards of the same thickness stabilise into the same dynamic cycles after the initial moisture dries.

Bergen

Simulating constructions with the same wood fibre boards in Bergen with two different starting points, the results show a variating degree of difference between the corresponding cases. When starting the simulations in January, the M values are at approximately the same level, and all cases have a yellow risk classification. Starting in the spring, all cases achieve a green classification, and the case with the 12 mm wood fibre board does not show any growth at all. The two thicker boards have higher M values, and a slight difference between the results. None of the cases has any reoccurring growth.

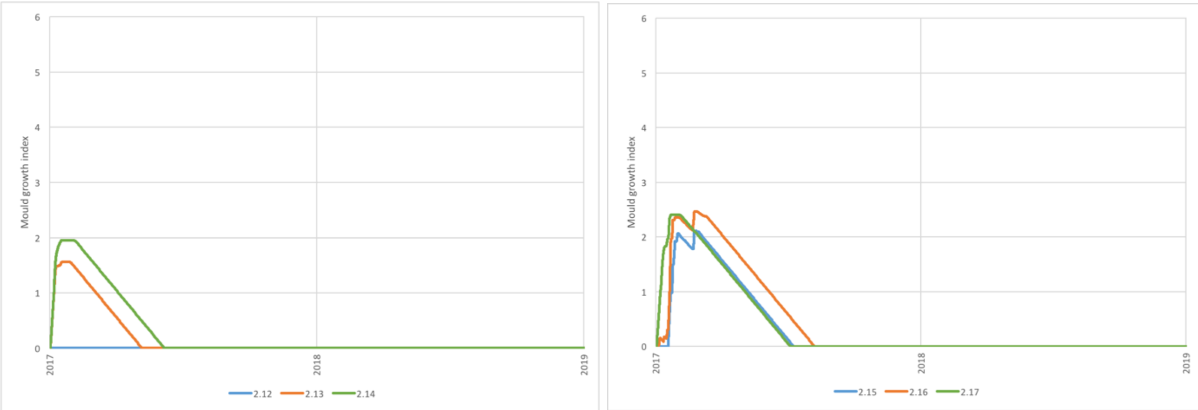

Figure 32: Mould Growth Index, note that the graphs start in their respective months, (a) Starting in May cases 2.12-2.14 (b) Starting in January cases 2.15-2.17

The RH levels also evolve differently in the initial phase, as in Trondheim, and show the same trend; The RH levels rise slightly above 80 % and are quickly reduced in the spring, while in the winter the values become higher and the time to RH_{min} increases.

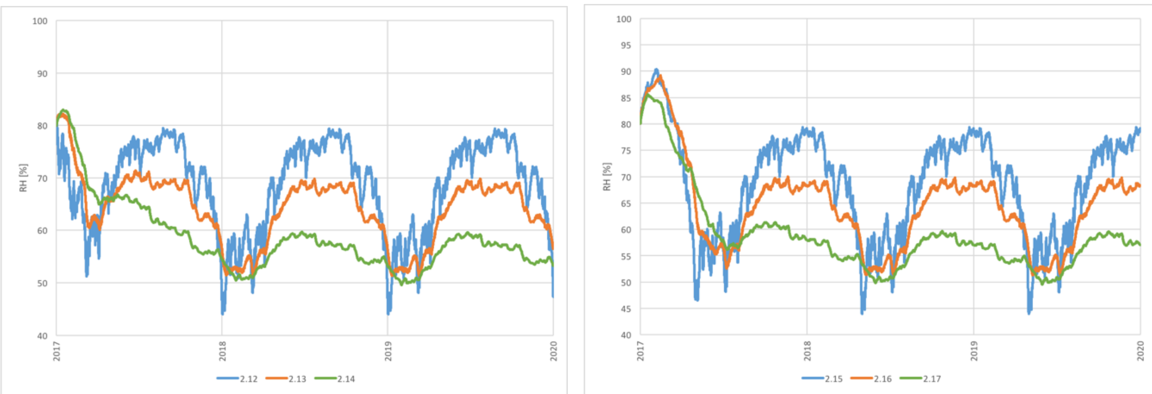

Figure 33: RH values spring vs winter initiation, note that the graphs start in their respective months, (a) Starting in May cases 2.12-2.14 (b) Starting in January cases 2.15-2.17

The results from both Bergen and Oslo, indicate that starting the simulations in the spring, rather than the winter, may be advantageous regarding both the initial mould growth levels and RH levels, because the increased temperature in this period seem to reduce the RH levels quickly and the temperature is not high enough to cause high levels of mould growth.

7.3.2. The Effect of the Thickness

The cases with WFB3 initiating the simulations in the spring, in both Trondheim and Bergen, are discussed briefly in this subchapter regarding the effect of the thickness.

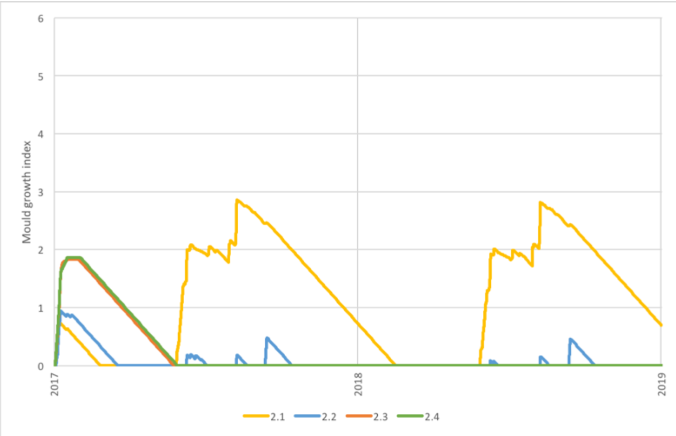

Figure 34: Mould Growth Index, Trondheim, cases 2.1-2.4 note that the year on the x-axis indicates May of each year

The weather barrier achieves the lowest initial M value, but has reoccurring growth in the dynamic cycles at a yellow level. The wood fibre boards are rated with a green classification in all cases, and the reoccurring growth of the 12 mm wood fibre board is negligible. The lack of thermal resistance seems to cause mould growth in the reference case in the dynamic stages, as the RH levels become too high, and the temperatures outside are sufficient to cause mould growth.

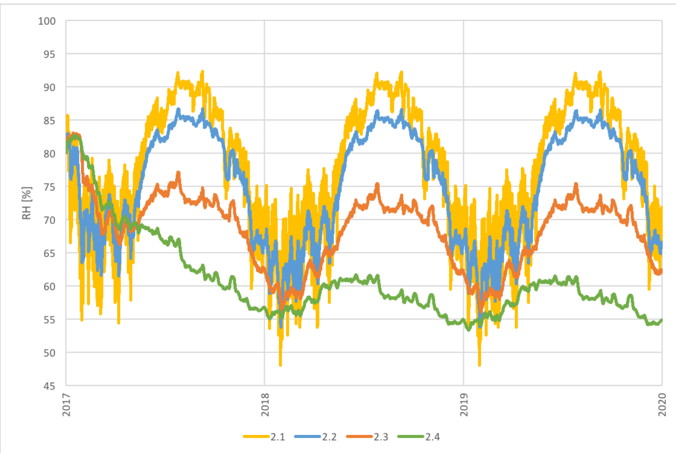

Figure 35: Mould Growth Index, Trondheim, cases 2.1-2.4 note that the year on the x-axis indicates May of each year

The reference case in Trondheim initially has the highest RH values, but the levels are reduced to an adequate quickly, and does not cause to much mould growth in the first phase. This is probably related to the lower vapour resistance of the conventional weather barrier.

The RH level of the two thickest wood fibre boards seems to develop more stable than the reference case and the 12 mm wood fibre board, most likely because of the increased vapour resistance with increased thickness. Therefore, these cases result in higher mould growth levels, probably because the RH values stay elevated longer. The same is to say about the result in Bergen. The increased thickness of the boards result in higher vapour resistance, and is not advantageous in the spring, when the outdoor temperatures are at a moderate level.

The RH high values of the 12 mm wood fibre boards in the dynamic cycles are of concern. It seems like the increased thermal resistance may not be sufficient to reduce the RH to a lower level. However, the thicker boards result in safe RH levels after the materials stabilise.

Both the reference case and the 12 mm wood fibre board in Bergen achieves zero growth. However, the two thicker boards, have some initial growth, but not at a concerning level. These results show, that there may be a possibility of reducing the initial growth to zero, or an acceptable level, if the conditions during the initiation period are favourable.

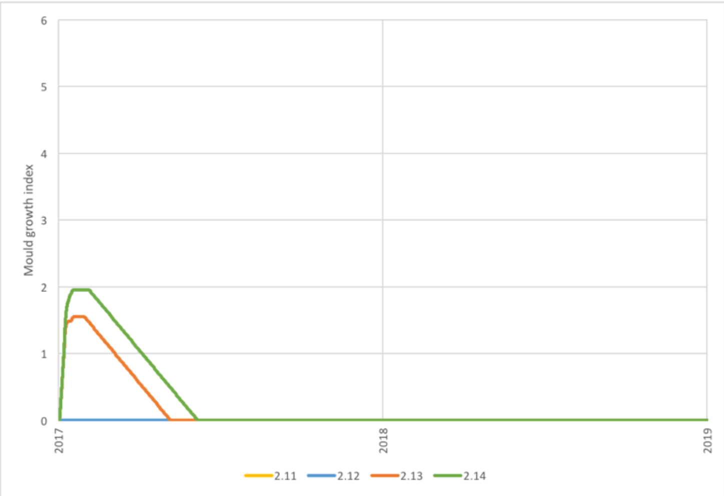

Figure 36: Mould Growth Index, Bergen, cases 2.11-2.14 note that the year on the x-axis indicates May of each year

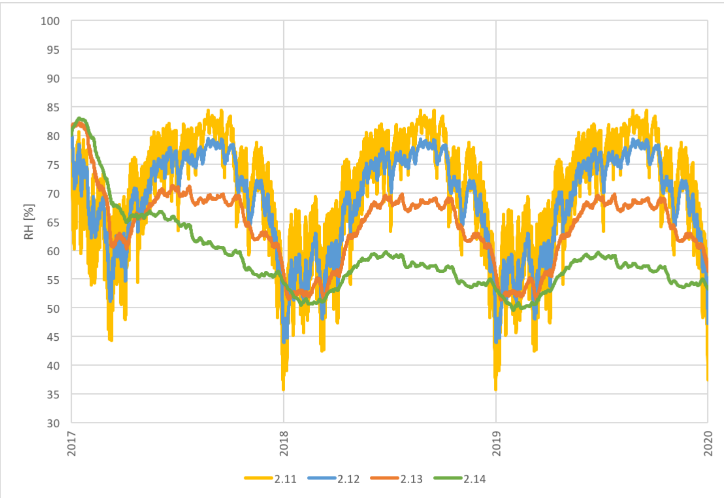

Figure 37: Mould Growth Index, Bergen, cases 2.11-2.14 note that the year on the x-axis indicates May of each year

7.3.3. The Influence of the Difference in Properties

The simulations are initiated in May in all of these cases. The influence of the different properties has on the moisture conditions and mould growth level is of interest, as it may give an indication of which properties is the most beneficial.

Wood Fibre Board 1 (WFB1) has a water vapour resistance factor of 16,67 and a lambda value of 0,049 W/mK, while Wood Fibre Board 3 (WFB3), has a water vapour resistance factor of 3 and a lambda value of 0,037 W/mK. The products have the combination of respectively the highest and lowest values of the all the products found in the product research.

The difference in the properties of the two products is noticeable in the M values. WFB3 achieves the lowest results and green risk classification in all cases. With WFB1, the two thicker wood fibre boards achieve a yellow risk classification, and the thinnest board has a M value slightly higher than with WFB1. The reoccurring growth with the 12 mm boards is slightly higher with WFB3, but is rated at a green risk level. The properties of WFB3 seems to be favourable from these results.

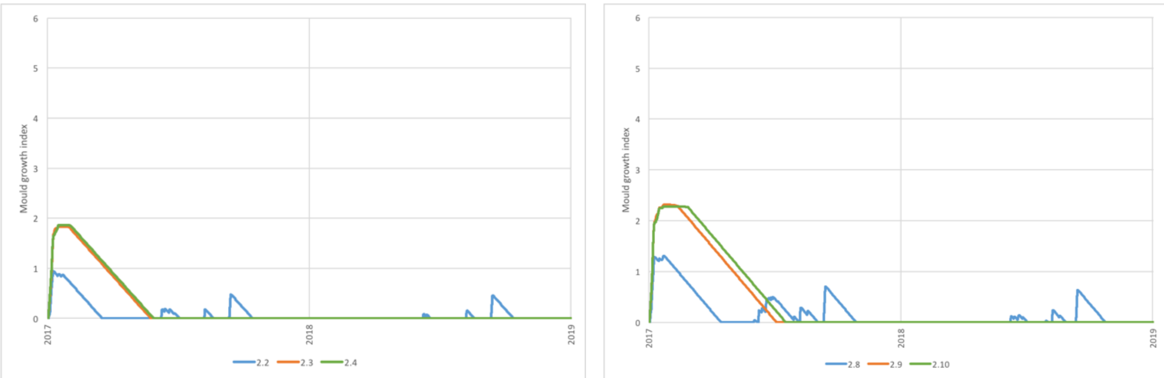

Figure 38: Mould Growth Index, note that the year on the x-axis indicates May of each year, (a) cases 2.2-2.4 (b) cases 2.8-2.10

The initial RH values are slightly different with the two types of boards, see **Feil! Fant ikke referansekilden.** and Figure 40. The values become a little higher with WFB1, but the values of the 12 mm boards seem to be more equal. However, there is still a noticeable change in the level of mould growth, as WFB3 results in a green classification while WFB1 achieves yellow with the 12 mm boards. With WFB3 the RH values of the 50 and 100 mm boards achieve more equal RH values than with WFB1, and therefore result in approximately the same initial M values, while with WFB1 there is a slightly larger difference in the M values of the two thicker boards.

In the dynamic stages, the difference in the properties is observed by the generally lower and more stable RH values of WFB3, most likely because of its more favourable properties. However, the difference of the 12 mm boards is not pronounced compared to the other thicknesses. This may be because the boards are thin and may be more affected by the outdoor conditions.

The results seem to indicate that WFB3 has the more favourable properties, which is not completely unexpected, as a lower vapour resistance is advantageous as it allows for more moisture to dry out, and the increased thermal resistance may result in a lower RH.

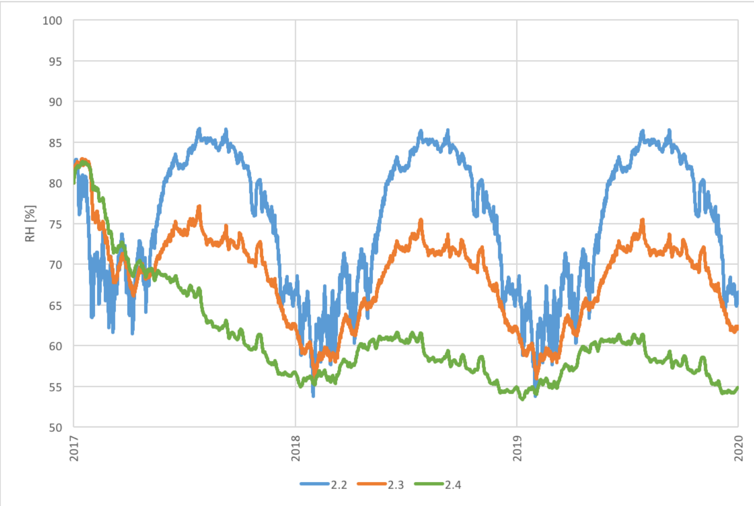

Figure 39: RH in cases 2.5-2.7 (The year on the x-axis indicates May in each year)

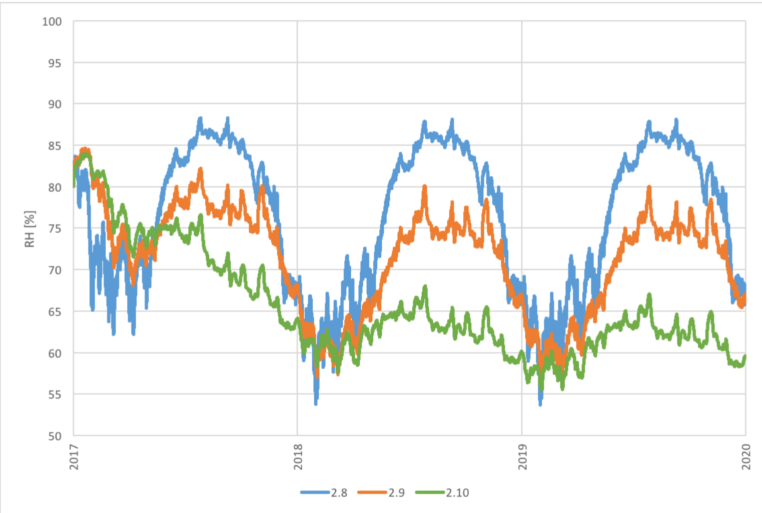

Figure 40: RH in cases 2.8-2.10 (The year on the x-axis indicates May in each year)

The results show that the different characteristics of the two boards influence the hygrothermal conditions and the mould growth. It is a bit unclear which of the properties have the most influence from these results, and preferably simulations should have been performed with more parameter variations and combinations of properties, to give a clearer understanding of the influence of the properties and which combination may be the most beneficial. Unfortunately, this was not included and there was no time to do this later on. However, based on these results, the 50 and 100 mm boards of both types seem to function well in the dynamic stages, as the RH is reduced to a safe level below 80 %, but in regard to the initial M values, WFB3 is more favourable, as the risk level is classified as green. The 12 mm boards seem not be adequate, as the RH levels are fairly high and close to the critical RH for both types of board, and may therefore be less robust solutions. See Appendix G.

7.4. Effect of a Higher Initial Moisture Content

The effect of a higher initial moisture content is simulated to investigate the initial conditions in the construction with a start of the simulation in May. The initial moisture is set to 90 % RH in the wood fibre cavity insulation layer. The results of these simulations are compared to the results of the corresponding cases, 2.1-2.4, that have the same parameter variations except for the higher moisture content. The moisture content of these cases is at a normal level, 80 % RH. The conventional weather barrier is included to compare against the results of the wood fibre boards.

The initial M values become high in all cases, and are classified with a red risk level. The wood fibre boards of 50 and 100 mm have a very similar development of the mould growth level. The thickest board achieve a slightly higher M value. The M value seems to increase with the thickness of the wood fibre board. This may be because the vapour resistance of the wall becomes higher with the increased thickness of the wood fibre board. The reference case and the 12 mm wood fibre board achieves the initial M lowest values, at approximately the same level. Both cases result in reoccurring growth, but in the case with the 12 mm wood fibre board, the level is considered safe, while in the reference case, the growth is considered to pose a possible risk. It seems to be beneficial with a lower vapour resistance, as the temperatures are higher at this time of year, and therefore the conditions for mould growth may be more favourable when the RH levels are high.

In the cases with a normal moisture content, the M values are much lower, and all cases with a wood fibre board result in a green classification. The reference case results in the lowest initial mould growth, but achieves the same dynamic cycle of mould growth as the cases with the reference case with a higher initial moisture content, after the initial excess moisture dries.

These results suggest that with wood fibre weather boards, the construction is not robust against higher initial moisture content, but may function well in constructions with a normal moisture content as the values in those cases are rated with a green risk level.

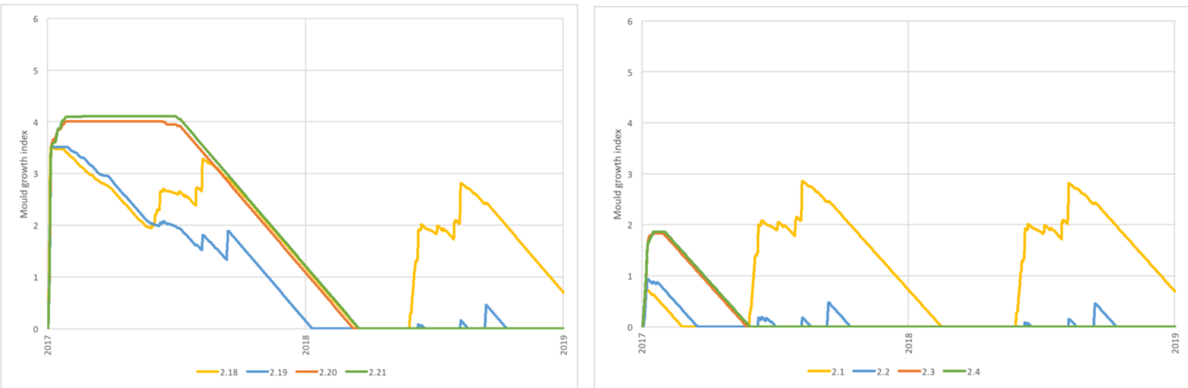

Figure 41: Mould Growth Index (The year on the x-axis indicates May in each year) (a) cases 2.18-2.21 (b) cases 2.2-2.4

The RH levels show that the constructions with the two thickest wood fibre boards seem to have a difficulty with drying the excess moisture, while the conventional weather barrier and the thinnest wood fibre board have a rapid reduction below RH_{min}, as indicated by the quicker reduction of the initial mould growth in these cases in Figure 42. These two cases seem to stabilise slightly faster, than the cases with 50 and 100 mm wood fibre boards. This could indicate that the thicker board are less robust against any possible water leaks, because the RH levels stay elevated for a long period.

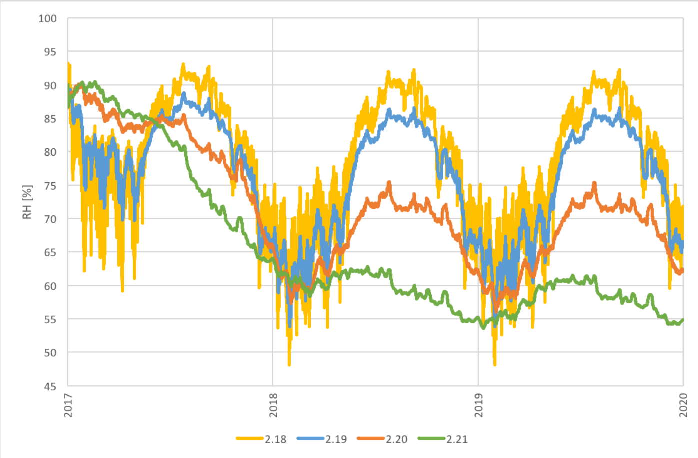

Figure 42: RH in cases 2.18-2.21 (The year on the x-axis indicates May in each year)

When the materials achieve at dynamic state, the advantages of the increased thermal resistance seem to be apparent, as the RH levels become lower with the increased thermal resistance of the wood fibre boards.

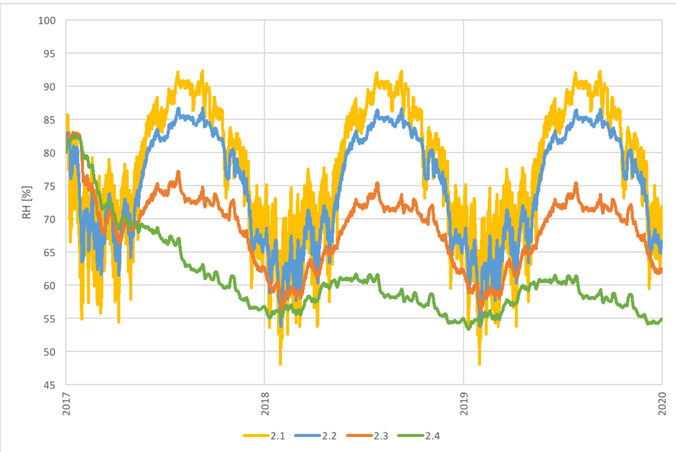

Figure 43: Mould growth in cases 2.1-2.4 (The year on the x-axis indicates May in each year)

Compared to the "normal situation", it takes more time before the cases with a higher initial moisture content stabilise, which is not unexpected, as a higher level of built-in moisture usually require longer time to dry in the same types of constructions. The RH values stabilise in the same dynamic cycles.

8 STUDY 3 – EXTERIOR RIGID FOAM INSULATION

8.1. Background

Some of the research in the literature study may supports using rigid foam boards as weather barriers (Tsongas, 1991, Tsongas, 1990, Norges Byggforskningsinstitutt, 1986). There are however a few concerns with rigid foam products. They may contribute to poor fire safety, as some of the products burn rapidly and release cause toxic smoke (Kallaos et al., 2014). The products may more robust against normal stresses in the earth, such as microorganisms (Byggforskserien, 2004a). One advantage with rigid foam, is that many of the products have a higher thermal resistance than traditional insulation materials (Byggforskserien, 2003a). Therefore, one may achieve the same level of thermal resistance in a wall, with a thinner material layer.

It would be interesting to investigate a rigid foam product, as it is very different from the wood fibre boards that were investigated in Study 1 and 2. One of the products found in the literature study seems to be promising, as it has a low vapour permeability, robust against moisture and is air and water tight. It does not contain any toxins and is more environmentally friendly than other similar products. In addition, it supposedly has good characteristics in terms of fire safety. Therefore, this product seems to be a good choice and may secure adequate moisture security. (Kingspan Insulation AS, 2017)

8.2. Simulation Cases and Parameter Variations

There are 25 simulation cases of the same construction with different parameter variations.

The product of rigid foam is indicated with RFWB (Rigid Foam Weather Barrier) in the simulation cases. A different conventional weather barrier is used in this study, and is indicated with WB2 in Table 10.

The rigid foam boards are tested in three different climates in cases 3.1-3.15. The thickness of the boards variate to investigate the effect this has on the conditions in the wall. The start of the simulations are in January in these cases.

In cases 16-25, the starting point of the calculations are changed to May, as this may influence the results in the initial phase.

Table 10: Simulation Cases in Study 3

Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Weather barrier: WB2	x					x					x					x					x				
RFWB 12 mm		x					x					x					x					x			
RFWB 25 mm			x					x					x					x					x		
RFWB 50 mm				x					x					x					x					x	
RFWB 80 mm					x					x					x					x					x
Climate: Trondheim	x	x	x	x	x											x	x	x	x	x					
Bergen						x	x	x	x	x											x	x	x	x	x
Oslo											x	x	x	x	x										
Start: January	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x										
May																x	x	x	x	x	x	x	x	x	x

Table 11: Parameter variations in Study 3

Weather Barrier material and thickness	The conventional weather barrier is used as a reference for evaluating the performance of the rigid foam boards. The thickness and characteristics of the material may have an impact on the hygrothermal conditions because of the difference in the vapour permeability and thermal resistance in the exterior part of the construction.
Climate	The climate is the main influence of the temperature and moisture conditions for a building. The robustness in different climates is of interest, as the risk level may change during different conditions. Trondheim, Bergen and Oslo are chosen, as they represent different types of climates.
Start of Simulation	The simulations are started in two different times of year. The starting dates are January 1st and May 1st. The conditions are quite different in these periods and may possibly influence the initial results

8.3. Results and Discussion of the Study

An overview of the results from the mould growth calculations are in Table 12. The results of both very sensitive and sensitive material classification is included. The material classification "very sensitive" was chosen, but the results of using classification "sensitive" was tested, as there is some uncertainty to which class is adequate. However, the discussion of the results is based on the results of "very sensitive".

The results are divided into subchapters, explaining the influence of different parameter variations. The complete results of this study are found in Appendix H

Table 12: Results of Study 3

Case	Very Sensitive		Sensitive	
	Maximum Mould Growth Index M	Maximum Reoccurring growth	Maximum Mould Growth Index M	Maximum Reoccurring Growth
3.1	5,744	1,806	4,667	0,576
3.2	5,722	0,000	4,805	0,000
3.3	5,695	0,000	4,826	0,000
3.4	5,359	0,000	4,447	0,000
3.5	5,125	0,000	4,181	0,000
3.6	5,283	0,000	4,073	0,000
3.7	5,492	0,000	4,500	0,000
3.8	5,526	0,000	4,631	0,000
3.9	5,398	0,000	4,506	0,000
3.10	5,141	0,000	4,233	0,000
3.11	5,913	0,000	2,119	0,000
3.12	5,879	0,000	3,774	0,000
3.13	5,866	0,000	4,574	0,000
3.14	5,760	0,000	4,682	0,000
3.15	5,386	0,000	4,401	0,000
3.16	3,687	1,806	1,587	0,576
3.17	4,039	0,000	2,326	0,000
3.18	4,281	0,000	4,281	0,000
3.19	4,205	0,000	3,036	0,000
3.20	3,995	0,000	2,796	0,000
3.21	2,093	0,000	0,677	0,000
3.22	3,512	0,000	1,933	0,000
3.23	4,242	0,000	2,964	0,000
3.24	4,326	0,000	3,162	0,000
3.25	4,182	0,000	3,006	0,000

8.3.1. The Effect of Increased Thermal Resistance

Trondheim

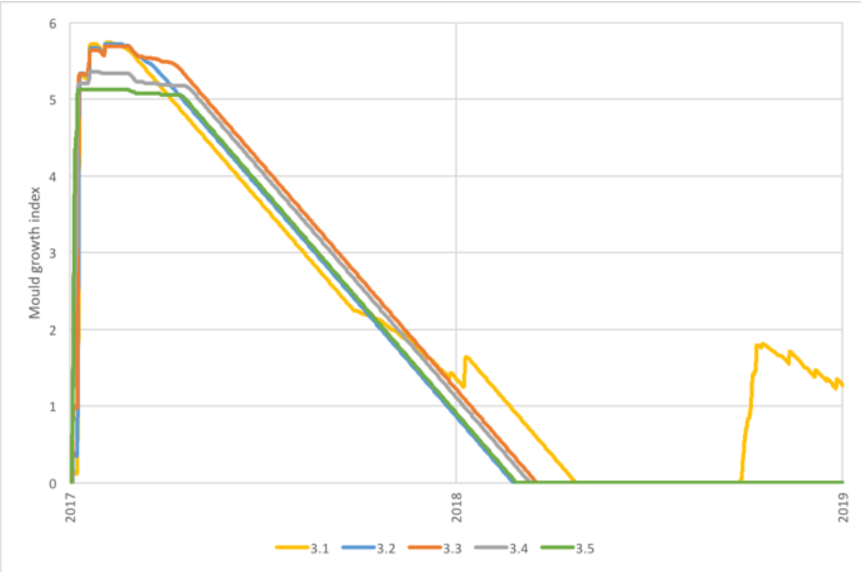

Figure 44: Mould Growth Index from cases 3.1-3.5

The RH levels became very high initially when starting the simulations in January. The reference case, 12 and 25 mm of rigid foam insulation result in values of close to 100 %, and there is a risk of condensation.

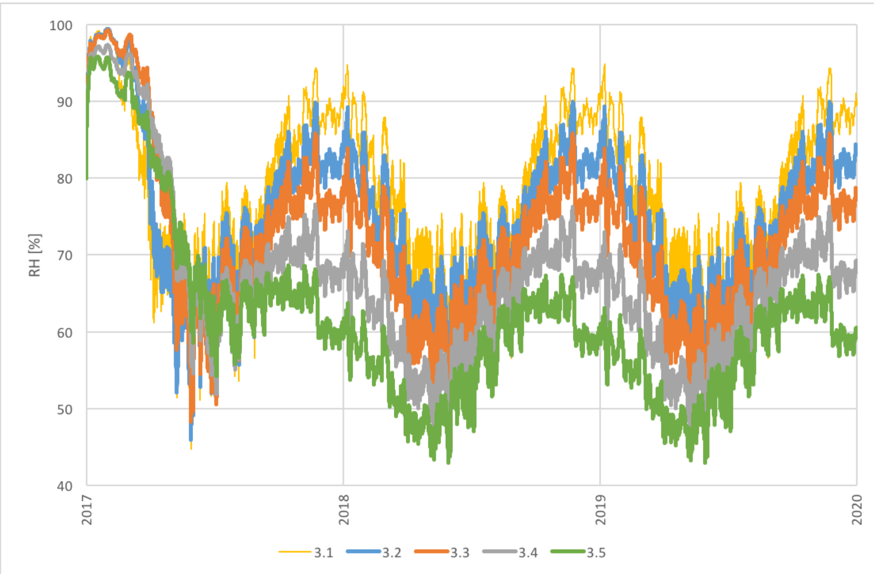

Figure 45: RH in cases 3.1-3.5

Bergen

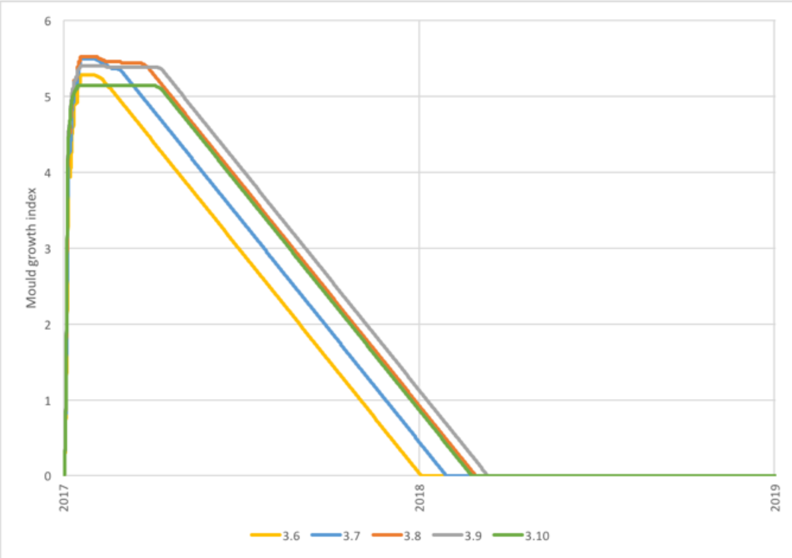

Figure 46: : Mould Growth Index from cases 3.6-3.10, (a) very sensitive (b) sensitive

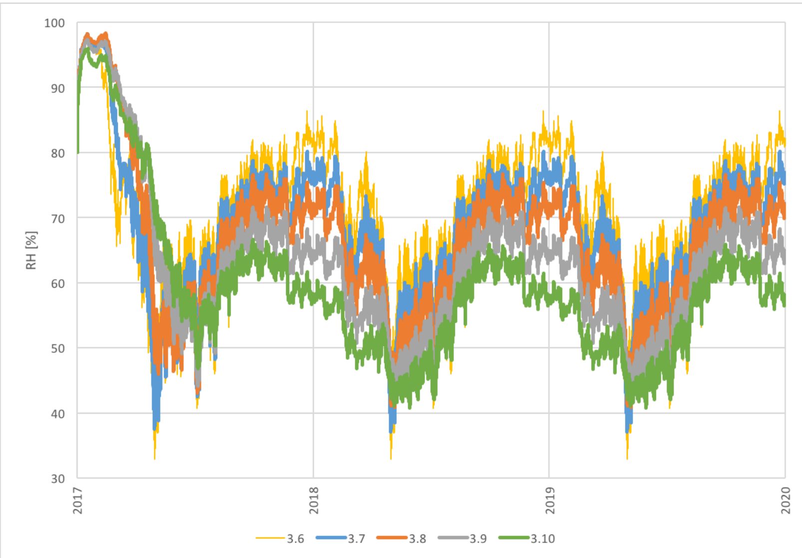

Figure 47: RH in cases 3.6-3.10

Oslo

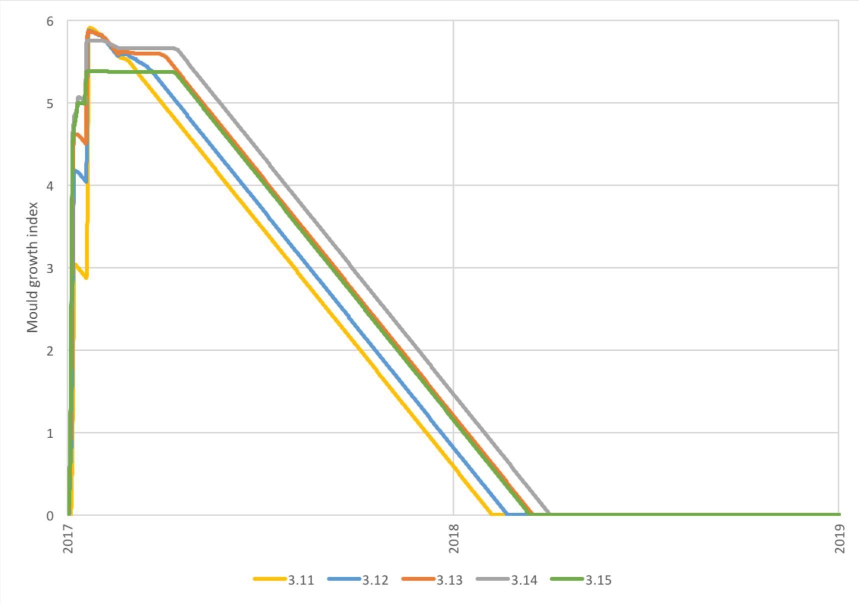

Figure 48: Mould Growth Index from cases 3.11-3.15

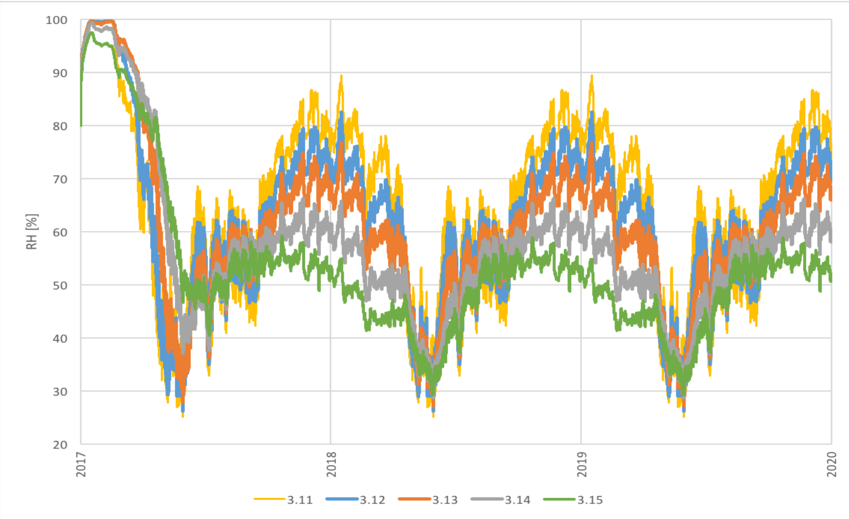

Figure 49: RH in cases 3.11-3.15

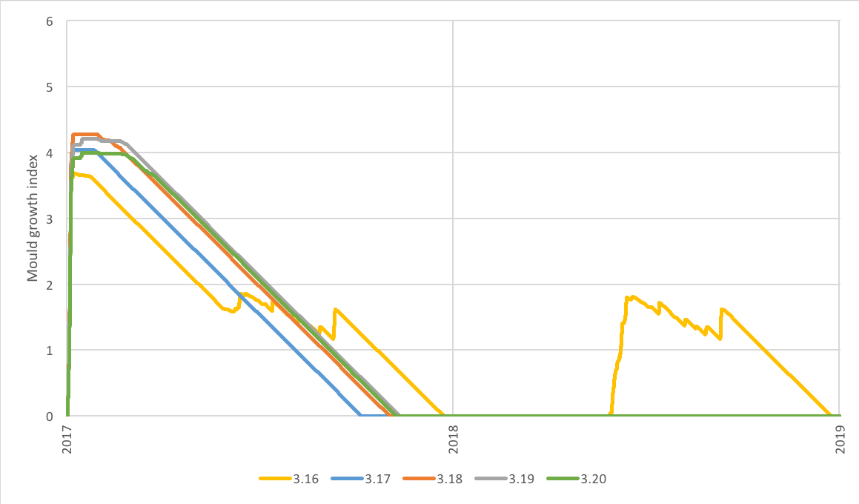

Figure 50: Mould Growth Index from cases 3.16-3.20

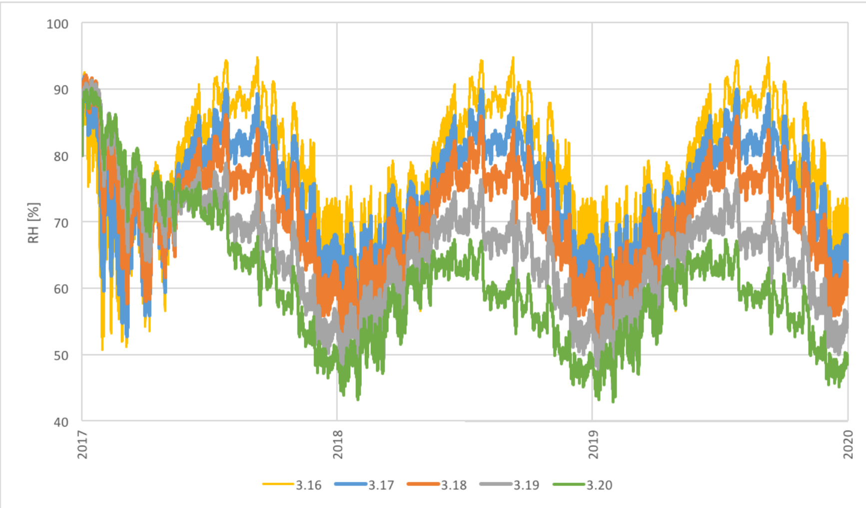

Figure 51: RH in cases 3.16-3.20

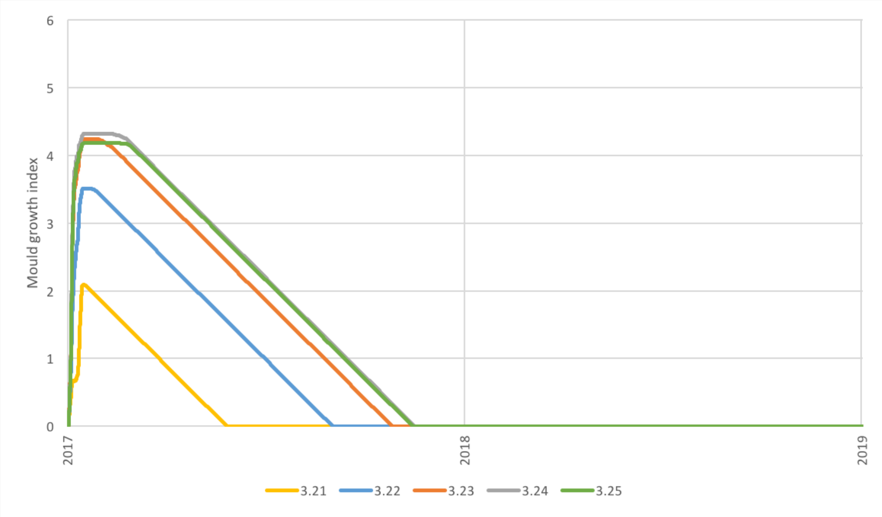

Figure 52: Mould Growth Index from cases 3.16-3.20

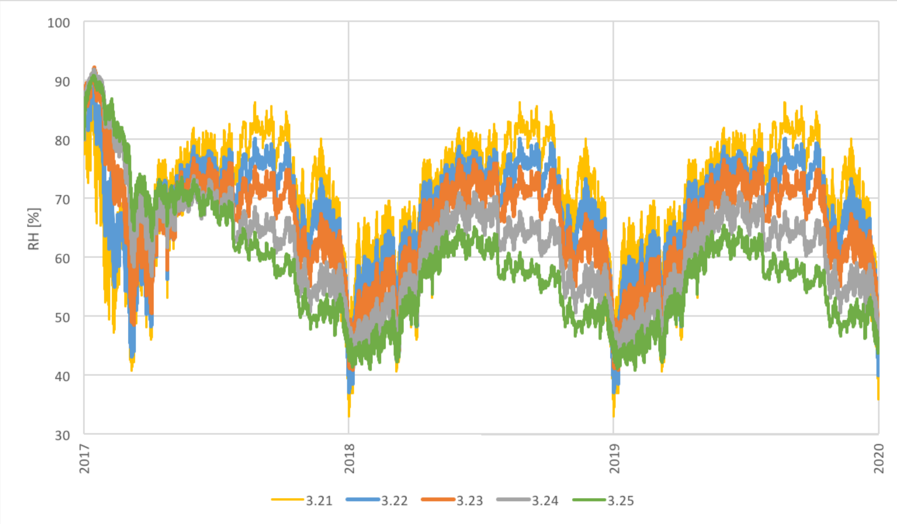

Figure 53: RH in cases 3.16-3.20

The result from Study 3. Show that when the simulations start in January, the product results in very high initial levels of mould growth and very high RH levels, up to 100 %, which may cause condensation. Starting in May, the initial mould growth is somewhat reduced, but the risk of condensation seems to be eliminated. The product does however result in low RH values after the initial moisture dries when thicker boards are used. This product should be further evaluated, as the results of the initial phases are concerning. The thicker boards do however show somewhat good results in the dynamic cycles, as the RH levels are at a safe level below 80%.

9 CONCLUSION

From the results in Study 1, it may be presumed that wood fibre boards function well as weather barrier, considering that in the stages of dynamic stability, there is no reoccurring mould growth of concern. However, in the initial phases of the simulation periods, mould growth of either yellow or red risk classification occur in all cases with wood fibre boards. Although the cases result in a green classification in the dynamic stages, the initial growth level may pose a risk. It may be desirable to achieve an acceptable level of growth in the initial stages, to eliminate the possible risk, as the fungi and spores may still survive inside the wall.

Regarding the RH values, the thicker wood fibre boards, of 50, 80 and 100 mm, achieve values below 80 % in the dynamic stages, irrespective of climate. The thinner boards, of 12 and 25 mm, show variating results in the dynamic phases in the different climates, but generally achieved values close to, or above 80 % RH. This may be concerning as these wood fibre boards may not be a robust solution.

Compared to the reference cases with a conventional weather barrier, all thicknesses of wood fibre boards achieve lower RH values in the dynamic cycles. The reference case does however result in lower initial mould growth levels than with the wood fibre boards. This may be related to the conventional weather barrier being more vapour open, allowing more the moisture to dry quicker, in addition to the lack of thermal insulation too low temperatures for mould growth in the monitor position. In some cases, the lack of thermal insulation in the exterior part may be an advantage, given that the product has a low vapour resistance. Still, the high RH values achieved in the winter with the conventional weather barrier may be of concern. It would most likely be preferable to use a weather barrier that achieves lower RH values throughout the entire year. Therefore, the thicker boards of wood fibre may be a good choice, if the initial mould growth can be accepted.

The results indicate that there is a fine balance between an appropriate combination of thermal resistance and vapour permeability, or in other terms the thickness of the material, as the constructions are influenced by the ambient conditions and therefore vary in different climates. The results are not unambiguous as to which solution is adequate due to the initial phases of the simulations, but wood fibre boards do seem to function well as a weather barrier, due to the reduction of the RH levels compared to the reference cases. The conventional weather barrier does not appear to be a robust solution, even though the conventional weather barrier achieves lower mould growth levels in some cases, as values above RH_{min} are achieved for all of the reference cases, and the conditions at monitor position is highly unstable.

In Study 2, the simulations in the spring show a reduction of the initial mould growth and RH levels. The RH values rise slightly in the beginning, and are quickly reduced. While in the winter, the RH values rise higher and require a longer time to dry below 80 %. Most of the cases with wood fibre boards result in a lob mould growth risk level, and one case results in zero growth. This indicates that it is possible to achieve adequate mould growth levels in the initial phases. And therefore, wood fibre boards may be a good option to use as weather barriers.

The result from Study 3. Show that when the simulations start in January, the product results in very high initial levels of mould growth and very high RH levels, up to 100 %, which may cause condensation. Starting in May, the initial mould growth is somewhat reduced, but the risk of condensation seems to be eliminated. The product does however result in low RH values after the initial moisture dries when thicker boards are used. This product should be further evaluated, as the results of the initial phases are concerning. The thicker boards do however show somewhat good results in the dynamic cycles, as the RH levels are at a safe level below 80%.

Overall, the wood fibre boards seem to be an adequate choice compared to the conventional weather barrier.

10 RECOMMENDATIONS FOR FURTHER WORK

Moisture safety in highly insulated wood-frame walls is a broad subject, and there is a need for more research considering future requirements, climate change and the fact that there may be some level of risk in the current traditional constructions. Because of limited time for this study, only a small part has been examined.

Recommendations for further work is to expand the three studies and include more parameters variations and inclusions of more effects. Other parameters which could be included is different types of vapour barriers, to investigate the effect the properties of the moisture barrier has on the conditions in the wall. Rigid foam insulation should be evaluated further.

In addition, other types of materials could be tried out. Different orientation of the wall should be considered, as this may influence the climatic loads on the construction. The solutions may be adequate for the orientation which is used, but might not be sufficient in other directions.

Studies investigating the effect of air leaks from perforations in the vapour barrier and water leaks, is also of interest, as this a cause severe damages, especially for cases with wood fibre insulation which is less resistant to moisture. Cases where a conventional weather barrier is placed between the cavity insulation and exterior insulation should also be evaluated, to examine if this solution could be more robust.

It would also be of interest to investigate other building parts than walls; roofs, floor and junctions between building parts, because this parts are exposed to different conditions than walls.

Bibliography

ALMÅS, A.-J., LISØ, K. R., HYGEN, H. O., ØYEN, C. F. & THUE, J. V. 2011. An approach to impact assessments of buildings in a changing climate. *Building Research & Information,* 39**,** 227-238.

BYGGFORSKSERIEN 1997. 700.117 Undersøkelse av fuktskader i bygninger.

BYGGFORSKSERIEN. 1998. *474.511 Vurdering av fuktsikkerhet. Kontrollpunkter* [Online]. SINTEF. Available: https://www.byggforsk.no/dokument/2564/vurdering_av_fuktsikkerhet_kontrollpunkter [Accessed].

BYGGFORSKSERIEN. 2003a. *471.010 Varmekonduktivitet og varmemotstand for bygningsmaterialer* [Online]. Available: https://www.byggforsk.no/dokument/209/varmekonduktivitet_og_varmemotstand_for_bygningsmaterialer [Accessed].

BYGGFORSKSERIEN. 2003b. 573.121 Materialer til luft- og damptetting. Available: http://bks.byggforsk.no/DocumentView.aspx?sectionId=2&documentId=598.

BYGGFORSKSERIEN 2004a. 573.344 Varmeisolasjonsmaterialer. Typer og egenskaper.

BYGGFORSKSERIEN. 2004b. *723.511 Etterisolering av yttervegger av tre* [Online]. Available: https://www.byggforsk.no/Document/Index/679/ - fig72 [Accessed].

BYGGFORSKSERIEN. 2005a. 421.132 Fukt i bygninger. Teorigrunnlag. Available: http://bks.byggforsk.no/DocumentView.aspx?sectionId=2&documentId=184.

BYGGFORSKSERIEN. 2005b. 701.401 Muggsopp i bygninger. Forekomst og konsekvenser for inneklimaet. Available: http://bks.byggforsk.no/DocumentView.aspx?sectionId=2&documentId=3231.

BYGGFORSKSERIEN 2006. 474.533 Byggfukt. Uttørking og forebyggende tiltak.

BYGGFORSKSERIEN. 2007. *523.255 Bindingsverk av tre. Varmeisolering og tetting* [Online]. SINTEF Byggforsk. Available: https://www.byggforsk.no/dokument/361/bindingsverk_av_tre_varmeisolering_og_tetting [Accessed].

BYGGFORSKSERIEN. 2008. 523.002 Yttervegger over terreng. Egenskaper og konstruksjonsprinsipper. Krav og anbefalinger. Available: https://bks.byggforsk.no/DocumentView.aspx?sectionId=2&documentId=348.

BYGGFORSKSERIEN 2013. 542.003 Totrinnstetning mot slagregn på fasader. Luftede kledninger og fuger.

DUPONT 2011. Weather Barriers are a Must with Exterior Foam Sheathing.

EDUARD, W. 2006. *The Nordic Expert Group for Criteria Documentation of Health Risks from Chemicals: 139. Fungal spores*.

FRAUNHOFER INSTITUTE FOR BUILDING PHYSICS 2016a. WUFI Pro 6.0 [Computer Program].

FRAUNHOFER INSTITUTE FOR BUILDING PHYSICS. 2016b. WUFI Pro 6.0 Online Help.

FRAUNHOFER INSTITUTE FOR BUILDING PHYSICS. 2016c. *WUFI Pro 6.0 Online Help* [Online]. [Accessed].

FRAUNHOFER INSTITUTE FOR BUILDING PHYSICS 2017. WUFI Mould Index VTT Help.

GEVING, S. & HOLME, J. 2010. Høyisolerte konstruksjoner og fukt. Analyse av fukttekniske konsekvenser av økt isolasjonstykkelse i yttervegger, tak, kryperom og kalde loft SINTEF Byggforsk.

GEVING, S. & HOLME, J. 2012. Mean and diurnal indoor air humidity loads in residential buildings. *Journal of Building Physics,* 35**,** 392-421.

GEVING, S., LUNDE, E. & HOLME, J. 2015. Laboratory Investigations of Moisture Conditions in Wood Frame Walls with Wood Fiber Insulation. *Energy Procedia,* 78**,** 1455-1460.

GEVING, S. & THUE, J. V. 2002. *Fukt i bygninger,* Oslo, Norges byggforskningsinstitutt.

GEVING, S. & TORGERSEN, S. E. 1997. Klimadata for fuktberegninger. Referanseår for 12 steder i Norge og klimadata for konstruksjoner mot grunnen.

GLAVA 2015. GLAVA Pluss System - Monteringsanvisning

GLAVA 2016. GLAVA Veggplate 31 - Monteringsanvisning.

GLAVA. 2017a. *GLAVA Pluss system på bindingsverksvegg* [Online]. Available: http://www.glava.no/bygg/losninger/byggkonstruksjoner/yttervegg/glava-pluss-system-pa-bindingsverksvegg/ [Accessed].

GLAVA. 2017b. *GLAVA veggplate 31 på bindingsverk* [Online]. Available: http://www.glava.no/bygg/losninger/byggkonstruksjoner/yttervegg/glava-veggplate-31-pa-bindingsverk/ [Accessed].

GULLBREKKEN, L. 2012. Omfordeling og uttørking av fukt i yttervegger av tre. *Norsk Bygningsfysikkdag 2012.* UBC Ullevaal Business Class, Oslo: SINTEF

HUKKA, A. & VIITANEN, H. A. 1999a. A mathematical model of mould growth on wooden material. *Journal of the International Academy of Wood Science,* 33**,** 475-485.

HUKKA, A. & VIITANEN, H. A. 1999b. A mathematical model of mould growth on wooden material. *Wood Science and Technology,* 33**,** 475-485.

HUNTON «n.d». Hunton Vindtett.

IPCC 2014. Climate Change 2014 Synthesis Report Summary for Policymakers Chapter.

ISOVER SAINT GOBAIN SE. 2013. *Därför ska vindskyddet monteras innan fasadisoleringen* [Online]. Available: http://www.isover.se/news/darfor-ska-vindskyddet-monteras-innan-fasadisoleringen [Accessed].

KALLAOS, J., BOHNE, R. A. & HOVDE, P. J. 2014. Long-Term Performance of Rigid Plastic Foam Building Insulation. *Journal of Materials in Civil Engineering,* 26**,** 374-378.

KAVGIC, M., MAVROGIANNI, A., MUMOVIC, D., SUMMERFIELD, A., STEVANOVIC, Z. & DJUROVIC-PETROVIC, M. 2010. A review of bottom-up building stock models for energy consumption in the residential sector. *Building and Environment,* 45**,** 1683-1697.

KINGSPAN INSULATION AS. *Kingspan Kooltherm K12 Stenderveggisolasjon* [Online]. Available: http://www.kingspanisolering.no/produkter/produkt/kooltherm-k12-stenderveggsisolasjon/ [Accessed].

KINGSPAN INSULATION AS Kooltherm K8 C Skallmursisolasjon.

KINGSPAN INSULATION AS. 2017. *Kooltherm K12 Stenderveggsisolasjon* [Online]. Available: http://spu.studio.crasman.fi/pub/Website+material/PDF+and+other+files/Own+instructions%2C+manuals%2C+brochures%2C+material/Kingspan+Kooltherm+K12+Stenderveggsisolasjon.pdf [Accessed].

KINGSPAN INSULATION LTD 2016. Declaration of Performance Kooltherm K12.

KINGSPAN INSULATION LTD. 2017. *Kooltherm K112 Framing Board* [Online]. Kingspan Insulation AS. Available: http://www.kingspaninsulation.co.uk/getattachment/918816d9-5349-4cb9-a195-6d42a99cf2ec/Kooltherm-K112-Framing-Board-pdf.aspx [Accessed].

KOMMUNAL- OG MODERNISERINGSDEPARTEMENTET. 2015. *Nye energikrav i nye bygg: -skjerpede krav, enklere regler* [Online]. Available: https://www.regjeringen.no/no/aktuelt/nye-energikrav-i-nye-bygg---skjerpede-krav-enklere-regler/id2461598/ [Accessed].

LOPEZ HURTADO, P., ROUILLY, A., VANDENBOSSCHE, V. & RAYNAUD, C. 2016. A review on the properties of cellulose fibre insulation. *Building and Environment,* 96**,** 170-177.
MUNDT-PETERSEN, S. O., HARDERUP, L.-E. & ARFVIDSSON, J. Important factors affecting the risk of mold growth in well-insulated wood frame walls in Northern European climates. Thermal Performance of the Exterior Envelopes of Whole Buildings XII, 2013.
NORGES BYGGFORSKNINGSINSTITUTT 1986. Report to Dow Chemical Europe - Field Test on Wallmate/Styrofam used in Timber Frame Walls, Project number 01825.
OJANEN, T., PEUHKURI, R., VIITANEN, H., LÄHDESMÄKI, K., VINHA, J. & SALMINEN, K. Classification of Material Sensitivity - New Approach for Mould Growth Modeling. 9th Nordic Syposium on Building Physics, 29 May - 2 June 2011 2011 Tampere, Finland. NSB.
OLSSON, L. 2011. Laboratoriestudie av träregelväggar med olika vindskydd. *SP rapport,* 56.
SALES DIRECTOR KINGSPAN INSULATION, T. S. 2017. *RE: Email correspondence.* Type to SVENNEVIG, T.
SIMONSON, C. J., OJANEN, T. & SALONVAARA, M. 2005. Moisture Performance of an Airtight, Vapor-permeable Building Envelope in a Cold Climate. *Journal of Thermal Envelope and Building Science,* 28**,** 205-226.
SINTEF CERTIFICATION. 2015. *Teknisk godkjenning - Hunton Vindtett / Hunton Bitroc* [Online]. [Accessed].
SONAE ARAUCO «n.d». AGEPAN UDP N+F.
SP SVERIGES TEKNISKA FORSKNINGSINSTITUT 2016. Prestandadeklaration för ISOVER glasull.
STEICO 2017a. Declaration of performence - Steico Therm Rigid Insulation.
STEICO 2017b. Steico Therm Dry.
STEICO «n.d». Why Steico - Advantages.
THUE, J. V., OUSTAD, M. & GUSTAVSEN, A. 2007. WUFI 1D Pro 4.1 Brukermanual.
TSONGAS, G. A. 1990. The Northwest Wall Moisture Study: A field study of moisture in the exterior walls of new northwest energy-efficient homes. *In:* MCELROY, D. & KIMPFLEN, J. (eds.) *Insulation Materials, Testing and Applications.* ASTM International.
TSONGAS, G. A. Effect of exterior insulating sheathing on wall moisture. Insulation Materials: Testing and Applications, 1991 Philadelphia, PA, United States
Gatlinburg, TN, USA. Publ by ASTM, 401-414.
VIITANEN, H., KRUS, M., OJANEN, T., EITNER, V. & ZIRKELBACH, D. 2015. Mold Risk Classification Based on Comparative Evaluation of Two Established Growth Models. *Energy Procedia,* 78**,** 1425-1430.

APPENDIX

Appendix A CLIMATE DATA

A.1. Outdoor

Trondheim

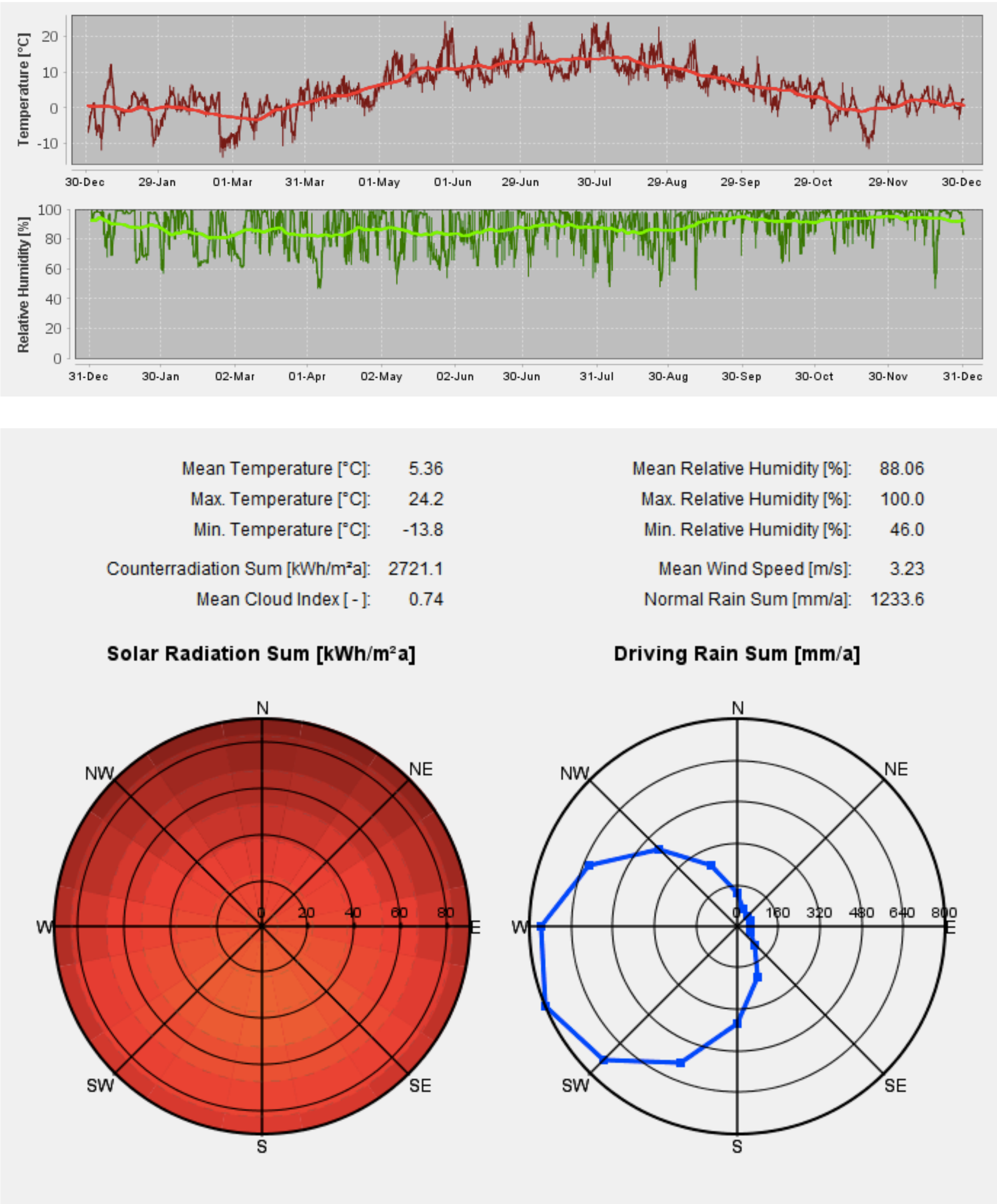

Figure 1; Figure 1: Climate data for Trondheim from the climate analysis in WUFI (Fraunhofer Institute for Building Physics, 2016a)

Bergen

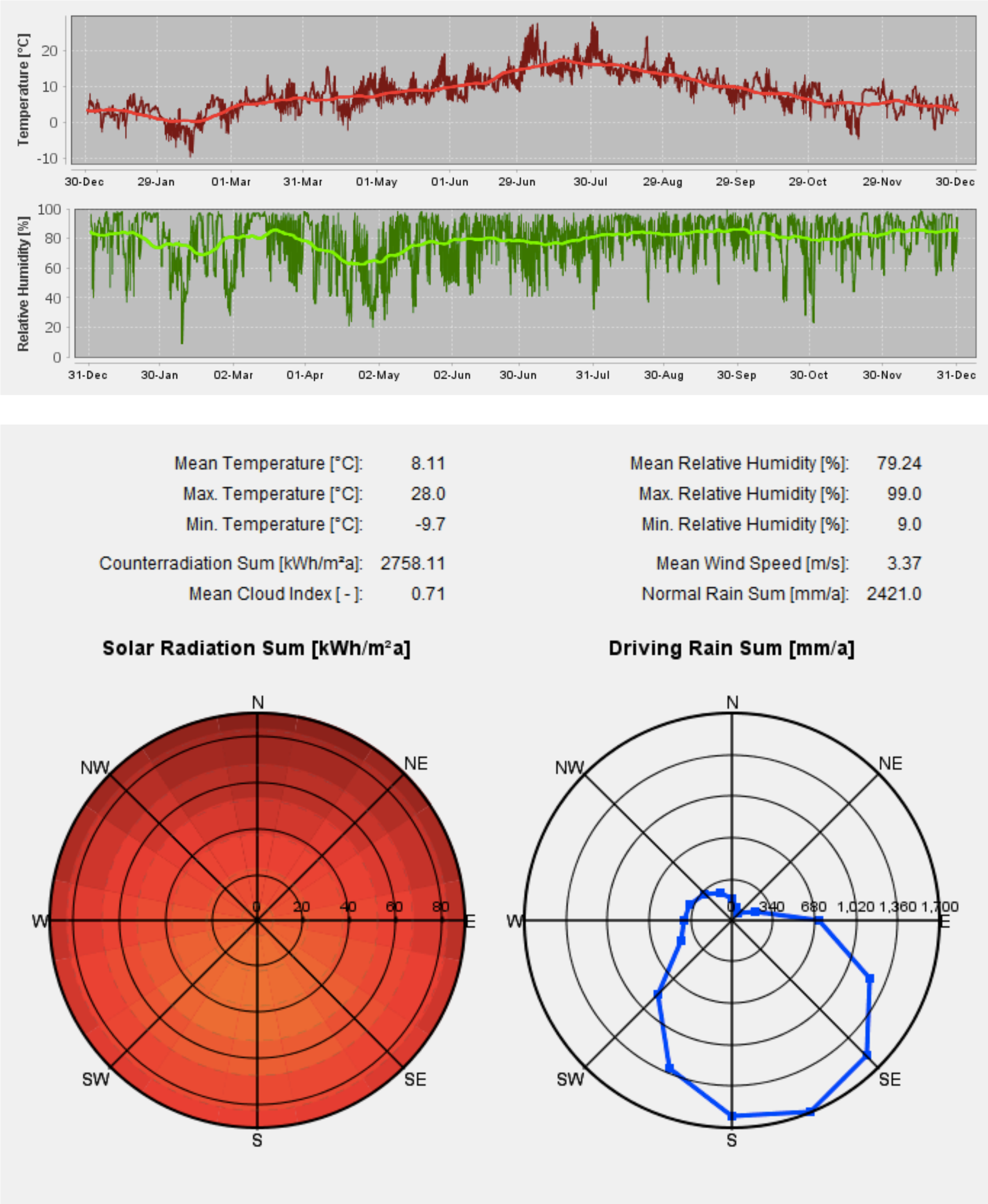

Figure 2: Climate data for Bergen from the climate analysis in WUFI (Fraunhofer Institute for Building Physics, 2016a)

Oslo

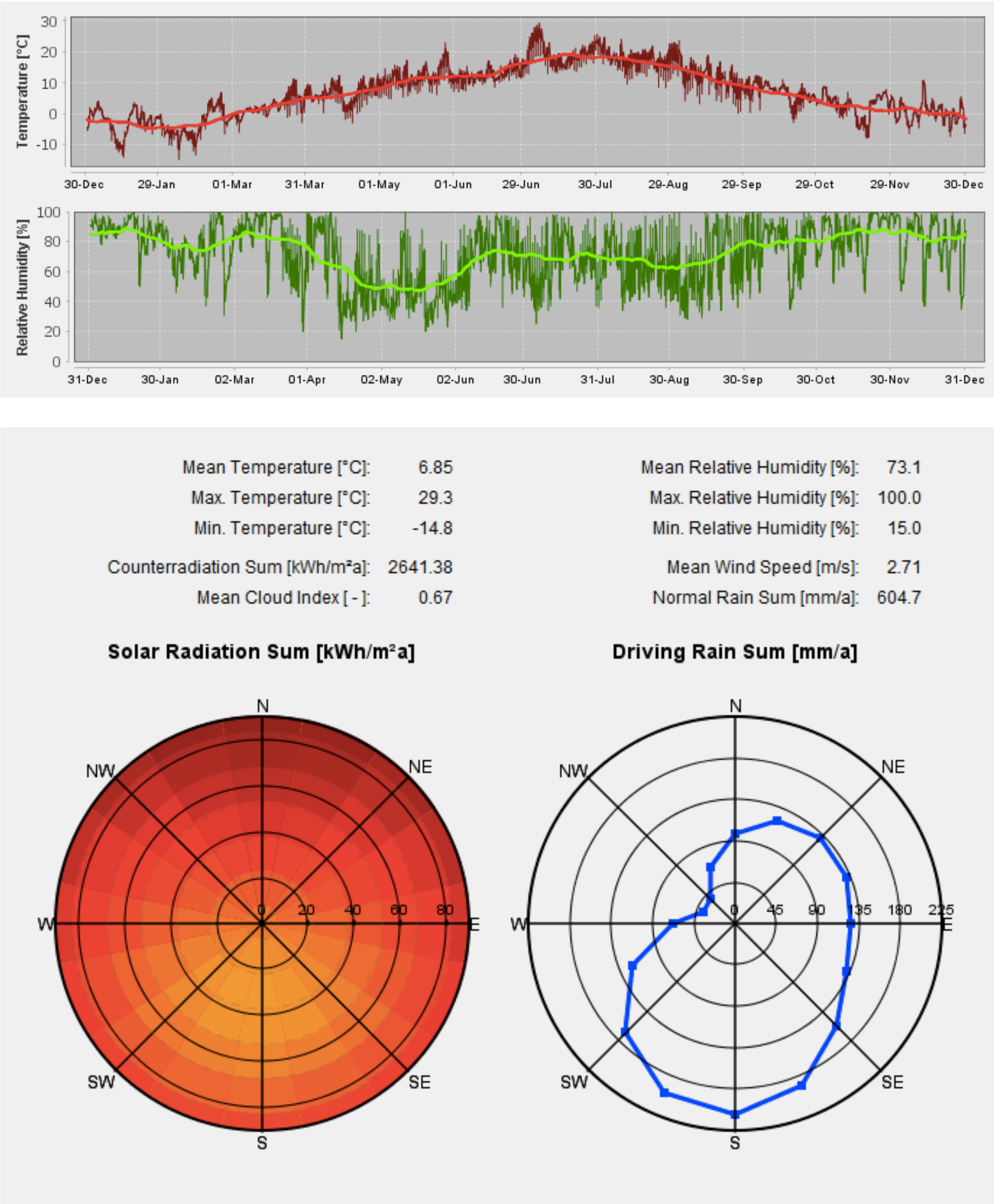

Figure 3: Figure 1: Climate data for Oslo from the climate analysis in WUFI (Fraunhofer Institute for Building Physics, 2016a)

A.2. Indoor Climate

Trondheim

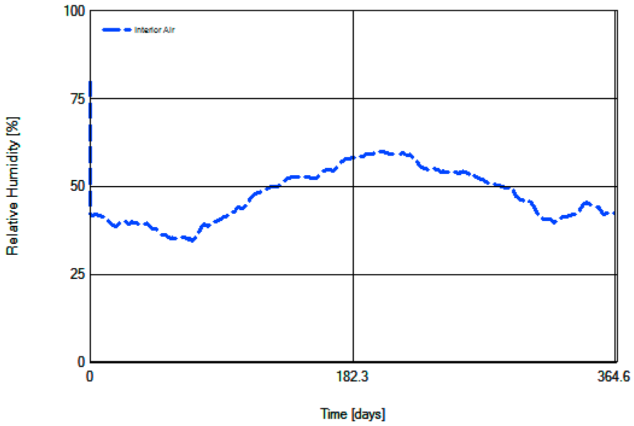

Figure 4: Indoor RH Trondheim, starting January 1st. (Fraunhofer Institute for Building Physics, 2016a)

Bergen

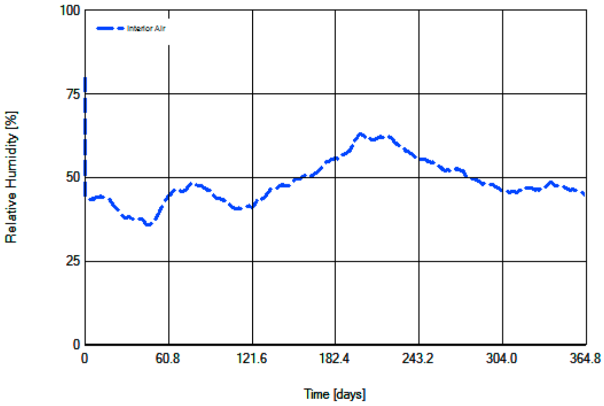

Figure 5: Indoor RH in Bergen, starting January 1st (Fraunhofer Institute for Building Physics, 2016a)

Oslo

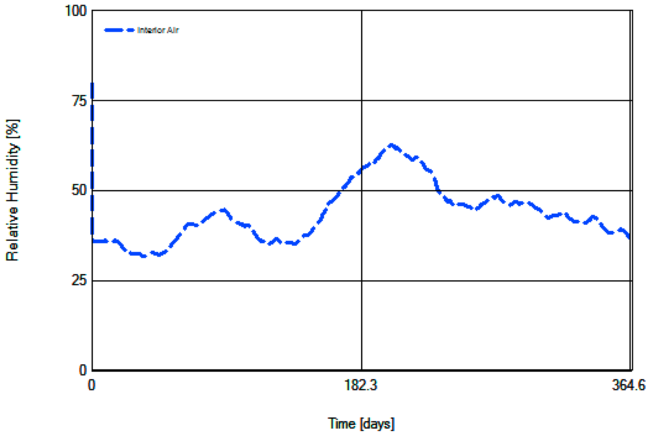

Figure 6: Indoor RH in Oslo, starting January 1st (Fraunhofer Institute for Building Physics, 2016a)

Appendix B MATERIALS IN THE MOISTURE CALCULATIONS

B.1. Materials Used in the Moisture Calculations

Exterior Cladding
A traditional wooden cladding of 19 mm spruce panel was chosen. Spruce is one of the most common materials for wooden claddings in Norway (Byggforskserien, 2012). This is a wood species which absorbs low amounts of water and is therefore a good choice, as it reduces the risk of damages. The material "Scandinavian spruce transverse direction II" from the WUFI database was used.

Air Layer
The air layer is the gap between the external cladding and the weather barrier, and has an important function for the constructions ability to dry out and remove moisture. The thickness of the gap is set to 20 mm, as recommended values are between 18-23 mm (Byggforskserien, 2012). In the WUFI material database there is a choice between an air gap either with or without additional moisture storage capacity. The option "with additional moisture storage capacity" is less numerically demanding, but gives a water content that is too high and the removal of moisture by air change takes longer than realistic (Fraunhofer Institute for Building Physics, 2016b). This option is not recommended by WUFI, and therefore, an air layer with additional moisture storage capacity was chosen.

The ventilation in the air layer is added by inserting an air exchange source, which is set to 50 h^{-1} constant, with mixing of the air from the outside of the construction.

Conventional Weather Barrier Type 1
Plastic foil products are a common choice of weather barrier material in Norwegian wood-frame construction, and therefore this type of product is used as a reference. A material from the WUFI database was chosen; "membrane of polypropylene on a polyethylene film", which has a low S_d-value of 0,017 m. This value is low compared to other options, but is within the range of typical weather barrier materials (Byggforskserien, 2003).

Conventional Weather Barrier Type 2
A second type of conventional weather barrier was used as a reference in Study 3. This material was also chosen from the WUFI material database; "weather resistive barrier (sd=0,2)". This product has a higher vapour resistance than the former. This product was chosen to be compared against the rigid foam boards, because this insulation material has a higher vapour resistance than the other options.

Wood Fibre Board – Type 1
The first wood fibre exterior insulation is based on a product which is commonly used as a weather barrier in Norway; Hunton Windproof. "Woodfibreboard, soft" from the WUFI material database was recommended as a basis for adding the product to the database. The density, thermal conductivity and vapour resistance of Hunton Windproof was found in the technical certification (SINTEF Certification, 2015), while the rest of the original material data was left unchanged.

Wood Fibre Board – Type 2
Agepan UDP N+F is another type of exterior wood fibre insulation, and was also recommended to use in the simulations. The product was found in the WUFI database. The vapour permeability of this product is lower than the former, but has a slightly higher thermal conductivity.

Wood Fibre Board – Type 3
Steico Therm Dry was found in the product research. This was the wood fibre board with the lowest lambda value and vapour resistance. The product was added to the database with "Woodfibreboard, soft" as a basis. The density, thermal conductivity and vapour resistance was found in the products datasheet and Declaration of Performance (Steico, 2017a, Steico, 2017b).

Rigid Foam Weather Board
Kingspan Kooltherm K12 was found during the product research. This product is a rigid thermoset phenolic insulation, with a low vapour resistance compared to similar products, and may therefore function well as a weather barrier (Kingspan Insulation AS, 2017). The product was added to the database, with "EPS (heat cond.: 0,04 W/mK – density 30kg/m^3)" from the WUFI database as a template. The thermal density, conductivity and vapour resistance was found in the product datasheet (Kingspan Insulation AS).

Wood Fibre Cavity Insulation
The wood fibre cavity insulation product which was chosen based on recommendations, and is a material from the WUFI database, called "Pavaflex".

Mineral Wool Cavity Insulation
Mineral wool is probably one of the most common insulation materials in residential wood frame buildings in Norway, and was therefore chosen as cavity insulation (Byggforskserien, 2004). A product from the WUFI material database was chosen; "Mineral Wool (heat cond.: 0,04 W/mK)".

Vapour Barrier
The vapour barrier is limited to one type, a conventional plastic product with an S_d-value of 70 m, which is within the recommended values for vapour barriers (Byggforskserien, 2003). "PE-membrane 0,15 mm (S_d=70)" from the material database in WUFI was chosen.

Interior Lining
The interior lining is limited to one material, a standard gypsum board, as this is a common choice. A product called "Gypsum Board" in from the WUFI database was used.

B.2. Overview of Material Properties

B.2.1. Properties of Basic Materials Which Apply in All Three Studies

Material	Bulk Density [kg/m³]	Porosity [m³/m³]	Heat Cap. [J/kgK]	Thermal Cond. [W/mK]	Vapour Res. [-]
Scandinavian spruce transverse direction II[1] *Exterior cladding*[2]	390	0,75	1600	0,13	108
Air Layer 20 mm; without additional moisture capacity *Air Layer*	1,3	0,999	1000	0,13	0,56
PE-Membrane 0,15 mm (Sd=70 m) *Vapour Barrier*	130	0,001	2200	2,2	70 000
Gypsum Board *Interior Lining*	850	0,65	850	0,2	8,3

B.2.2. Properties of Materials in Study 1

Material	Bulk Density [kg/m³]	Porosity [m³/m³]	Heat Cap. [J/kgK]	Thermal Cond. [W/mK]	Vapour Res. [-]
Membrane of polypropylene on a polyethylene film *Weather Barrier Type 1*	130	0,001	1500	3	17
Wood fibre board, soft *Wood Fibre Board Type 1*	270	0,83	1700	0,049	16,67
Agepan UDP N+F *Wood Fibre Board Type 2*	289	0,75	2100	0,051	4,4
Pavaflex *Wood Fibre Cavity Insulation*	53	0,96	2100	0,039	1,35
Mineral Wool (Heat cond.; 0,04 W/mK) *Mineral Wool Cavity Insulation*	60	0,95	850	0,04	1,3

---

[1] Name of the material in the WUFI database in bold writing
[2] Name used in the product description in Appendix B.1 in cursive

B.2.3. Properties of Materials in Study 2

Material	**Bulk Density** [kg/m³]	**Porosity** [m³/m³]	**Heat Cap.** [J/kgK]	**Thermal Cond.** [W/mK]	**Vapour Res.** [-]
Membrane of polypropylene on a polyethylene film *Weather Barrier Type 1*	130	0,001	1500	3	17
Weather Resistive Barrier (Sd=0,2) *Weather Barrier Type 2*	130	0,001	2300	2,3	200
Wood fibre board, soft *Wood Fibre Board Type 1*	270	0,83	1700	0,049	16,67
Wood fibre board, soft *Wood Fibre Board Type 3*	110	0,83	2100	0,037	3
Pavaflex *Wood Fibre Cavity Insulation*	53	0,96	2100	0,039	1,35

B.2.4. Properties of Materials in Study 3

Material	**Bulk Density** [kg/m³]	**Porosity** [m³/m³]	**Heat Cap.** [J/kgK]	**Thermal Cond.** [W/mK]	**Vapour Res.** [-]
Weather Resistive Barrier (Sd=0,2) *Weather Barrier Type 2*	130	0,001	2300	2,3	200
EPS (Heat cond.; 0,04 W/mK – density 30kg/m³) *Rigid Foam Weather Board*	35	0,95	1500	0,02	38
Mineral Wool (Heat cond.; 0,04 W/mK) *Mineral Wool Cavity Insulation*	60	0,95	850	0,04	1,3

B.3. Sorption Curves of Chosen Materials

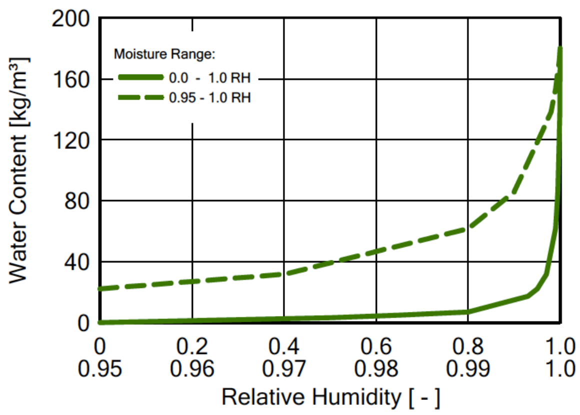

Figure 7: Sorption Curve Pavaflex (Fraunhofer Institute for Building Physics, 2016a)

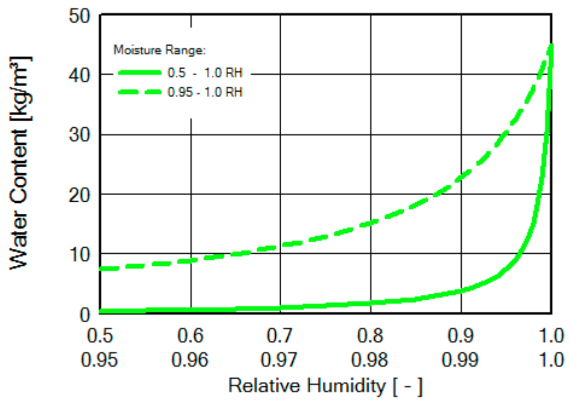

Figure 8: Sorption Curve Mineral Wool Mineral Wool (Heat cond.; 0,04 W/mK) (Fraunhofer Institute for Building Physics, 2016a)

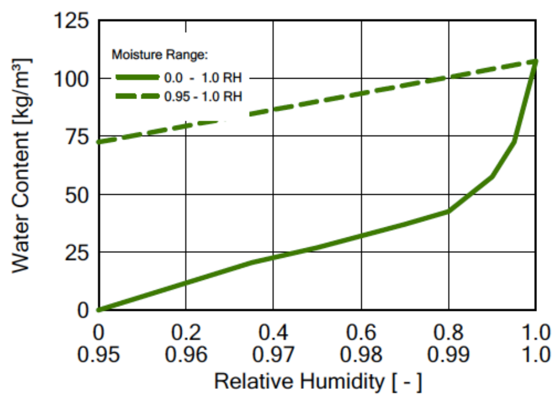

Figure 9: Sorption Curve Wood Fibre Board, soft (Fraunhofer Institute for Building Physics, 2016a)

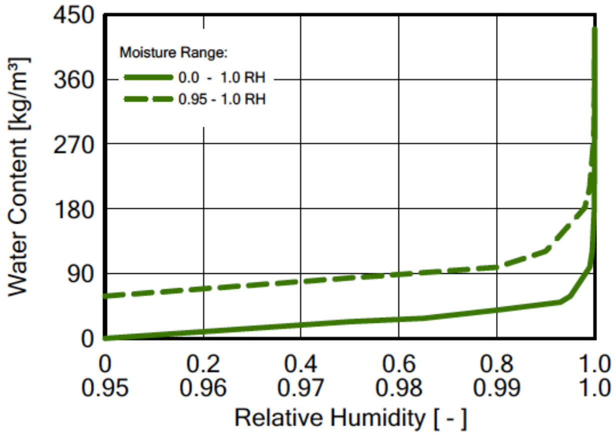

Figure 10: Sorption Curve AGEPAN UDP N+F (Fraunhofer Institute for Building Physics, 2016a)

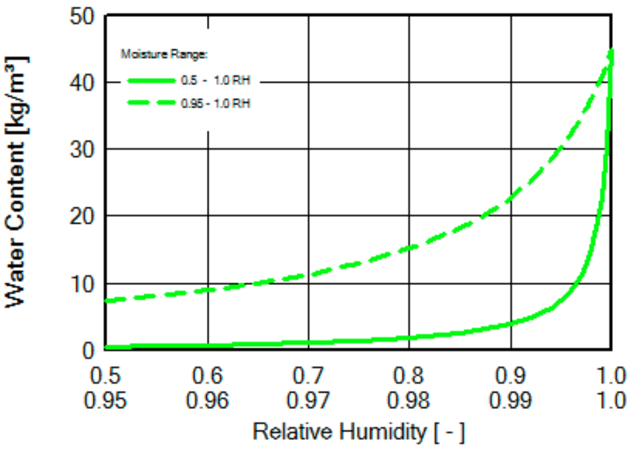

Figure 11: Sorption Curve EPS (Heat cond.; 0,04 W/mK – density 30kg/m3) (Fraunhofer Institute for Building Physics, 2016a)

Appendix C DATA INPUT IN THE MOISTURE SIMULATIONS

C.1. Data Input in WUFI

This is an explanation of the settings which were chosen in the simulation program, and is mainly based on WUFI online Help function found in the program and the WUFI manual (Thue et al., 2007). Some of these settings apply to all three studies, in some cases because these are default settings for the construction type.

Assembly of Component

The construction part is made into a one-dimensional component in WUFI by adding layers and choosing respective thickness and material for the different layers. Sources of moisture, heat or air exchange can be added to layers if necessary. The construction used in the simulations has a ventilated airgap, therefore, an air exchange source must be applied to the air gap, to simulate the effect of the ventilation. The ventilation in the air layer is added by inserting an air exchange source, which is set to 50 h^{-1} constant, with mixing of the air from the outside of the construction in all cases.

Grid

A grid divides the layers into smaller elements, which is necessary for the calculation of the component. The grid can be made manually, but the automatically generated grids are usually sufficient for normal calculations. There are two options for automatic grids; Automatic 1 and Automatic 2. Both options were tested in the first study. Automatic 1 resulted in fewer convergence failures and less difference between the balances, and was therefore chosen. To eliminate numerical errors, the adjustment of the grid was set to fine.

Rain Load Coefficients

The rain load for a component is usually determined by the amount of driving rain. The driving rain coefficient is dependent on the rain and wind conditions at the chosen location. Two other factor affect the coefficient, R1 and R2, which depends on the components location in the building. For vertical components R1 is zero. R2 is set to the default setting for short buildings up to 10 m, which is 0,07 s/m. This equals a location in the centre of a façade.

Surface Transfer Coefficients

The surface transfer coefficient for the external side defines how the component is affected by the surroundings. The heat resistance is related to heat exchange with the surroundings, and is set to the default value for walls of 0,0588 m^2W/K. This value includes both radiative and convective heat exchange.

Instead of modelling a thin layer for surface treatment for the construction, one can add a separate surface coating. A thin layer of surface treatment usually will not affect the thermal conditions, but it may have an impact on the water vapour diffusion. This setting gives an extra diffusion resistance at the surface of the component. In this case, it is not necessary as this layer may have little effect on the wall construction behind the cladding because of the air gap.

The short-wave radiation absorptivity is the fraction of total short-wave radiation that is absorbed by the building part, and is affected mainly by the colour of the surface. One of the automatic options was chosen; “Wood (spruce): painted brown”, which gives a short-wave radiation absorptivity of 0,8.

The long-wave radiation emissivity is the heat loss by thermal radiation that is emitted by the surface. This factor is usually not considered separately, but included in the heat resistance factor. Including this factor separately could give a better result, but when performing test simulations, it caused to many numerical errors and was therefore excluded.

Ground short-wave reflectivity is the short-wave global radiation that the ground reflects. The standard value of 0,2 will be used. The adhering fraction of rain is dependant chosen to be dependant of the inclination, which gives a value of 0,7.

For the interior surface, the heat resistance is set to 0,125 m^2K/W automatically. No coating is chosen for the internal wall.

Numerics

There are options for the how the calculations are performed in the numerics section. The default settings was used, which includes both thermal and moisture simulations, and increased accuracy.

C.2. Overview of Data Input Study 1

Parameter	Setting
Grid	Automatic 1 Fine
Sources	Air Layer: Air exchange 50 h^{-1} constant from the left-hand side
Orientation	North
Inclination	90°
Building Height/Driving Rain Coefficient	Short building up to 10 m R1=0 R2=0,07
Heat Resistance External Wall	0,0588 m^2K/W
S_d-value External Wall	No coating
Short-Wave Radiation Absorptivity	0,8 Wood (spruce) painted brown
Explicit Radiation Balance	-
Ground Short-Wave Reflectivity	0,2 Standard value
Adhering Fraction of Rain	0,7 (Dependent of inclination)
Heat Resistance Interior Surface	0,125 m^2K/W
S_d-value Interior Surface	No coating
Initial Temperature in Component	23°C constant in component
Initial Relative Humidity in Component	0,8 constant across component 0,9 in one layer
Calculation Period	01.01.17-31.12.19
Climate	Trondheim/Bergen/Oslo
Indoor Climate	Temperature: 23°C RH: User defined

C.3. Overview of Data Input Study 2

Parameter	Setting
Grid	Automatic 1 Fine
Sources	Air Layer: Air exchange 50 h^{-1} constant from the left-hand side
Orientation	North
Inclination	90°
Building Height/Driving Rain Coefficient	Short building up to 10 m R1=0 R2=0,07
Heat Resistance External Wall	0,0588 m^2K/W
S_d-value External Wall	No coating
Short-Wave Radiation Absorptivity	0,8 Wood (spruce) painted brown
Explicit Radiation Balance	-
Ground Short-Wave Reflectivity	0,2 Standard value
Adhering Fraction of Rain	0,7 (Dependent of inclination)
Heat Resistance Interior Surface	0,125 m^2K/W
S_d-value Interior Surface	No coating
Initial Temperature in Component	23°C constant in component
Initial Relative Humidity in Component	0,8 constant across component 0,9 in one layer
Calculation Period	Winter: 01.01.17-31.12.19 Summer: 01.05.17-01.05.20
Climate	Trondheim/Bergen
Indoor Climate	Temperature: 23°C RH: User defined

C.4. Overview of Data Input Study 3

Parameter	Setting
Grid	Automatic 1 Fine
Sources	Air Layer: Air exchange 50 h^{-1} constant from the left-hand side
Orientation	North
Inclination	90°
Building Height/Driving Rain Coefficient	Short building up to 10 m R1=0 R2=0,07
Heat Resistance External Wall	0,0588 m^2K/W
S_d-value External Wall	No coating
Short-Wave Radiation Absorptivity	0,8 Wood (spruce) painted brown
Explicit Radiation Balance	-
Ground Short-Wave Reflectivity	0,2 Standard value
Adhering Fraction of Rain	0,7 (Dependent of inclination)
Heat Resistance Interior Surface	0,125 m^2K/W
S_d-value Interior Surface	No coating
Initial Temperature in Component	23°C constant in component
Initial Relative Humidity in Component	0,8 constant across component
Calculation Period	Winter: 01.01.17-31.12.19 Summer: 01.05.17-01.05.20
Climate	Trondheim/Bergen
Indoor Climate	Temperature: 23°C RH: User defined

Appendix D QUALITY CONTROL OF THE SIMULATIONS

Two indicators were used to evaluate the quality of the simulations in WUFI; the balance of the water flow and the number of convergence errors. Balance 1 and 2 should preferably be equal, and the number of convergence errors should be kept to a minimum. A slight difference between the balances and few convergence errors may be acceptable (Fraunhofer Institute for Building Physics, 2016b). In Study 1, the simulations were tested with both settings for automatically generated grids distribution, as the distribution of the grid may be the cause of errors and a large difference in the balance (Fraunhofer Institute for Building Physics, 2016b). The results are displayed in the table below. Based on the results, Automatic 1 was chosen for all studies.

The water flow balances and number of convergence errors were checked after each simulation, and the number of convergence errors were few, usually zero, and the difference in the mass balance in the studies was low, in some cases zero. Some simulation cases were rejected because of of too many errors if they could not be reduced. The results and quality of the simulations are assumed to be adequate. However, the results of the calculations may be somewhat underestimated, as one cannot model the wooden elements of the construction in correctly in the one-dimensional computer program.

Table 1: Automatic 1 versus Automatic 2 setting for automatically generated grid in Study 1

Case	**Auto 1**			**Auto 2**		
	Conv. Errors	**Balance 1**	**Balance 2**	**Conv. Errors**	**Balance 1**	**Balance 2**
1	1	-0,9	-0,95	0	-0,91	-0,99
2	0	-0,82	-0,86	1	-0,8	-1,2
3	2	-0,78	-0,94	1	-0,78	-1,0
4	2	-0,87	-0,99	0	-0,87	-1,07
5	1	-1,07	-1,23	0	-1,07	-1,3
6	1	-1,25	-1,36	7	-1,26	-1,67
7	0	-1,18	-1,32	0	-1,19	-1,94
8	0	-1,17	-1,32	0	-1,15	-1,81
9	0	-1,15	-1,39	1	-1,17	-1,58
10	3	-1,29	-1,51	0	-1,3	-1,62
11	4	-1,53	-1,68	4	-1,54	-2,49
12	3	-1,73	-1,86	2	-1,73	-2,03
13	1	-1,58	-1,59	0	-1,59	-1,66
14	0	-1,58	-1,58	0	-1,59	-1,63
15	1	-1,60	-1,61	3	-1,61	-1,71
16	0	-1,81	-1,81	0	-1,82	-1,88
17	0	-2,33	-2,33	1	-2,34	-2,44
18	0	-0,17	-0,20	1	-0,17	-0,47
19	1	-0,06	-0,12	2	-0,06	-0,24
20	0	-0,15	-0,23	1	-0,14	-0,40
21	0	-0,64	-0,70	7	-0,64	-0,91
22	0	-3,68	-3,72	0	-3,68	-3,85
23	0	-3,49	-3,53	0	-3,48	-3,98
24	2	-3,25	-3,37	1	-3,25	-3,59
25	4	-3,24	-3,70	4	-3,24	-3,70

Appendix E THE VTT MODEL

E.1. Further Description of the Model

The VTT-model was used to calculate the risk of mould growth. The model was introduced in Chapter 2, and is further explained in this appendix. The equations and information and are from Hukka and Viitanen (1999a) and Ojanen et al. (2011).

The complete model for growth rate in favourable conditions is given by the following equation (Hukka and Viitanen, 1999b):

$$\frac{dM}{dt} = \frac{1}{7\exp(-0{,}68 lnT - 13{,}9 \ln RH + 0{,}14W - 0{,}33SQ + 66{,}02)} k_1 k_2$$

where:
$M = Mould\ index$
$k_1 = growth\ coefficient\ depentant\ of\ mould\ growth\ level$
$k_2 = coefficient\ which\ takes\ into\ account\ the\ upper\ limit\ for\ mould\ growth\ M_{max}$
$W = Timber\ species\ (0 = \text{Pine}, 1 = \text{Spruce})$
$SQ = surface\ quality\ (0 = \text{sawn surface}, 1 = \text{kiln dried quality})$

The correction coefficients, k_1 and k_2 (Hukka and Viitanen, 1999b):

$$k_1 = \begin{cases} 1 & when\ M < 1 \\ t_v/t_m - 1 & when\ M > 1 \end{cases}$$

where:
$t_v = regression\ equation\ for\ growth\ above\ M = 1$
$t_m = regression\ equation\ for\ response\ time$

$$k_2 = 1 - exp[2{,}3(M - M_{max})]$$

M_{max} is a limiting value that the Mould index does not rise above, independent of the time available in favourable conditions. This equation is from the improved model, and includes the parameters A, B and C, which takes into the account the sensitivity classification of other materials than wood (Ojanen et al., 2011):

$$M_{max} = A + B\frac{RH_{crit} - RH}{RH_{crit} - 100} - C\left(\frac{RH_{crit} - RH}{RH_{crit} - 100}\right)^2$$

One of the main factors for mould to appear, is the RH. The critical RH for mould growth is a function of the temperature. This equation describes the RH for mould growth for temperatures between 0-40°C (Hukka and Viitanen, 1999b)::

$$RH_{crit} = \begin{cases} -0{,}00267T^3 + 0{,}160T^2 - 3{,}13T + 100{,}0 & when\ T \leq 20 \\ 80\% & when\ T \geq 20 \end{cases}$$

During non-favourable conditions, the model takes into account the decrease in mould activity (Hukka and Viitanen, 1999b):

$$\frac{dM}{dt} = \begin{cases} -0{,}032 & when\ t - t_1 \leq 6h \\ 0 & when\ 6h\ \leq t - t_1 \leq 24\ h \\ -0{,}016 & when\ t - t_1 > 24h \end{cases}$$

where:
$t - t_1 = the\ time\ passed\ from\ the\ beginning\ of\ the\ dry\ period$

From the improved model of Ojanen et al. (2011), a correction factor, C_{mat}, for the decline during non-favourable conditions for different types of materials was included:

$$\frac{dM}{dt_{mat}} = C_{mat} * \frac{dM}{dt_0}$$

The correction coefficient, C_{mat}, is based on experimental findings shown in the figure below Ojanen et al. (2011).

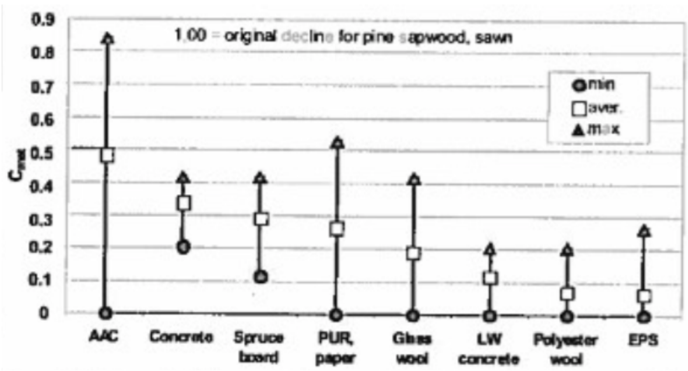

Figure 12: The relative decline intensity of mould (C_{mat}) on different materials (Ojanen et al., 2011)

Table 2: Description of the decline (Ojanen et al., 2011)

C_{eff}	Description
1,0	Pine in original model, short periods
0,5	Significant relative decline
0,25	Relevantly low decline
0,1	Almost no decline

Table 3: Mould growth sensitivity classes (Ojanen et al., 2011, Fraunhofer Institute for Building Physics, 2017)

Sensitivity class	**Materials**
Very sensitive	Pine sapwood, untreated wood
Sensitive	Glued wooden boards, PUR with paper surface, spruce, planed wood, paper coated products, wood based boards
Medium resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool
Resistant	PUR polished surface, glass and metal products, materials with efficient protective compound treatments

Table 4: Parameters for the different sensitivity classes (Ojanen et al., 2011)

Sensitivity class	**k_1**		**k_2 (M_{max})**			**RH_{min}**
	M<1	**M>1**	**A**	**B**	**C**	**%**
Very sensitive (vs)	1	2	1	7	2	80
Sensitive (s)	0,578	0,386	0,3	6	1	80
Medium resistant (mr)	0,072	0,097	0	5	1,5	85
Resistant (r)	0,033	0,014	0	3	1	85

E.2. Choice of Sensitivity Class in the VTT-model

Sensitivity class “very sensitive” was chosen for the wooden elements in the monitor position in the constructions, based on the uncertainties of which class may be adequate, due to reasons mentioned in Chapter 2. In addition, the material sensitivity class of “sensitive” was tested, to examine the difference in the results, as this class may be sufficient depending on the quality of the material.

Material Classification Very Sensitive

- The parameters A, B, C, k_1 and k_2 are governed by the sensitivity class, which results in A=1, B=7, C=2, k_1=1, k_2=2
- Spruce is chosen, resulting in W= 0
- Surface quality is assumed to be sawn surface, SQ=0
- The material is assumed to have the same decline as in the original model, C_{mat}=1

Material Classification Sensitive

- The parameters A, B, C, k_1 and k_2 are governed by the sensitivity class, which results in A=0,3, B=6 C=1, k_1=0,578, k_2=0,386
- Spruce is chosen, resulting in W= 0
- Surface quality is assumed to be sawn surface, SQ=0
- The material is assumed to have the same decline as in the original model, C_{mat}=1

Appendix F RESULTS OF MOISTURE SIMULATIONS - STUDY 1

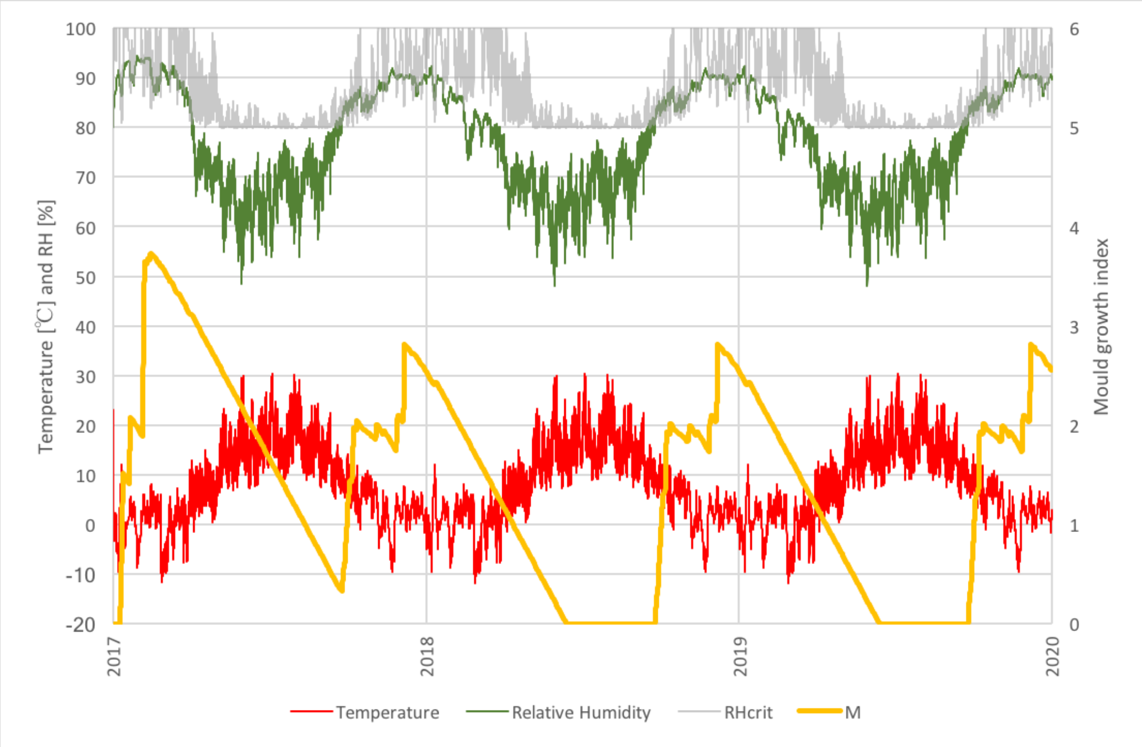

Figure 13: Case 1.1.

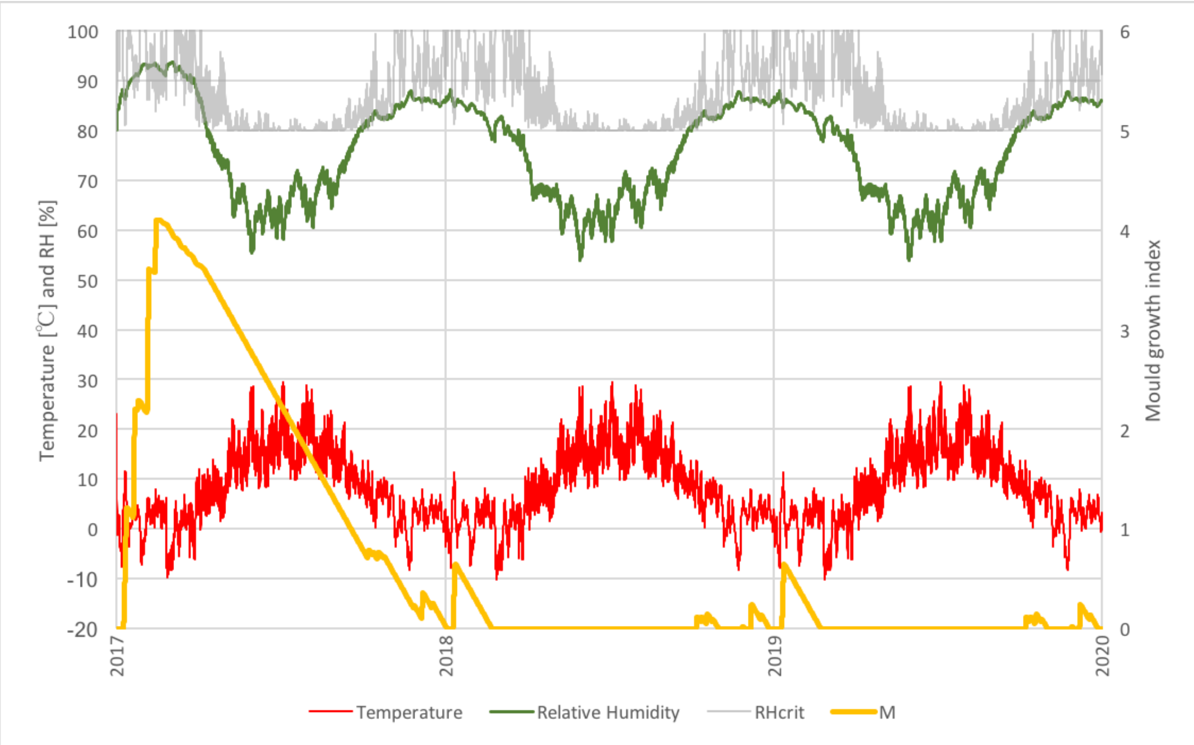

Figure 14: Case 1.2

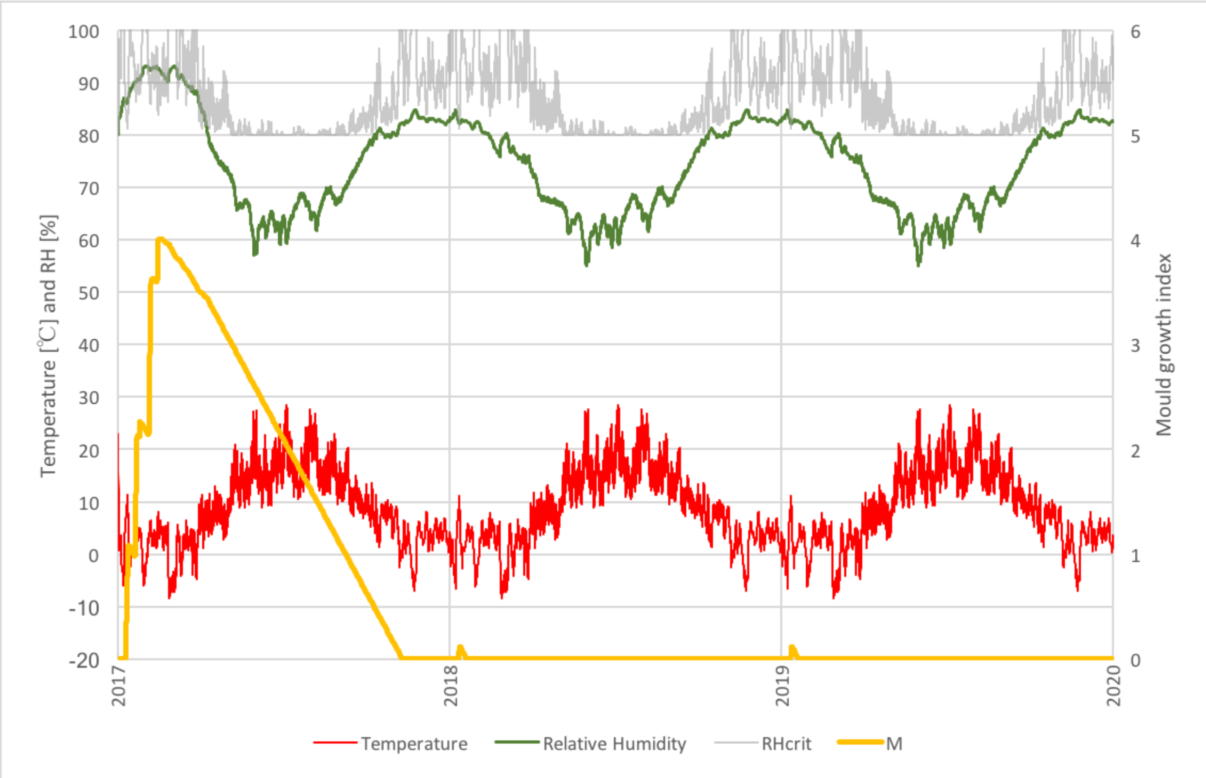

Figure 15: Case 1.3

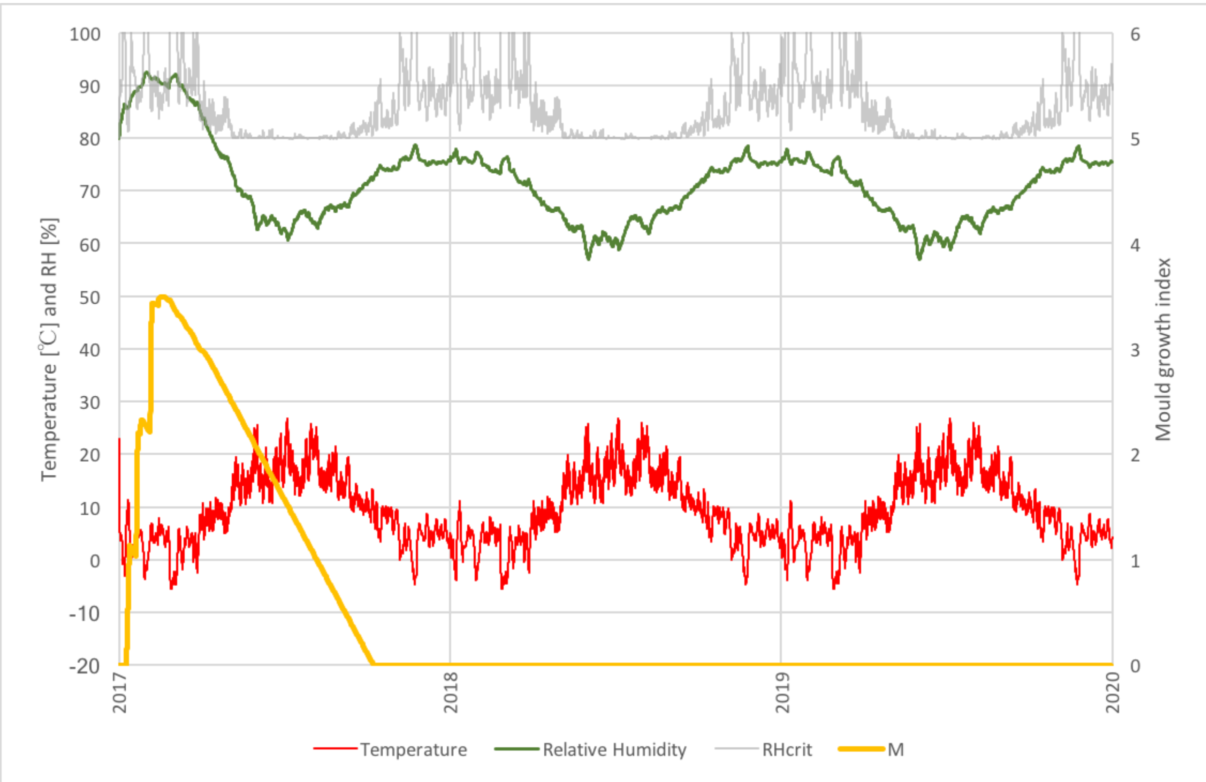

Figure 16: Case 1.4

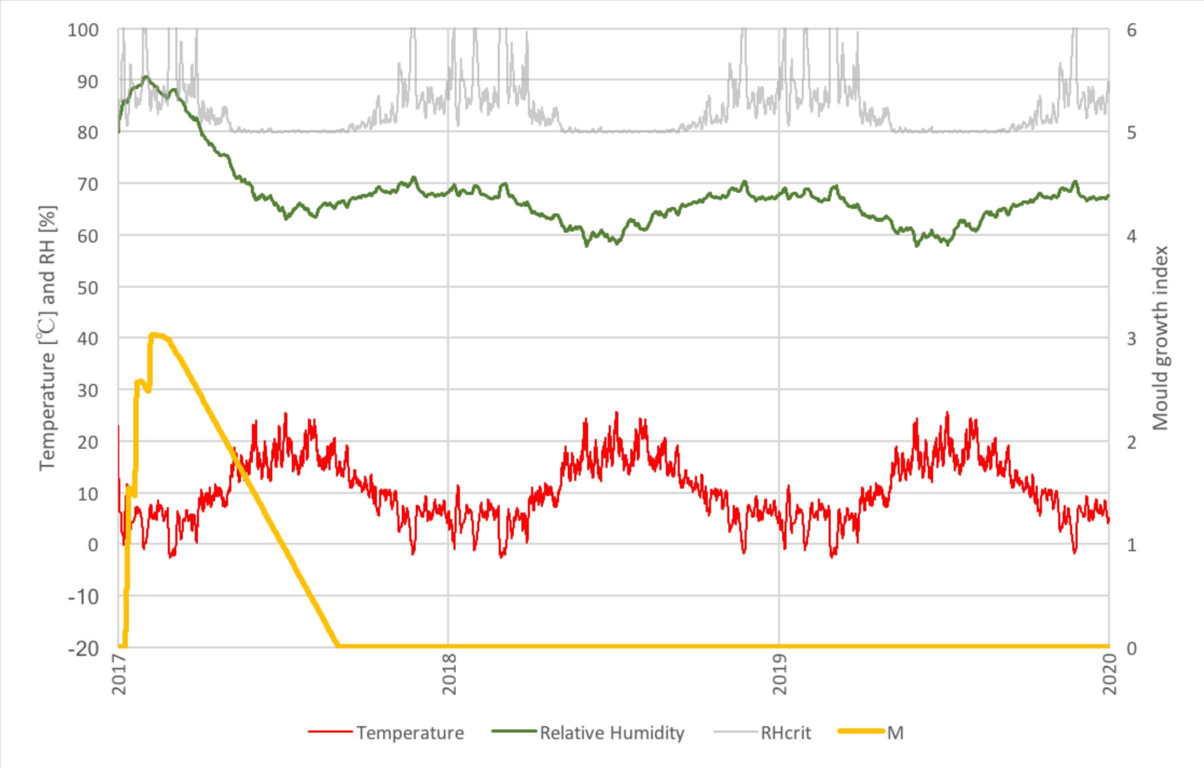

Figure 17: Case 1.5

Figure 18: Case 1.6

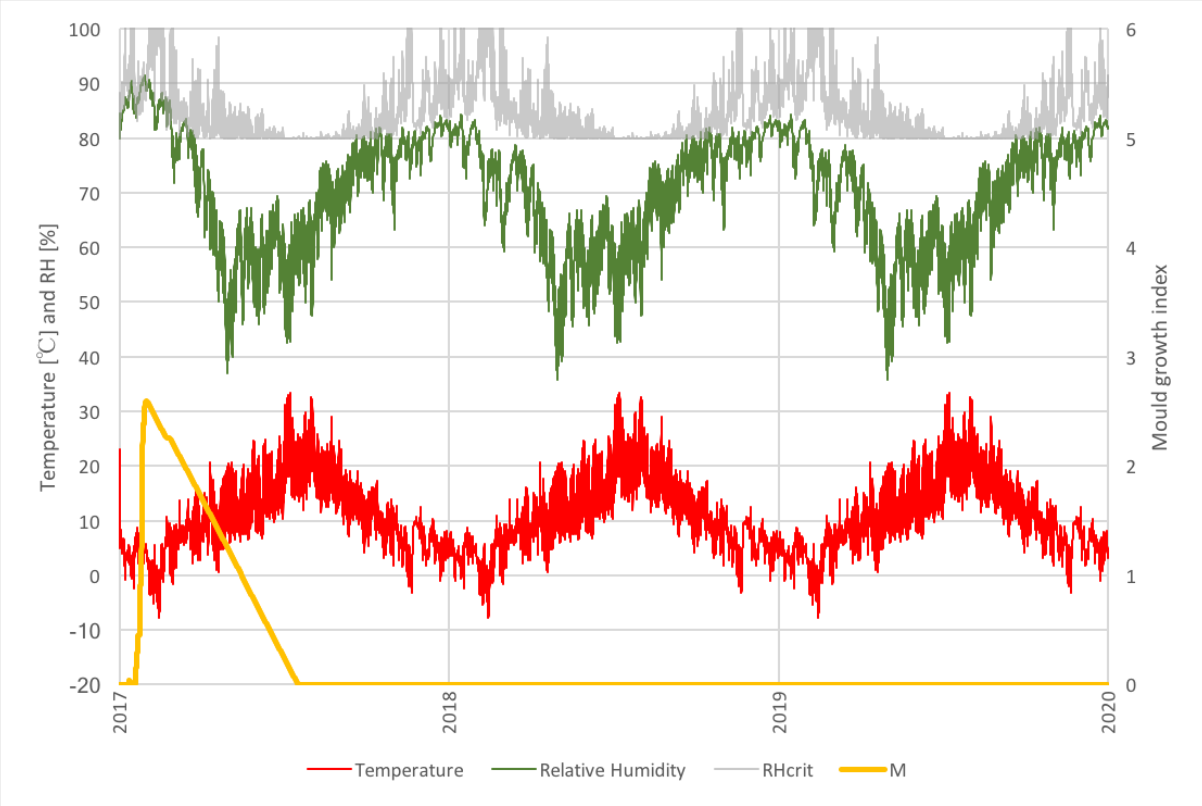

Figure 19: Case 1.7

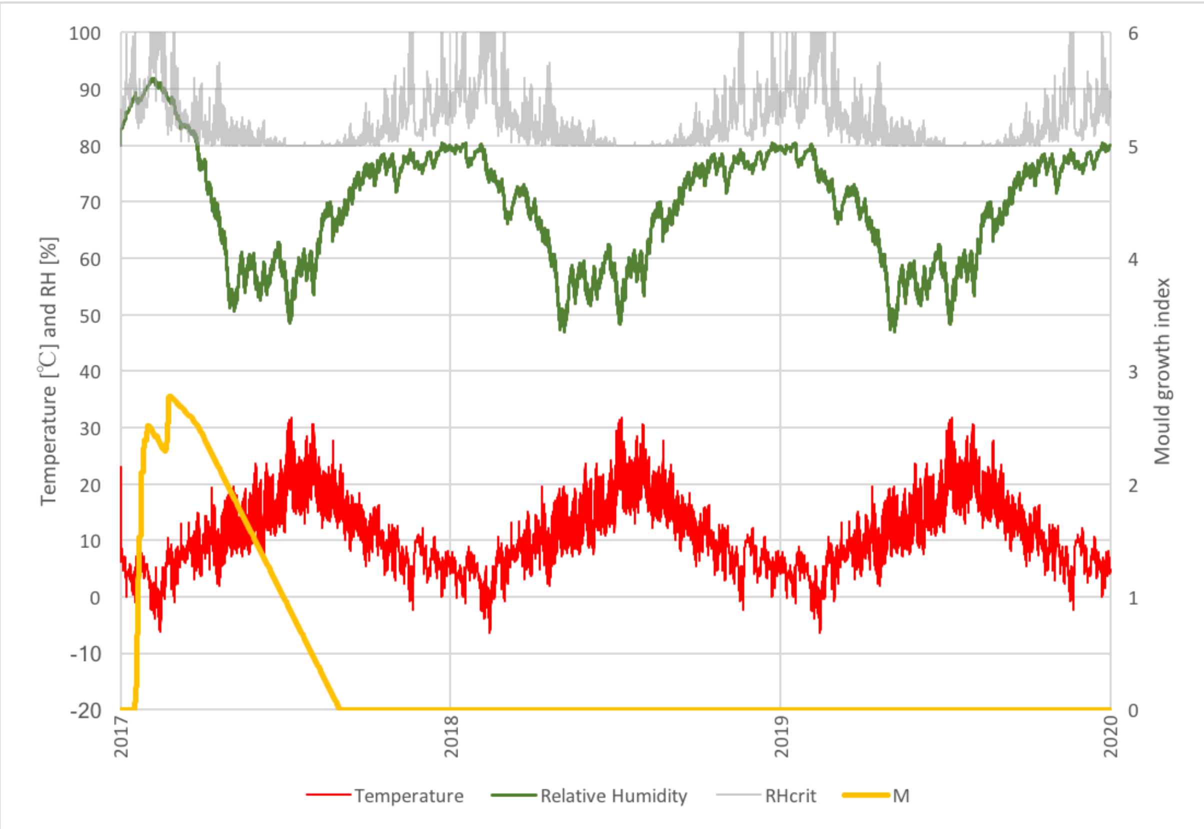

Figure 20: Case 1.8

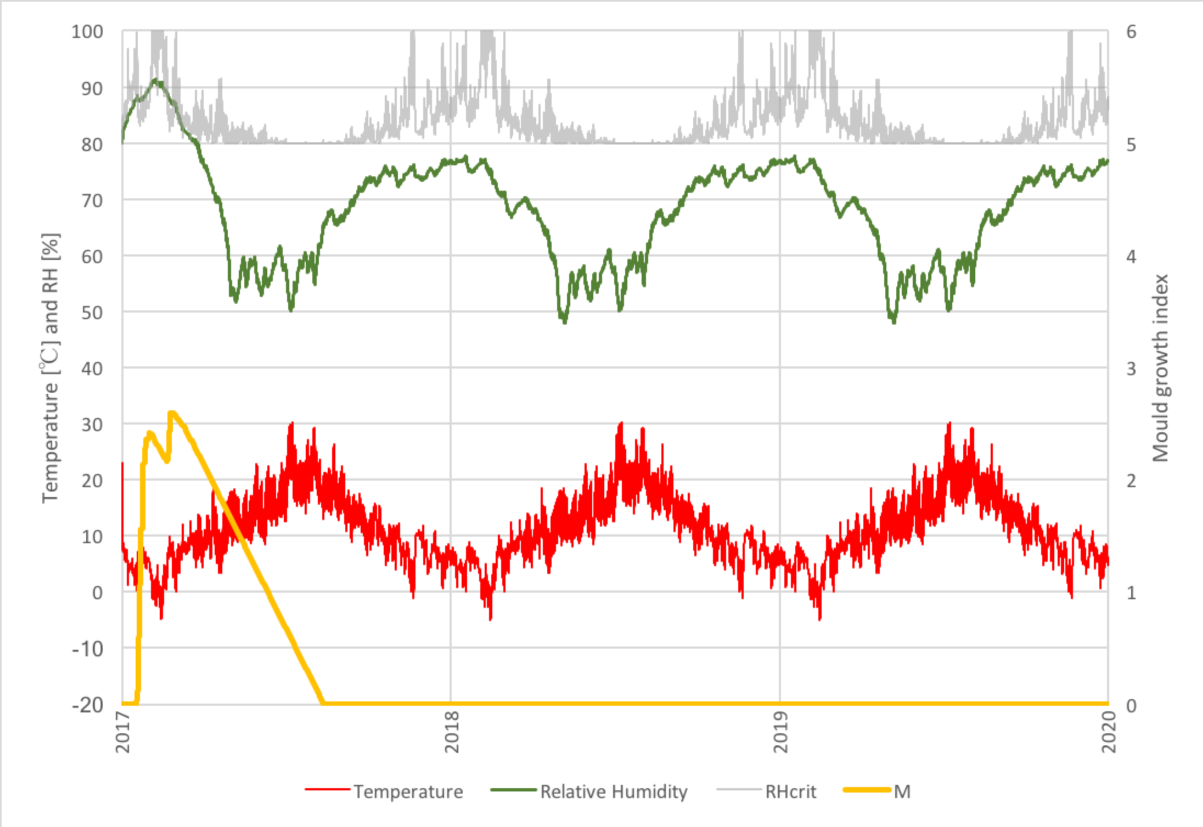

Figure 21: Case 1.9

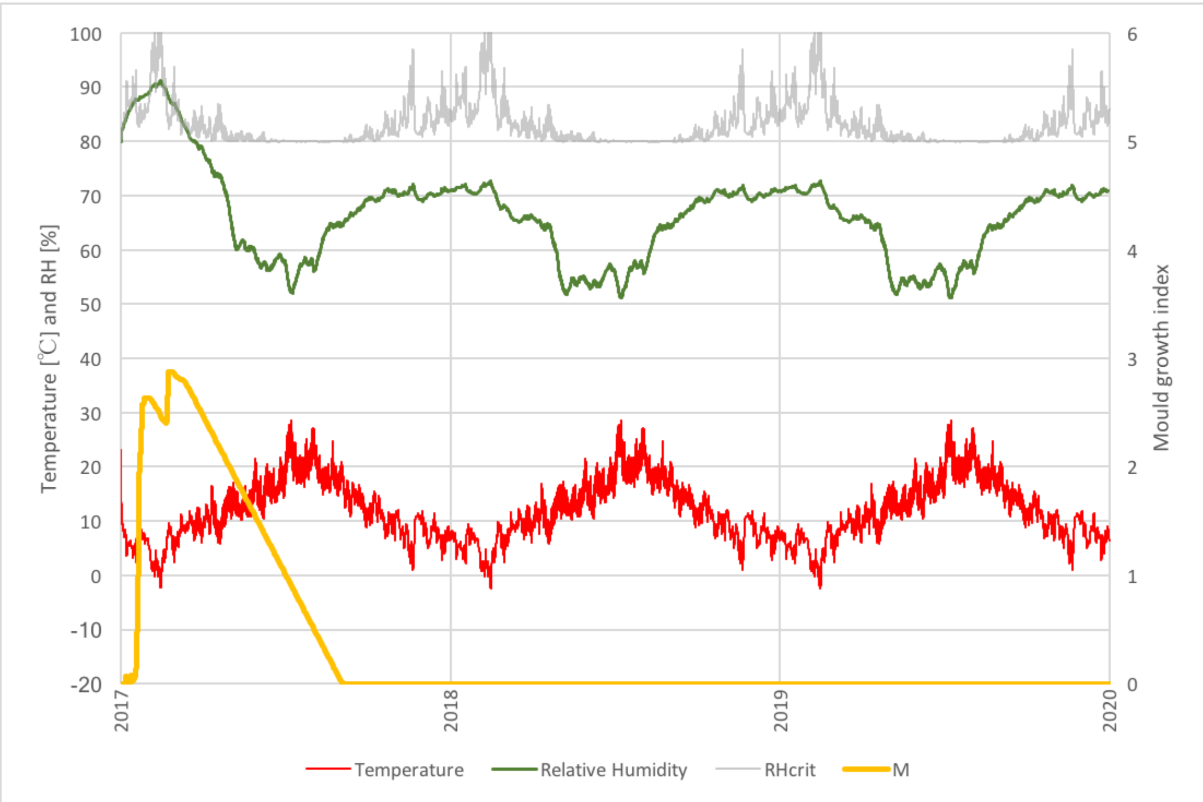

Figure 22: Case 1.10

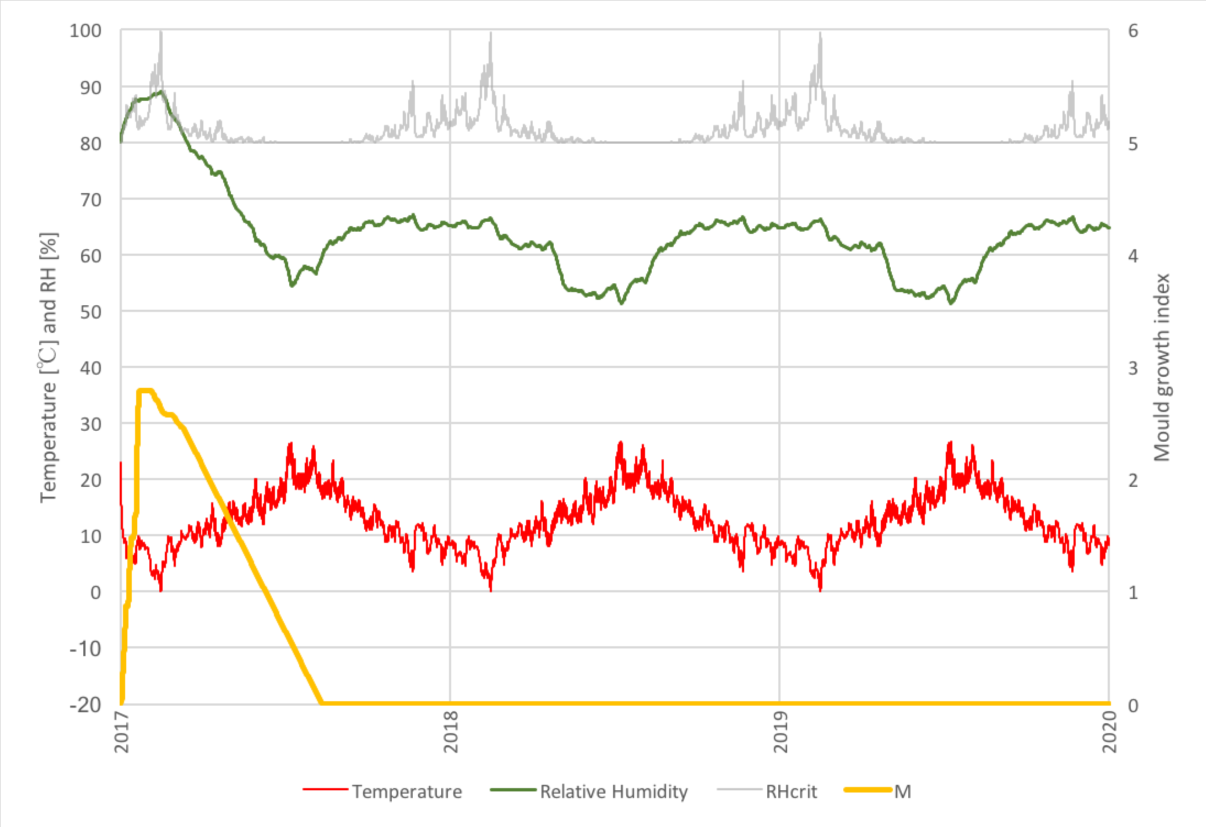

Figure 23: Case 1.11

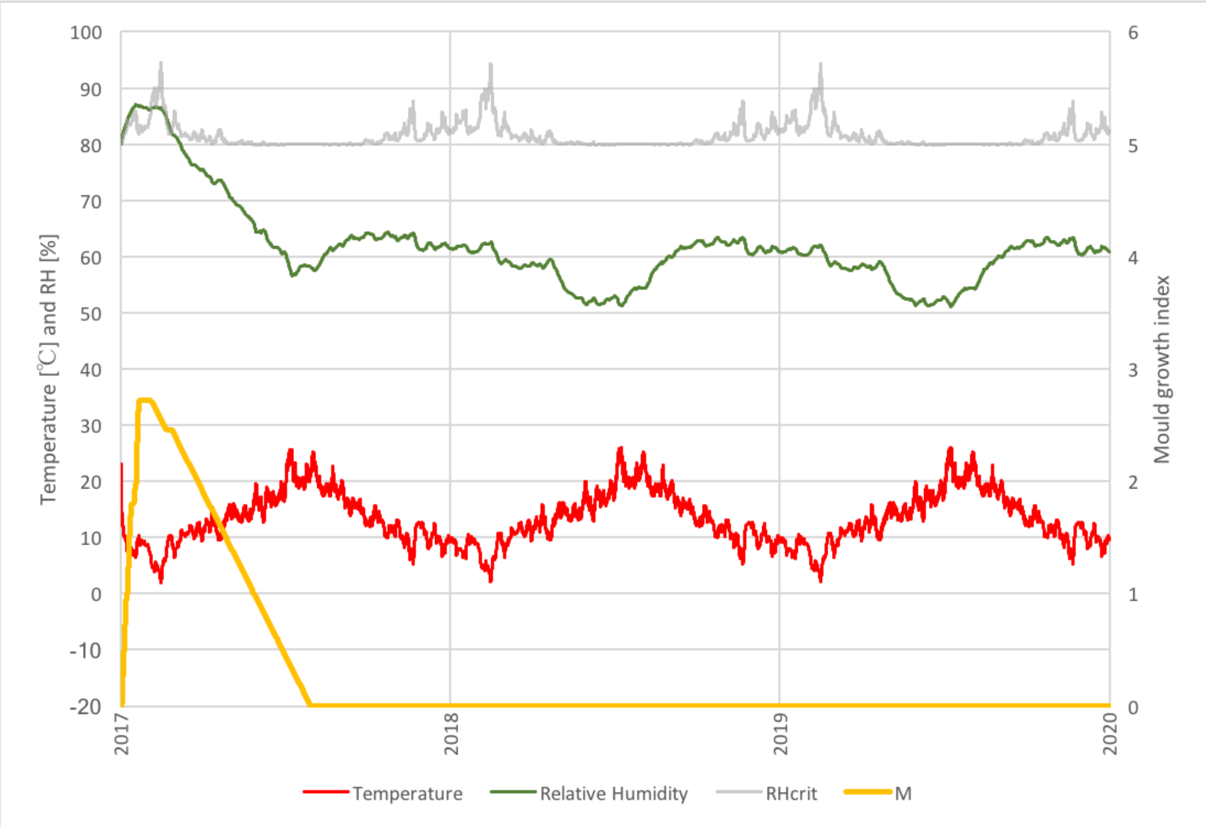

Figure 24: Case 1.12

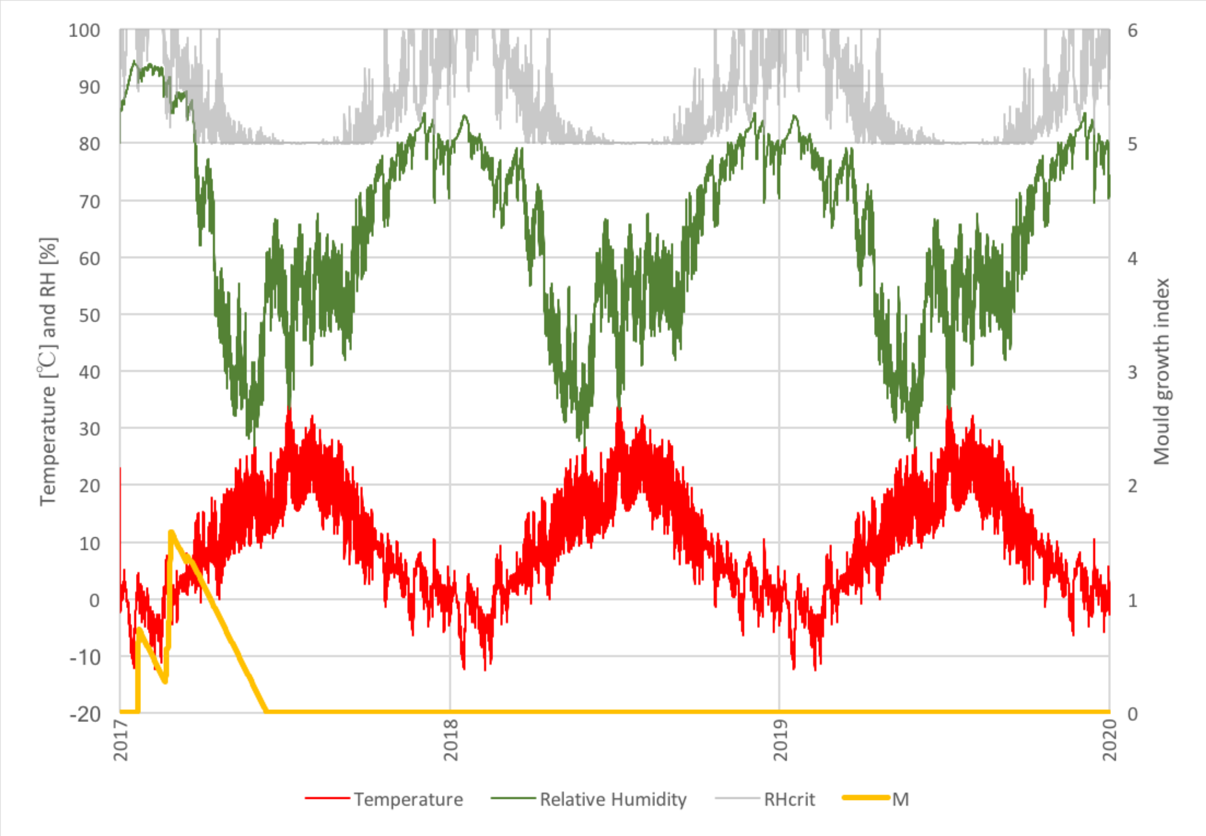

Figure 25: Case 1.13

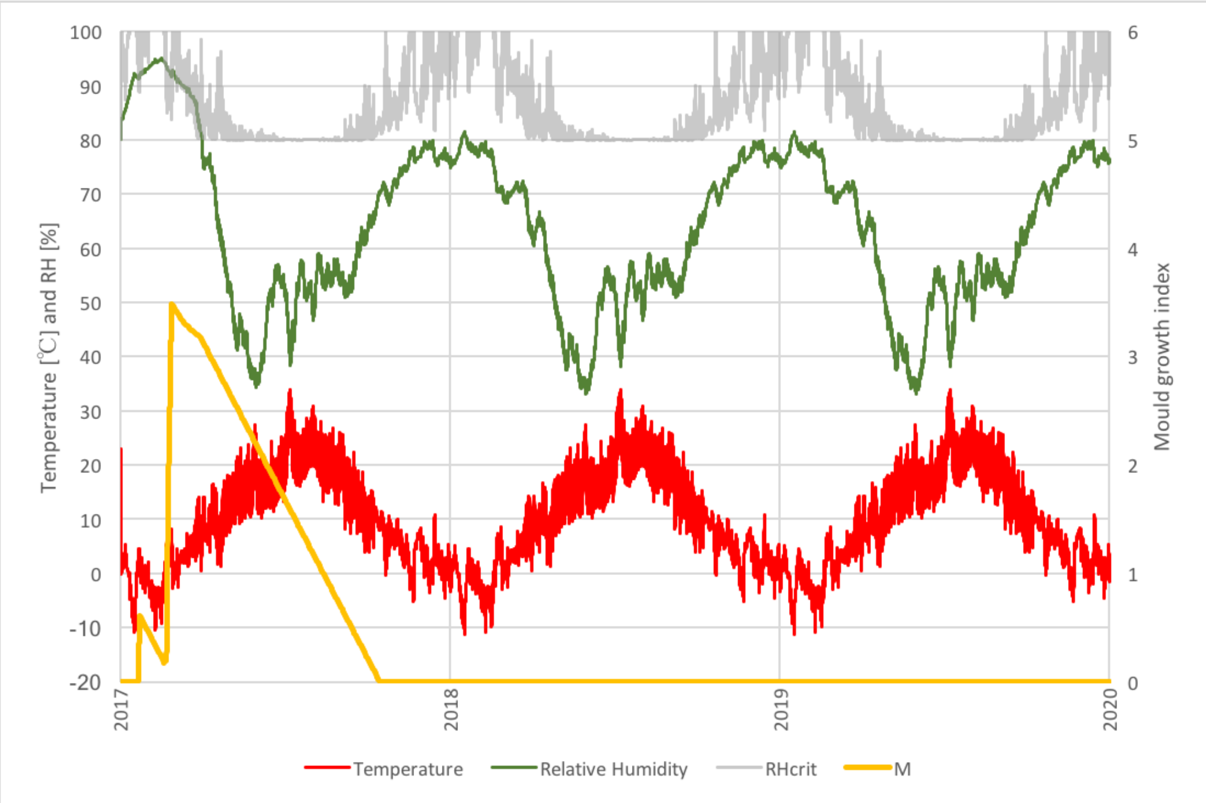

Figure 26: Case 1.14

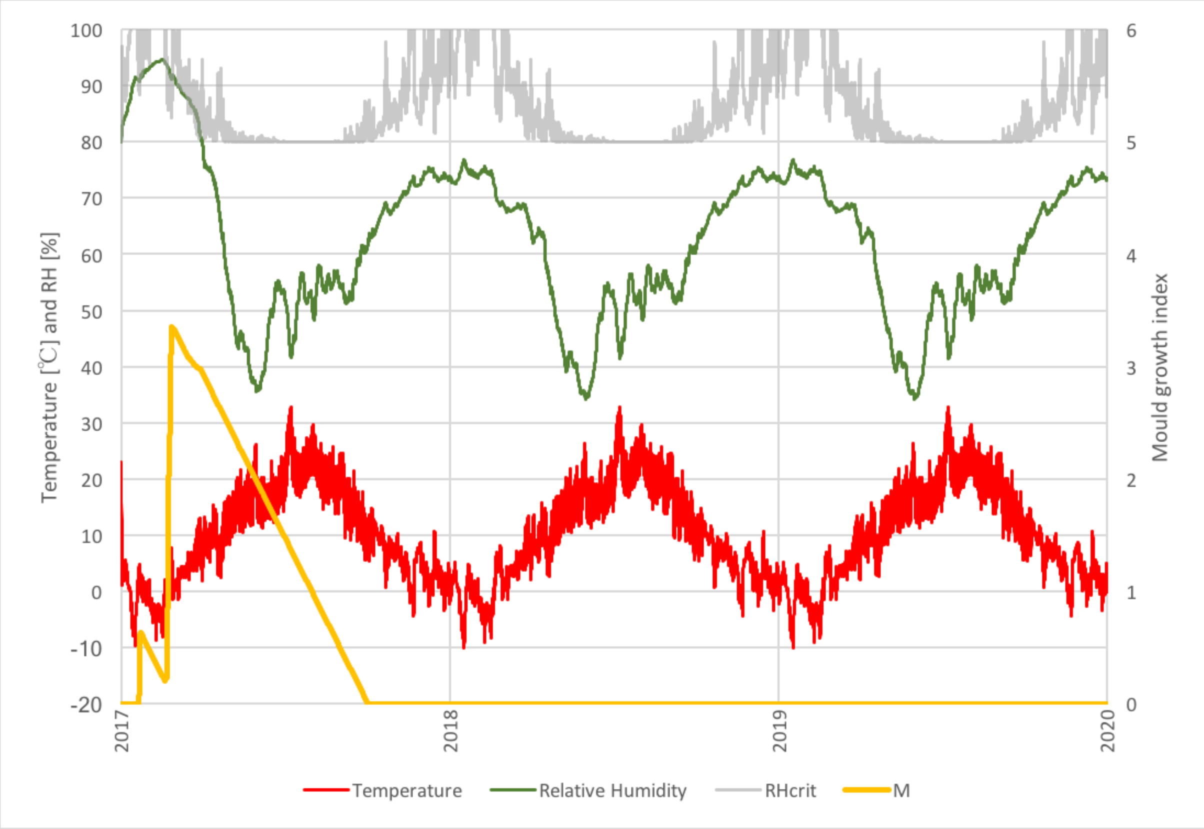

Figure 27: Case 1.15

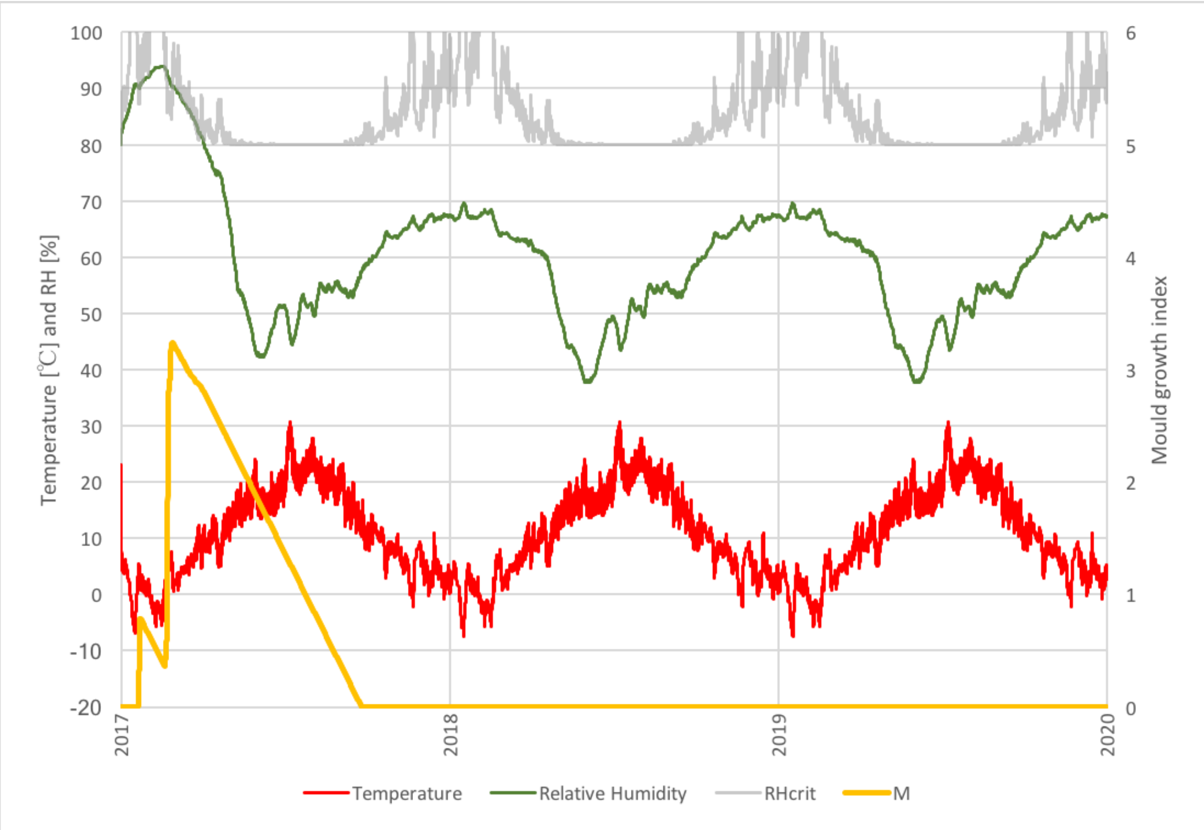

Figure 28: Case 1.16

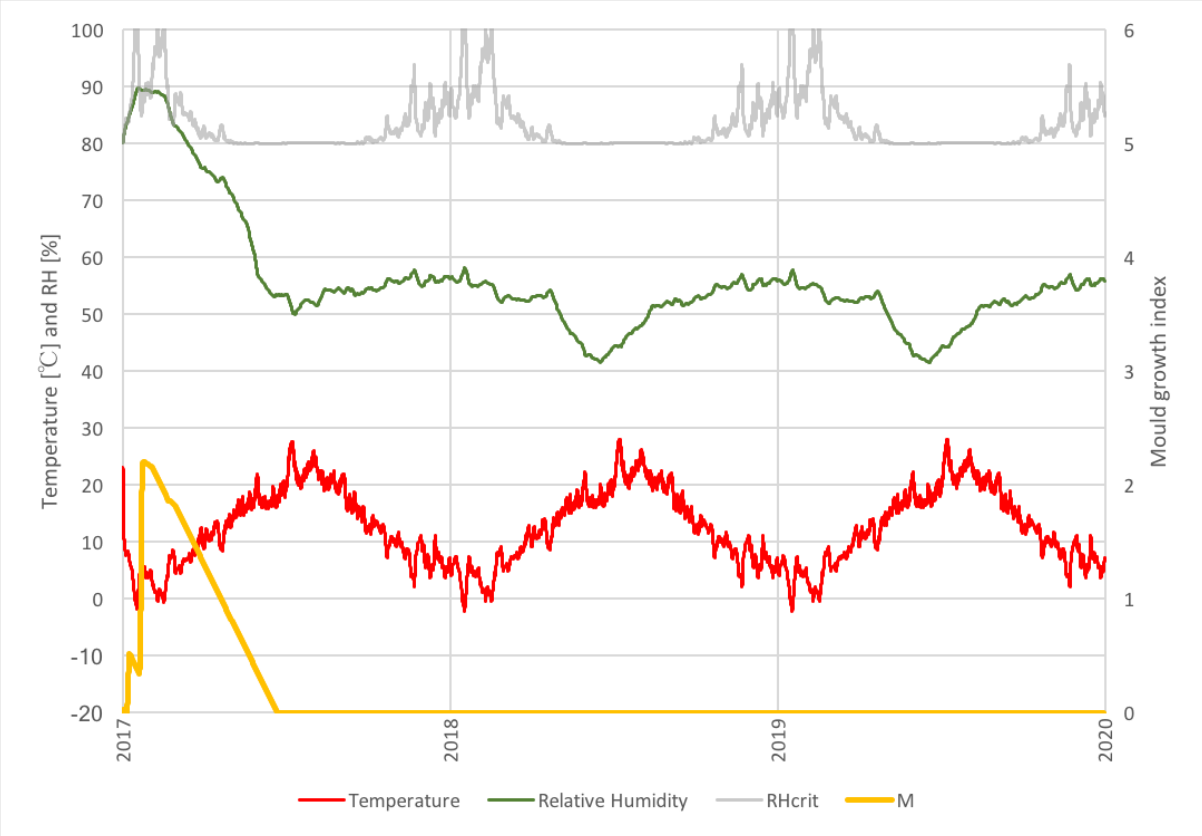

Figure 29: Case 1.17

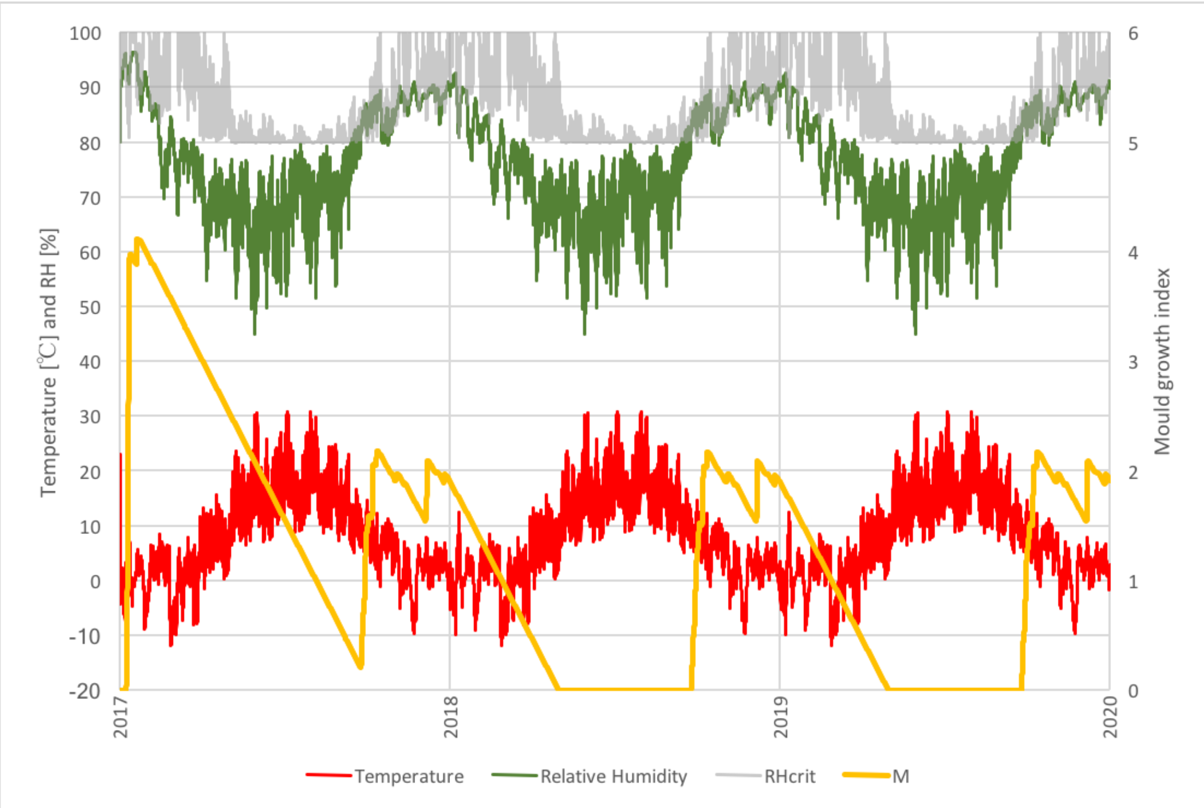

Figure 30: Case 1.18

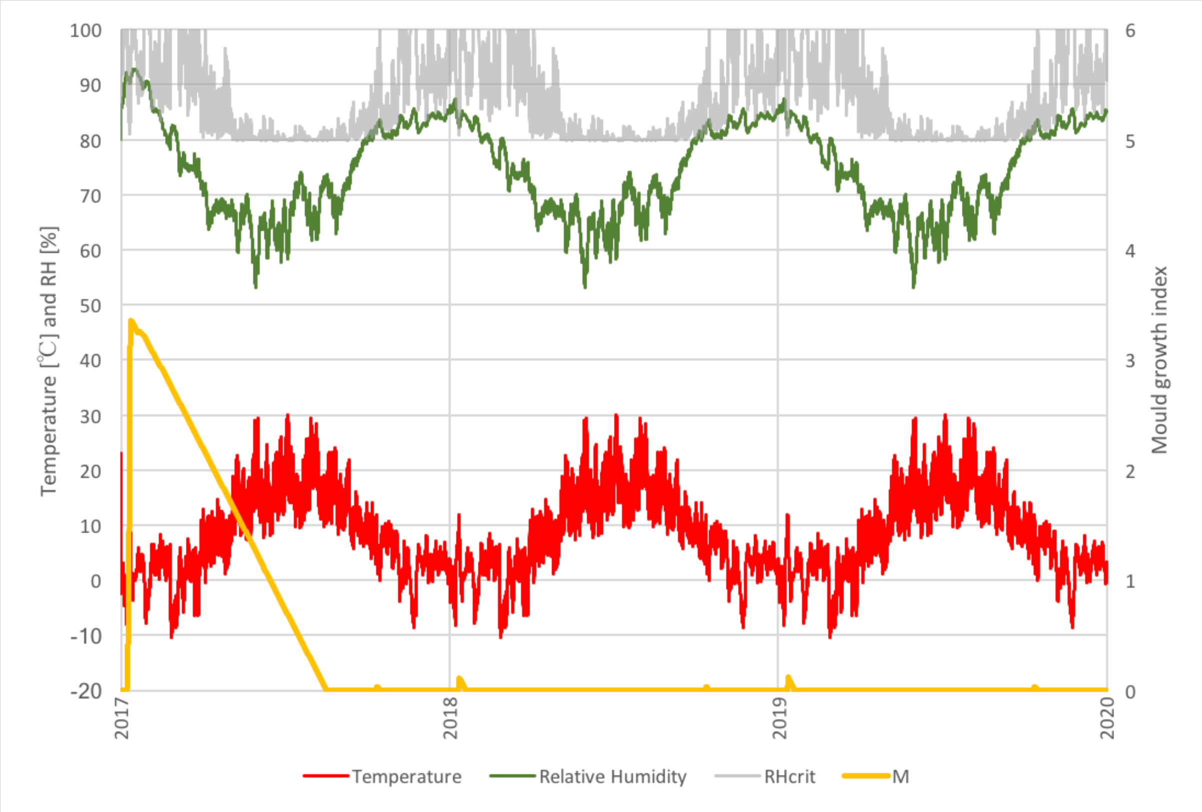

Figure 31: Case 1.19

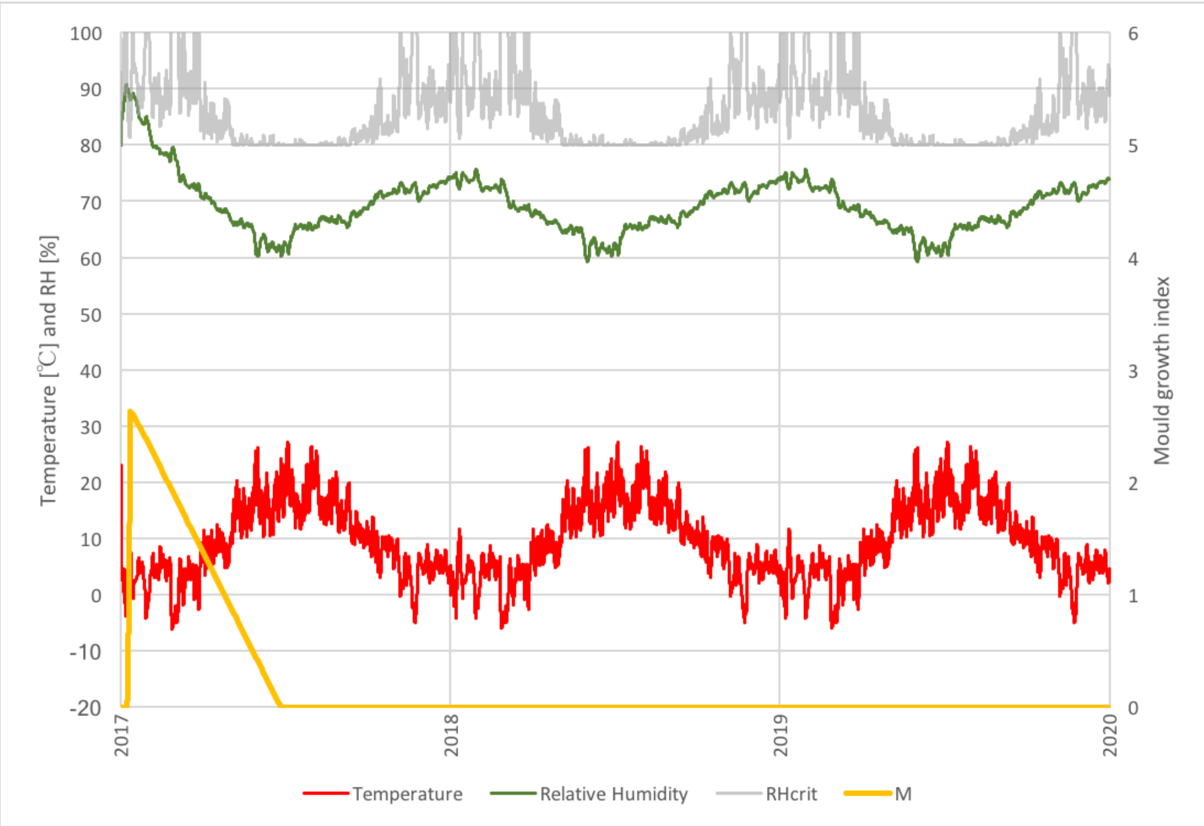

Figure 32: Case 1.20

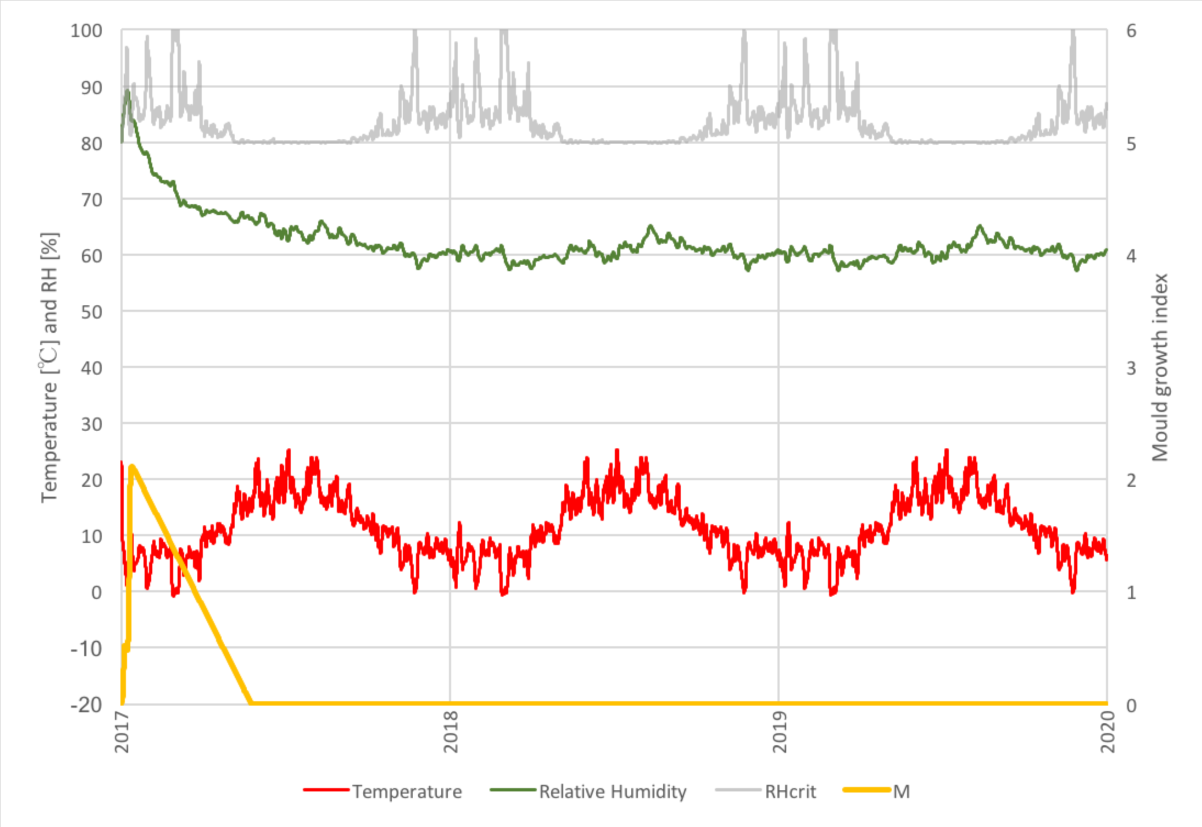

Figure 33: Case 1.21

Figure 34: Case 1.22

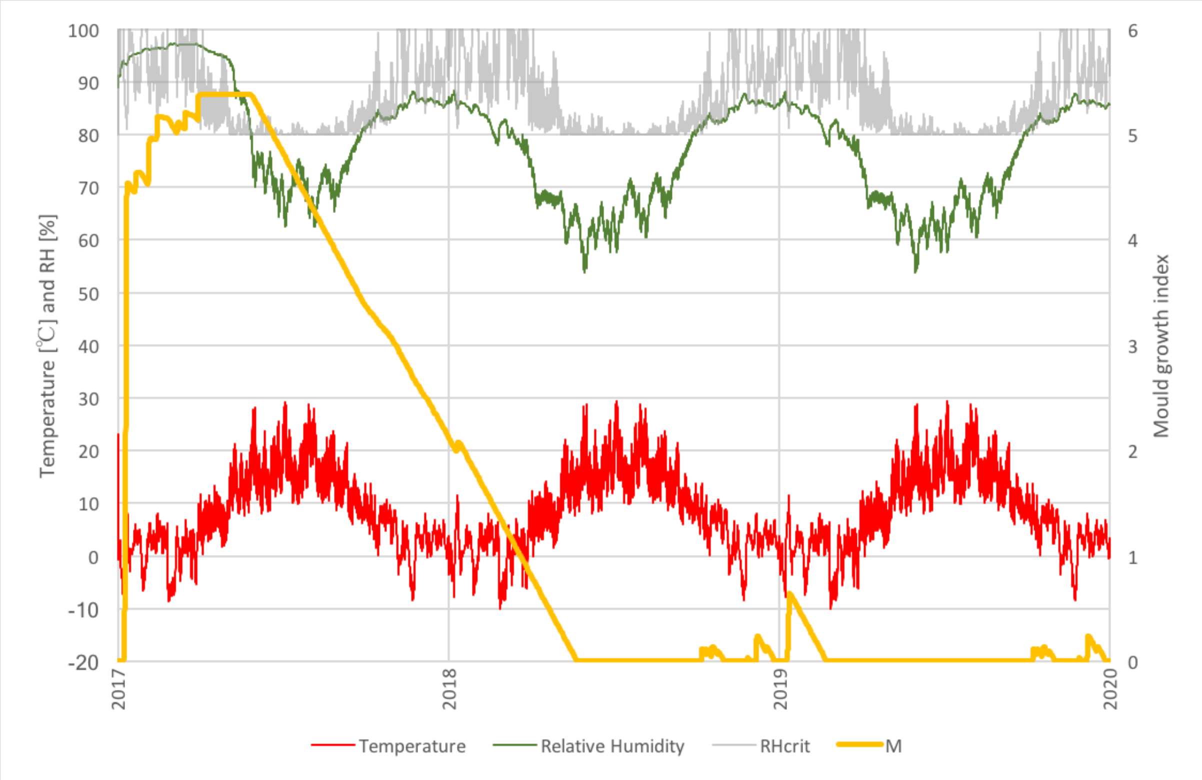

Figure 35: Case 1.23

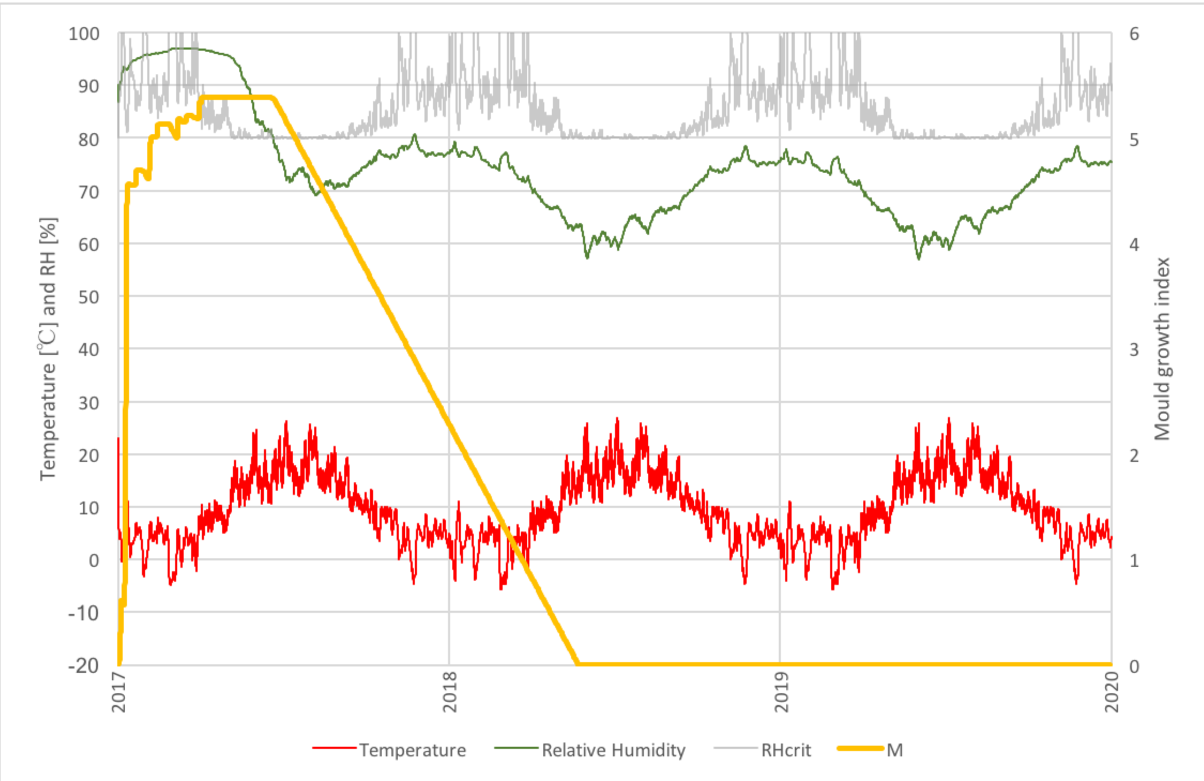

Figure 36: Case 1.24

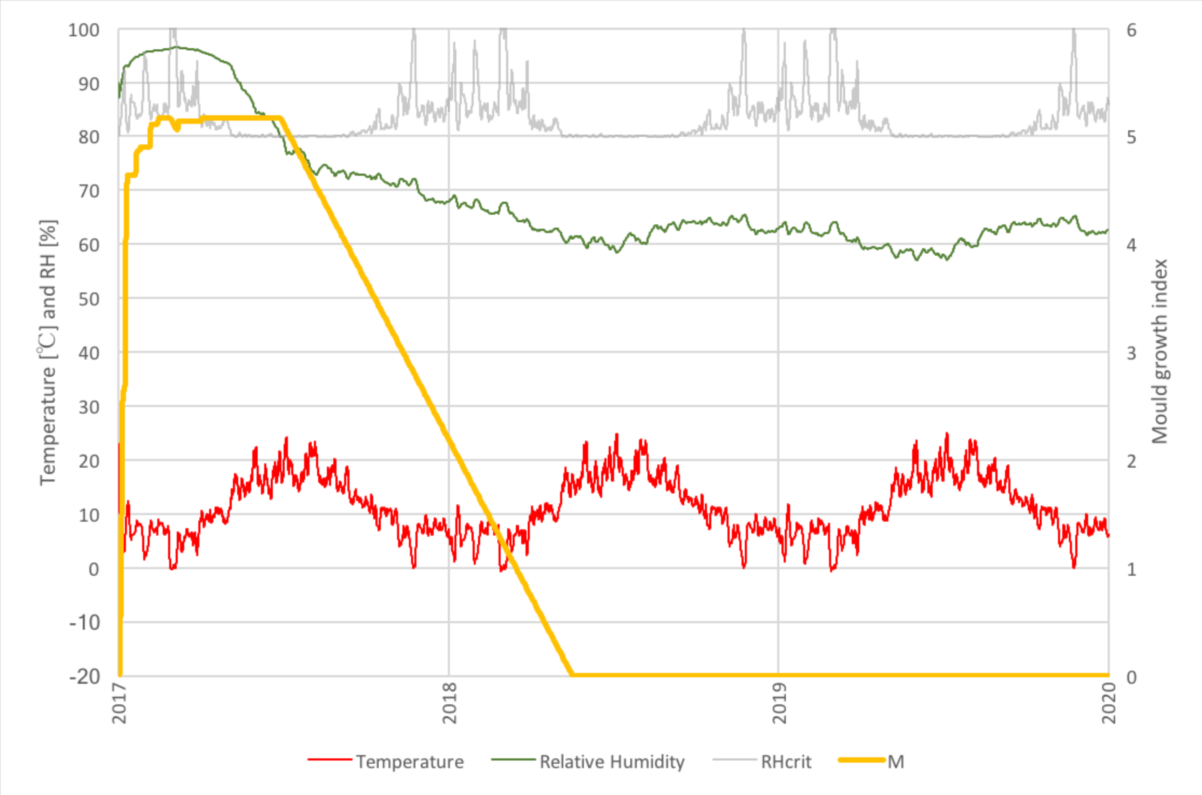

Figure 37: Case 1.25

Appendix G RESULTS OF MOISTURE SIMULATIONS - STUDY 2

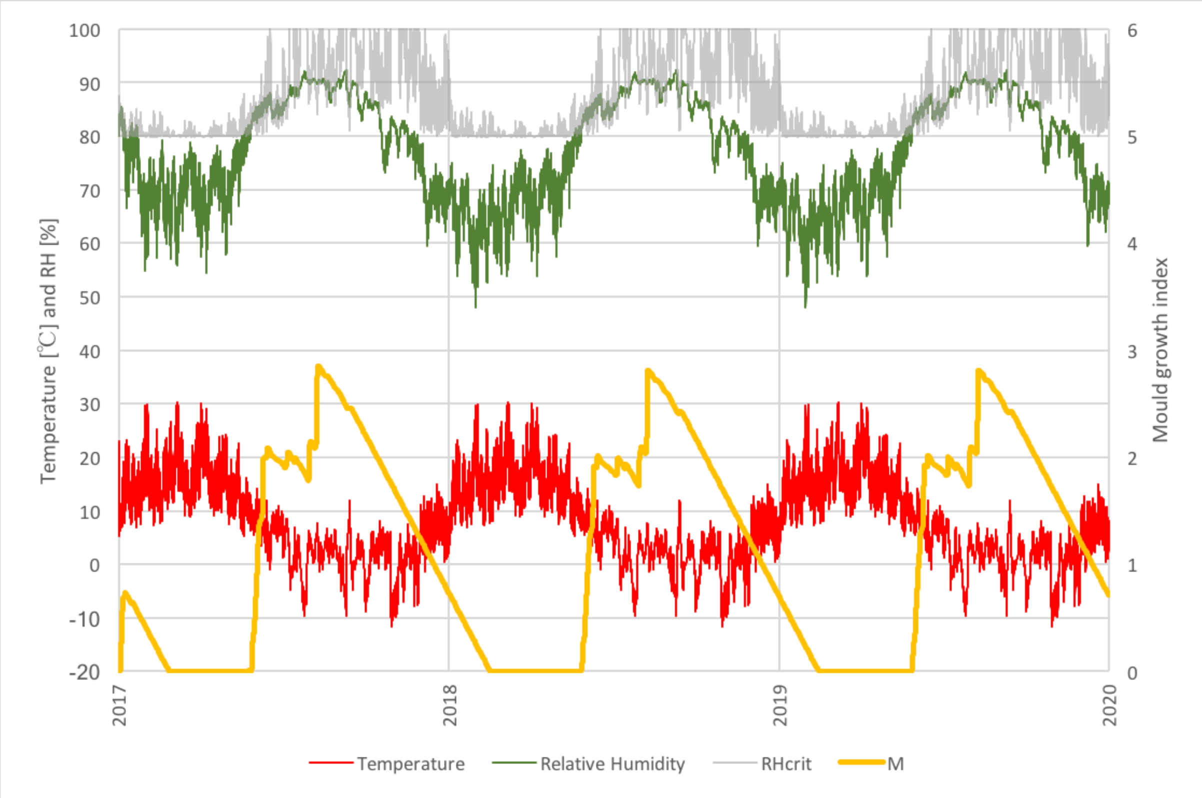

Figure 38: Case 2.1

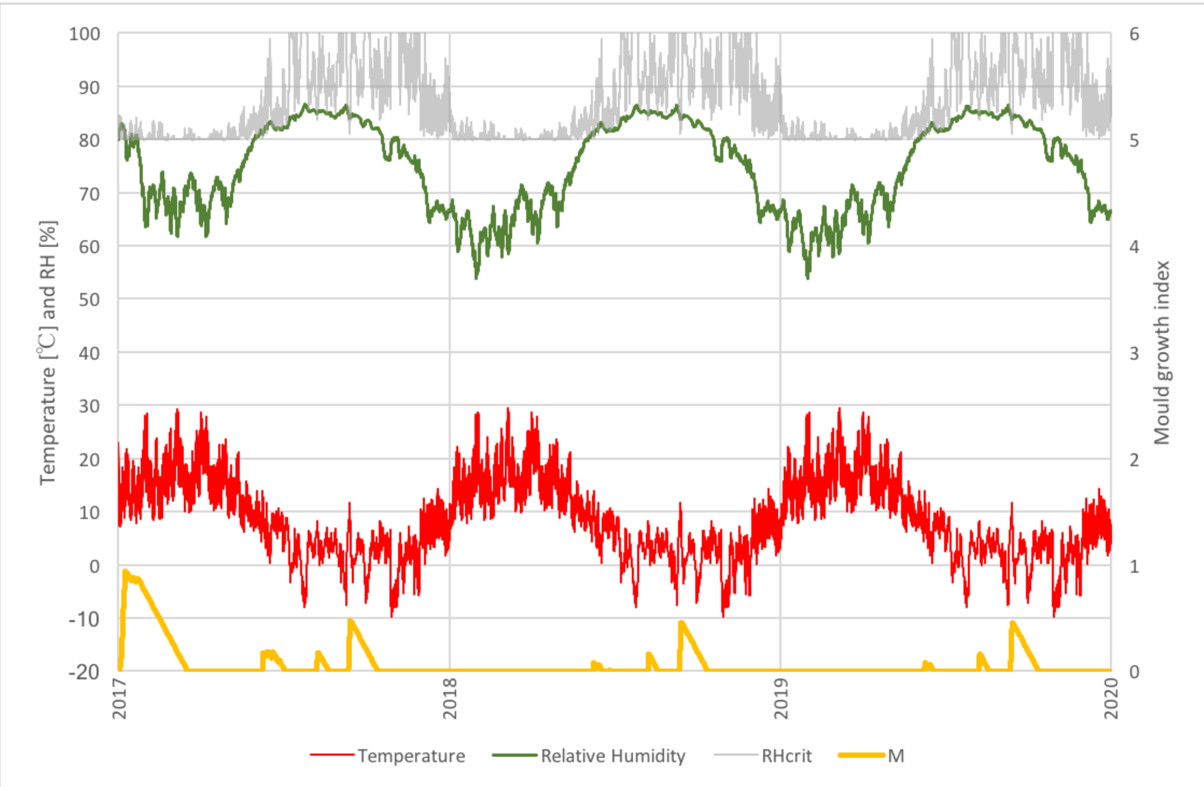

Figure 39: Case 2.2

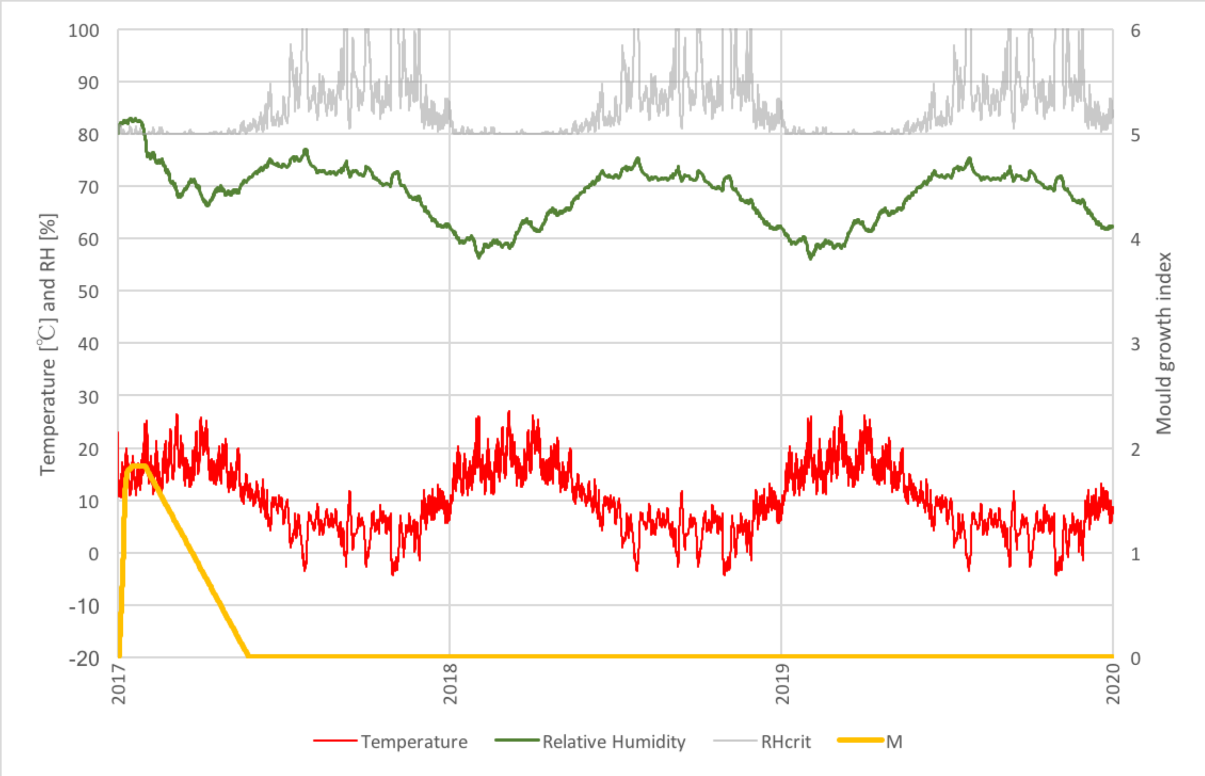

Figure 40: Case 2.3

Figure 41: Case 2.4

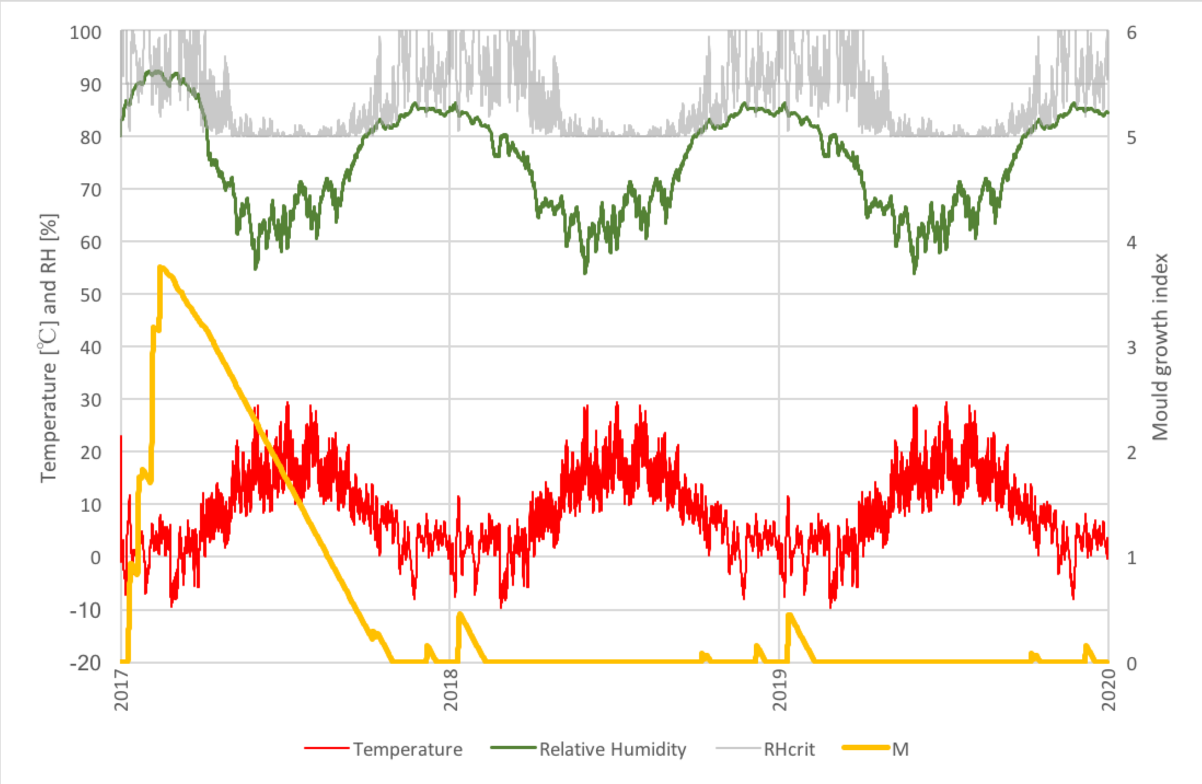

Figure 42: Case 2.5

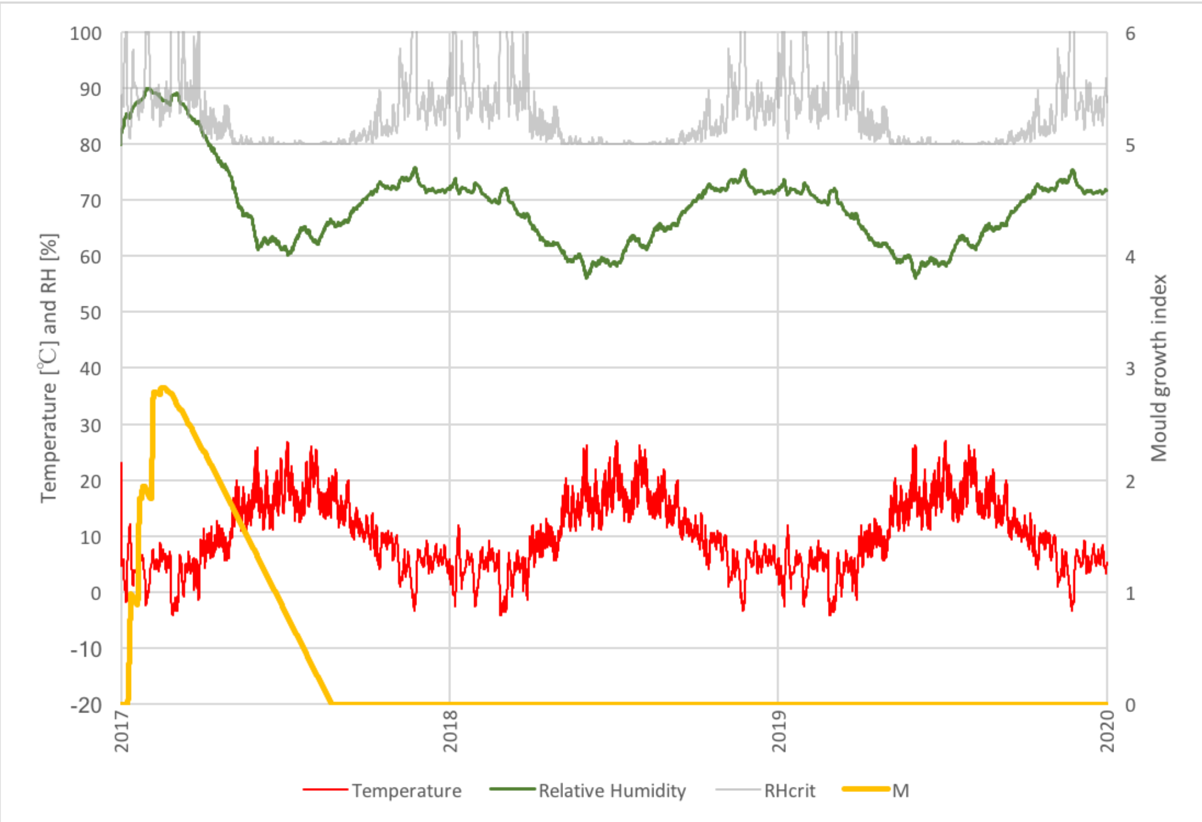

Figure 43: Case 2.6

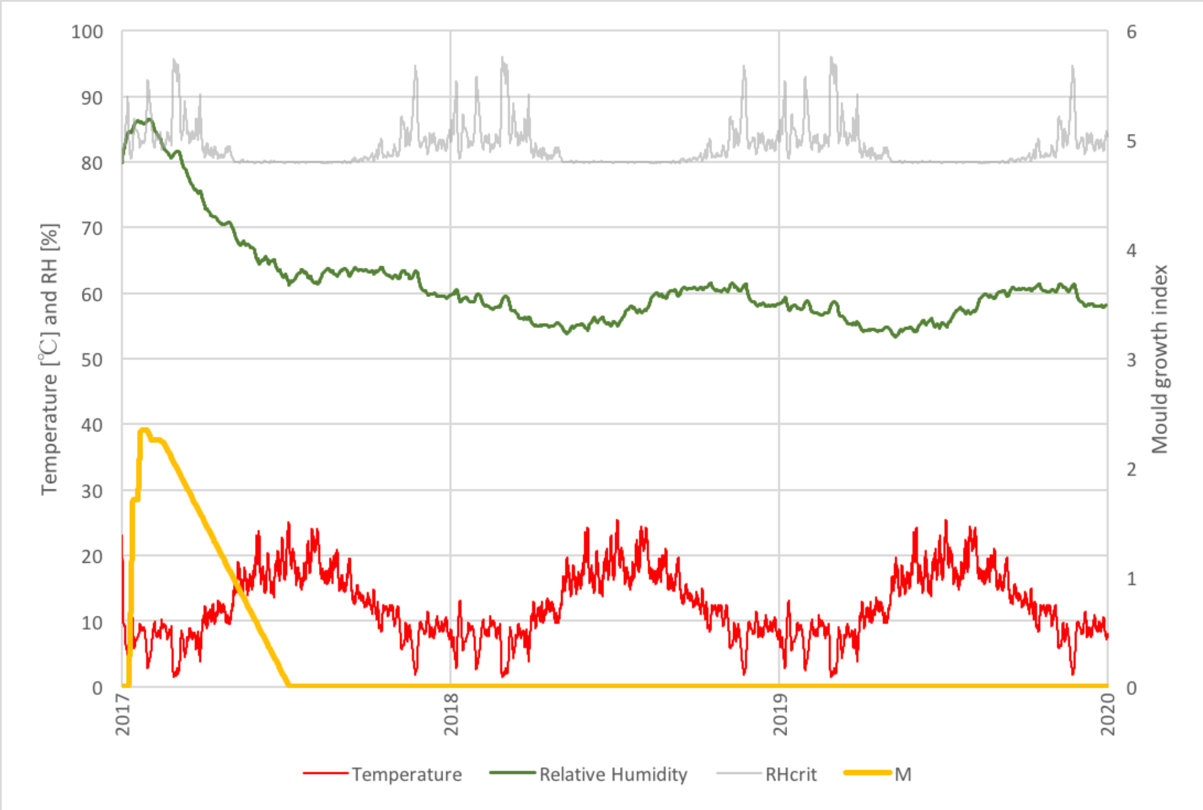

Figure 44: Case 2.7

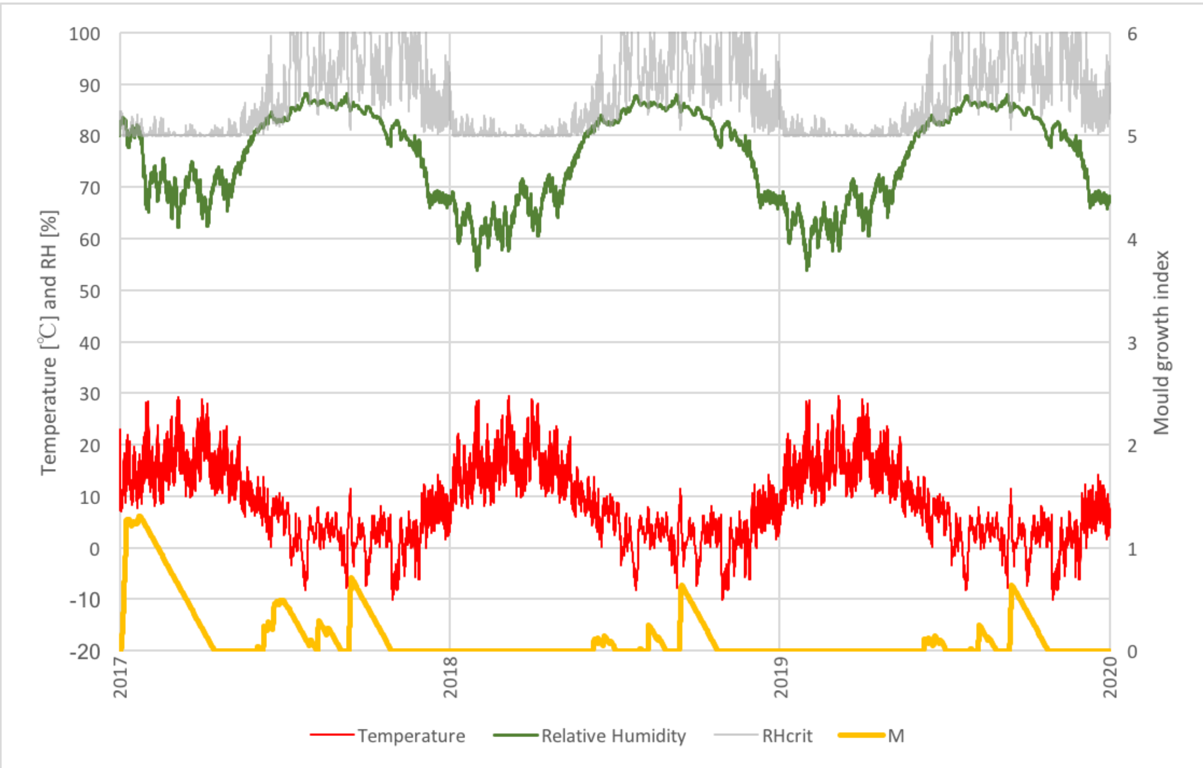

Figure 45: Case 2.8

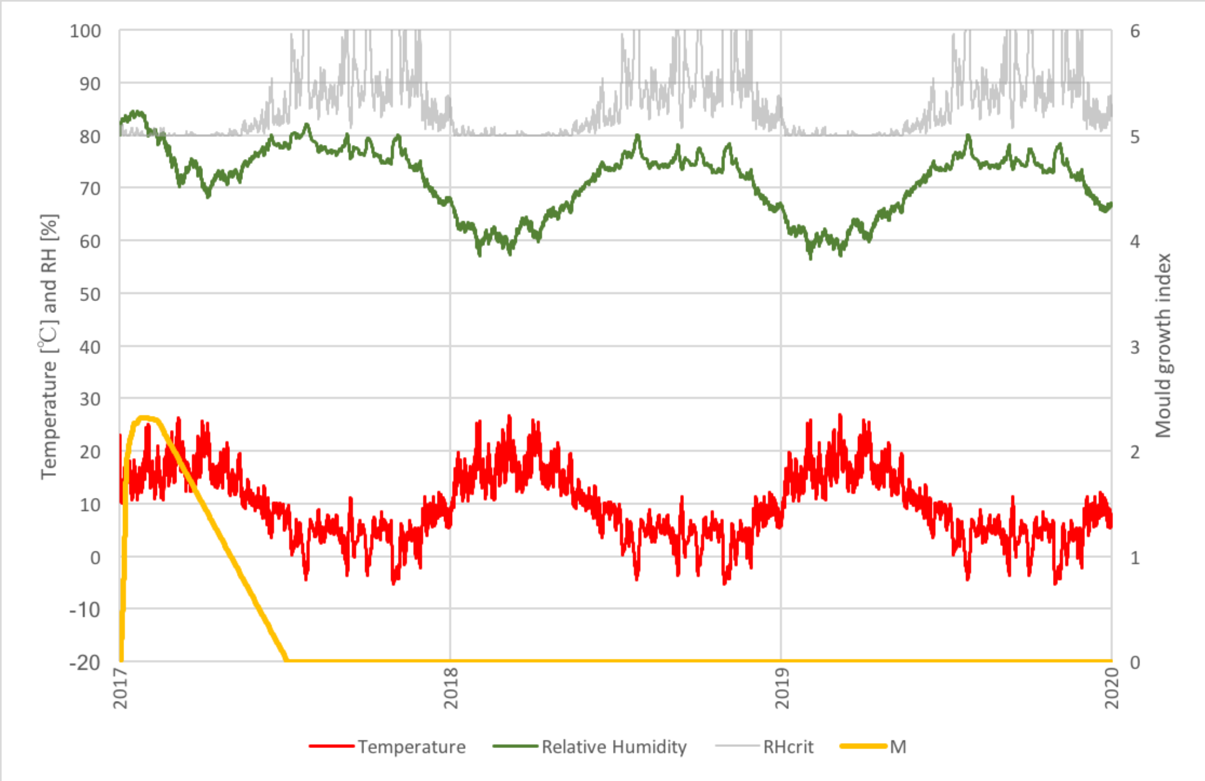

Figure 46: Case 2.9

Figure 47: Case 2.10

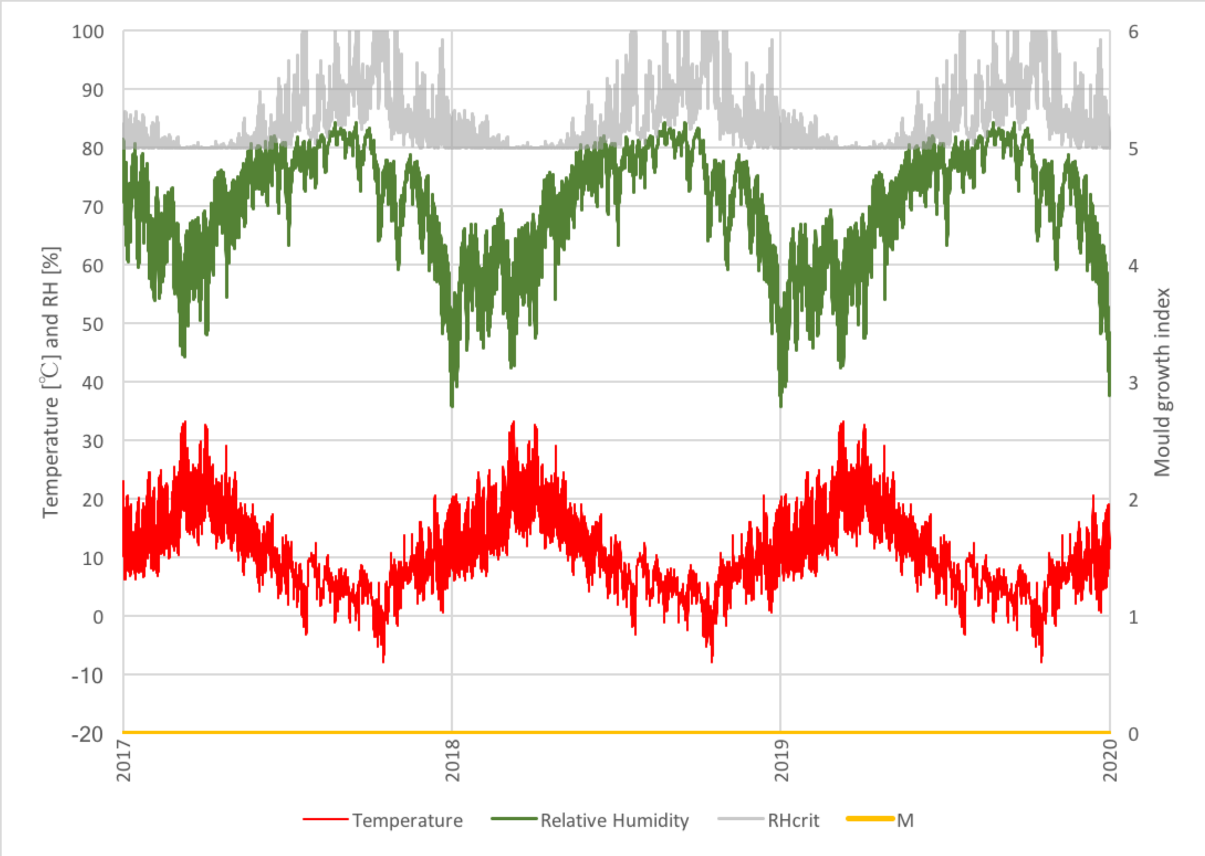

Figure 48: Case 2.11

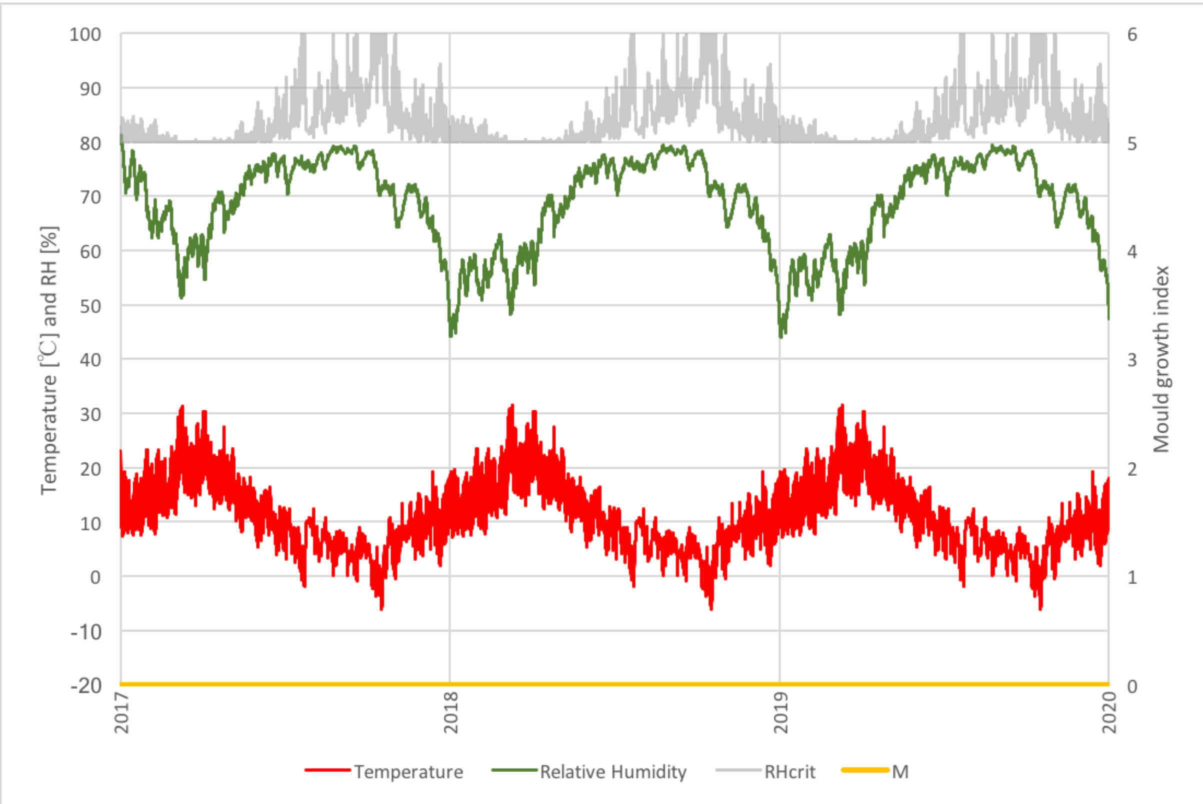

Figure 49: Case 2.12

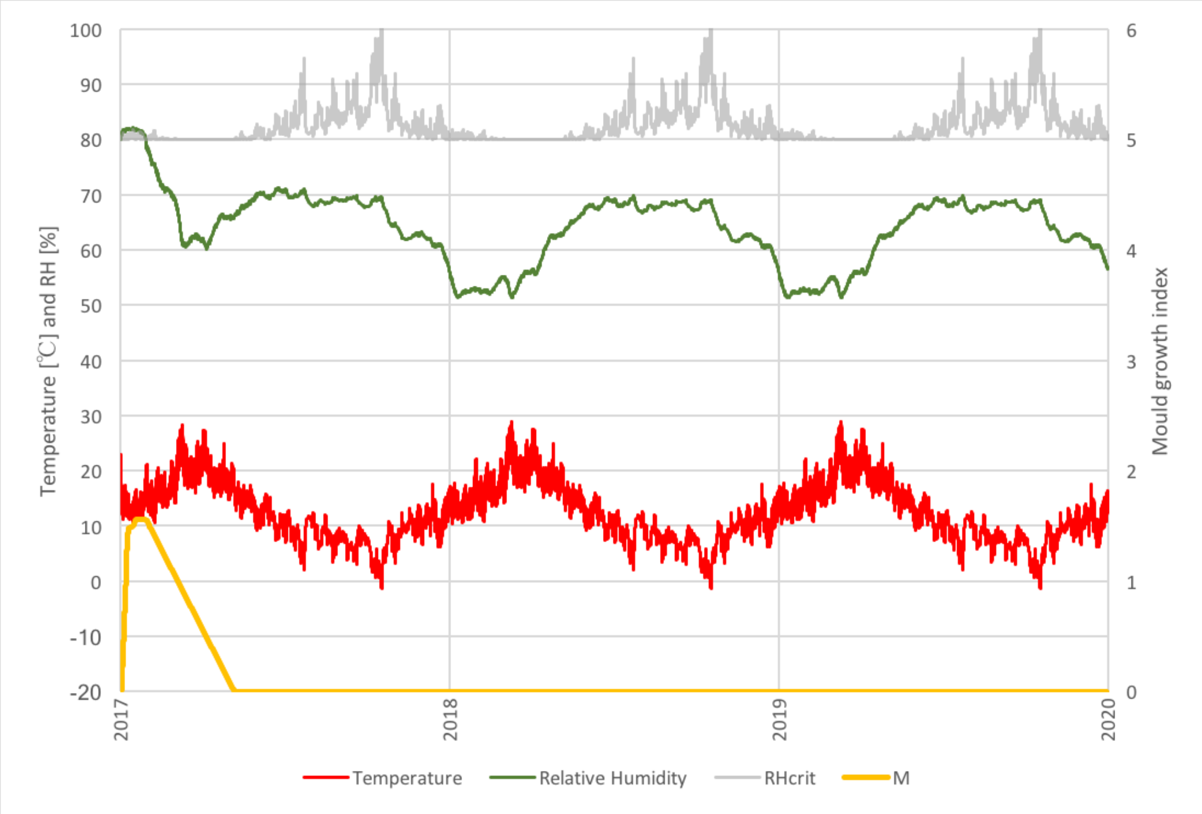

Figure 50: Case 2.13

Figure 51: Case 2.14

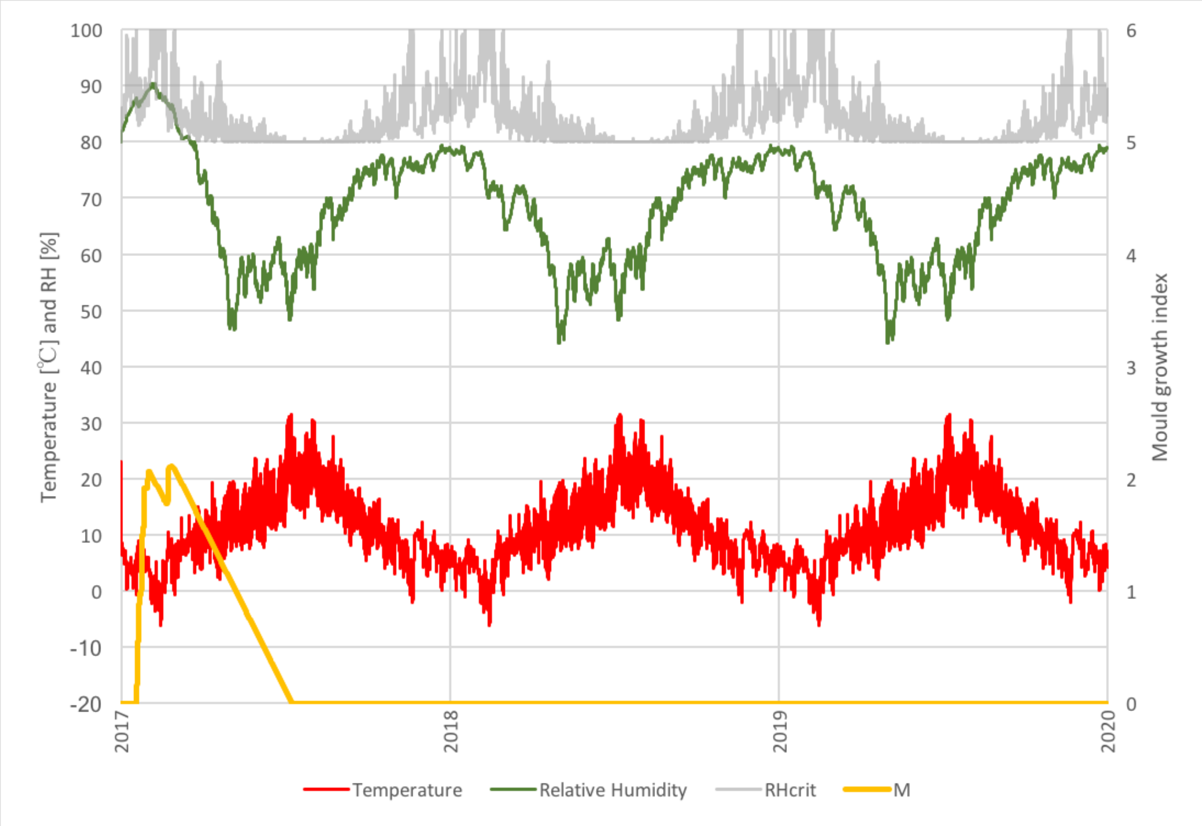

Figure 52: Case 2.15

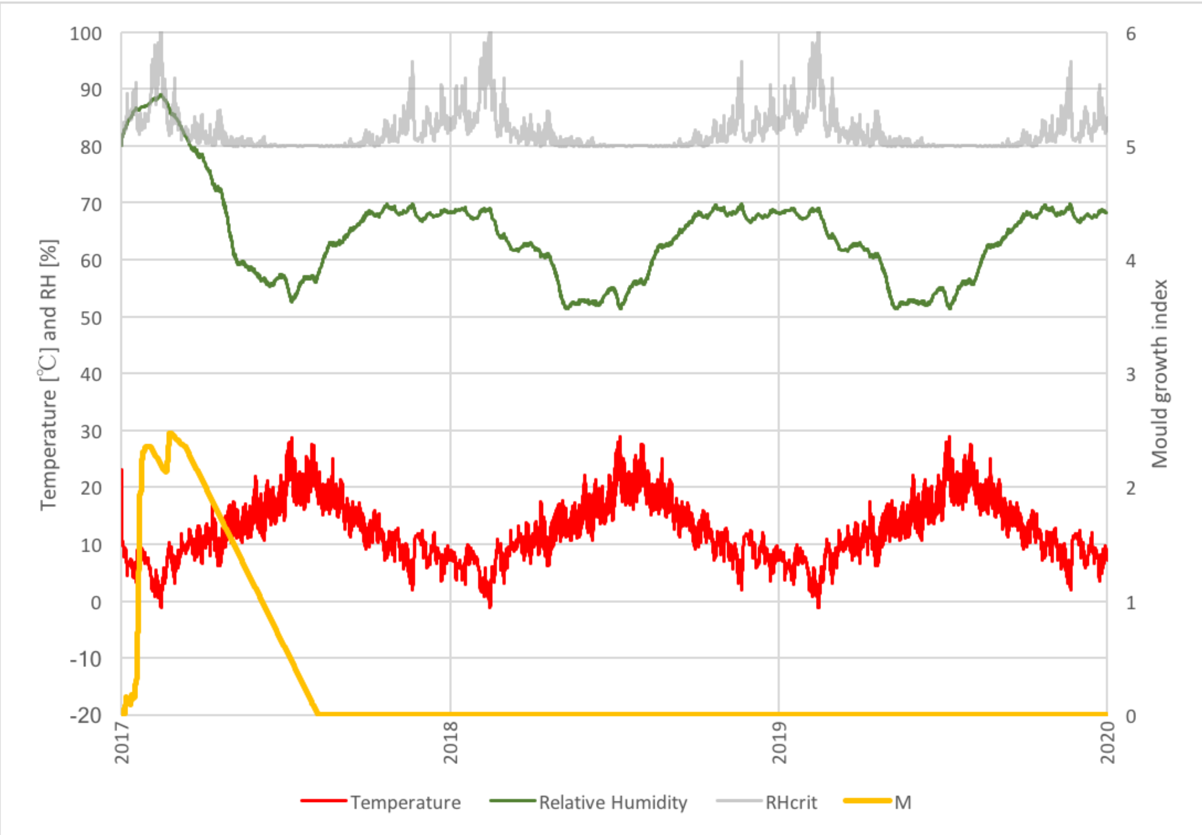

Figure 53: Case 2.16

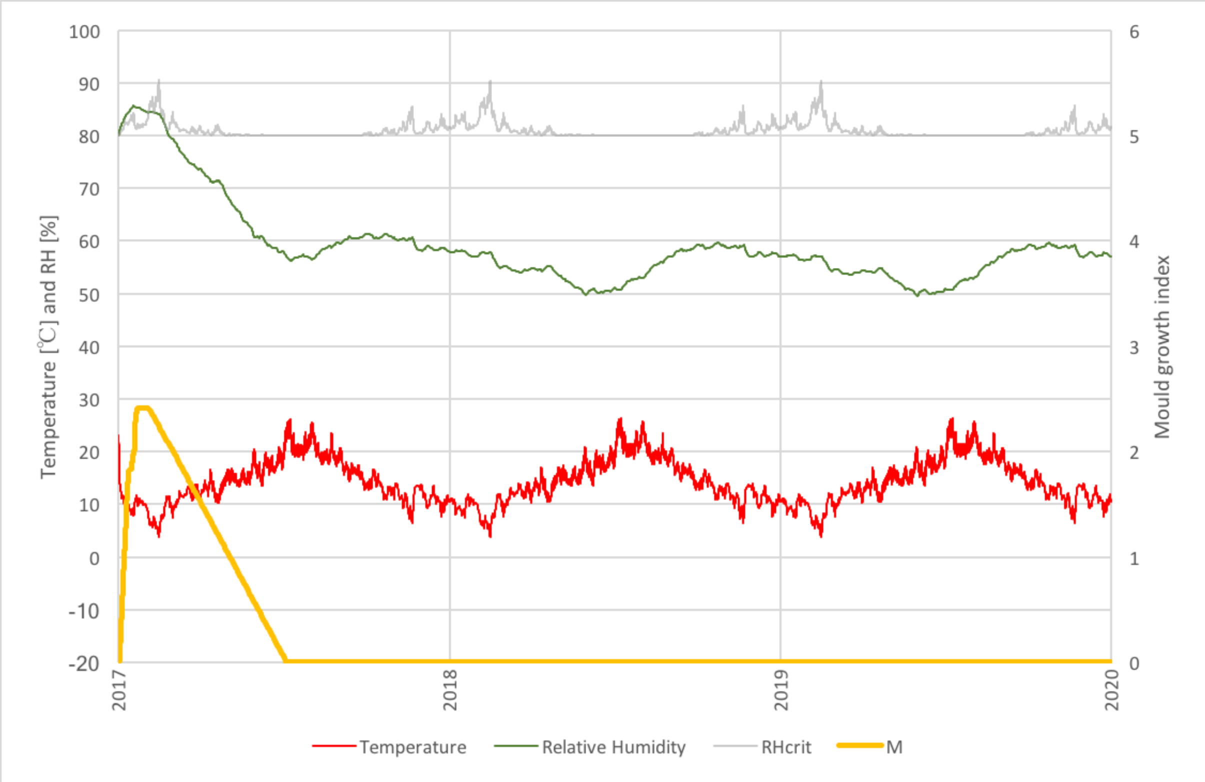

Figure 54: Case 2.17

Figure 55: Case 2.18

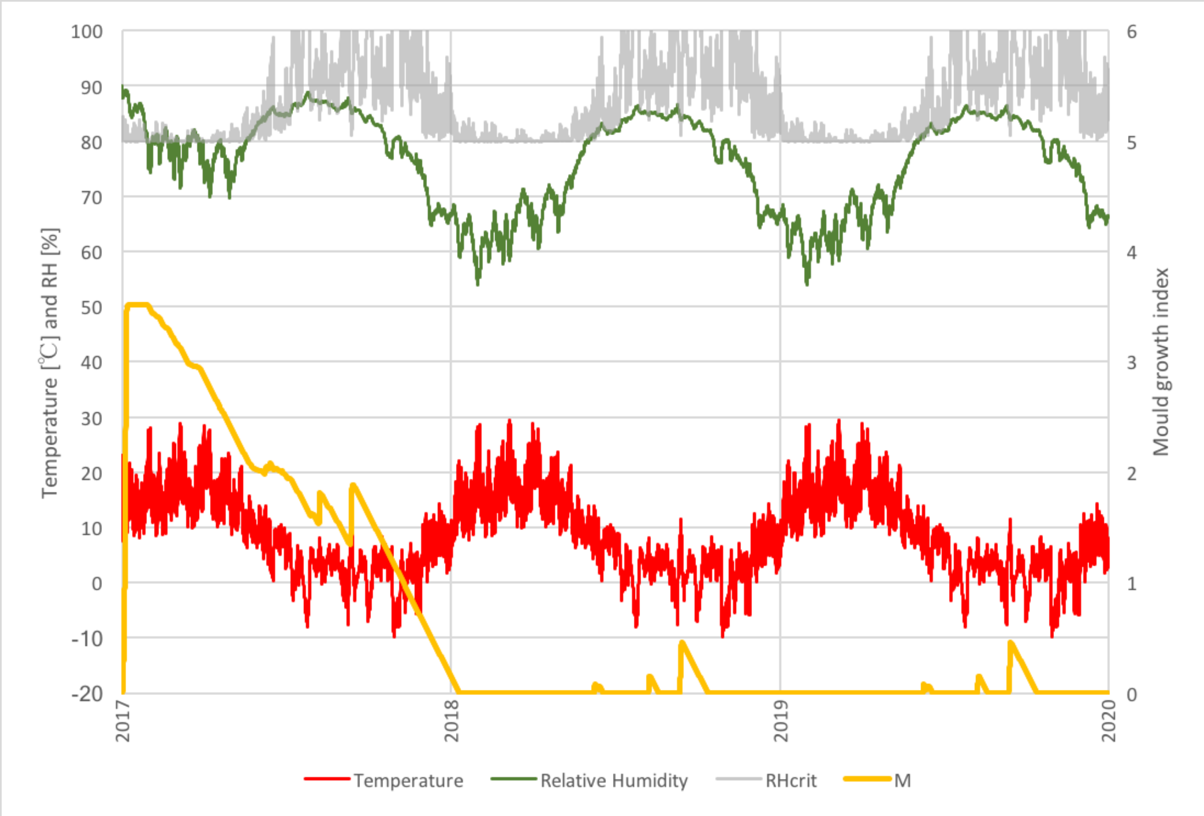

Figure 56: Case 2.19

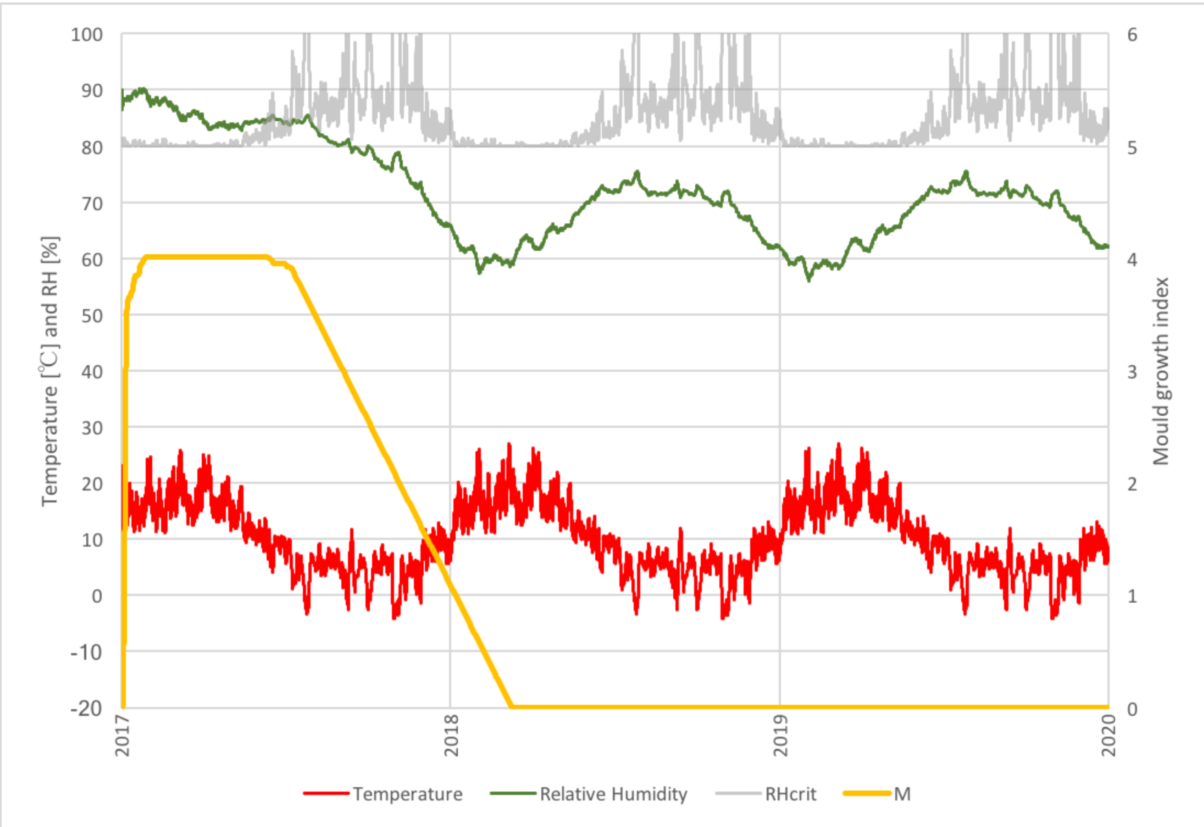

Figure 57: Case 2.20

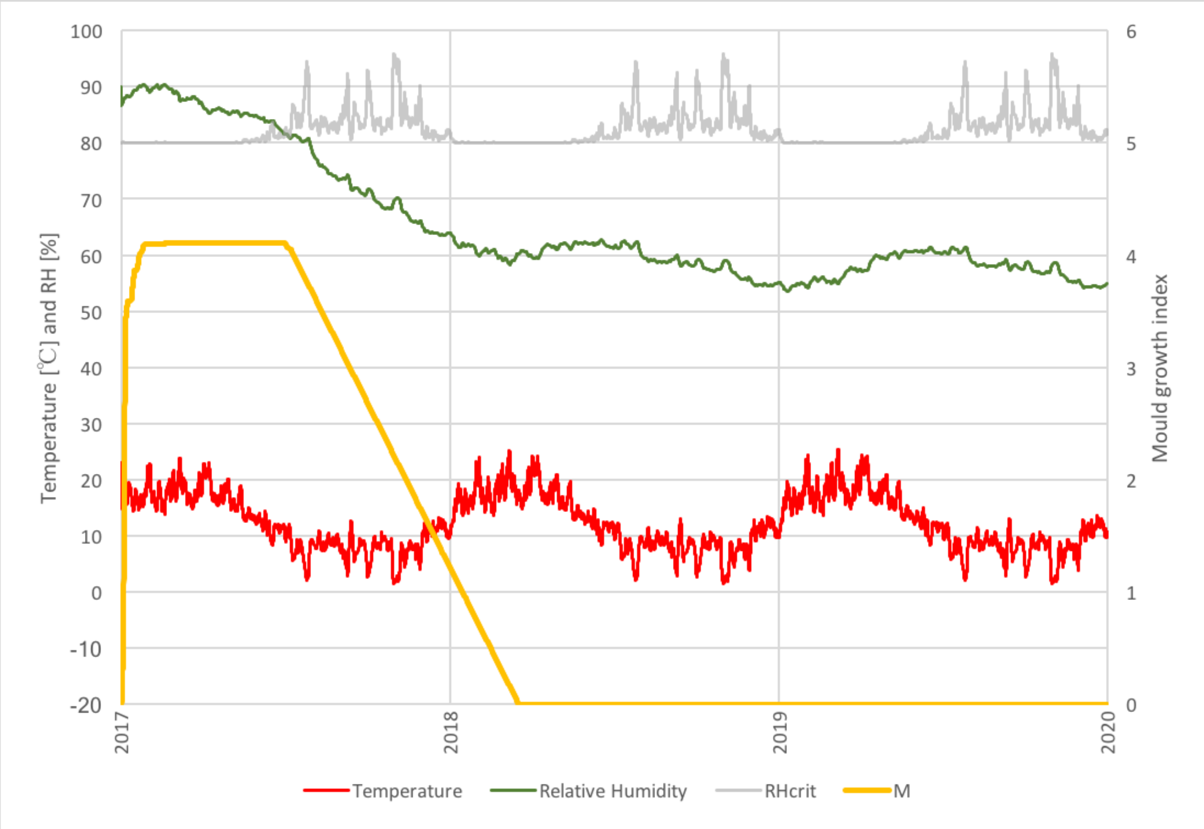

Figure 58: Case 2.21

Appendix H RESULTS OF MOISTURE SIMULATIONS - STUDY 3

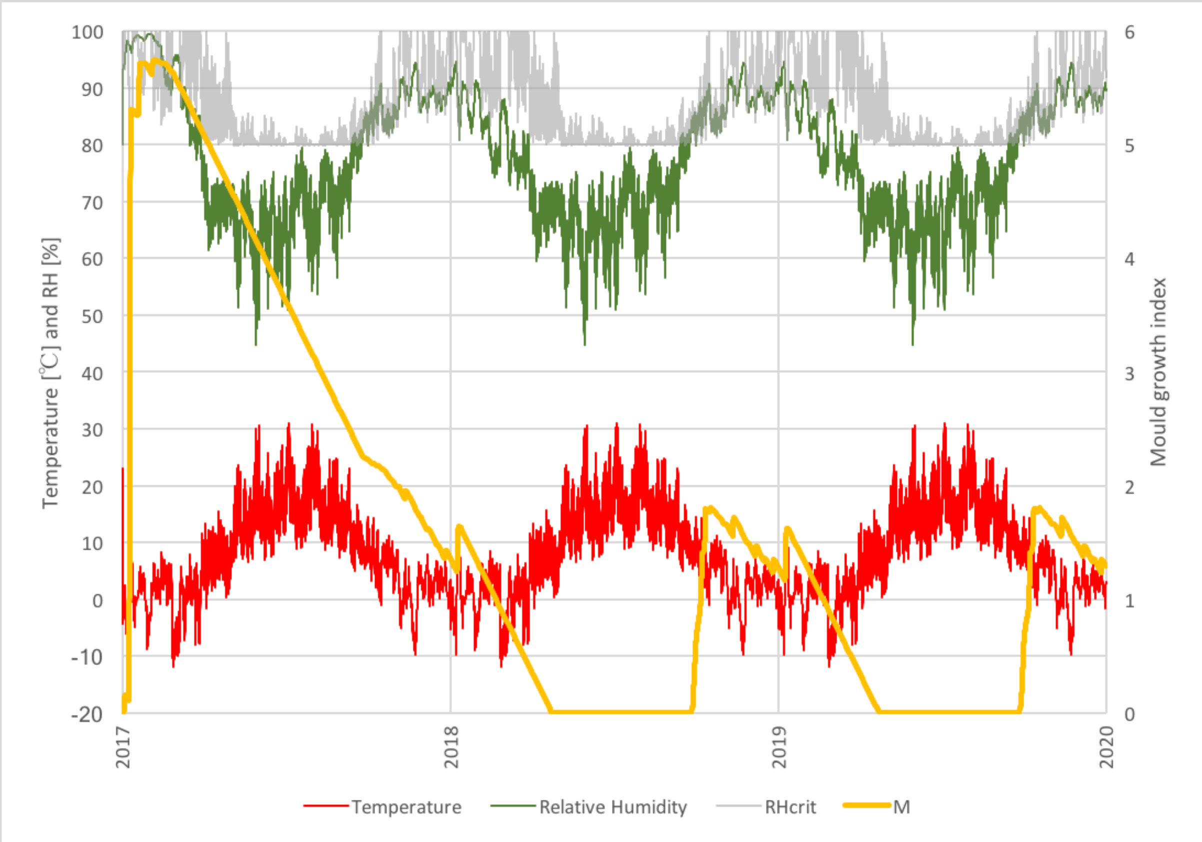

Figure 59: Case 3.1

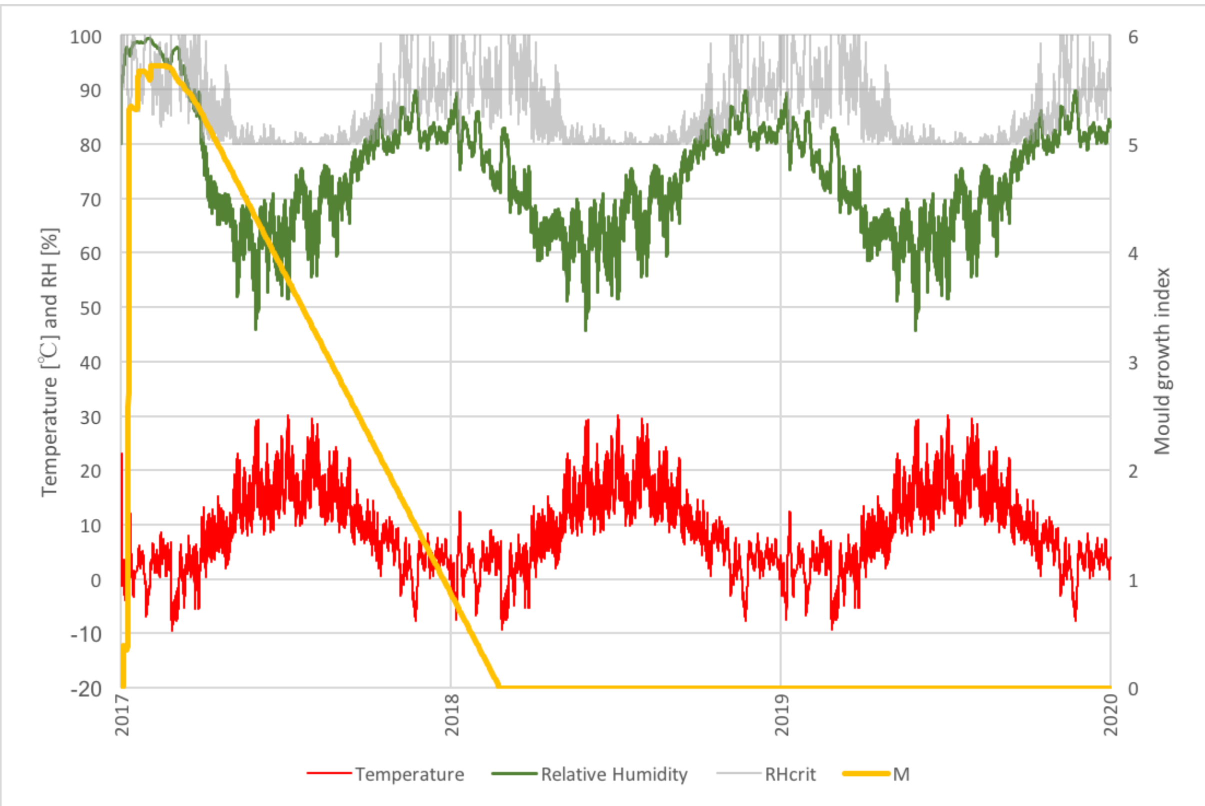

Figure 60: Case 3.2

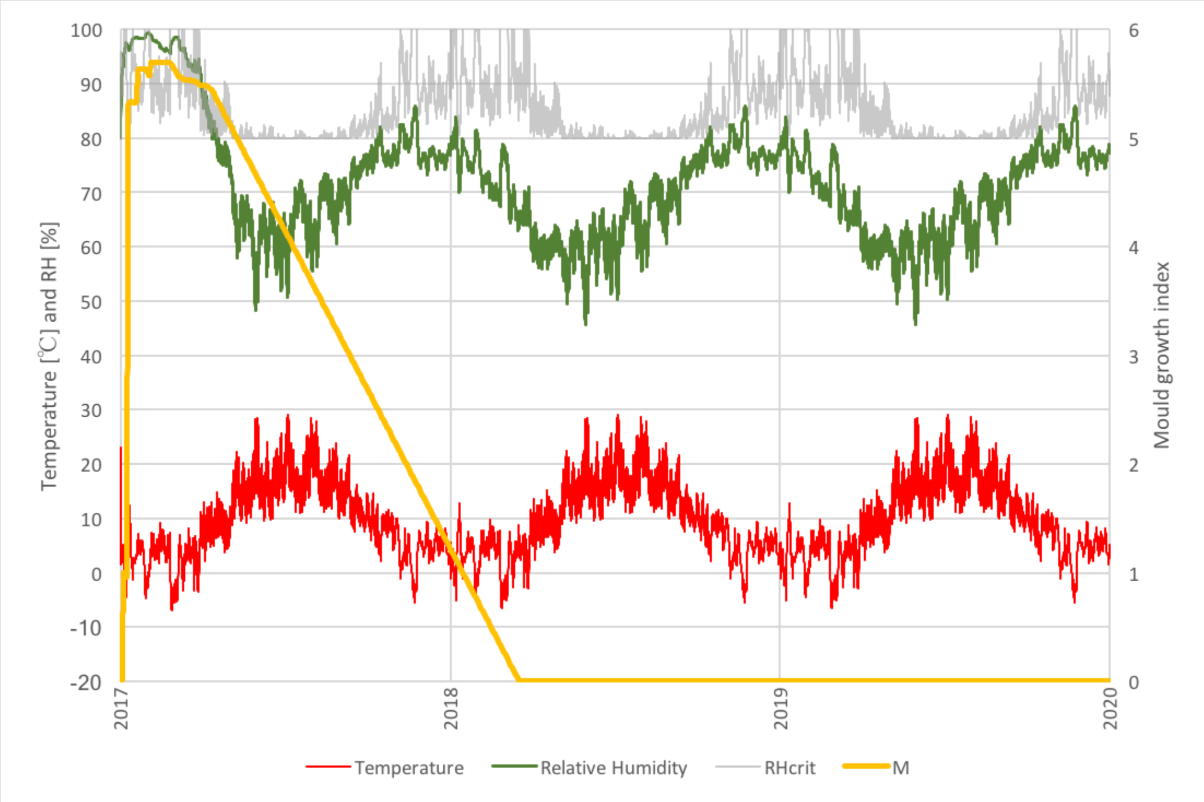

Figure 61: Case 3.3

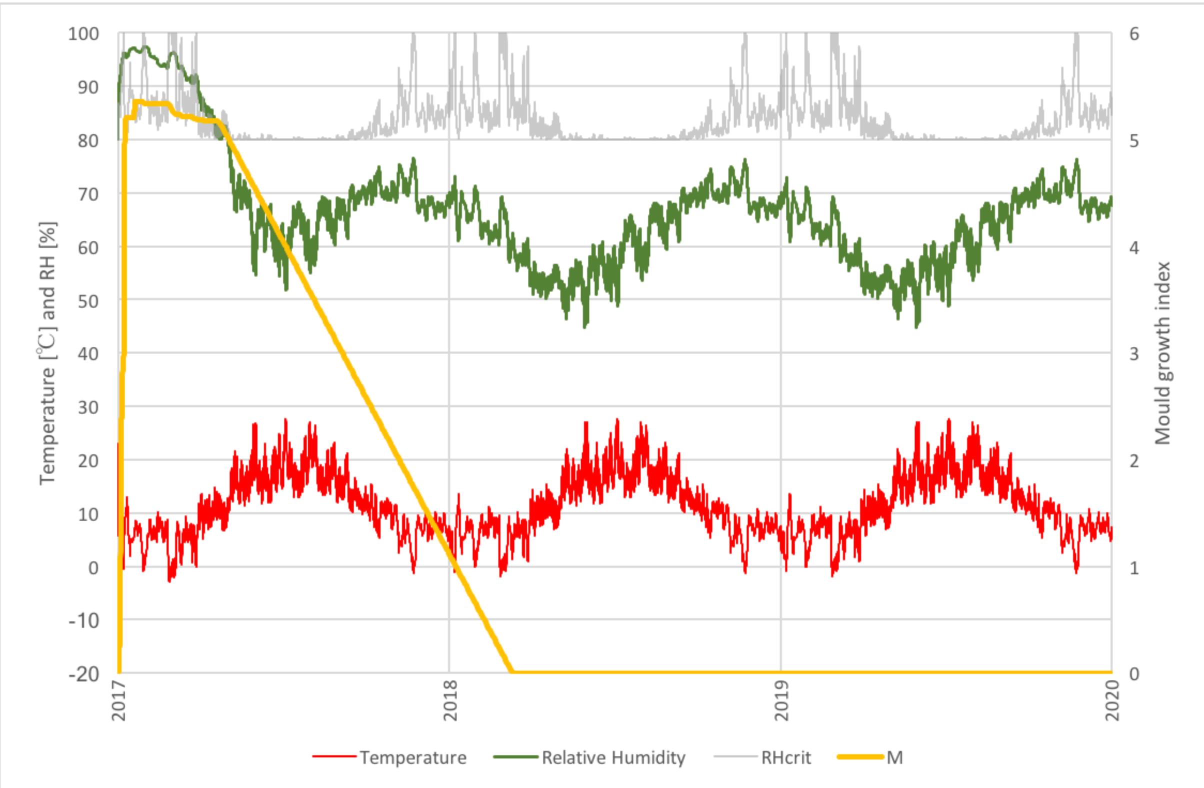

Figure 62: Case 3.4

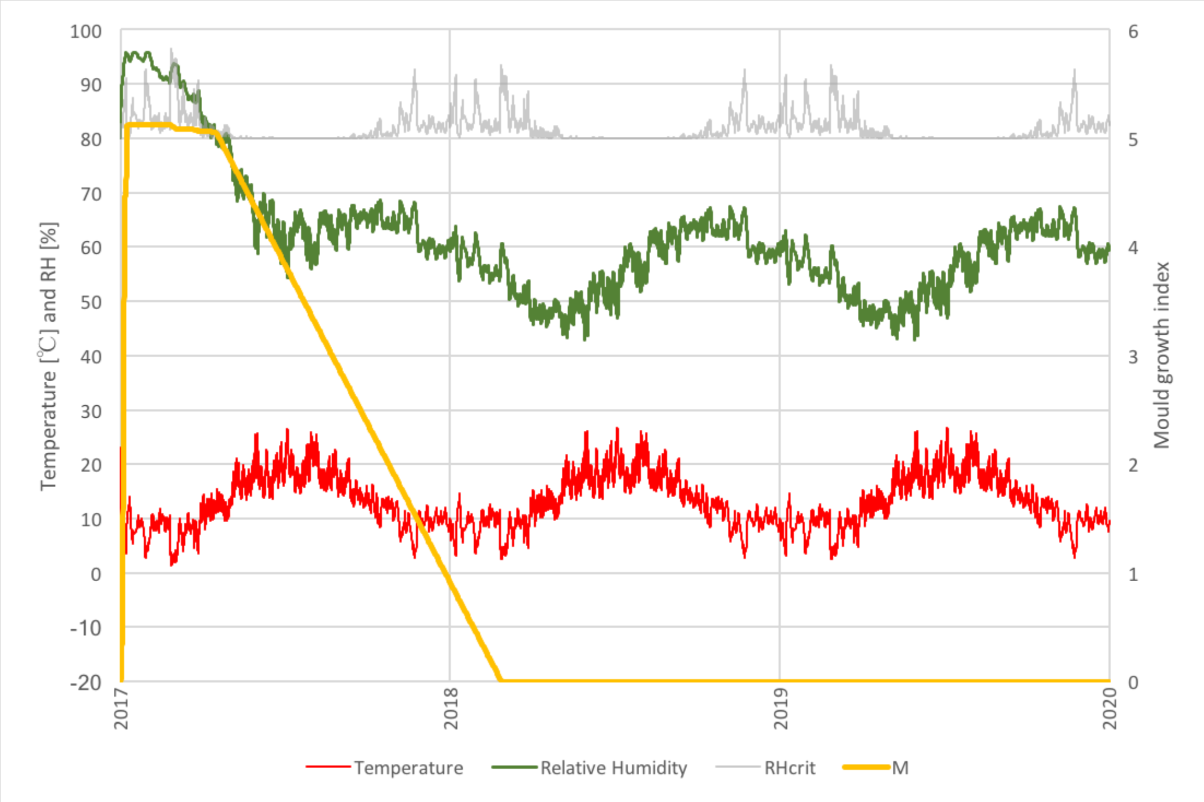

Figure 63: Case 3.5

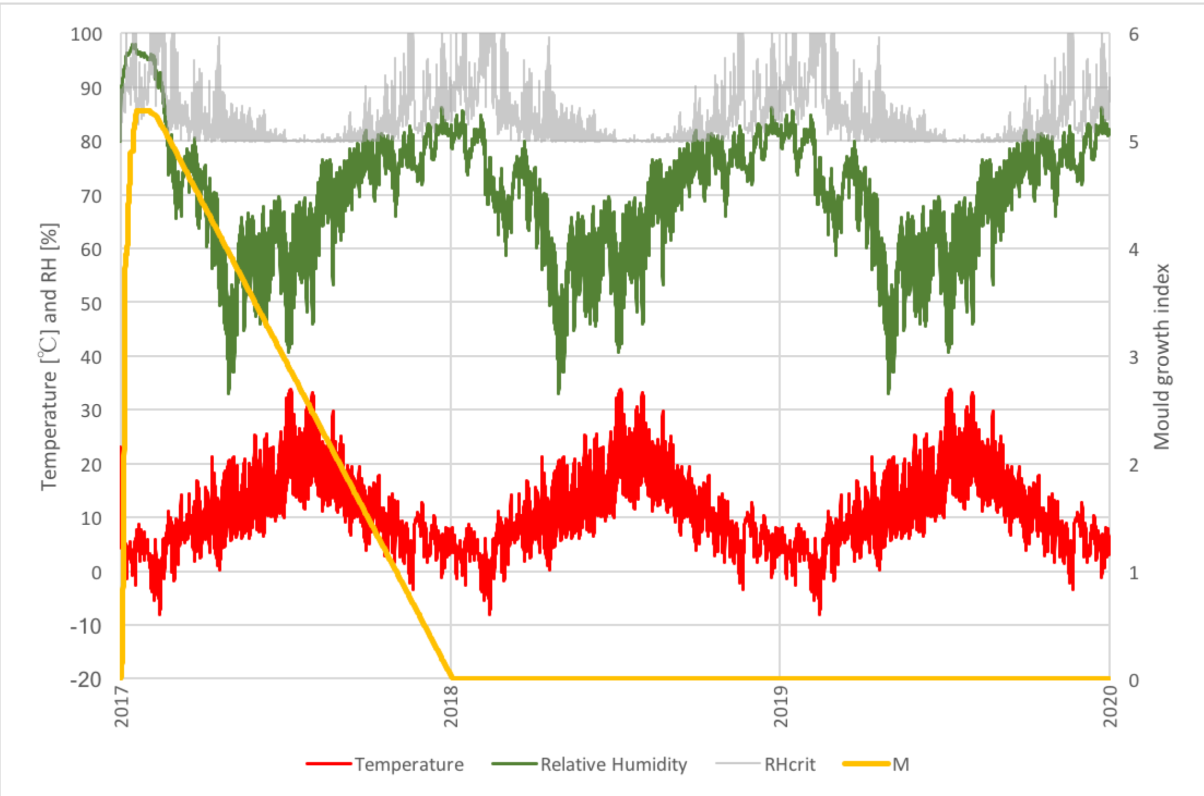

Figure 64: Case 3.6

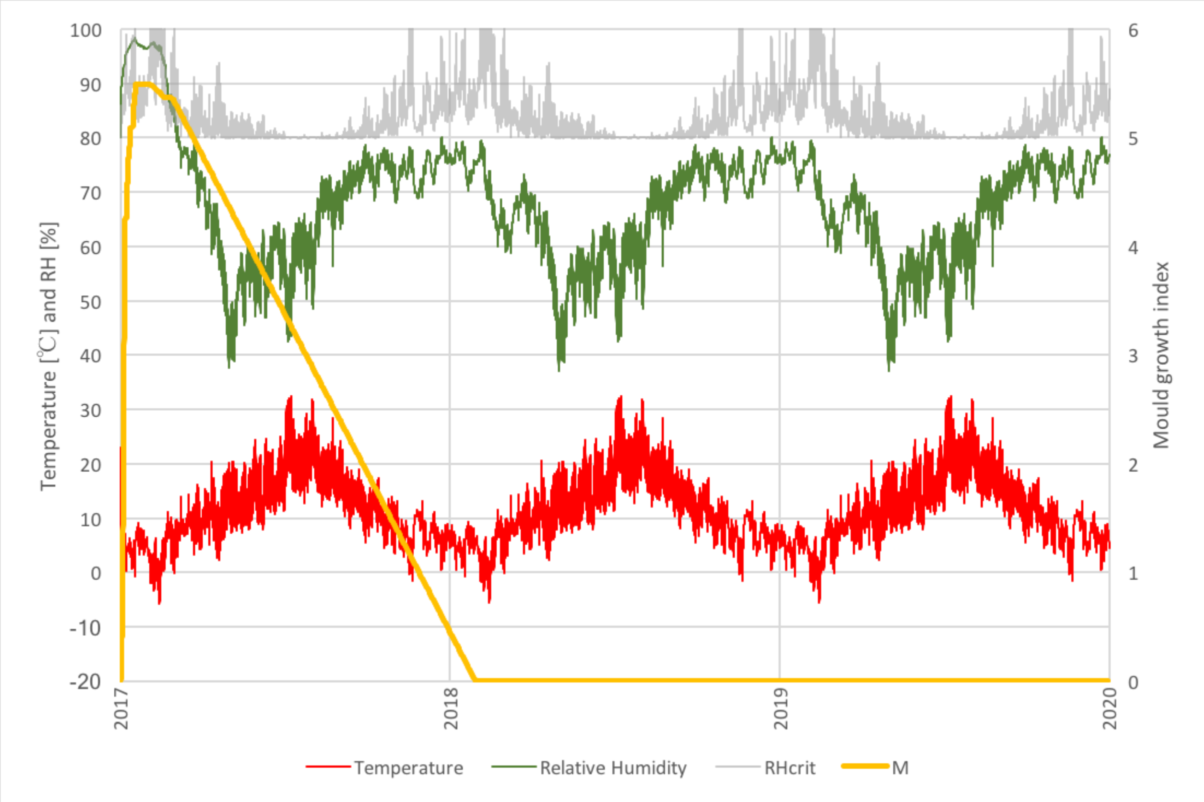

Figure 65: Case 3.7

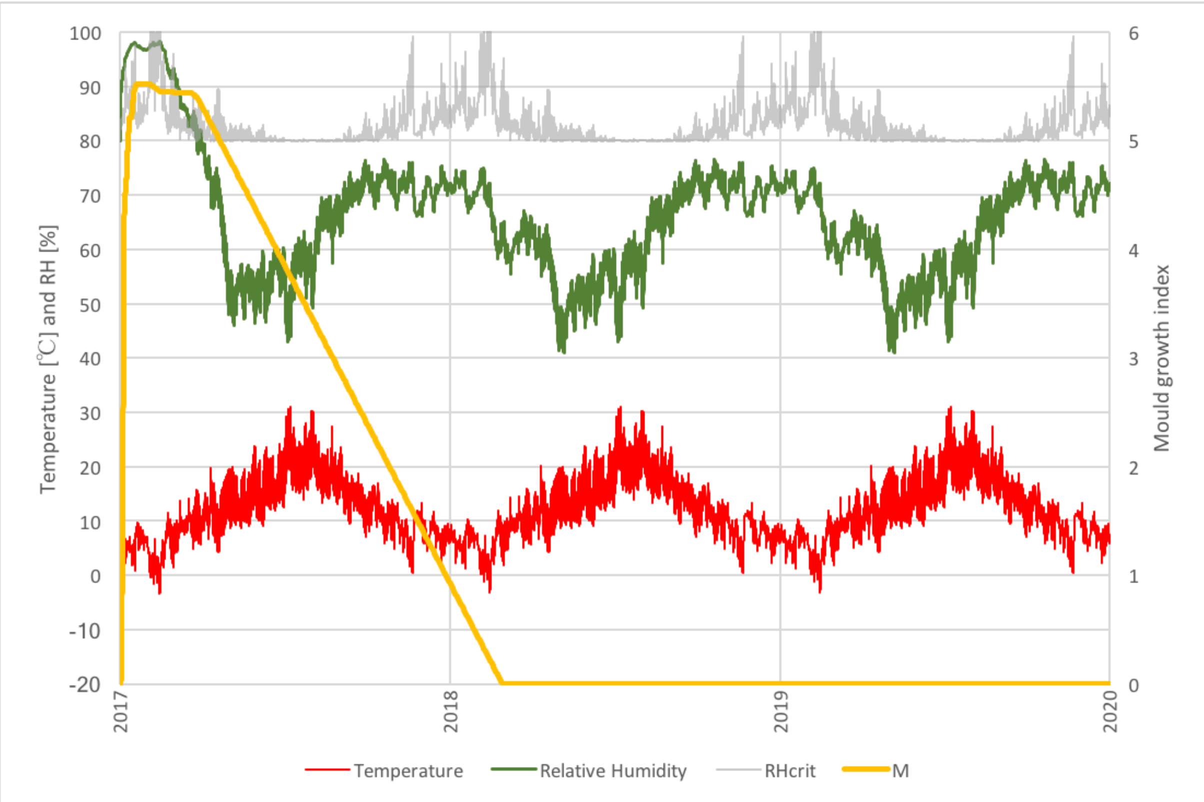

Figure 66: Case 3.8

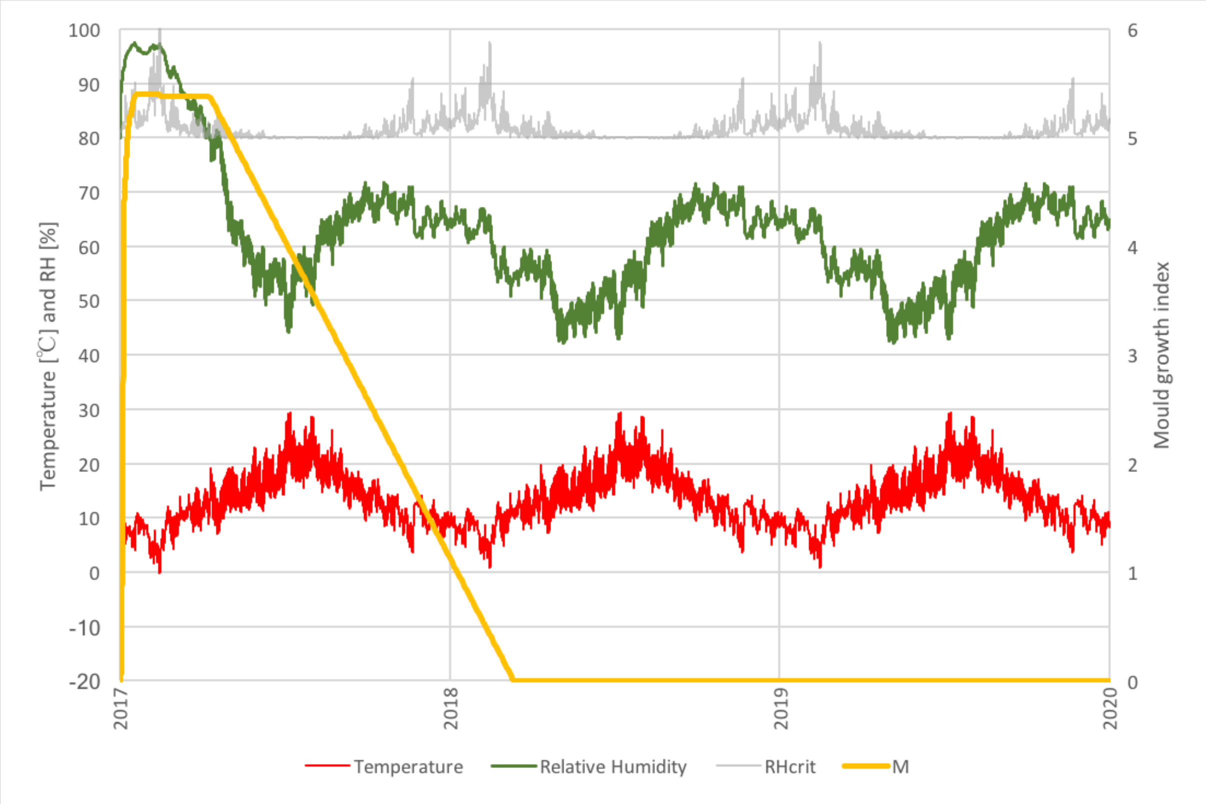

Figure 67: Case 3.9

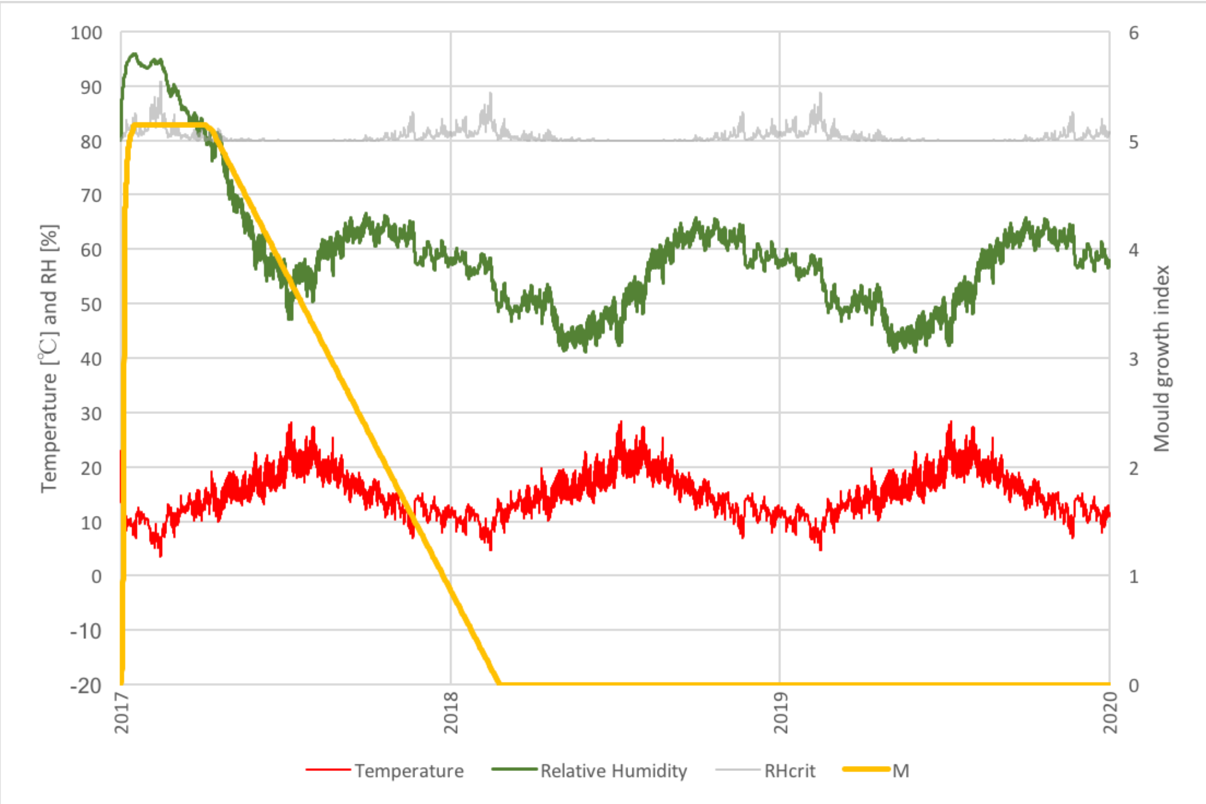

Figure 68: Case 3.10

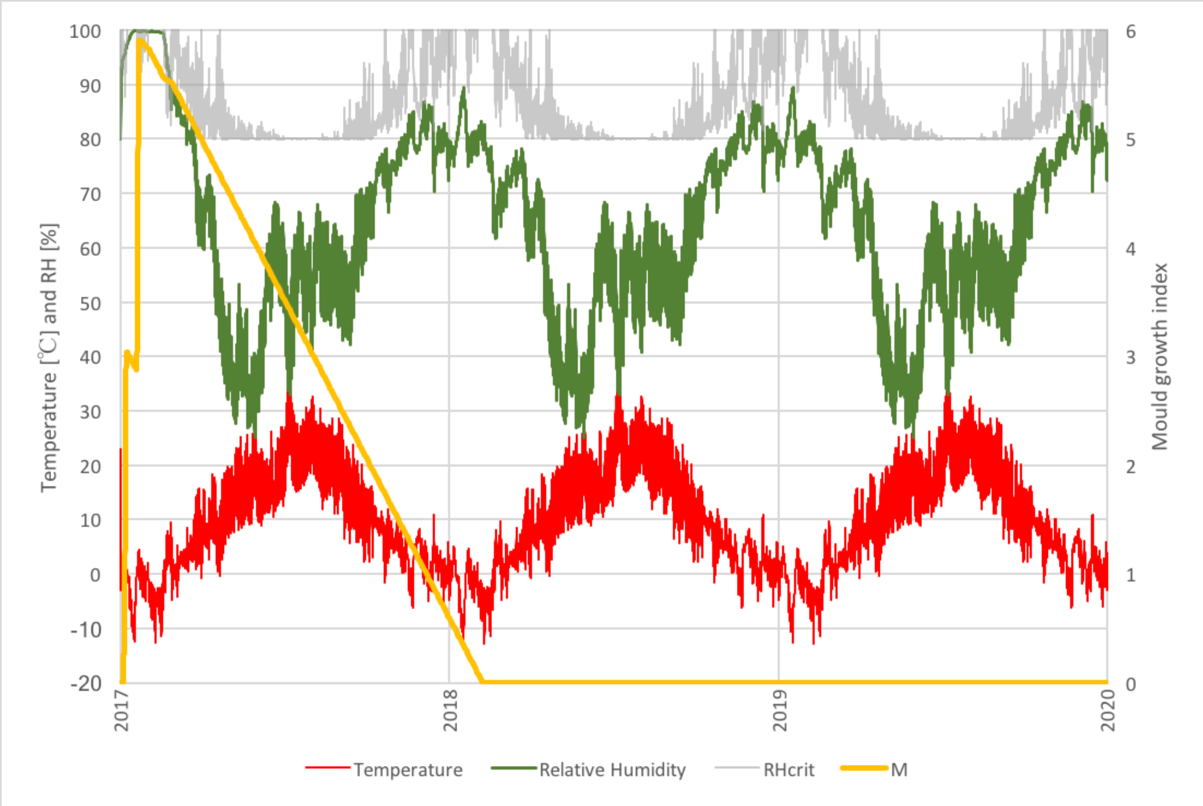

Figure 69: Case 3.11

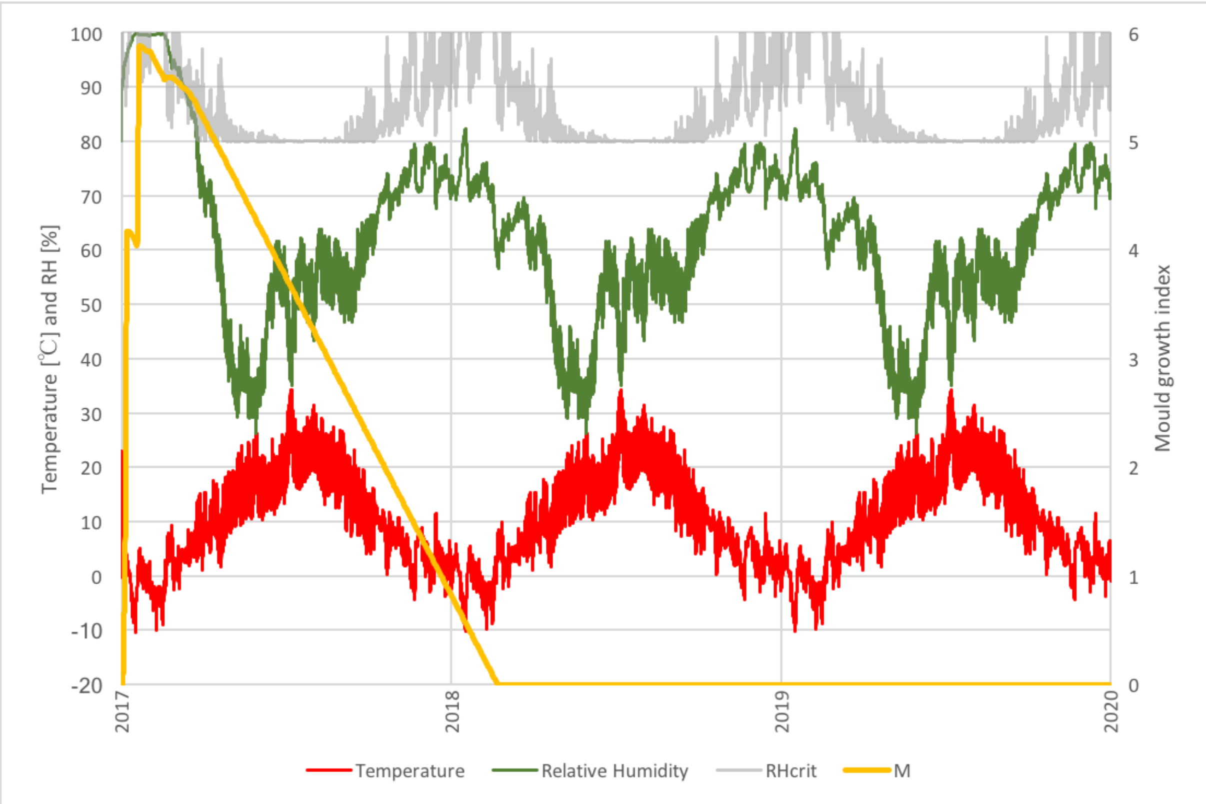

Figure 70: Case 3.12

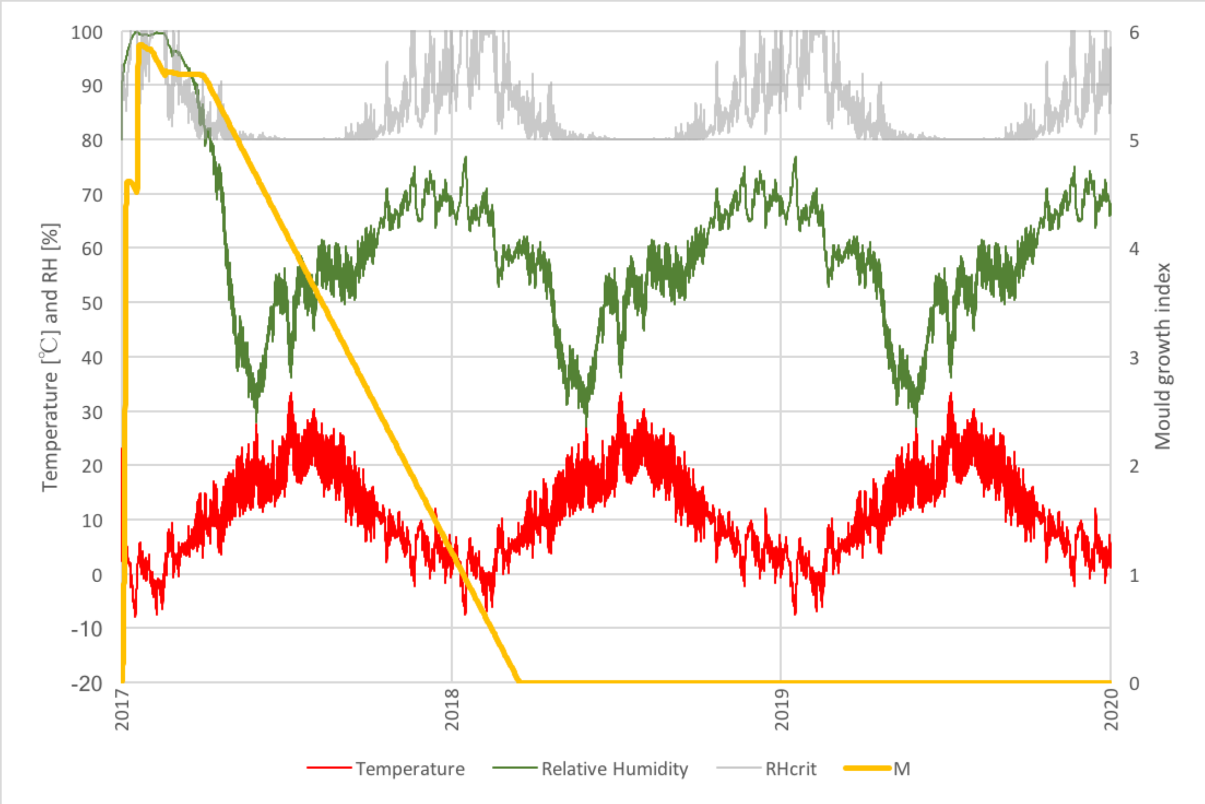

Figure 71: Case 3.13

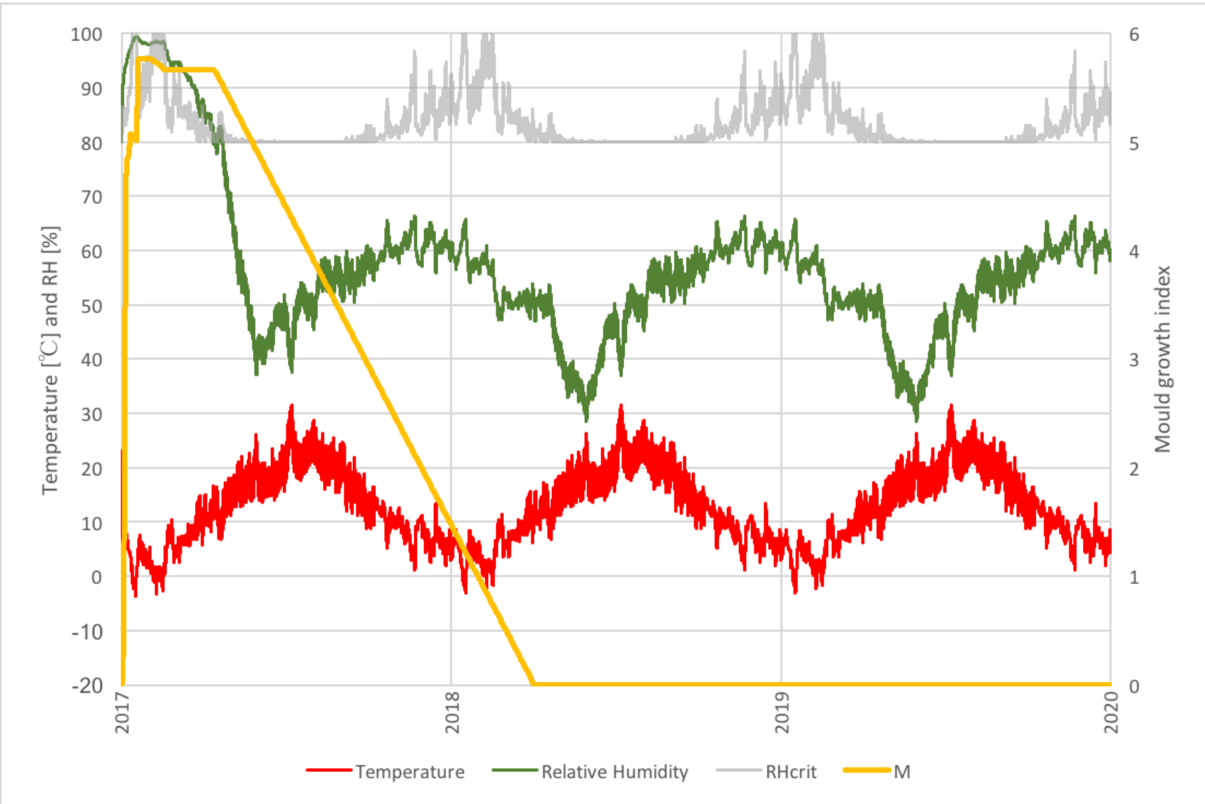

Figure 72: Case 3.14

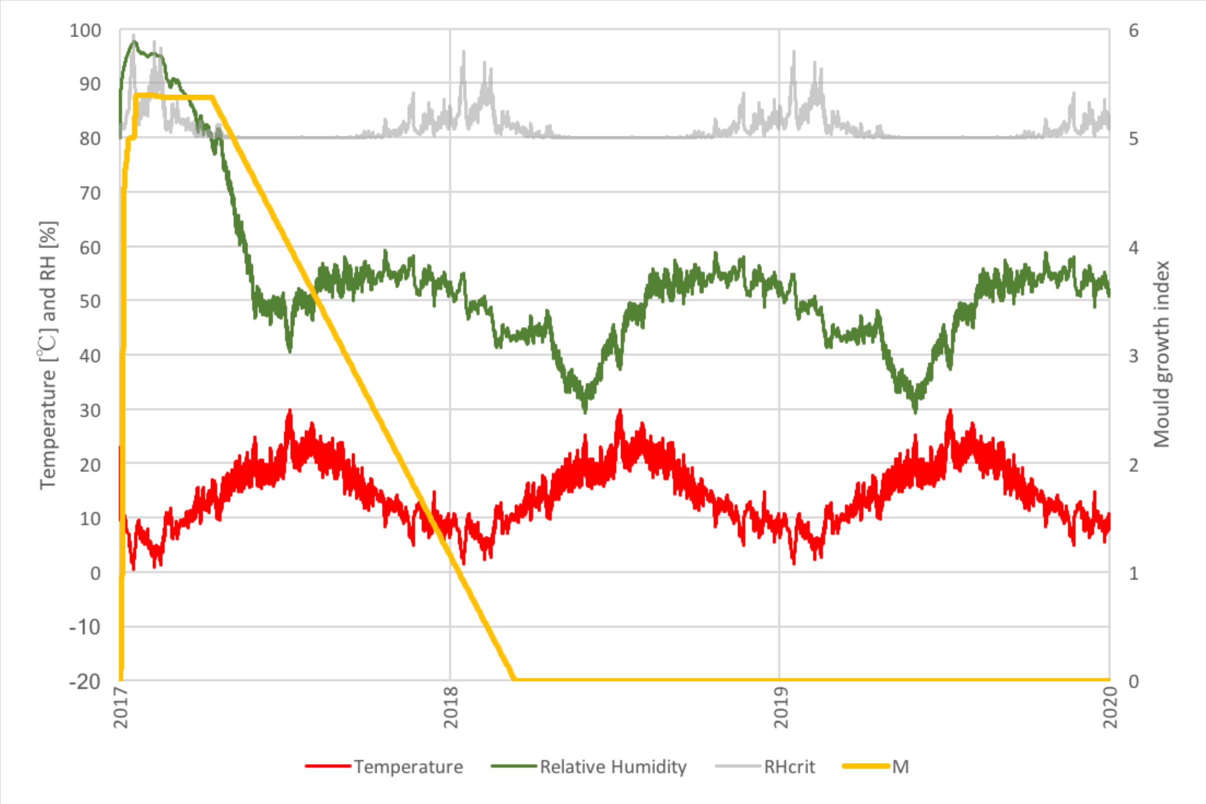

Figure 73: Case 3.15

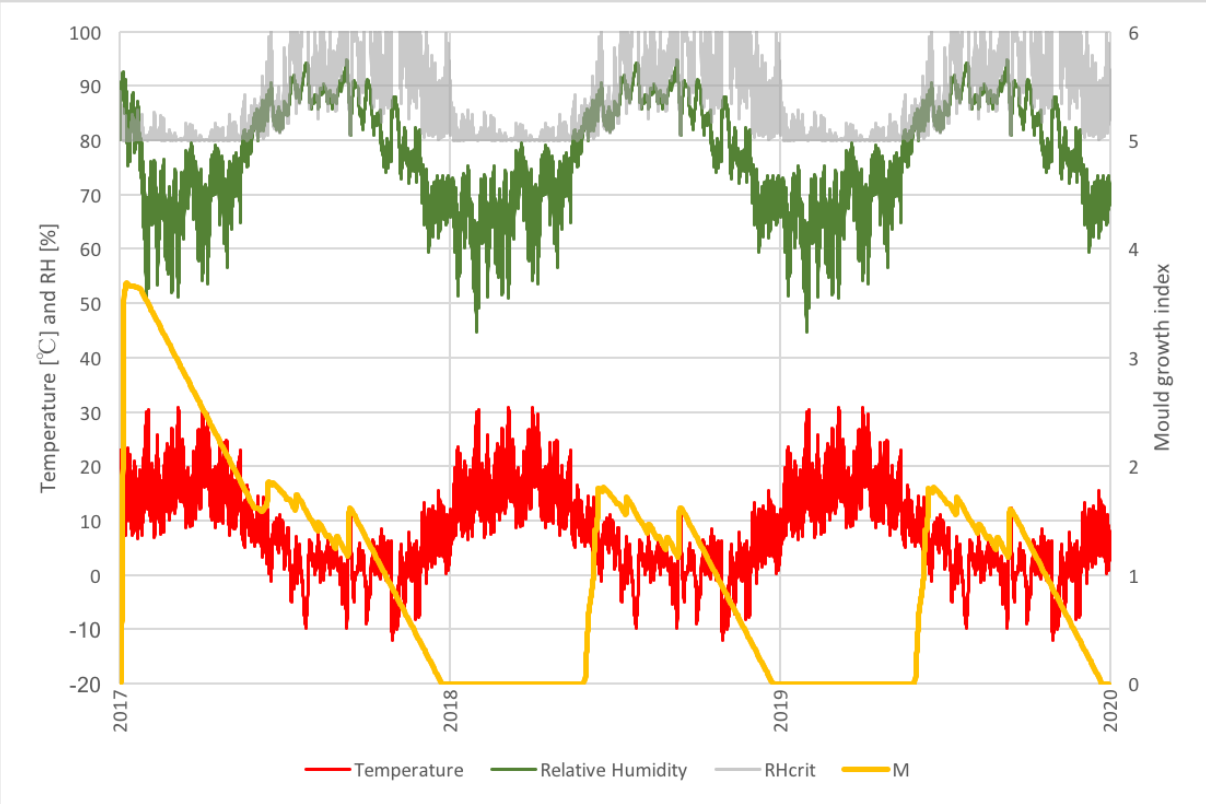

Figure 74: Case 3.16

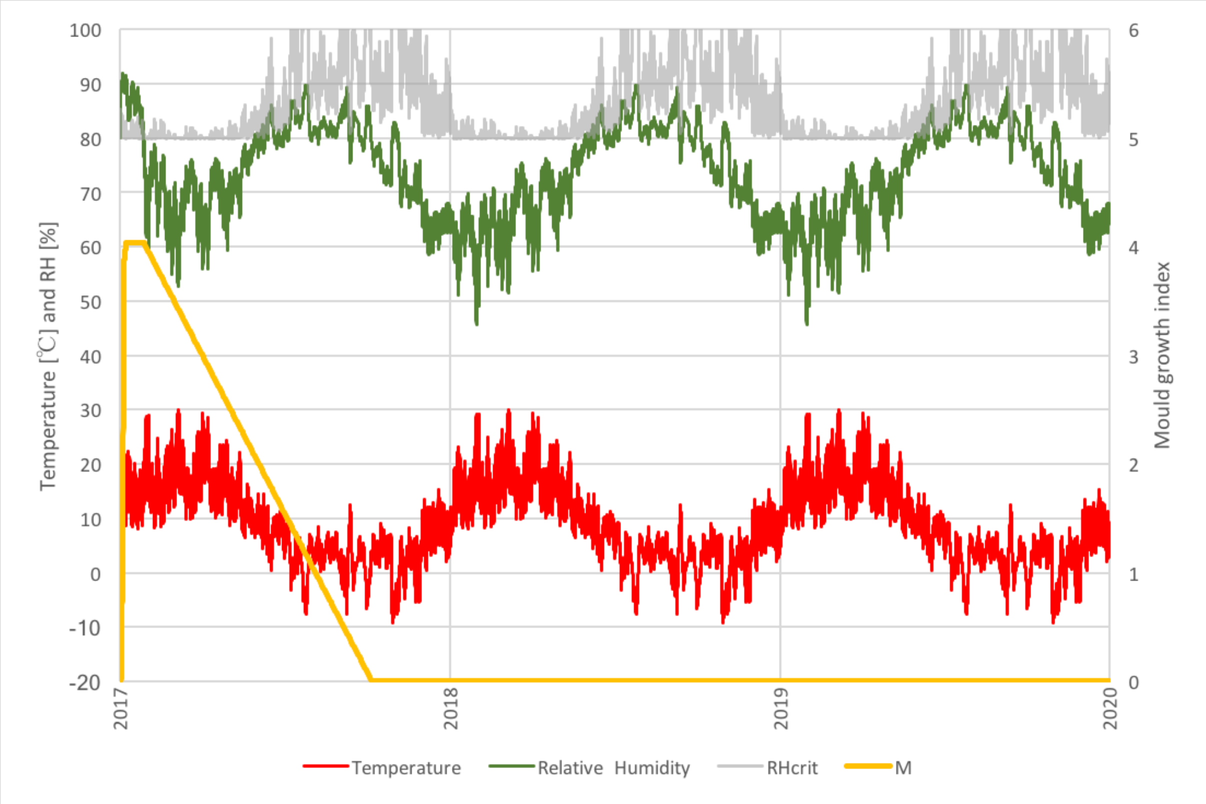

Figure 75: Case 3.17

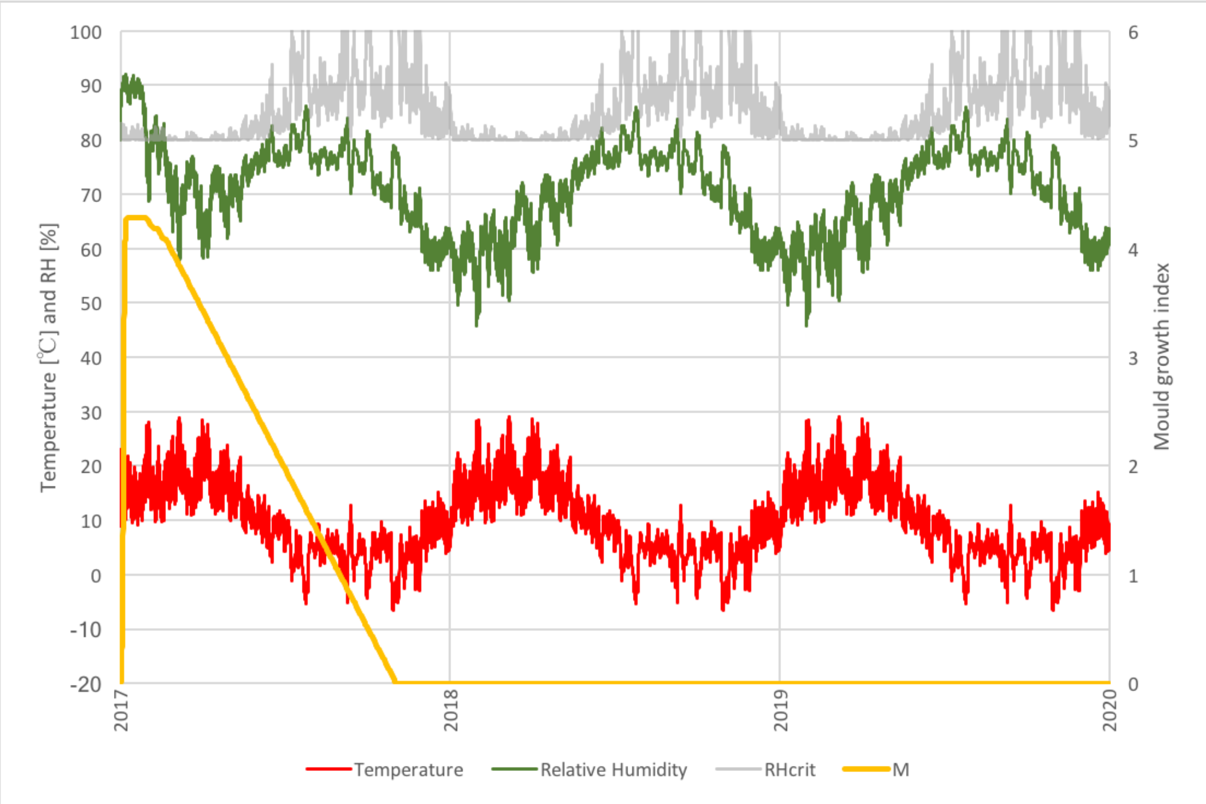

Figure 76: Case 3.18

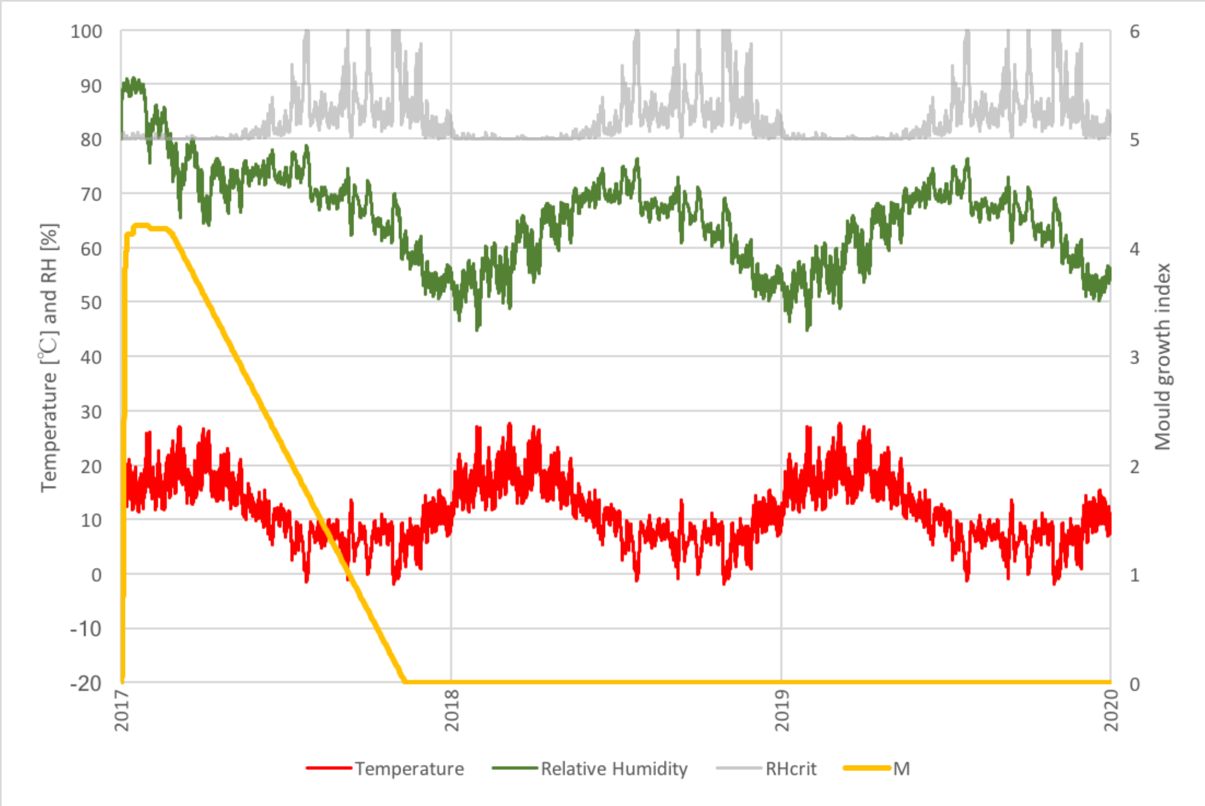

Figure 77: Case 3.19

Figure 78: Case 3.20

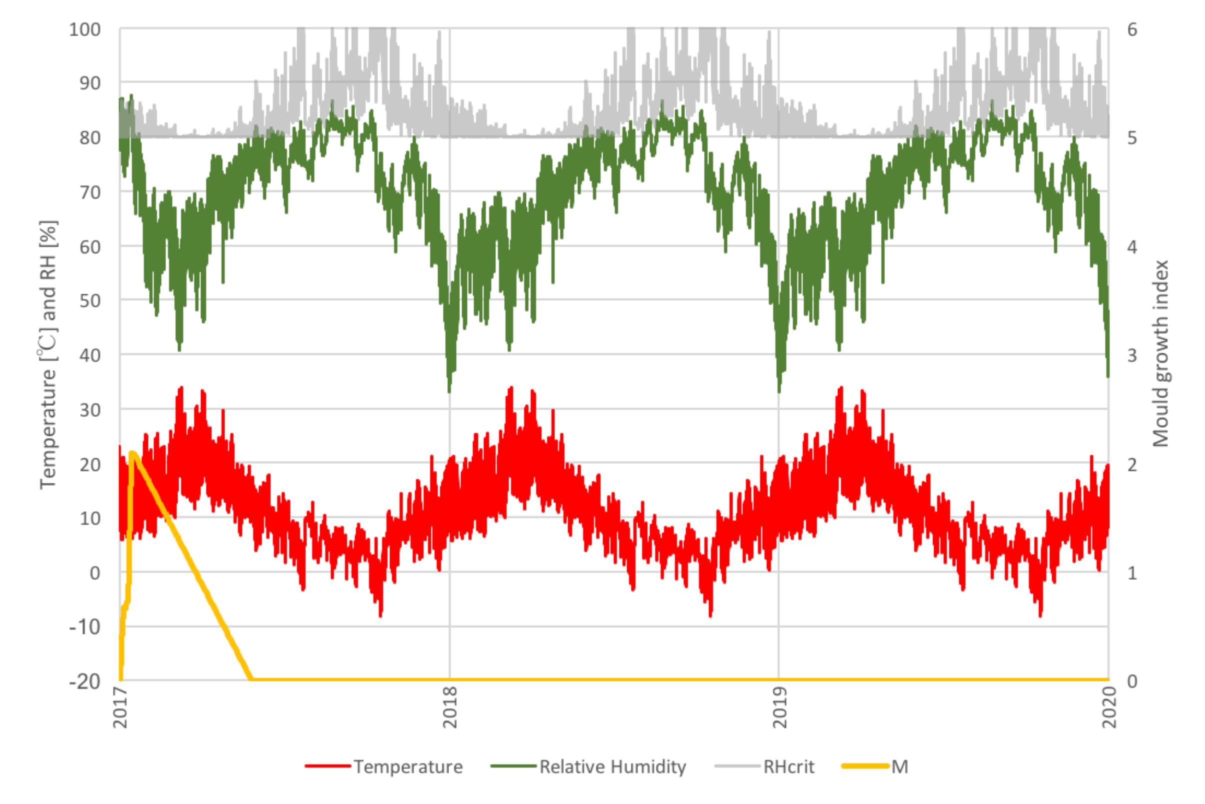

Figure 79: Case 3.21

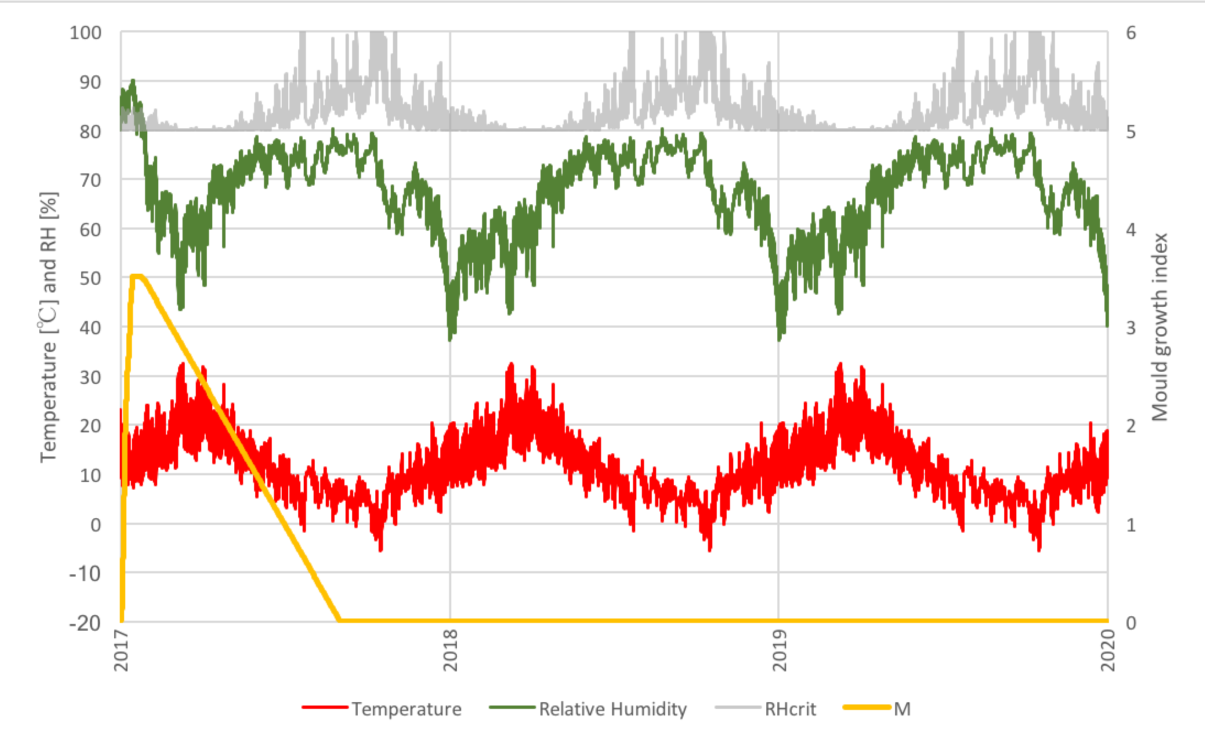

Figure 80: Case 3.22

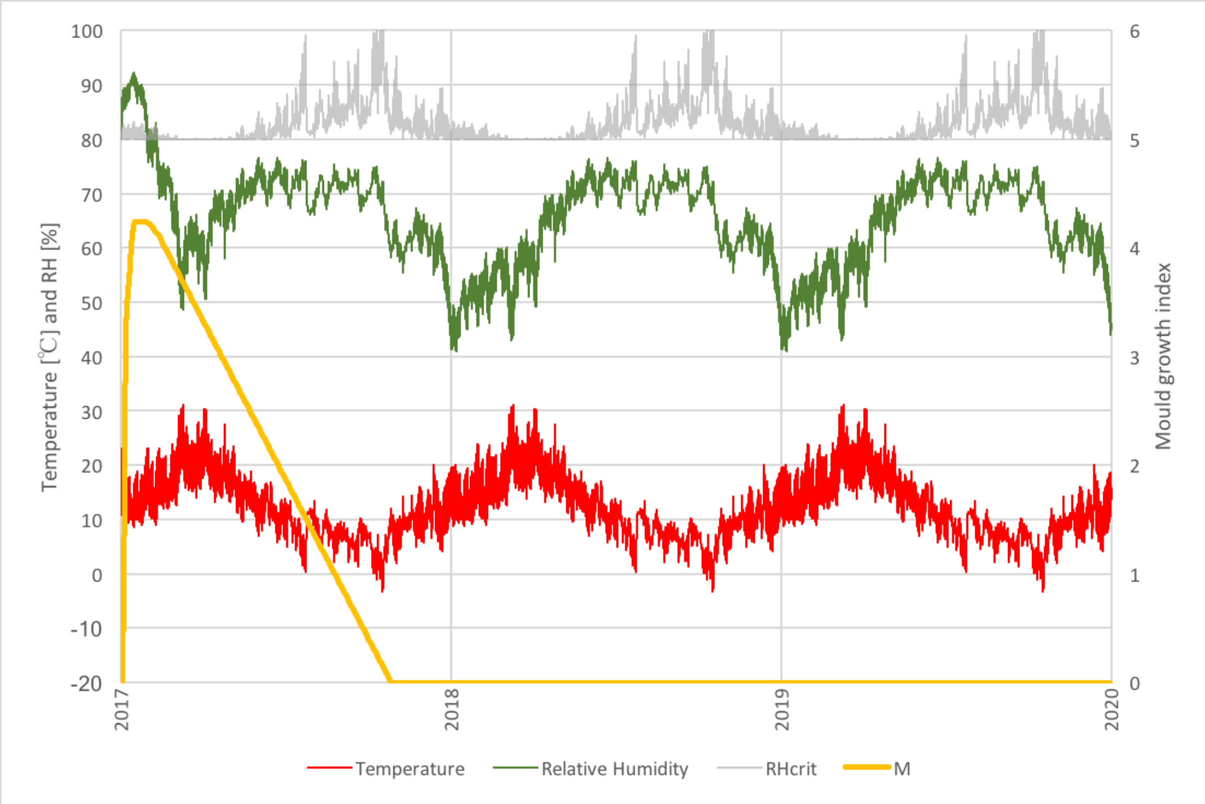

Figure 81: Case 3.23

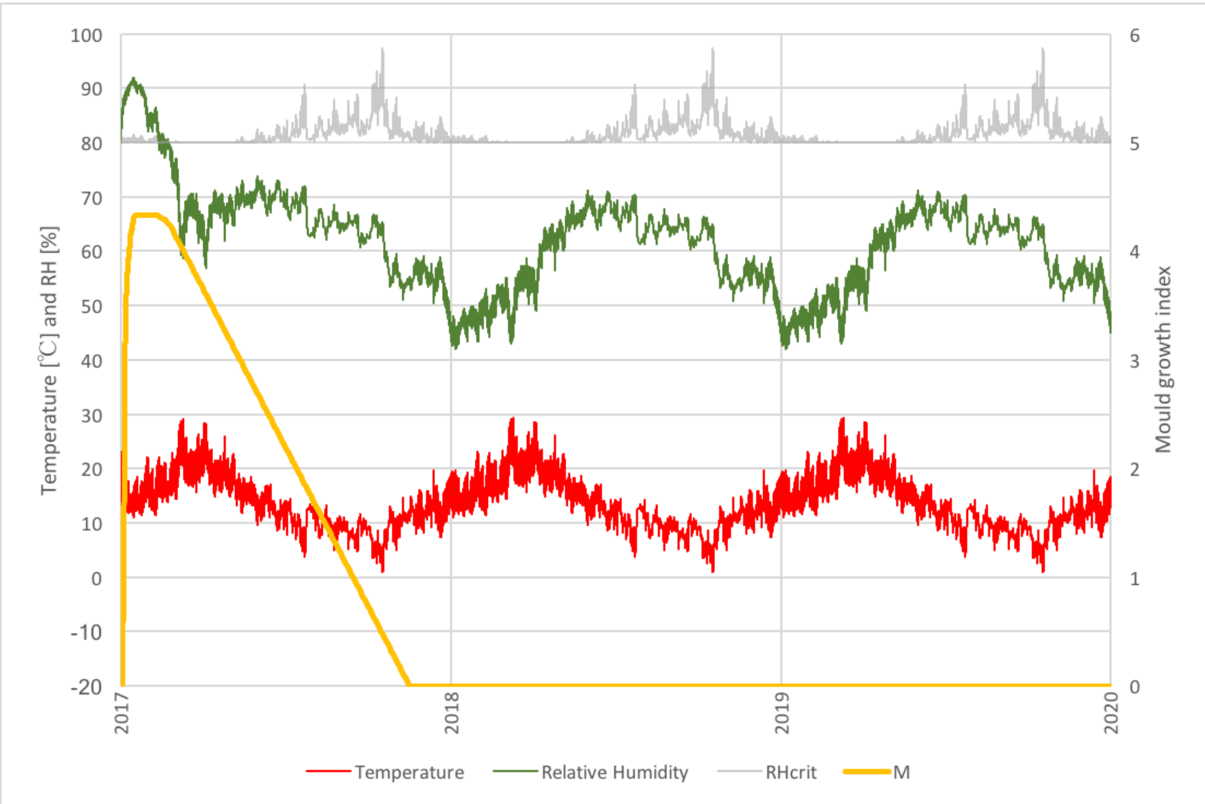

Figure 82: Case 3.24

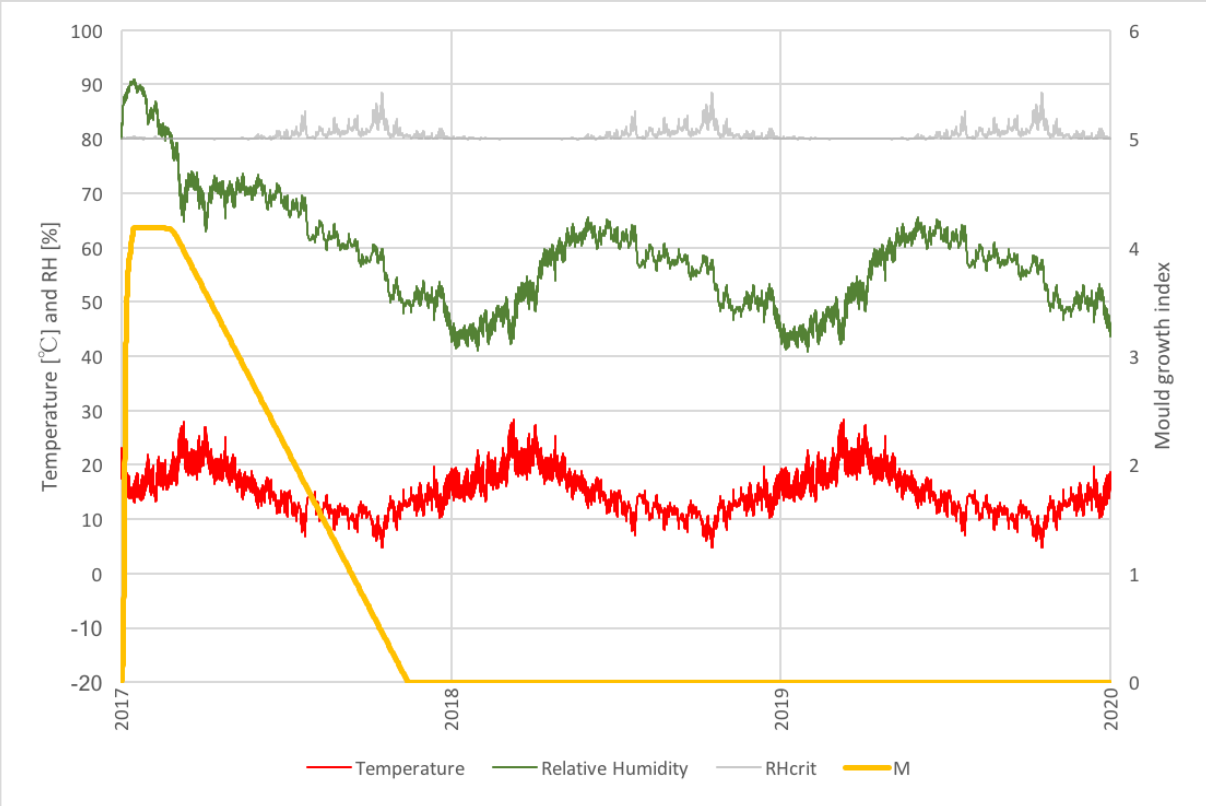

Figure 83: Case 3.25