An evaluation of two well insulated structures

From a hygrothermal and mould growth perspective in Swedish climates

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Keywords

Mould growth, Moisture, Cathedral roof, Attic, Hygrothermal, WUFI, Mould models

Division of labor between authors

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Literature study – Mould	Filip Josefsson
Literature study – WUFI	Filip Josefsson
Literature study – Mould models	Oskar Cederlund
Method	Oskar Cederlund & Filip Josefsson
Results	Oskar Cederlund & Filip Josefsson
Discussion	Oskar Cederlund & Filip Josefsson
Conclusions	Oskar Cederlund & Filip Josefsson

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Malmö the 1st of June 2015

Oskar Cederlund

Filip Josefsson

Nomenclature

ACH	Air Change per Hour
BBR	Boverkets Byggregler (Swedish Building Regulations)
Existing climate	Refers to the obtained weather data between years 1990-1998, from Petter Wallentén
Future climate	Refers to modified climate files according to climate scenario RCP 8.5.
IAQ	Indoor Air Quality
mVOC	Microbial Volatile Organic Compound
OBO	Ospecificerad Byggnadsrelaterad Ohälsa (Unspecified Building related Illness)
pH	Logarithmic measurement of acidity
RCP	Representative Concentration Pathways
RH	Relative Humidity
SBS	Sick Building Syndrome
SP	Sveriges Tekniska Forskningsinstitut (Technical Research Institute of Sweden)
VOC	Volatile organic compound

Contents

Abstract

Moisture is considered to be a severe problem in outdoor ventilated attics in Sweden today (2015), and almost 60% of all single family houses and 10% of all multifamily houses have problems with mould growth correlated to moisture in the attics. Increased insulation layers and new heating systems in combination with a more humid climate have increased the risk of such problems.

This study has focused on investigating the moisture and mould growth potential in a well-insulated outdoor ventilated attic and a cathedral roof in four different climate zones in Sweden; Lund, Stockholm, Borlänge and Luleå. The study was performed by modelling and simulating the structures in the hygrothermal software WUFI 5.3 with climate data from Lund, Stockholm, Borlänge and Luleå from the year 1990-1998 from SMHI. The structures were also investigated from a future-climate perspective, using modified data obtained from climate scenario RCP 8.5 considering parameters such as temperature, wind velocity and annual precipitation. The outputs of the critical parts of the structures were analysed for the risk of mould growth with four different mould growth prediction models: VTT-model, MRD-model, m-model and WUFI-Bio.

The hygrothermal results showed that the cathedral roof has more fluctuating conditions compared to the attic. The relative humidity there is generally lower throughout the year, except during winter. The mould model results were inconsistent in their assessments, especially in Lund and Stockholm, while Borlänge and Luleå had fewer conflicting results. In general the cathedral roof performed better in cold climates, and the attic performed better in warmer climates. The future climate generated significantly worse situation for both structures in all locations.

From our results general conclusions could be drawn. In Lund and Stockholm there was significant risks of mould growth in both structures, the recommendation is, based on accessibility, to construct an attic. In Borlänge it did not really matter what structure was chosen, the choice can be based on other preferences such as design, economics, etc. In Luleå, the cathedral roof was recommended, based on the results from the future climate. The spread of results from the mould predication models reflected the complicated processes of modelling mould growth. The study showed that it is important to be well aware of the models limitations and to treat the predictions as indications/suggestions more than truths.

1 Background

The average person spends, approximately 90% of their lifetime indoors and over 1,2 million people have indoor air related health problems in Sweden, according to the article *Beware of miracle cure against sick houses* (*Varning för mirakelkur mot sjuk hus)* (Wiklund, 2015). Sick Building Syndrome [SBS] caused by inadequate Indoor Air Quality (IAQ) have been connected to pollutants such as radon, asbestos, formaldehyde etc. and also associated with spores from mould (Cooley, et al., 1998). The report *the condition of our houses (Så mår våra hus)*, from 2007, showed some troubling facts about the moisture conditions for Swedish buildings, 30% of all single family houses and 10% of all multifamily houses have problems with mould growth. Attics and crawlspaces are singled out as the two most concerned building parts (Boverket, 2009). One study shows that 60% of all attics in Sweden have mould growth on a microscopic level, which is caused by moisture problems. (Ahrenens, et al., 2007). The fundamental physics is that when air gets colder, the saturation point decreases and the relative humidity increases, leading to higher risk for mould growth (Johansson, 2014).

New requirements regarding energy saving measures for buildings will be implemented in the Swedish regulations in year 2020. If these measures are not handled properly, this could lead to even higher moisture levels in buildings and building parts e.g. the attic due to less heat transmission. The national goal regarding moisture related problems in buildings by The Swedish National Board of housing, Building and Planning is: *The proportion of buildings with moisture damage relevant to the indoor environment will in 2020 be less than 5% of the total building stock.* (Boverket, 2009). Furthermore, in the Swedish building regulations (Boverket) it is stated that*: Buildings should be designed in a way that moisture cannot create damages, bad smell, hygienic inconveniences or microbial growth that can affect the health of people.* (Boverkets byggregler, 18, 2011). Due to increasing energy restrictions in combination with growing moisture problems, the building sector is facing a challenge to combine energy efficient-building methods, moisture safety design and traditional outdoor ventilated attics (2015). Further, the climate is changing due to increased levels of greenhouse gases in the atmosphere. The consequences are hard to foreseen, but generally, a warmer and more humid climate is expected in Sweden, which places new demands and challenges on buildings constructed today.

An outdoor ventilated attic is a common structure in Sweden, which has been used for a long time. A more recent alternative is a cathedral roof, which is characterized by having the insulation in the roof structure itself, unlike the attic where the insulation is placed in the system of joints. This type of structure is considered to be more complicated to build. Instead of the attic space it has a small or no air gap, a factor that influences the moisture condition in the structures. Determining the ventilation rates in an attic space or in an air gap has been proven to be difficult. It varies depending on wind speed, temperature, orientation relative to the building, air gap openings, positioning of the openings etc. Dependent on the properties of the air gap or attic space, and prevailing climate, too much or too little outdoor ventilation can be problematic from a moisture perspective (Mundt-Petersen, 2013)).

Hygrothermal softwares are commonly used to determine the moisture levels in structures. Combined with mould growth models, predications can be used to evaluate the risk of mould growth. There are several different mould growth models. However, the complicated interaction between relative humidity, temperatures, type of mould species, materials etc. creates a discrepancy between the predications from mould growth models and reality. Early models often only considered temperature and RH, while more modern empirical models and isopleth models also considers increase and decline in mould growth based on more factors found in experiments (Verekeen, et al., 2012).

1.1 Previous work

In the Swedish Construction Industry´s Organisation for Research and Development [SBUF] report *Risk analysis of ventilated cold attic constructions* (Riskanalyser för ventilerade kallvindskonstruktioner) 5 different outdoor ventilated attics located in Gothenburg were analysed from a moisture safety perspective (Hagentoft, et al., 2012). By using validated simulation methods they have determined the structures hygrothermal situation. The results are partly presented with a mould index number, describing the risk of mould growth in the structure. Their results show that an active solution with a fan that ventilates the attics during periods when it is drier outside than inside, is the safest option.

From an energy, technical and durability perspective, an active solution, such as fans, is not ideal. It is therefore meaningful to investigate whether another type of solution, the cathedral roof is an alternative to the attic. (Samuelson, et al., 2006).

1.2 Aim

The project aim of this thesis work is to compare and evaluate a cathedral roof and an attic structure in different climate zones in Sweden from a hygrothermal and mould growth perspective. Also to analyse and compare mould models. This was performed by:

- Designing and theoretically comparing two commonly used roof structures in Sweden: an outdoor- ventilated attic and a cathedral roof.
- Performing hygrothermal simulations of these two structure types in four different climate zones in Sweden: Lund, Stockholm, Borlänge and Luleå, see Figure 1.1.
- Investigating the condition in the roof structures for these locations by applying future climate scenarios.
- Finally, we analysed the risk for mould growth by using four different mould growth models.

Figure 1.1 Studied locations in Sweden

1.3 Questions

- In comparison to a conventional attic, can the cathedral roof contribute to a more moisture safe environment?
- Do the models predict the same mould growth potential?
- How do the structures perform in a future climate?

1.4 Methods used in this study

Background study: The first part of this study is a literature review. It includes sources from legal documents, published research reports and theses.

Hygrothermal simulations: The one dimensional software WUFI 5.3 pro was used to simulate the hygrothermal conditions in the structures.

Mould predictions: The results from WUFI were used in four mould growth models to calculate and predict the risk and the extent of mould growth in the structures.

Study objects: The reference structures were designed and their properties were determined based on:

1. Likely design choice today (2015), that is well insulated structures and commonly used materials from the Swedish building stock.
2. Worst case scenarios when solutions were equally common.

Personal communication: The reference structures were developed with help of assistant professor Petter Wallentén at the Division of Building Physics, LTH at Lund University.

Laboratory observations: Although real field measurements were not used in this study, a biological understanding was formed from lectures, laboratory observations and field trips to attics with onset of mould with help of senior researcher Yujing Li.

1.5 Boundaries and limitations

Due to time limit of 20 weeks, there are no measurements included in this study. Instead a detailed study of the climate data has been conducted. This thesis work only considers wooden structure commonly used in Sweden. Four mould models are used in the evaluation, the VTT-model, MRD-model, the m-model and WUFI-bio. These are representative models commonly used. The models have different mould growth assessment time. To get comparable results the assessment time was set to one year.

Future climate scenarios used in this thesis only consider annual changes between year 2040 and year 2050, mean values from one climate scenario was used, RCP 8.5.

Questions regarding economy, social, health issues, worsening air quality, structural issues due to decay fungi or moisture load, and user behaviour will not be considered in this thesis.

2 Literature study

Roof is the top structure of a building, which has the function of shielding the building against precipitation and other weathering conditions. However, this part of the structure can also be problematic due to moisture and mould problems developed in the structure. A common roof structure in Sweden is the outdoor ventilated attic, but alternative solutions have been suggested to replace these traditional structure in order to avoid such moisture problems associated with it.

Nowadays the most common structures used in Sweden are: outdoor ventilated attics and cathedral roofs. It is not well known which of these structure performs best in different climate zones in Sweden, especially not when the challenges of climate change are included.

2.1 Outdoor ventilated attics

The outdoor ventilated attic (See Figure 2.1) is a common structure in Sweden. In a historical context, this type of structure was practical due to its simple structure. Before the oil crisis in the 1970´s, buildings were less insulated than today. The small amount of insulation led to significant heat transfer through the house envelope, which could be high enough to melt the snow on the roof. Water from melted snow can cause problems when it freezes on the soffits, creating icicles and potentially blocking gutters and downpipes. The attic space worked as a temperature equalizer and prevented the snow from melting on the roof (Sandin, 2004). In more recent years, campaigns from the authorities that promote energy saving measures combined with higher energy prices led that to increased insulation thickness installed on the attic floor. Consequently, less heat is able to escape from inside of the buildings. The original main function of the attic as a temperature equalizer is no longer necessary. From previously being a way to avoid warm roofs, the reason to build attics today is a question of building tradition and economics since it is cheaper to build (SBUF, 2013).

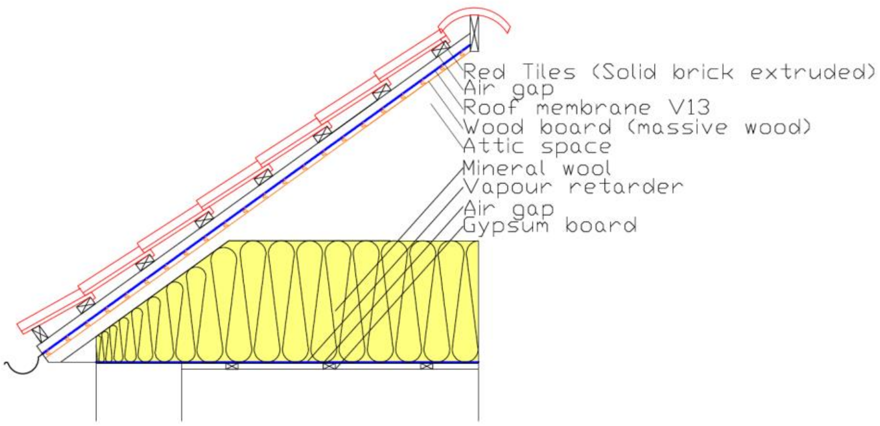

Figure 2.1 Section of an attic and its components (Drawn in AutoCAD)

2.2 Cathedral roof

The cathedral roof (See Figure 2.2) can either be ventilated or unventilated. The air gap is usually located beneath the cladding and above the insulation layer in the ventilated structure (see Figure 2.2). In the unventilated structure the insulation layer is attached directly to the cladding. (Lidgren, 2010). For this type of structure it is important that the wooden board under the roof is open for diffusion. In the ventilated structure, the air gap is a ventilated space connected to the outdoors. The main function of this space is to ventilate or drive out any moist air or water, which may penetrate the structure.

Mould growth problems can be difficult to detect due to the inaccessible and placement of the sensitive buildings components e.g. organic materials, claddings or insulation materials in cathedral roofs. An added, exterior insulation layer above the air gap can in some cases reduce the risks of moisture problems due to less over cooling during clear nights, see chapter 2.3.5.

When erecting the roof it is essential to be careful when applying the vapour barrier since even small holes in the membrane can cause moisture damages to the structure due to leakages. In this sense, the air gap has an important role as ventilator. Using a cathedral roof without a ventilated air gap has higher risk of moisture damages in case of leakages from indoors. (Mundt-Petersén, 2015).

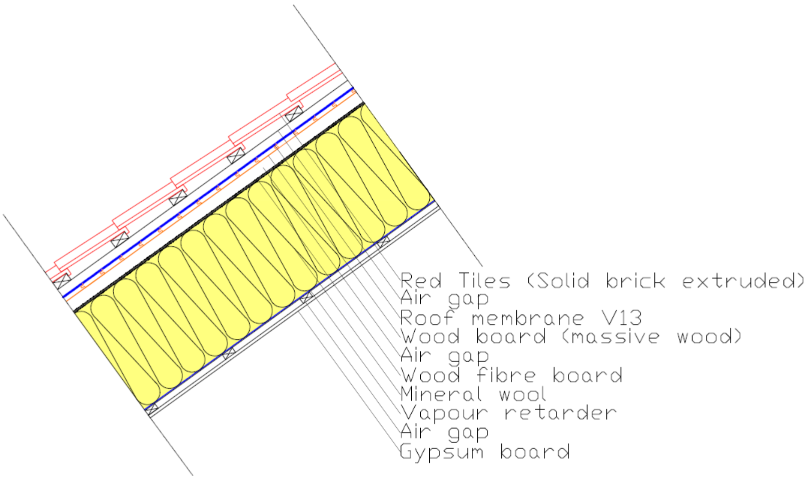

Figure 2.2 Section of a cathedral roof and its components. (Drawn in AutoCAD)

2.3 Moisture balance in roof structures

Air always contains a certain amount of water vapour. The maximum amount of water that air can hold is called the *saturated water concentration* or *saturated vapour content,* which is expressed as v_s in kg/m^3. The saturated vapour content is directly linked to the temperature. At higher temperatures, air can contain higher amounts of water vapour. Figure 2.3 illustrates how the saturation point in air varies with temperature. (Sandin, 2004).

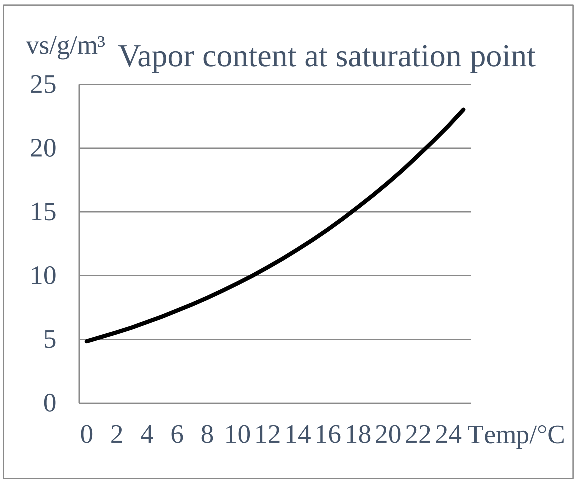

Figure 2.3 Saturated vapour content as a function of temperature

The vapour content at saturation point is of less practical use compared to the *relative humidity* ϕ (RH). The relative humidity is defined as the ratio between the actual vapour content, *v*, and the saturated vapour content in the air at a specific temperature as seen in equation (1). Relative humidity is dimensionless and is usually expressed as a percentage.

$$\varphi = v/v_s \qquad (1)$$

If the actual vapour content reaches the vapour content at saturation ($\varphi > 100\%$) the excess water will pass from vapour to free water. This phenomenon is called condensation. This can occur if a warm air stream gets cooled down by a cool surface, for instance at a poorly insulated window (Sandin, 2004).

2.3.1 Moisture sources

Moisture affecting a roof structure derives from various sources from both indoors and outdoors. The vapour content indoors is determined by the outdoor vapour content since buildings are ventilated with outdoor air, and naturally influences the RH inside the building. In Sweden, the outdoor RH varies between 80-90% in the winter and 60-80% in the summer. The RH indoors varies approximately between 30% in the winter and 60% in the summer. This is due to temperature differences between indoors and outdoors.

The moisture production indoors (*g/h*) pertains to the amount of vapour added to the indoor air from building occupants, plants, indoor activities, such as cooking, washing etc. The moisture production leads to *excess moisture* in the indoor air and is expressed in Kg/m^3. It usually varies between 2-4 g/m^3 depending on the occupancy rate. Excess moisture can enter a roof structure from either diffusion, convection or a combination of both. One of the main tasks of the ventilation system, besides of sustaining a good indoor air quality, is to remove the excess moisture from the buildings. (Sandin, 2004).

Outdoor moisture sources are normally rain and snow. Under influence of wind, which gives it a horizontal direction, it is called driving rain. The water drops have both vertical and horizontal directions. How driving rain affects a roof structure depends on its orientation, surrounding buildings, wind velocity and prevailing wind direction.

2.3.2 Protection against moisture diffusion

It is crucial to prevent this excess moisture to be transported into the roof structure. Diffusion requires a medium in vapour phase. The driving force is the difference in concentration of molecules between mediums, see Figure 2.4. The amount of vapour transported depends on how vapour tight the material is, which separates the different air volumes. The material is given an *sd*-value which indicates its *diffusion resistance,* expressed as the equivalent meters of air layer having the same resistance. Diffusion is a slow process.

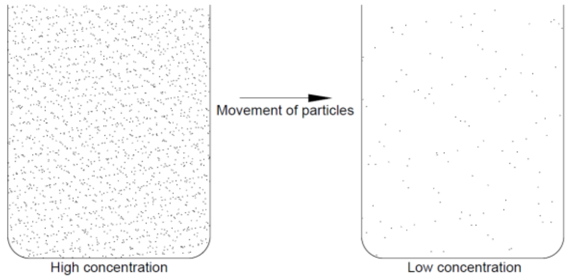

Figure 2.4 Vapour diffusion from high concentration to low concentration (drawn in AutoCAD)

To avoid excess moisture from penetrating the structure from the indoors via diffusion, a vapour barrier is needed. It should be installed on the interior part of the wall. It is typically made of a non-permeable material such as plastic sheeting. (Sandin, 2004).

2.3.3 Protection against convection

Under the influence of wind, temperatures and ventilation systems, pressure differences in the air will occur and then cause the transportation of moisture. This is called convection. Pressure differences between the air gap or attic space and indoors could potentially transport excess moisture into the roof structure. In these cases the airstream usually goes from a warmer environment to a colder environment, the saturation point in the air decreases, and RH rises. While diffusion usually is a slow process, moisture transport through convection can be significantly faster. See Table 2.1 for a comparison between diffusion and convection through a 250 mm thick wall. Convection is the dominating moisture transport whenever there is a leak. Since airtightness is accommodated by the vapour barrier, the key to avoid critical levels of convection is to block penetrations from indoors. Tight sealants around joints and voids are crucial to minimize the total moisture load.

Table 2.1 Moisture transport thorough a 250 mm thick wall, comparison between diffusion and convection (Sandin, 2004)

Type of structure	**Amount of condensable moisture ($* 10^{-8}$ kg/m²s)**	
	Diffusion	**Convection**
Homogenous aerated concrete	12.8	2.5
Brickwork of aerated concrete	12.8	406
500 mm wide aerated concrete elements with 0.2 mm cracks between them	12.8	11.1
500 mm wide aerated concrete elements with 1 mm cracks between them	12.8	920

From Table 2.1 it is clearly shown that diffusion is unaffected by voids, and that convection is small for tight layers without cracks. But even for small openings (0.2 mm) convection is as high as diffusion. At even wider cracks (1 mm), convection is the dominating moisture transport. Leakages around chimneys, pipes and hatchways leading up to the attic, are common examples of when convection occurs in buildings, see Figure 2.5

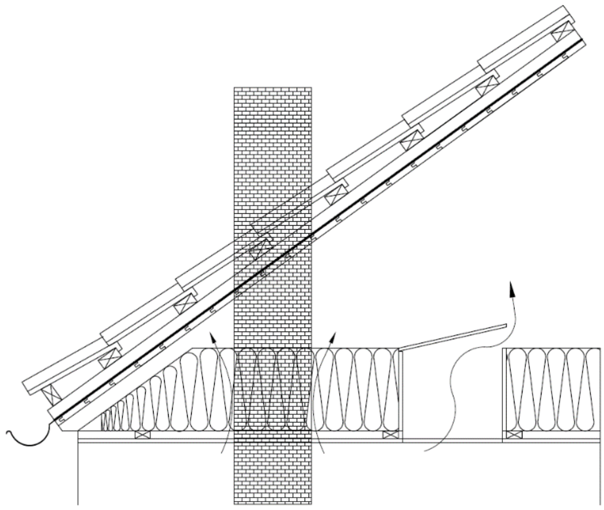

Figure 2.5 Convection through cracks and voids in the system of joints (drawn in AutoCAD)

2.3.4 Protection against precipitation

The roof is constructed with two barriers with a ventilated gap in-between to protect the building against rain and snow. The first layer is commonly made of a water tight material, e.g. tiles or metal sheeting. Its main function is to protect the underlying sensitive materials such as wood beams. (SP, Sveriges Tekniska Forskningsinstitut, 2010) The first layer often consists of ceramic tiles which are commonly used in Sweden. This roofing material has a long durability and a high water resistance. Also the roof colour affects the absorption of solar radiation and therefore the temperature and relative humidity in the structure. Light colours absorb short-wave radiation (visible light) and reflect long-wave radiation (heat). This will lead to a lower temperature than if the tiles are dark coloured. (Mundt-Petersén, 2015).

The second layer consists of a waterproof material, e.g. asphalt paper. It blocks water that has been pushed in behind the tiles by either driving rain or through leaks in the tiles. Building structures such as roofs and walls must be able to dry out in case of water penetrations and at the same time prevent water from entering.

2.3.5 The effects of night sky radiation

Another source that can increase the RH in the roof structure is long-wave, night-sky radiation. This phenomenon can lower the temperature in the whole attic space or air gap. To reduce the cooling and thereby the risk of too high RH, an insulation layer can be installed on top of the wooden boards. See Figure 2.6.

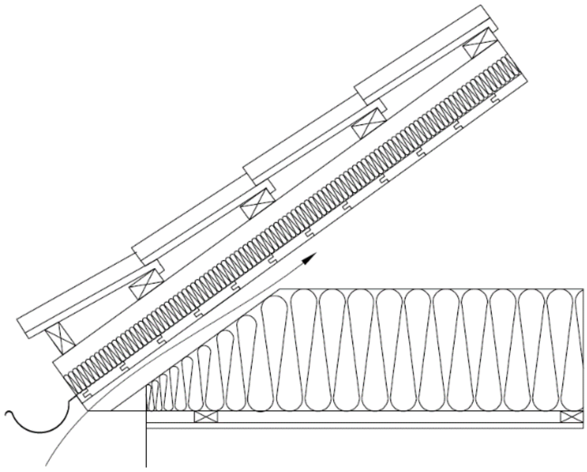

Figure 2.6 A complementary insulation-layer in the roof reduces the effects of night sky radiation, but also affect the drying out potential during sunny days (drawn in AutoCAD).

However, this also mitigates the drying effect due to solar radiation during sunny days. The effect of this insulation layer depends on the balance between warm and cold days and the weather conditions. (Hagentoft, et al., 2012). Studies suggest that it is generally more effective in northern Sweden that in the south. (Mundt-Petersén, 2015).

2.3.6 Air gaps

The ventilation rates fluctuates greatly in air gaps and depend on a number of factors. Main influencing factors are wind pressure and air movement due to temperature differences, especially when solar radiation heats the surface of the roof. It is therefore difficult to estimate or generalize a static air flow.

According to Falk (Falk, 2014) a ventilation rate of 230-310ACH (Air Change per hour) could be expected in the outermost air gap of a rendered rain-screen wall with a wooden structure during the period between October to February in Lund.

According to Mundt-Petersén a ventilation rate of 30ACH is reasonable in the inner air gap under the wood board in a cathedral roof. The same study investigated the effects of having an air change rate between 3 and 300. The results showed that 3 ACH was considered insufficient to ventilate any possible moisture load in the air gap, while 300ACH was considered too high, since the high ventilation rates decreases the temperature and increases the relative humidity in the air gap. Higher ventilation rates in the air gap may have a negative effect on the conditions on the surface of the insulation layer, especially in northern climates (Mundt-Petersen, 2013).

The most common way to ventilate an attic is either through gable or soffit ventilation. The ventilation rates vary depending on the size of the openings. In 1998 Walker and Forrester measured ventilation rates of two test houses at the University of Alberta. They found that the ventilation rates often were between 2 and 4 air changes per hour when the temperature difference between indoor and outdoor was the dominant force (Walker, et al., 1995). This conforms to the calculation guide, RäknaF, which recommends a default value of ACH of 3 in the attic. (Wallentén, et al., 2015).

2.3.7 Insulation

An increased thickness of insulation lowers the temperature in the layer next to the insulation and thereby increases the RH (SP, 2013). The effects of increasing the insulation thickness was highlighted in (Mundt-Petersén, 2015) where studies revealed increasing RH for insulation thicknesses up to 400mm. The moisture conditions seemed to get worse with even higher insulation thicknesses but to a smaller degree.

The same author examined the effects of mineral, cellulose fibre and polystyrene insulation materials in the roof. He concluded that mineral insulation and cellulose fibre resulted in similar climate conditions in the structures. The vapour-tight polystyrene gave, on the other hand, other results. Since moisture in the polystyrene can get trapped in the component, it was not recommended in roof structures (Mundt-Petersén, 2015).

2.3.8 Critical moisture levels

Some moisture in structures is inevitable. The structures resistance to moisture is decided by its assigned materials. The risk of mould growth occurring is dependent on the material properties, since every material has its own critical moisture level. The critical moisture levels are fundamental for mould growth models, which describe how RH and temperature changes a materials susceptibility for mould growth. The data which describe the correlation between RH, temperature and mould growth are normally investigated in laboratory studies. Material samples are incubated under certain temperature and RH conditions under certain periods of time, and their mould growth levels are then evaluated. Pernilla Johansson et al. conducted a literature review to summarize research that has been done regarding critical moisture levels. The study resulted in the values presented in Table 2.2. The values refer to the materials surface. The exact duration is not specified. (Johansson, et al., 2005)

Table 2.2 suggested critical moisture levels by SP (Johansson, et al., 2005)

Material group	Critical moisture levels RH (%)
Wood and wood based material	75-80
Gypsum board with paperboard	80-85
Mineral wool	90-95
Extruded polystyrene	90-95
Concrete	90-95

In BBR it is stated that RH 75% should be used for materials when their critical moisture levels are not known. (Boverkets byggregler, 18, 2011). When using the type of data in Table 2.1 and BBR:s limit there is no need to know the temperature and duration time since mould growth seldom occur in these ranges. Another way to present the critical moisture levels are seen in Figure 2.7. The lines describe how critical moisture levels depend on time, for how long a certain condition is allowed to occur before a critical mould growth has developed. (Viitanen, 1996). When comparing Table 2.2 and Figure 2.7 it is clear that mould growth is strongly dependent on not only RH, but also temperature and time.

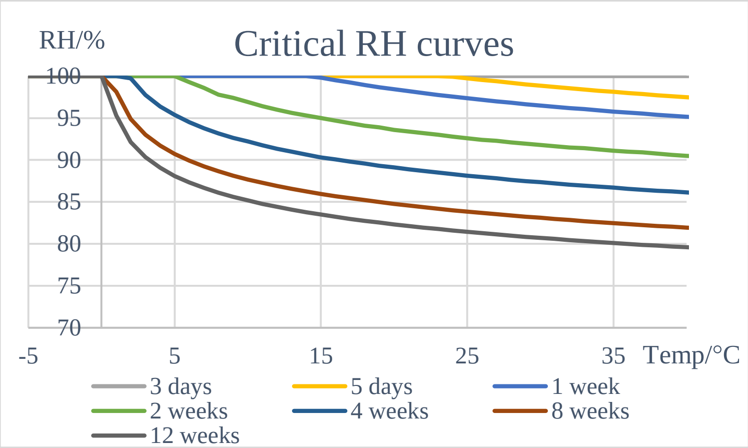

Figure 2.7 Critical RH curves for pine. (Viitanen, 1996).

2.4 Mould

High moisture levels in attics are a common building problem in Sweden and approximately 60% of the damaged wooden constructed attics could be related to moisture damages caused by high RH. Another 24% is caused by leakages due to damages to the climate envelope (Kalagasidis, et al., 2007). The most noticeable moisture problems in buildings are connected to mould or rot fungi. (Johansson, 2014).

2.4.1 Biological background

Mould is the general term of micro fungi. The development of mould can be divided into growth stages. Briefly explained as in Figure 2.8; spores from mould germinates on a surface when specific conditions are met. The spores grows into hyphae which then develops into mycelium and conidiophores. Sporulation from the conidiophores occurs under the reproduction stage (Johansson, 2014). Usually, the spores (sexual) and conidia (asexual) are inaccurately referred to as, spores. (Ikeda, et al., 2012) Hyphae on different material surfaces obtained from laboratory work can be seen in Figure 2.9 and Figure 2.10.

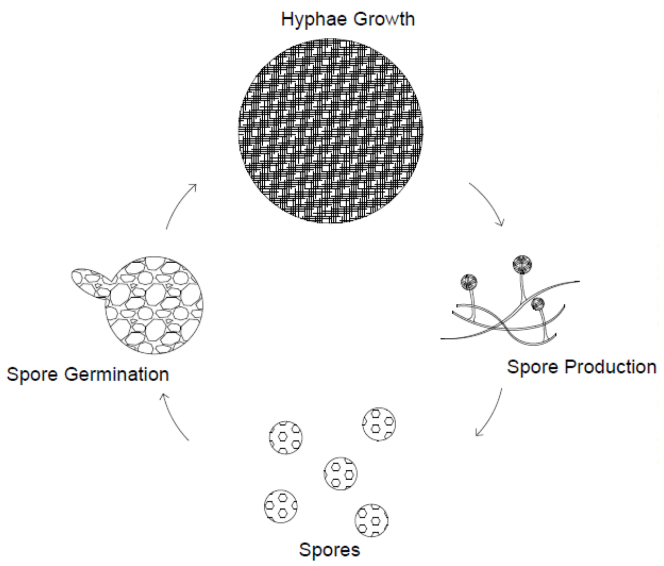

Figure 2.8 illustration of mould development (mould 2009)

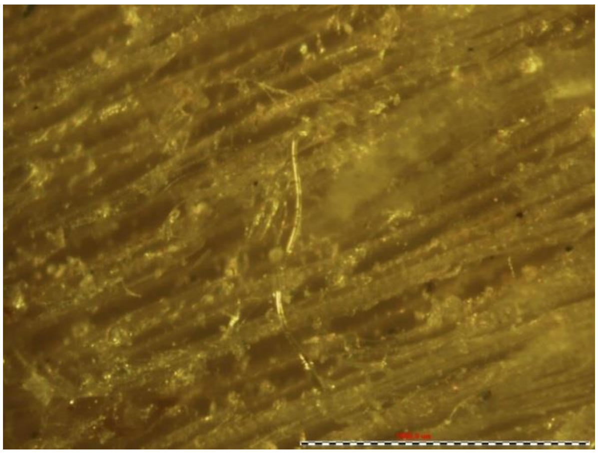

Figure 2.9 Example of a hypha on a piece of wood (100x) picture taken by the authors.

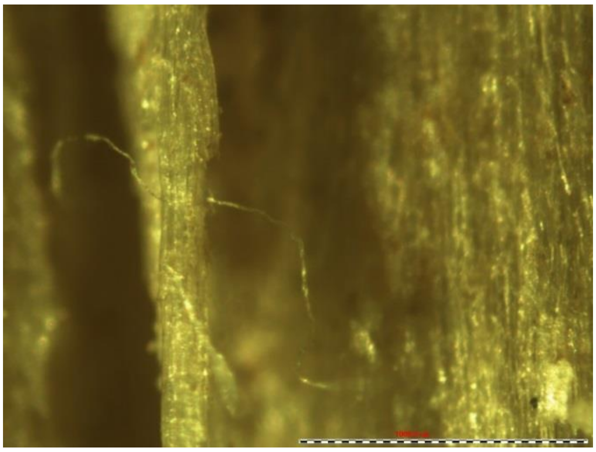

Figure 2.10 Example of a hypha on a piece of plywood (100x) picture taken by the authors.

Apart from mould there are other microorganisms that can grow on organic materials. Mould, decay fungi (*rot fungi*), blue-stain fungi and bacteria are just a few examples. (Viitanen, 1996).

2.4.2 Mould related health problems

Mould plays an important role in the indoor air related health problems. The sense of smell influences how people will perceive the environment. For example, the sense of mould is associated with an unhealthy environment, even though the concentration or mould spores might be too low for actually being harmful to the human body.

2.4.2.1 IAQ and SBS

Mould and mould odour have been associated with a variation of symptoms such as headaches, tiredness, difficulties breathing, nauseas, fevers, runny nose etc. These symptoms can be referred to as Sick Building Syndrome (SBS) caused by inadequate indoor air quality (IAQ). Microbial Volatile Organic Compound (mVOC) is the substance produced from mould when it grows and has an acrid, recognised odour. (Ayanbimpe, et al., 2012)

Mould spores are easily airborne due to its small size and can enter the human body through air ways or from food in-take (Ayanbimpe, et al., 2012). Moulds have potential to cause health problems as they spread allergens during their development. Some mould can cause allergic reactions such as asthma, irritations to the skin, respiratory problems and infections (U.S. Environmental Protection Agency, 2010). In other cases, mould contamination has been related to mental illness such as depression (Ayanbimpe, et al., 2012). Effects of inadequate indoor quality have also been related to stress symptoms, which have a negative effect on performance and productivity (Wiklund, 2015). Some mould produce toxic substances called mycotoxins. Mycotoxins can be derived from different moulds species and materials and can affect human health in various ways. Some toxics may affect the organs functionality which can cause inflammations and affect the nervous- and immune systems. (Ayanbimpe, et al., 2012). A common specie of fungi normally associated with production of mycotoxins and SBS is *Stachybotrys*, which is also referred to as black mould (Cooley, et al., 1998). A study focused on investigating symptoms from moisture damaged- and microbial contaminated buildings, with attention to mould. The participants in this study showed fewer symptoms when the moisture source was attended. (Ayanbimpe, et al., 2012).

Other possible indicators of microbiological contamination are: odour, visible mould, condensation or material discolouring. The damages varies depending on what specie of fungus that has developed.

Although mould is associated with health issues, it is difficult to address whether health problems can be directly linked to mould or spores in the indoor environment (Li, 2007). There is an uncertainty of the origin of the illness related to buildings. This uncertainty is called OBO, *Unspecified Building related Illness* (Ospecificerad Byggnadsrelaterad Ohälsa) (Wiklund, 2015)

2.4.3 Material degradation

Besides of health risks, constructional deformations can be the consequence of contamination from decay funguses. Depending on their properties, decay fungi can be categorized into three groups. The most common type of fungus in severe moisture damaged buildings is the brown rot. Other examples of decay fungus are white rot and soft rot (Viitanen, 1996). Dry rot is one of the most destructive and harmful fungi due its ability to transport water through dry materials (Li, 2007). Dry rot can even develop on dry materials and transport water from a water source several meters away.

2.4.4 Factors affecting mould growth

Mould exists naturally in the human environment and can be found everywhere in the surroundings. There is a great variation of mould species in the world, approximately 1.500.000 (Ayanbimpe, et al., 2012). In buildings, organic materials such as wood are distinguished as the most critical components to mould growth. In nature, mould has an important role as a degrader of biological organisms such as dead animals and plants. Mould reproduces itself by emitting spores (sporulation) which typically have a higher resistance to fluctuating temperatures and relative humidity than mould itself. Besides nutrition other important factors influencing mould development are the vapour content, relative humidity, temperature, pH and oxygen. (Johansson, 2014). The amount of accessible water is recognized as one of the most crucial factors for moulds development (Hens, 2009). This will be explained in more detail in chapter 2.4.5. In dwellings, mould and rot can have a negative effect on the indoor climate e.g. sharp odour and structural degradation.

The variation of mould species is great and they thrive differently in different climates. Moulds optimal growth temperature is in the range of the common indoor temperature in dwellings, 20-30°C (Li, 2007) and in higher relative humidity, above 60% (Johansson, 2014) Due to the high amount of moisture sources indoors, the relative humidity is normally higher than outdoors. (See chapter 2.3.1). Favourable conditions are therefore often met in the indoor environment. From a mould germinating perspective, the critical relative humidity level for an organic building material is within the range of 75-80% (Viitanen, 1996). The time of exposure is also relevant when determining whether mould will germinate on a surface or not. (Viitanen, et al., 1998)

2.4.5 Water activity

Mould requires water activity *(a_w)* to grow and is defined and determined by the accessible water in the material, expressed as the relative humidity in equilibrium (when the relative humidity is equal between the material and the surrounding air) (Parra, et al., 2004). By determining the water activity needed for a specific mould to germinate, it is possible to categorize the species into sub-groups called primary (<0.8 a_w), secondary (0.8-0.9 a_w) and tertiary colonisers (<0.9 a_w) (Nielsen, 2002). Mould species that can germinate in dry environments with low water activity are called *Xerophilic* fungus (>0.60 a_w). Fungus with a tolerance of >0.90 a_w is referred to as field fungus (Lacey, o.a., 1986) Organic components are especially susceptible to mould growth since fungus can grow at lower water activity due to high starch content in wood based materials (Johansson, 2014). There is a possibility that mould will develop on an inorganic material if organic materials, such as dust, sediments on its surface. Other potential materials susceptible to fungus growth are gypsum boards, wallpapers, textiles, PVC, polyethylene and concrete. In some cases, even paint can increase the vulnerability of a surface making it even more susceptible to mould growth (Nielsen, 2002). The properties, such as PH, of the material and its accessible water in relation to the surrounding environment are vital to understand for which conditions a specific fungi can grow. Each material has therefore a critical moisture level determining when the conditions are favourable for mould development, see chapter 2.3.8.

2.5 WUFI

WUFI is an acronym for Wärme und Feuchte instationär, developed at the Fraunhofer Institut für Bauphysik in Germany. It is a calculation software where the hygrothermal conditions of multilayer structures can be examined. The programme is based on laboratory experiments and real measurements from reference buildings. The software can examine the effects of different material properties which can be compared and analysed. The program can, for example, be used to determine moisture levels in the structure for specific climates.

There are different WUFI programs available with different functions, both one-dimensional and two-dimensional versions. The main differences between them is that the two-dimensional software has the capacity to calculate the effects of thermal bridges (Martin, et al., 2009).

2.5.1 Climate data

The climate data has been recognizes as an essential parameter and influences the results from the hygrothermal simulations substantial. Locating a structure in an appropriate reference climate could be of great importance if real measurements or evaluation to real cases are not conducted.

Choosing the appropriate weather file can be difficult since there is a great variation of parameters affecting the outdoor conditions. Such as wind, solar radiation, temperature, relative humidity. The location of the simulation can be specified by browsing through a series of climate data by picking the location from a map in the software's database. The software also gives the possibility to create climate files with data obtained from other sources, for example from meteorological institutes. There is a large variety of weather data available for WUFI. Three data types can be distinguished; measured- , realistic- ("synthetic data") or laboratory data. Typically the weather data consists of data received from real measurements from meteorological stations. Synthetic data is weather data created by models and could include calculated amounts of solar radiation depending on solar positioning and cloud cover. Laboratory data is weather data created in lab-environment. Some weather data, e.g. WUFI´s standard data, only consist of average or mean-values which could be inappropriate for certain hygrothermal simulations. The data can be based on hourly, yearly or calculated mean-value measurements. The situation of when a specific weather data should be used depends on what type of simulation is to be executed.

Below is a list of file formats available for WUFI with a short explanation.

- Test Reference Year [TRY] datasets*:* Does not consider effects of solar radiation and consist of a single reference year between1948-1975.
- International Weather Year for Energy Calculation [IWC]: Developed by ASHRAE and consists of 18 years of hourly logged data, with estimated solar radiation and consideration to rain intensity.
- The German National Meteorological Service [DAT]: No consideration to rain.
- WUFI ASCII climate format [WAC]: Web Application Companions, developed by WUFI. Considers both rain and radiation.
- WUFI binary climate file [WBC]: proprietary format, can only be used in WUFI
- EnergyPlus Weather file [EPW]: Developed by the U.S. Department of Energy.

In WUFI four different indoor climate standards can be chosen; EN 13788, PrEn 15026, ASHRAE 160 and Sine Curves. Different degrees of moisture loads depending on the prevailing climate (low, medium and high moisture loads) can be assigned using EN13788, PrEN15026 and sine-curve. Some of the main differences between the standards are:

- The PrEN15026 (numerical) is considered to be a more detailed standard since it is using hourly data in its calculations.
- The EN13788 (steady-state) is considered to be a more simplified version, using monthly mean values in its calculations. This standard does not consider built-in

moisture etc. Unlike PrEN 15026 (The European Provisional Standard), EN13788 (The European Standard) uses a constant indoor climate in its algorithm.
- ASHRAE 160 considers the effects of an air-conditioning system etc.
- Sine-curves allow you to use predefined sinus-shaped curves for different moisture loads.

(Zirkelbach, et al., 2013)

2.5.2 Future climate

To investigate how the structure would sustain in a future climate requires modified climate data, using anticipated fluctuating parameters, to be implemented. The modifications can be made by using accessible predicted climate scenarios. There are different climate scenarios available: RCP 2.6, RCP 4.5, and RCP 8.5. Without any consideration to seasonal variations, the values are expressed as a single number representing a whole year. This number gives an indication of how the weather will change in comparison to existing measurements

- RCP 2.6: Powerful climate policy means that greenhouse gas emissions will culminate in 2020, radiative forcing reaches 2.6 W / m² in 2100.
- RCP 4.5: Strategies for reducing greenhouse gas emissions means that the radiative forcing is stabilized at 4.5 W / m² by 2100.
- RCP 8.5: Increasing greenhouse gas emissions means that the radiative forcing reaches 8.5 W / m² in 2100.

The models above have been run from year 1961 to 2100. The meteorological period 1961-1990 is first used to validate the model. The model results from 1961-1990 can be compared with observations from the same period to see how well the model can represent the current climate. The period 1961-1990 is then used as a reference when predicting how the climate is changing. The results for the future are compared with the average for the period 1961-1990. (SMHI, 2011).

2.5.3 Climate parameters in WUFI

Following subchapters describes how WUFI handles input data from climate files.

2.5.3.1 Solar radiation

The solar radiation (W/m^2) is a crucial factor when considering drying potentials. The solar radiation can be derived into direct, diffuse and global radiation (global is the sum of diffused and direct). In some cases, the weather stations which only consider global radiation on a horizontal surface which makes the other parameters difficult to predict. The global radiation is enough if the investigated surface is located horizontally. WUFI calculate the effects of global radiation on a surface with another inclination, however, the diffuse and direct radiation data needs to be separated in the weather file.

2.5.3.2 Rain

Since the data considering normal rain usually consists of horizontal measurements, WUFI coverts the data into actually amounts by assessing the surface inclination, height and azimuth. The normal rain is used to calculate the effects of driving rain using the prevailing wind direction and wind velocity. The effect of wind is only taken into account when driving rain (*Ltr/m^2h*) is considered. The amount of driving-rain is also affected by the inclination of the surface which determines the driving rain factor. In WUFI, the driving rain load is calculated using normal rain, wind velocity and wind direction from the weather file according to equation (2).

$$\text{Driving rain load} = \text{rain} \cdot (\text{R1} + \text{R2} \cdot \text{wind velocity}) \quad (2)$$

R1 and R2 are called driving rain coefficients. R1 is determined by how much of the *normal rain* that hits the surface. R2 is how much normal rain is affected by wind velocity.

2.5.3.3 Long-wave counter radiation

There is a constant exchange of thermal radiation between a surface of a building and the surrounding environment. Counter radiation (*W/m²)* is expressed as the long-wave radiation emitted from the surrounding, especially ground reflection and radiation form the atmosphere. This is accounted for in the software by compiling information regarding cloud cover, relative humidity and air temperature. Counter radiation could be accounted for by adding additional radiation to the *convective heat transport*. This is performed by WUFI automatically. The issue with compiling these factors is that the program assumes that the two heat factors are transported in the same direction, which is not always the case. For example when simulating situations that requires higher accuracy, when considering the effect of night sky radiation.

To be able to consider the effects of emitting thermal radiation (radiative emissivity) from the surroundings, orientation and inclination of the surface must be known. This can normally be accounted for when using weather file format WAC. As mentioned in previous chapter, the data normally consists of information on a horizontal plane. In some cases, if information regarding counter radiation is missing, WUFI can estimate the influence of this parameter by using information from other, known weather elements. For example, cloud cover data could be used to estimate the counter radiation from the atmosphere. (IBP, 2013).

2.5.3.4 Barometric Pressure

The influences of the barometric pressure *(hPa*) are important for hygrothermal calculations and simulations and it affects the vapour transport. If the measured values are not obtained, WUFI will calculate an estimated pressure depending on the location. (IBP, 2013).

2.5.3.5 Limitations in WUFI

- The one-dimensional version of WUFI does not consider thermal bridges.
- The level of details are limited, corners and other structure details are not considered.
- Ventilation rates in air gaps are in real conditions fluctuating greatly depending on a variation of factors. See chapter 2.3.6. It is, however, added as a static number in WUFI.
- WUFI has difficulties handling effects of free water in the structure. It is difficult to determine how much water will penetrate the structure in a real case due to poor workmanship or rain etc.
- The materials in the library do not consider hysteresis
- WUFI does not consider the effects of shading from surrounding buildings or other subjects. This means that WUFI considers the buildings located uninfluenced by its

surrounding objects. However the user can reduce the sun, or make other changes to take this into consideration.

2.1 Mould models

Mould models are used to predict the development of growth in specific conditions. Many different models have been developed throughout the years. The models consider different parameters in their calculations, such as; hibernation, duration and material properties. Following chapter will describe the different mould models used in this study.

2.1.1 The VTT-model

VTT-model is an empirical mould prediction model developed by Hukka and Viitanen. The first VTT-model from 1996 was based on experiments on spruce and pine where the data were used to create a mathematical model for mould growth. This was one of the first models to take fluctuating climates into account. (Verekeen, et al., 2012).

The growth development is expressed by the mould index, (M). The index ranges from 0-6 where 0 indicates no mould growth and 6 a full coverage (see Table 2.3). The index number can be used as a design criterion in the procurement process, specifying the maximum allowed mould index in a certain building part or building.

Table 2.3 General mould index description and corresponding rates of mould growth in VTT-model (Viitanen, 1996)

<table>
<tr><th>Index</th><th>Growth rate</th><th>Description</th><th></th><th></th></tr>
<tr><td>0</td><td>No mould growth</td><td></td><td></td><td></td></tr>
<tr><td>1</td><td>Small amounts of mould on surface</td><td>Initial stage of growth</td><td rowspan="4">Microscopic level (40x)</td><td></td></tr>
<tr><td>2</td><td><10% coverage of mould on surface</td><td></td><td rowspan="5">Visually detectable</td></tr>
<tr><td>3</td><td>10-30% coverage of mould on surface, or <50% coverage of mould (microscope)</td><td>New spores produced</td></tr>
<tr><td>4</td><td>30-70% coverage of mould on surface, or >50% coverage of mould (microscope)</td><td>Moderate growth</td></tr>
<tr><td>5</td><td>>70% coverage of mould on surface</td><td>Plenty of growth</td><td></td></tr>
<tr><td>6</td><td>Very heavy, dense mould growth covers nearly 100% of the surface.</td><td>Coverage around 100%</td><td></td></tr>
</table>

2.1.1.1 Updated VTT-model

The VTT-model has been expanded to be valid for other materials than just spruce and pine. The investigated materials are spruce board (with glued edges), concrete (maximum grain size 8 mm), aerated concrete, cellular concrete, polyurethane thermal insulation (PUR, with paper surface and with polished surface), glass wool, polyester wool and expanded polystyrene (EPS). The growth intensity factor (k_1) was determined by logging the time it took for mould growth to increase from index 1 to index 3 at 22°C and 97% RH for the different materials.

Then the results were compared to a reference material, pine, in the same environment and new mould growth intensity factors and set back equations were developed. (Verekeen, et al., 2012)

2.1.2 The m-model

The m-model is a mould growth model developed by Skanska. It has the function of calculating mould growth in fluctuating conditions and in different materials, mainly wooden based materials. The tool enables comparisons of different structures and their mould growth potential in certain environments. (Berggren, et al., 2010). Swedish building regulations (BBR) have been implemented in this model by applying Viitanens mould growth index 1 which, in this model, is the maximum allowed mould growth. (Togerö, et al., 2011). The input data consider relative humidity, temperature and time (*t*) which could be obtained from logging, measurements or a hygrothermal software like WUFI.

2.1.3 The MRD-model

The MRD-model (Mould Resistance Design-model) is a mould growth model developed within the WoodBuild programme by the wood-building industry. The input data in the MRD-model can consist of real weather measurements, laboratory experiments or outputs from hygrothermal calculation software's like WUFI. Depending on the surrounding conditions, the program calculates a dose as a function of exposure time. The Dose is also expressed in time, ($D_{(t)}$) and fluctuates depending on how favourable the conditions are for mould development. High dose corresponds to favourable conditions, a low dose corresponds to unfavourable conditions. This dose should be compared to a critical dose called D_{crit}. D_{crit} depends on what material is tested and is the critical threshold for mould initiation in a specific reference climate. (Thelandersson, et al., 2012)

2.1.4 WUFI-Bio

WUFI-bio is a plugin software to WUFI. RH, temperature and time, for a material or monitored position, are exported from WUFI to WUFI-bio which gives a mould growth prediction, either as mm/year or as mould index number from the VTT-model scale, seen in Table 2.3, in chapter 2.1.1.

WUFI-bio is a tool based on Sedlbauers work *Predictions of mould fungus formation on the surface of and inside building components* from 2001 (Sedlbauer, 2001) and Sedlbauers, Krus and Breuers conference paper *Mould growth predictions with a new bio-hygrothermal method and its application in practice* from 2003 (Sedlbauer; Martin; Breuer, 2003).

The transient bio-hygrothermal model is based on the spore´s osmotic potential which enables it to take up water from its environment. The moisture absorption is modelled as a diffusion transport through the spore wall. The spore is assigned an *sd* value which describes the latency of moisture exchange with the environment. When a certain critical vapour content in the spore is reached, the spore germinates. When the spore has germinated, thus initiating mycelium growth, the growth rate is dependent on the ambient temperature and humidity according to a growth isopleth system using time steps. During dry periods the fungi cease to grow, but do not decline.

Sedlbauer divided materials into subdivisions to take the influence of building substrate into account, including possible contaminations according to Table 2.4.

Table 2.4 Sedlbauers subdivisions separating materials depending on the substrate category.

Substrate category 0	Optimal culture medium
Substrate category 1	Biologically recyclable building materials like wall paper, plaster cardboard, building materials made of biologically degradable raw materials, materials for permanent elastic joints.
Substrate category 2	Biologically adverse recyclable building materials such as renderings, mineral building materials, certain wood as well as insulation materials not covered by cat. 1.
Substrate category 3	Building materials that are neither degradable nor contains nutrients.

See table 2.5 for an overview of the different mould predication models.

Table 2.5 Summarizing table of important characteristics of mould models.

Models	**RH**	**Temp.**	**Reduction**	**Growth below 0° C**	**Time steps**	**Materials**	**Growth assessment time**
m-model	YES	YES	Yes. Both favourable and unfavourable climate. Reduction in growth possible.	Hibernates at -5°C	Normally Hourly, or max. 3 h	4 sensitivity classes	1 year
MRD	YES	YES	Yes. Both favourable and unfavourable climate. Reduction in growth possible.	Hibernates at 0.1°C	Hourly	Wood based	>1 year
VTT	YES	YES	Yes. Both favourable and unfavourable climate. Reduction dependant on duration of dry periods.	Delay in mould growth at 0°C	Hourly	Yes, in updated VTT	>1 year
WUFI-bio	YES	YES	Yes, Both favourable and unfavourable climate. No reduction, only delay.	No growth below 0°C	Can vary	4 different substrate categories	1 year

2.1.4.1 Remarks mould growth models

No mould growth model presented in this paper is applicable for exterior surfaces. Increased humidity due to rain would indicate an elevated mould risk, meanwhile UV-radiation and heating from the sun in reality prevents mould from growing.

3 Method

All hygrothermal simulations have been performed in WUFI 5.3. The locations investigated were chosen from different representative parts of Sweden, see Figure 3.1.

- Lund, located in the south-west of Sweden.
- Stockholm, the capital of Sweden located on the east coast.
- Borlänge, located in the middle of Sweden.
- Luleå, located in the north-east part of Sweden.

Each roof structure was simulated for ten years in each location. According to the WUFI manual, the duration of a hygrothermal simulation should be set to at least two years. (Zirkelbach, et al., 2013). The time step was set to hourly. According to the report *on the fungal defacement of interior finishes*, the moisture levels are more deterministic for the mould growth compare to temperature (Adan, 1994). Consequently the worst year was determined by examine the RH curves from WUFI to find the most deviant values which was further analysed in the mould models. The same year was used for the same location for both existing and future climate, for a better comparison between the two structures.

The effects of changing the air change rates in the constructions were performed, seen in Appendix E – Sensitivity analysis, ACH1, 3 and 5 ACH in the attic and 15, 30 and 45 ACH in the cathedral roof were examined. A lower ACH will generally contribute to a higher relative humidity in both constructions meanwhile the effects were smaller between the 30-45 and 3-5ACH. The assigned air change rates, 3 ACH in the attic and 30ACH in the cathedral roof, were considered appropriate based on the ACH sensitivity analysis and the literature review, see chapter 2.3.6 Air gaps.

Leakages from indoors were calculated manually according to Appendix C. The leakages are dependent on pressure differences caused by wind and temperature. The wind speed is obtained from the climate file, the building height was set to 8 meters. The hole was assumed to be 3 mm in diameter. The Diffusion was not considered since convection is the dominant moisture transport for this hole size. See Table 2.1.

Figure 3.1 The investigated locations in Sweden

3.1 WUFI settings - attic

See Figure 3.2 for a schematic illustration of the attic structure, Figure 3.3 show the same structure in WUFI. The materials and dimensions chosen from WUFIs internal database are included in Table 3.1. Table 3.2 lists moisture sources set in WUFI for each position marked with a letter. WUFI cannot consider differences in ceiling height in the attic space. Therefore an average value had to be determined to represent the attic space height. This was assumed to be 160 mm. The air change rate was set to 3 ACH according to chapter 2.3.6.

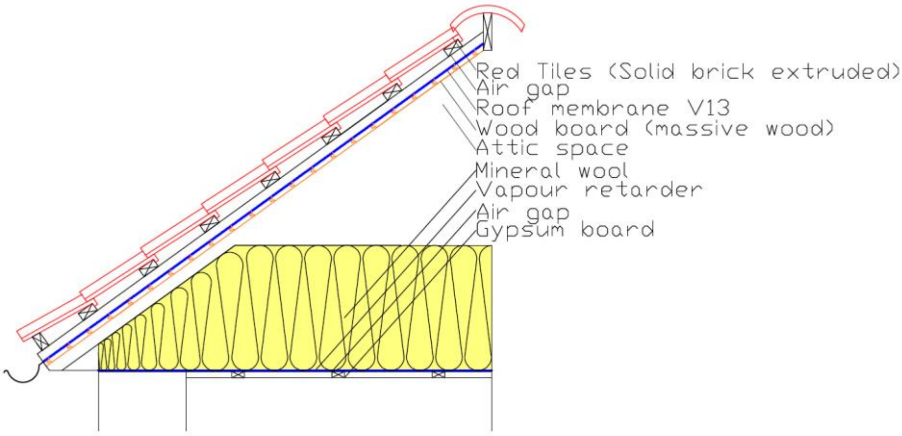

Figure 3.2 An illustration of the attic (drawn in AutoCAD).

Table 3.1 Material dimensions, starting from the outside

Materials	Width [mm]
Tiles	25
Air gap	70
roof membrane	1
Wood board	22
Cold attic space	160
Insulation	500
Vapour retarder	1
Air gap	25
Gypsum	13

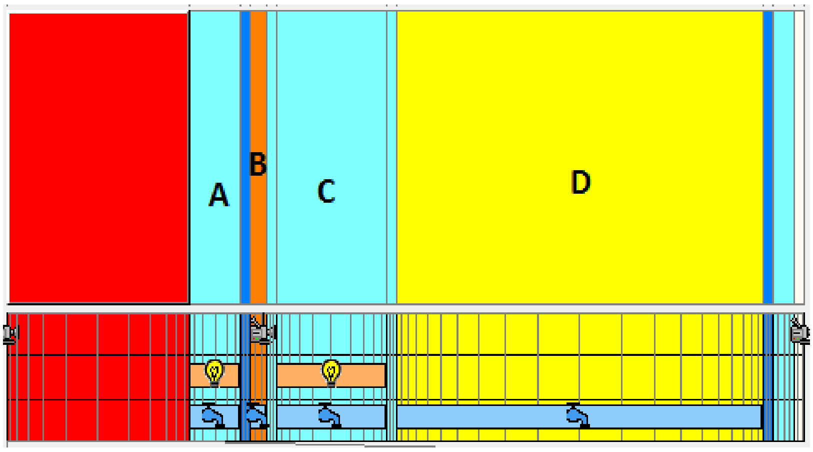

Figure 3.3 The attic structure in WUFI.

Table 3.2 Added moisture sources in the attic.

A	200 ACH
B	0.1% driving rain to consider leakages from outdoors.
C	3 ACH in the middle section of the air gap
D	Leakages from indoors, see Appendix C for calculation method

3.2 WUFI settings - cathedral roof

Figure 3.4 show a schematic illustration of the cathedral roof. Figure 3.5 display the corresponding WUFI model. Table 3.3 show the materials and dimensions, and Table 3.4 for the moisture sources for each position marked with a letter. The air change rate was set to 30 ACH according to chapter 2.3.6.

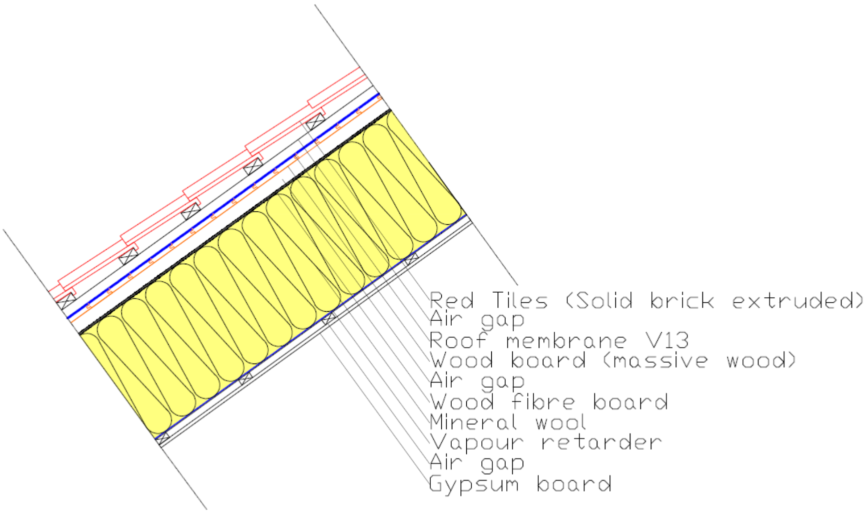

Figure 3.4 An illustration of the cathedral roof (drawn in AutoCAD).

Table 3.3 Material dimensions, starting from the outside

Materials	Width [mm]
Tiles	25
Air gap	70
Roof membrane	1
Wood board	22
Air gap	50
Insulation board	4
Mineral insulation	500
Vapour retarder	1
Air gap	25
Gypsum board	13

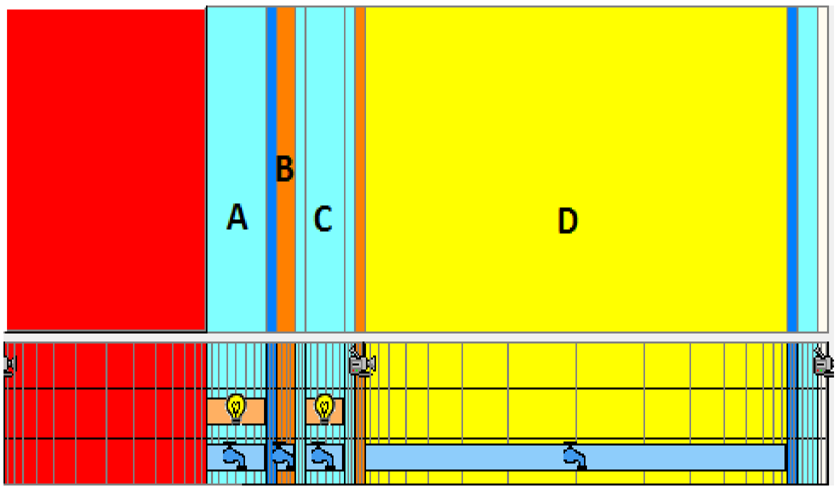

Figure 3.5 The cathedral roof in WUFI. The colours correspond to the same layers in

Table 3.4 Added moisture sources in the cathedral roof

A	200 ACH
B	0.1% driving rain to consider leakages from outdoors.
C	30 ACH in the middle section of the air gap
D	Leakages from indoors, see Appendix C for calculation method

3.3 Roof tilt and orientation

The roof structures are in several aspects designed to be energy efficient, and accordingly the roof tilt was decided to have an optimal inclination for harvesting solar energy. As seen in Figure 3.6 it is between 30° and 35°. I this study 30° was used because the optimal angle in northern Sweden is lower due to lower solar height. However, the attic insulation layer is horizontal which is the deterministic factor in WUFI, consequently the attic roof angle was set to 0° in WUFI.

The orientation was set to north, which is the worst case, due to more shading compared to the other orientations.

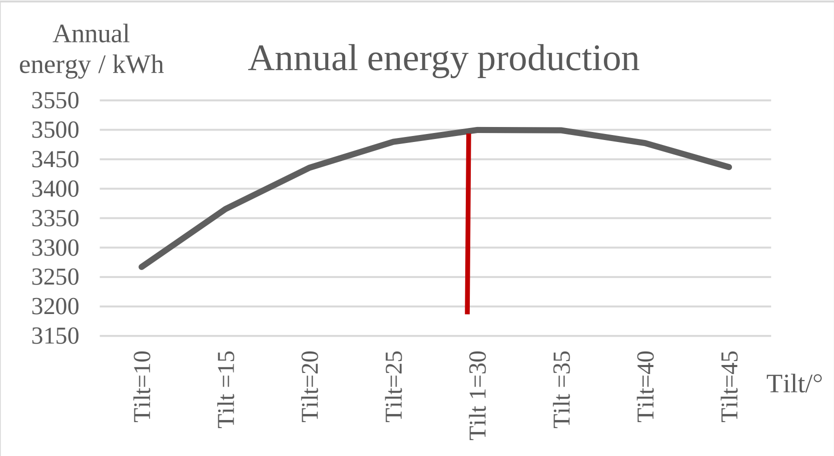

Figure 3.6 Optimal roof tilt with consideration to annual energy output. Simulation made in System Advisor Model (SAM) for location Lund.

3.4 Shared settings in WUFI

Following setting have been assigned to both structures.

3.4.1 Outdoor climate

WUFI ASCII Climate format-file [WAC] consisting of real measurements between years 1990-1998 obtained from Petter Wallentén were used. To evaluate the structures in future climates, the climate files were modified with scenario data between the years 2040-2050 according to RCP 8.5. Since the RCP 8.5 consists of data from nine different models, the mean values from each model were used. See appendix B for more detailed future climate data, and the used correction factors.

3.4.2 Indoor climate

Since the PrEN15026 standard is considered a more detailed climate standard using hourly data, than EN13788, it was used in this study. Normal moisture load was used which is typically between 30-60% RH.

3.4.3 List of settings in WUFI

The general settings for both structures are listed and described in Table 3.5.

Table 3.5 Shared settings in WUFI.

Parameter	**Input data**
Orientation	north
Tilt	30° for cathedral roof / 0° for attic.
height	-
Driving rain coefficient	R1: 1 [-] R2: 0 [s/m] (default numbers)
Surface transfer coefficients (Exterior surface)	
Heat resistance [m^2K/W]	0,0526 (Roof)
Sd-Value [m]	[-] no sd-value was set
Short-Wave Radiation Absorptivity	0,67 (Tiles, Red)
Long-Wave Radiation Emissivity	0,9 (Tiles Red)
Explicit Radiation Balance	
Ground Long-Wave Emissivity [-]	0,9 (Default)
Ground Long-Wave Reflectivity [-]	0,1 (Default)
Cloud index [-]	0,66 (Default)
Ground Short-Wave Reflectivity [-]	0,2 (Default)
Adhering Fraction of Rain [-]	1,0 (depending on inclination of component, Default for roofs)
Surface transfer coefficients (Interior surface)	
Heat resistance [m^2K/W]	0,125 (Default for roofs)
Sd-Value	[-] no sd-value was set
Initial conditions	
Initial temperature in component	Constant across component (20℃)
Initial moisture in component	In each layer
layers	**Vapour content [kg/m^3]**
See appendix A for list of materials.	
Numeric	
Heat transport Calculation	Turned on
Moisture Transport Calculation	Turned on
Use temperature ad moisture dependency	Turned on
Adaptive Time Step Control	Enable (Steps: 3, Max. stages: 5)
Numerical parameters	
Increased Accuracy	Turned on
Adapted Convergence	Turned on
Geometry (Cartesian)	Turned on

3.5 Method mould models

Following chapter describes how the mould models studied calculates a predicted mould growth and what factors they consider.

3.5.1 VTT-model

In the VTT-model, the mould growth is determined by calculating a mould index, (M). It is calculated using equation (3).

$$\frac{dM}{dt} = \frac{1}{7 * \exp(-0.68 lnT - 13.9 lnRH + 0.14W - 0.33SQ + 66.02)} * k_1 * k_2 \qquad (3)$$

Where:

T is temperature

RH is relative humidity

W is the examined wood specie (0=pine and 1=spruce)

SQ is the surface quality (0 is a sawn surface, 1 is kiln dried wood).

K_1 represent the growth intensity and it is calculated using equation (4).

$$k_1 = \begin{cases} 1 & when\ M \leq 1 \\ \dfrac{2}{t_{M=3}/{t_{M=1}}^{-1}} & when\ M > 1 \end{cases} \qquad (4)$$

Where $t_{M=1}$ is the time it takes (in weeks) to reach index 1, and $t_{M=3}$ is the time it takes to reach index 3. These values are called the response time and is, for constant temperatures and humidity conditions, calculated using equation (5a) and (5b).

$$t_{M=1} = \exp(-0.68 * \ln(\theta) - 13.9 * \ln(RH) + 0.14 * W - 0.33 * SQ + 66.02) \qquad (5a)$$

$$t_{M=3} = \exp(-0.74 * \ln(\theta) - 12.72 * \ln(RH) + 0.06 * W + 61.50) \qquad (5b)$$

K_2 represents the moderation of growth between 4<M<6 according to equation (6).

$$k_2 = \max[1 - \exp\big(2.3 * (M - M_{max})\big); 0] \qquad (6)$$

Where M_{max} is the maximum mould index level and depends on the surrounding conditions according to equation (7).

$$M_{max} = 1 + 7 * \left(\frac{RH_{crit} - RH}{RH_{crit} - RH}\right) - 2 * \left(\frac{RH_{crit} - RH}{RH_{crit} - 100}\right)^2 \qquad (7)$$

RH_{crit} is the RH-limit for mould germination and depends on the temperature. It is calculated according to equation (8).

$$RH_{crit} = \begin{cases} -0.00276\theta^3 + 0.160\theta^2 - 3.13\theta + 100, when\ \theta < 20℃ \\ RH_{min}, when\ \theta \geq 20℃ \end{cases} \qquad (8)$$

Mould growth delay will occur during unfavourable conditions. This condition is dependent on the critical RH from equation 8 and the temperature. The model exclude the possibility of any growth in temperatures below 0°C and above 50°C. The mould index declination depends on the duration of the unfavourable condition, where *t* is the time from moment t_1, when the conditions changed from growth to outside growth conditions. See equation (9).

$$\frac{dM}{dt} = \begin{cases} -0.032, when\ t - t_1 \leq 6\ h \\ 0, when\ 6h \leq t - t_1 \leq 24\ h \\ -0.01667, when\ t - t_1 > 24\ h \end{cases} \tag{9}$$

(Tuomo, et al., 2011)

3.5.1.1 Updated VTT-model

In the updated VTT-model, new mould growth intensity factors and set back equations have been developed (equation (10) and (11)). The updated VTT-model have divided the tested materials into 4 different categories see table Table 3.6.

See Table 3.7 for k_1, k_2, A, B, C and RH_{min} for different sensitivity classes. Equation (10) displays the updated equation.

$$M_{max} = A + B * \left(\frac{RH_{crit} - RH}{RH_{crit} - RH}\right) - C * \left(\frac{RH_{crit} - RH}{RH_{crit} - 100}\right)^2 \tag{10}$$

Table 3.6 Sensitivity classes and the corresponding materials in the updated VTT-model.

Sensitivity class	Materials
Very sensitive	Pine, sapwood
Sensitive	Glued wooden boards, PUR with paper surface, spruce
Medium resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool
Resistant	PUR with polished surface

Table 3.7 factors influencing the updated VTT-model.

Sensitivity class	k_1	k_1	M_{max} (influence on k2)			RH_{min} (%)
	(M<1)	(M≥1	A	B	C	
Very sensitive	1	2	1	7	2	80
Sensitive	0.578	0.386	10.3	6	1	80
Medium resistance	0.072	0.097	0	5	1.5	85
Resistance	0.033	0.014	0	3	1	85

The materials will influence a potential decline in mould growth, a constant relative factor C_{mat} is defined for the different materials mentioned above. By use of this coefficient, the original decline model (equation (9)) can be applied in the updated model according to equation (11).

$$\frac{dM}{dt_{mat}} = C_{mat} * \frac{dM}{dt_0} \tag{11}$$

The factor C_{mat} is introduced in Table 3.8.

Table 3.8 decline classes in the updated VTT-model.

Decline class	**Description**
1	Pine in original model
0.5	Significant decline
0.25	Relatively low decline
0.1	Almost no decline

3.5.2 The m-model

By calculating an m-index using following equations, the mould growth is predicted in the m-model.

The m-index is calculated according to equation (12).

$$m = \frac{RH_{act}(t)}{RH_{crit}\big(T(t)\big) * \gamma} \tag{12}$$

RH_{act} is the current moisture content in a material at the given time, t

RH_{crit} is critical moisture levels at temperature T at the given time, t

γ is a safety factor, usually set to 0.98.

The critical moisture levels are based on Viitanens work from figure 2.7, which have been modified for other time steps, hence forth called *duration lines*. See Figure 3.7.

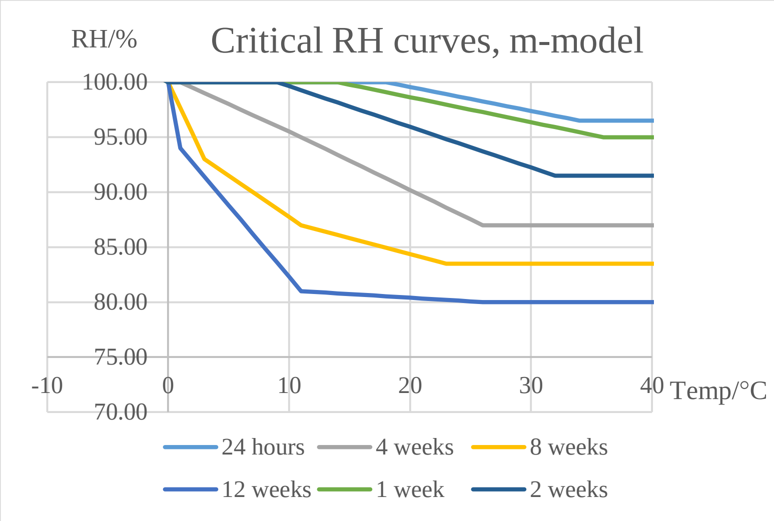

Figure 3.7 Critical moisture levels with safety factor 0.98.

Six calculations are performed simultaneously for each duration line and for every material or monitor position investigated. The data should consist of hourly- or three hour values. If the relationship m≥1 is true for any of the six duration lines, the critical moisture level have been exceeded. Every exceeded duration line is added to the total accumulated risk.

The model consider periods of unfavourable conditions for mould growth. To be able to consider fluctuations in relative humidity in steady temperatures, a factor called *dry periods* has been introduced to consider mould growth reduction. The size of the reduction factor (β) varies depending on the duration line and how unfavourable the conditions are. The dry periods can be divided into groups depending on the period duration, displayed in Table 3.9. The reduction factor is multiplied with the total risk time in dry periods which gives the reduction compared to the total accumulated risk time according to equation (13).

$$\beta = (\frac{RH_{act}}{RH_{crit}})^{\theta} = m^{\theta} \tag{13}$$

θ, depends on what duration line (see Figure 3.7) the calculation is made for according to Table 3.9.

Table 3.9 The reduction factor is decided by the duration line..

Duration line	Reduction factor
1, 2 and 4 weeks	$\theta_1 = 1.7$
8 and 12 weeks	$\theta_2 = 1.2$
24 hours	$\theta_3 = 4.5$

The accumulated time of risk is reset to zero if unfavourable climate lasts longer than 3 weeks for all 6 calculations. This prevents the accumulated risk time of exceeding critical conditions when simulating for longer periods.

The results from the m-model can be expressed either as the accumulated risk time or as the quotient between the accumulated risk time divided by the duration line called Kritisk

VaraktighetsKvot [KVK]. A KVK higher than 1 indicates that mould growth, in theory, has been initiated. Due to uncertainties regarding the model, the material and the climate a KVK above 0.7 is considered a risk (Berggren, et al., 2010).

Table 3.10 Calculated reduction factor of the accumulated risk time depending on the duration of the dry period.

Dry Period	**Time step (duration relationship) (*24h*)**	**Time step (duration relationship) (*1w, 2w, 4w, 8w, 12w*)**
0h-6h	Normal accumulated risk time (no reduction)	Normal accumulated risk time (no reduction)
6h-14h	The accumulated risk time is reduced by a factor which depends on how unfavourable the dry climate is, maximum reduction is 70%.	Normal accumulated risk time (no reduction)
24h-1w	Normal accumulated risk time (no reduction)	Normal accumulated risk time (no reduction)
1w-3w	Normal accumulated risk time (no reduction)	The accumulated risk time is reduced by a factor which size depends on how unfavourable the dry climate is, maximum reduction is 20% for *8w* & *12w* and 40% for *1w*, *2w* and *4w*.
3w	The accumulated risk time is reset.	The accumulated risk time is reset.

3.5.3 MRD-model

In the MRD-model, the growth is calculated by determining a Dose ($D_{(t)}$) using following equations.

The surface is confirmed mould free if following relationship is true:

$$D_{(t)} < D_{crit}$$

The program uses a calculated *half-day dose* (D_{12}), which consists of values obtained during a 12 hours interval, using average relative humidity and temperatures.

The first step is to define the *half-day dose* calculated in equation (14).

$$D_{12} = D_{\emptyset}(\emptyset_{12}) * D_T(T_{12}) \tag{14}$$

The total dose with consideration to time of exposure is determined in equation (15).

$$D_{(t)} = D(0{,}5n_{12}) = \sum_{1}^{n_{12}} D_{12i} = \sum_{1}^{n_{12}} D_{\emptyset}(\emptyset_{12i}) * D_T(T_{12i}) \tag{15}$$

The time of exposure is given by: ($t = 0{,}5 * n_{12}$)

T_{12i} is the average temperature in a 12 hours interval in period, *i*.

$\emptyset_{12i}$ is the average relative humidity in a 12 hours interval in period, *i*.

n_{12} is the total number of 12 hour intervals during *t* days.

To be able to determine whenever a material specimen performs well under certain conditions a reference climate is defined. This is to determine the dose and to evaluate the results. In this reference climate the critical time for initiated growth of mould, t_{crit} is expressed in equation (16).

$$D_{crit} = D_{(t_{crit})} = \sum_{1}^{2t_{crit}} D_{\emptyset}(\emptyset_{ref,i}) * D_T(T_{ref,i}) = t_{crit} \tag{16}$$

The given reference climate will result in a dose expressed in days equal to 1.0. Climate conditions with another relative humidity and temperature will result in another value. Above 1.0, if the environment is favourable for mould growth and below 1.0, if the conditions are less favourable.

The initial stage of mould growth is assumed to begin when following relationship has been reached. This is when the critical dose is equal to the critical time according to equation (17).

$$D_{crit} = t_{crit} \tag{17}$$

D_{crit} and t_{crit} can be seen as properties for a specific material.

Consideration to regression of mould is shown in the model. This will occur during dry periods. The model considers less favourable conditions to occur when: $\emptyset < 75\% \quad T < 0{,}1°C$. The dose is in this case determined in equation (18).

$$D_{\emptyset}(\emptyset_{12}) = -2{,}118 + 0{,}0286\emptyset_{12} \qquad when\ 60 < \emptyset_{12} \leq 75\% \tag{18}$$

$$D_{\emptyset}(\emptyset_{12}) = -0{,}4, \qquad when\ \emptyset_{12} \leq 60\%$$

Where $D_{\emptyset}(\emptyset_{12}) = -0{,}4$ is total the regression.

The MRD-model can be summarized with equation (19), describing how the calculated dose is compared to the critical dose for a material in the reference climate.

$$g[\emptyset(t), T(t)] = 1 - d_{rel} = 1 - \frac{D[\emptyset(t), T(t)]}{D_{crit}} \tag{19}$$

This is the *limit state function* expressed as the time dependent climate dose $(D[\emptyset(t), T(t)])$ divided with the critical dose(D_{crit}).

d_{rel}: Is also called the MRD-index and is an indicator describing the mould growth potential.

A Dose can also be expressed as a MRD-index. A value above 1.0 is considered being beyond the accepted threshold. In practice, index 1.0 indicates microscopic, visible development of mould which corresponds to mould growth index 2 in Pernilla Johansson's scale.

2. *Sparse but clearly established growth; often Conidiophores are beginning to develop.*

A lower critical value would be considered a measurement on the safe side. (Thelandersson, et al., 2014).

3.5.4 WUFI-Bio

When inserting the results from WUFI in WUFI-Bio, a substrate category is determined and assigned. Substrate category 1 was chosen and is presented below.

Sedlbauer divided materials into subdivisions to take the influence of building substrate into account, including possible contaminations according to Table 3.11.

Table 3.11 Sedlbauers subdivisions, separating materials depending on the substrate category. Note that WUFI-Bio only consider category 0-2.

Substrate category 0	Optimal culture medium
Substrate category 1	Biologically recyclable building materials like wall paper, plaster cardboard, building materials made of biologically degradable raw materials, materials for permanent elastic joints.
Substrate category 2	Biologically adverse recyclable building materials such as renderings, mineral building materials, certain wood as well as insulation materials not covered by cat. 1.
Substrate category 3	Building materials that are neither degradable nor contains nutrients.

3.6 Settings mould models

Settings in the mould growth models are presented below. The MRD-model was tested for two types of materials in order to detect the materials impact in mould growth evaluation. The limited time and space excluded this to be done for more than one mould model.

WUFI-bio

- Substrate class 1

M-model

- Safety factor: 0.98
- Material factor 1.0

MRD

- Materials: Spruce and pine
- Material factor (D_{crit}): 1.0

VTT

- Material: 1
- Surface structure: 1
- Material class: sensitive

4 Results

4.1 Results from WUFI

The hydrothermal status the attic and cathedral roof structure in four cities were simulated with climate data from year 1990-1998. The year with the highest frequency of high relative humidity were chosen to be analysed further in the mould models. The simulation results from WUFI are presented in graphs displaying temperature and RH in the chosen monitor position of the roof structures. The graphs present values for both existing and future climates. The temperatures are rather similar between the structures, while the RH fluctuates much more in the cathedral roof compared to the attic. Generally the future RH is around 1% higher, due to increased rain fall, and the temperature about 3°C higher compare to existing climate.

Lund

Table 4.1 displays climate data for 10 years for both existing and for future climate in Lund. The figures below presents the year that was examined in the mould models.

Table 4.1 Climate data for Lund displaying mean values for a 10 years period. Future values in parenthesis.

Mean Temperature	9.4°C (11.5°C)	**Mean RH**	80%
Max. Temperature	29.2 °C (31.3°C)	**Max RH**	100%
Min. Temperature	-4.8 °C (-2.7°C)	**Min RH**	31%
Counterradiation	2724.8kWh/m^2	**Mean wind speed**	3.22m/s (2.53m/s)
Mean cloud index	66%	**Normal Rain**	625mm/m^2 (717mm/m^2)

Figure 4.1 displays the relative humidity for 10 years in the monitor position in the cathedral roof using existing climate in Lund.

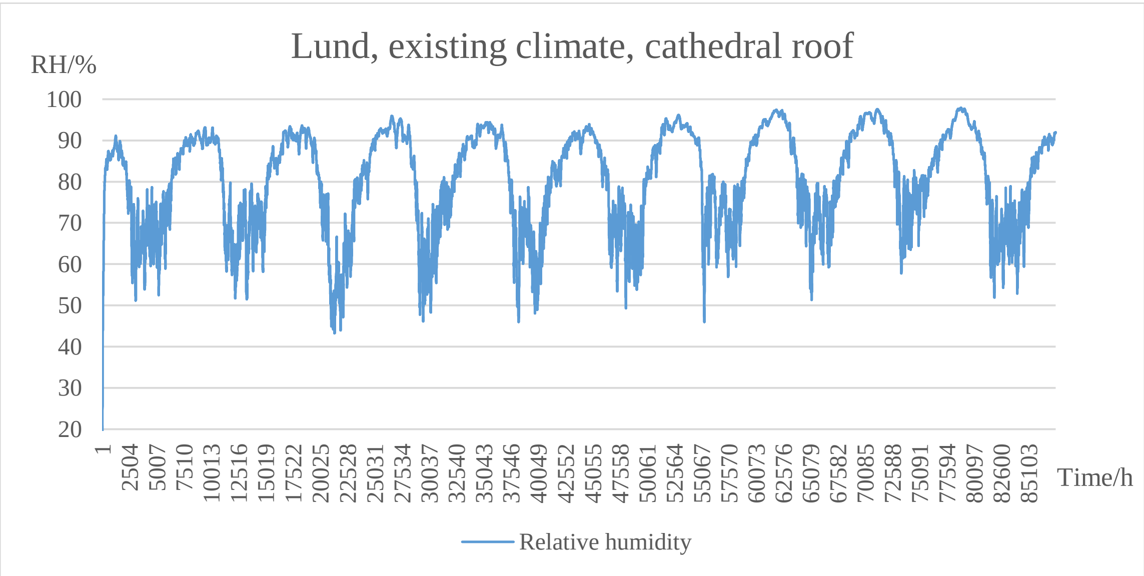

Figure 4.1 Results from the monitor position in the cathedral roof for a 10 years period

From Figure 4.1 the worst year was picked based on the highest RH, this is year 6. According to Figure 4.2, the cathedral roof has its lowest RH around 45 % during spring and highest around 98% during winter. The attic has its lowest RH around 75% in the autumn and highest around 90% during spring. See Figure 4.3.

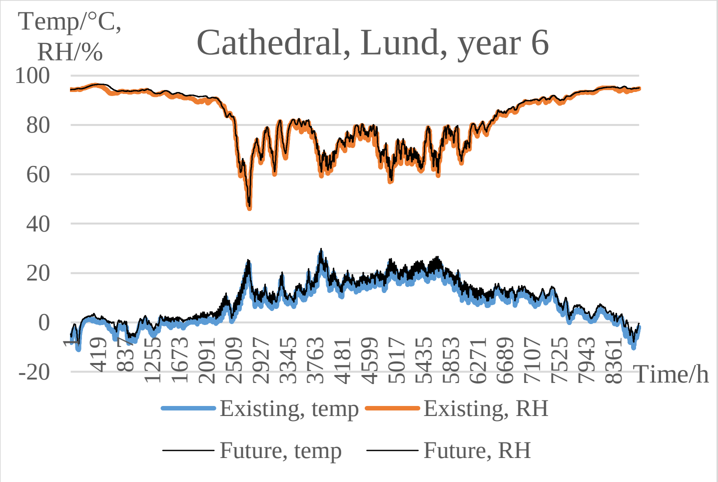

Figure 4.2RH and temperature in the cathedral roof, for both climates in Lund

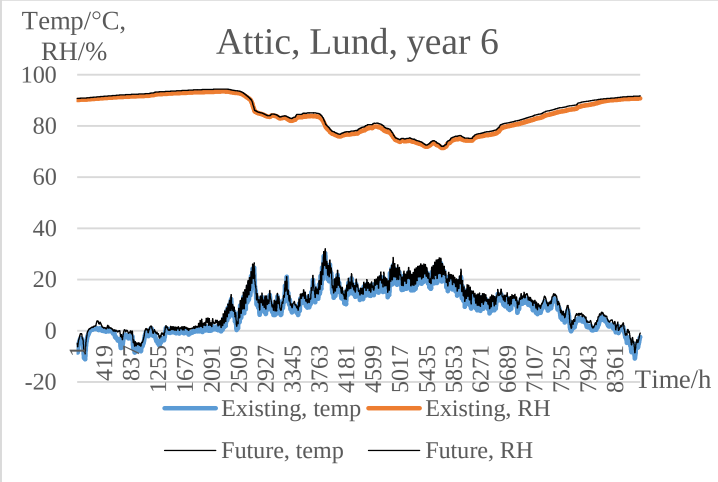

Figure 4.3RH and temperature in the attic, for both climates in Lund.

Stockholm

Table 4.2 displays climate data for 10 years for both existing and for future climate for Stockholm. The figures below presents the year that was examined in the mould models.

Table 4.2 Climate data for Stockholm. Future climate values in parenthesis.

Mean Temperature	8.2°C (10.6°C)	**Mean RH**	75%
Max. Temperature	28.1°C (30.5°C)	**Max RH**	100%
Min. Temperature	8.8°C (-6.4°C)	**Min RH**	25%
Counterradiation	2764.1kWh/m^2	**Mean wind speed**	3.20m/s (3.81m/s)
Mean cloud index	66%	**Normal Rain**	643mm/m^2 (701mm/m^2)

Figure 4.4 displays the relative humidity for 10 years in the monitor position in the cathedral roof using existing climate in Stockholm.

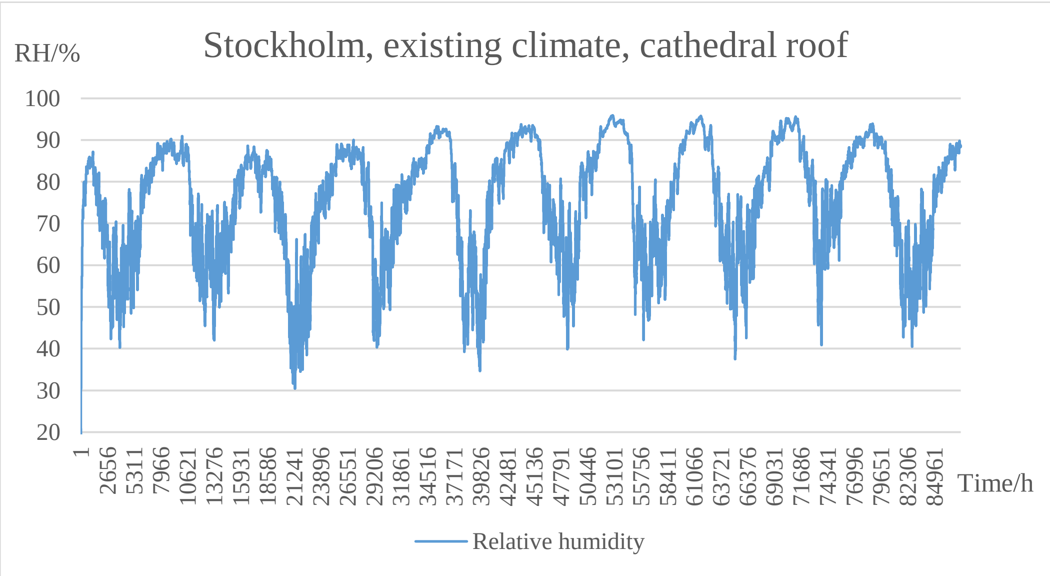

Figure 4.4 Results from the monitor position in the cathedral roof for a 10 years period.

From Figure 4.4 the worst year was picked based on the highest RH, this is year 4. According to Figure 4.5, the cathedral roof has its lowest RH below 40 % during spring and summer and highest around 95% during winter. The attic has its lowest RH around 60% during summer and the highest around 95% during spring. See Figure 4.6.

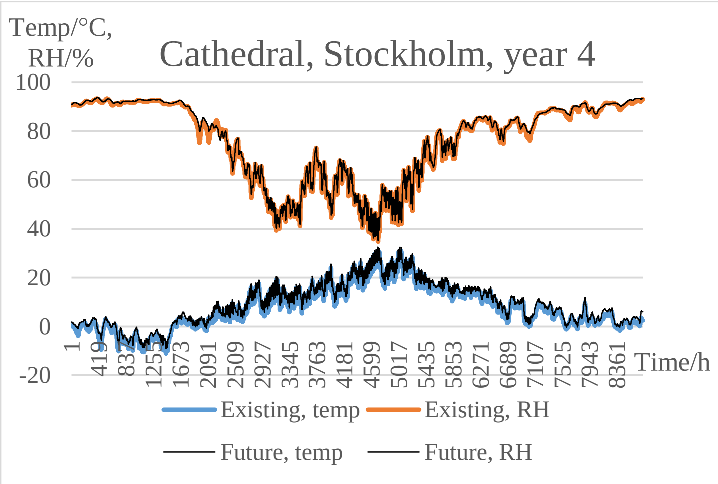

Figure 4.5 RH and temperature in the cathedral roof, for both climates in Stockholm.

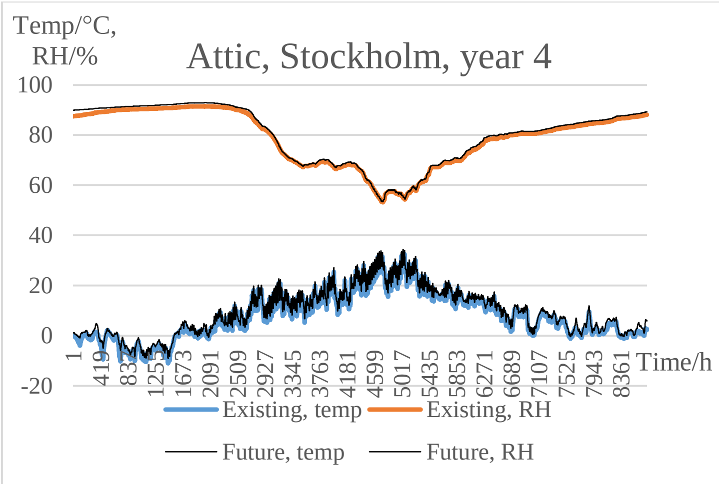

Figure 4.6 RH and temperature in the attic, for both climates in Stockholm.

Borlänge

Table 4.3 displays climate data for 10 years for both existing and for future climate for Borlänge. The figures below presents the year that was examined in the mould models.

Table 4.3 Climate data for Borlänge. Future climate values in parenthesis.

Mean Temperature	7.0°C (9.8°C)	**Mean RH**	73%
Max. Temperature	29.2°C (32°C)	**Max RH**	100%
Min. Temperature	-13.5°C (-10,8°C)	**Min RH**	25%
Counterradiation	2566.8 kWh/m^2	**Mean wind speed**	3.46m/s (4.45m/s)
Mean cloud index	66%	**Normal Rain sum**	612mm/m^2 (699mm/m^2)

Figure 4.7 displays the relative humidity for 10 years in the monitor position in the cathedral roof using existing climate in Borlänge.

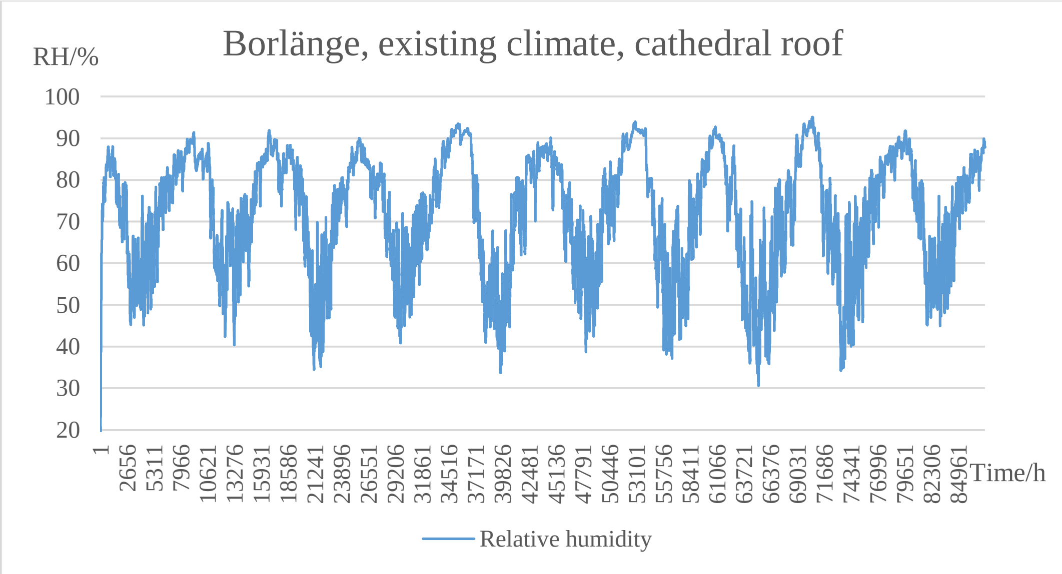

Figure 4.7 Results from the monitor position in the cathedral roof for a 10 years period.

From Figure 4.7 the worst year was picked based on the highest RH, this is year 4. According to Figure 4.8, the cathedral roof has its lowest RH around 35 % during spring and summer and the highest around 90% during late winter. The attic has its lowest RH around 55% during summer and the highest around 90% during late winter. See Figure 4.9.

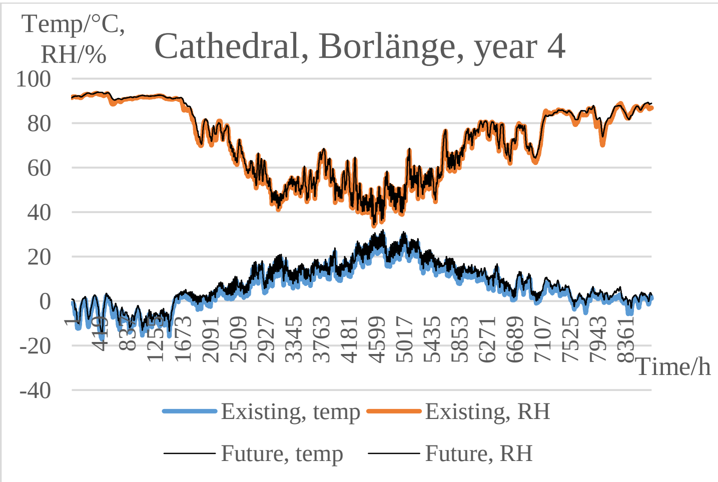

Figure 4.8 RH and temperature in the cathedral roof, for both climates in Borlänge.

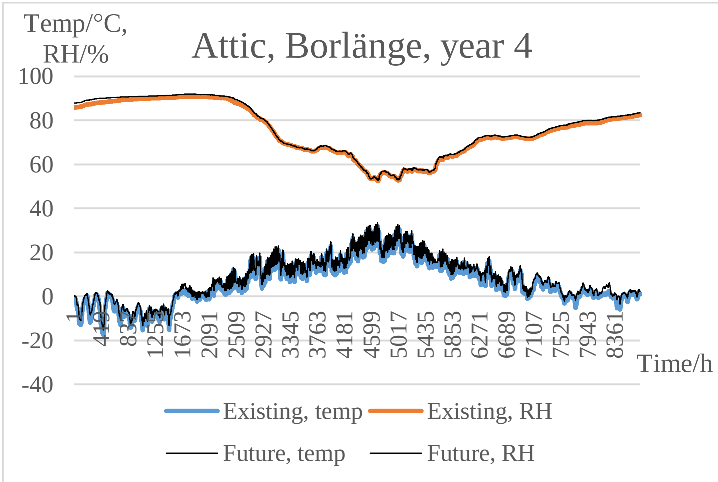

Figure 4.9 RH and temperature in the attic, for both climates in Borlänge.

Luleå

Table 4.4 displays climate data for 10 years for both existing and for future climate in Luleå. The figures below presents the year that was examined in the mould models.

Table 4.4 Climate data for Luleå. Future climate values in parenthesis.

Mean Temperature	3.7°C (7.1°C)	**Mean RH**	77%
Max. Temperature	25.6°C (29°C)	**Max RH**	100%
Min. Temperature	-26°C (-22.6°C)	**Min RH**	25%
Counterradiation	2551kWh/m^{2}a	**Mean wind speed**	3.18m/s (3.03m/s)
Mean cloud index	66%	**Normal Rain**	515mm/m^2 (601mm/m^2)

Figure 4.10 displays the relative humidity for 10 years in the monitor position in the cathedral roof using existing climate in Luleå.

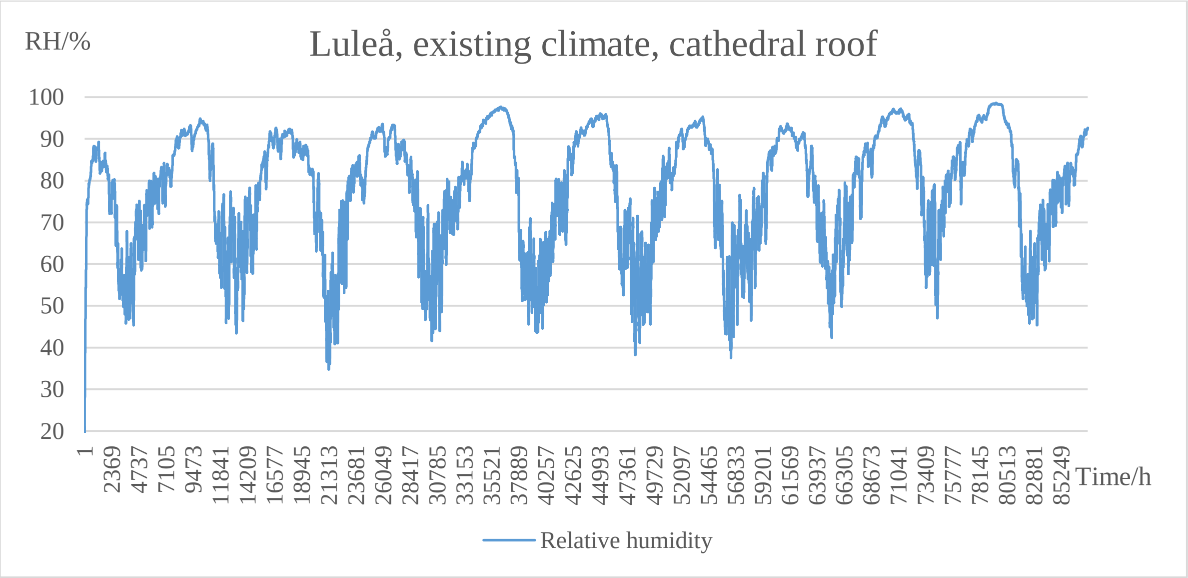

Figure 4.10 Results from the monitor position in the cathedral roof for a 10 years period.

From Figure 4.10 the worst year was picked based on the highest RH, this is year 4. According to Figure 4.11, the cathedral roof has its lowest RH just above 40 % during spring and summer and highest almost at 100% during late winter. The attic has its lowest RH around 60% during summer and the highest 95% during spring. See Figure 4.12.

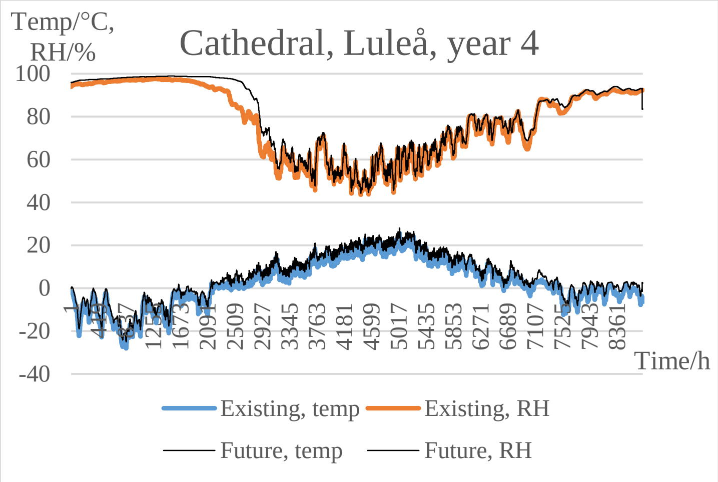

Figure 4.11 RH and temperature in the cathedral roof, for both climates in Luleå.

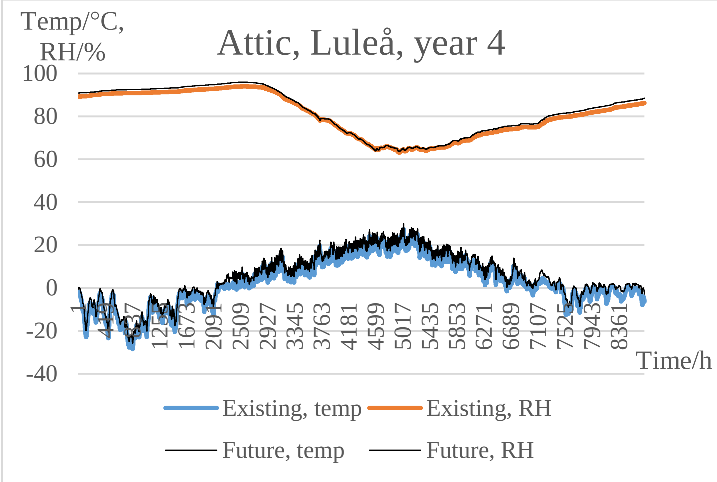

Figure 4.12 RH and temperature in the attic, for both climates in Luleå.

4.2 Results mould models

A short climate analysis displaying the mean values for 8 years is presented for each location in the beginning of each chapter. The (Kritisk VaraktighetsKvot) KVK-value for each duration line in the m-models can be seen in Appendix D.

WUFI-Bio and the m-model only handles one year predictions and even though the MRD-model and the VTT-model can give assessments for longer periods the results are based on one year to be comparable. All models assumes no mould growth in the beginning of the simulated period.

4.2.1 Existing climate

The results presents mould growth development according to four mould models of each location during the analysed year. Each model has a critical level shown as the red line in the figure. When the growth exceeds the critical line, it indicates as at risk. The higher levels it is above the critical level indicates the higher level of risk for mould growth.

4.2.1.1 Lund

WUFI-bio

According to WUFI-bio both types of roof structures have risks to mould growth in this chosen year. The cathedral roof exceeds the critical line in November and reaches a maximum mould growth of 58 *mm/year*. The attic exceeds the critical line in September and reaches a maximum mould growth of 75 *mm/year*.

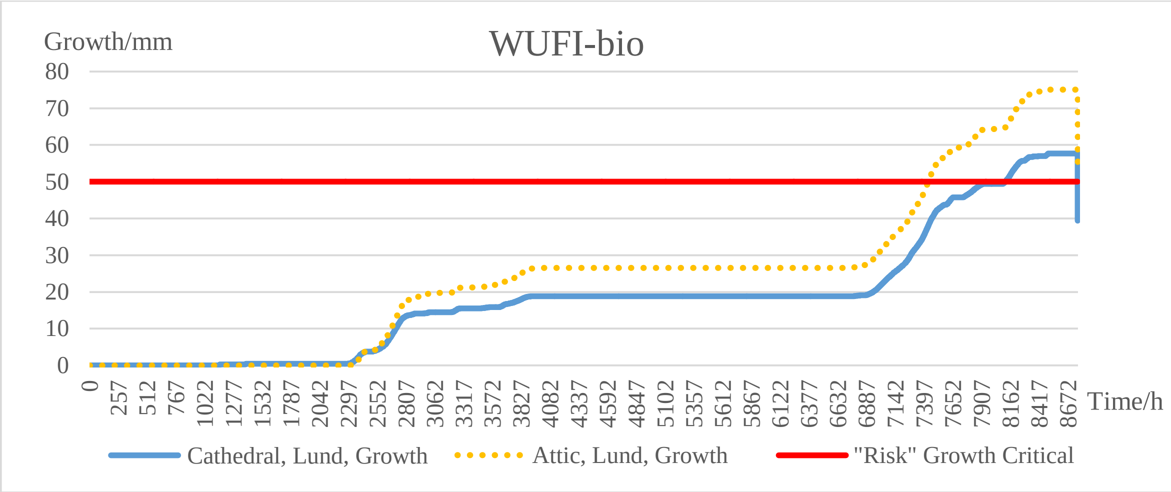

Figure 4.13 WUFI-bio results for attic and cathedral roof in Lund. Note that the critical line corresponds to the growth, not the index.

M-model

The >12, >8 and >4 weeks duration lines exceeds the critical line for the cathedral roof. It is assessed to be at *risk* for the >12 weeks duration line, *high risk* for the >8 weeks duration line and *low risk* for >4 weeks duration line. Both lines exceed the critical threshold mainly during autumn and winter. No other duration lines indicates any risk. The overall assessment for the cathedral roof is at *high risk*.

The >12 and >8 weeks duration lines exceeds the critical line for the attic. It is assessed to be at *risk* for the >12 weeks duration line and *low risk* for the >8 weeks duration line. Both lines exceed the critical threshold mainly during spring. No other duration lines is indicates any risk. The overall assessment for the attic is at *risk*.

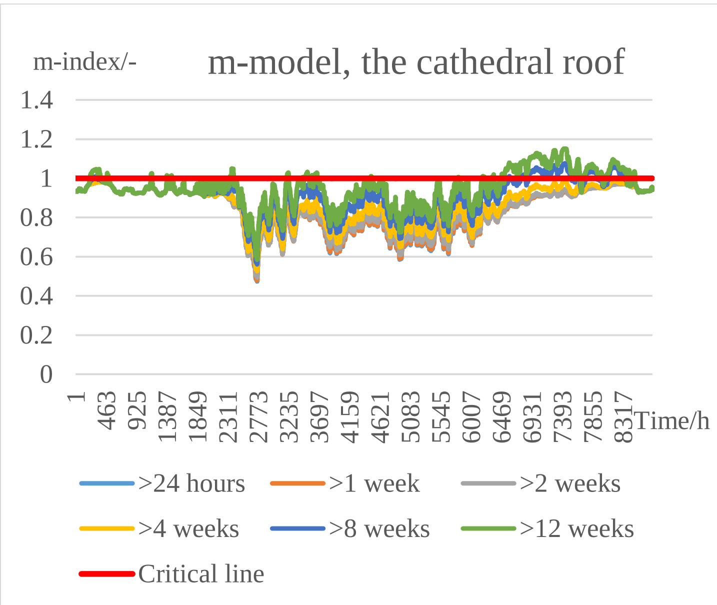

Figure 4.14 m-model results for cathedral roof in Lund.

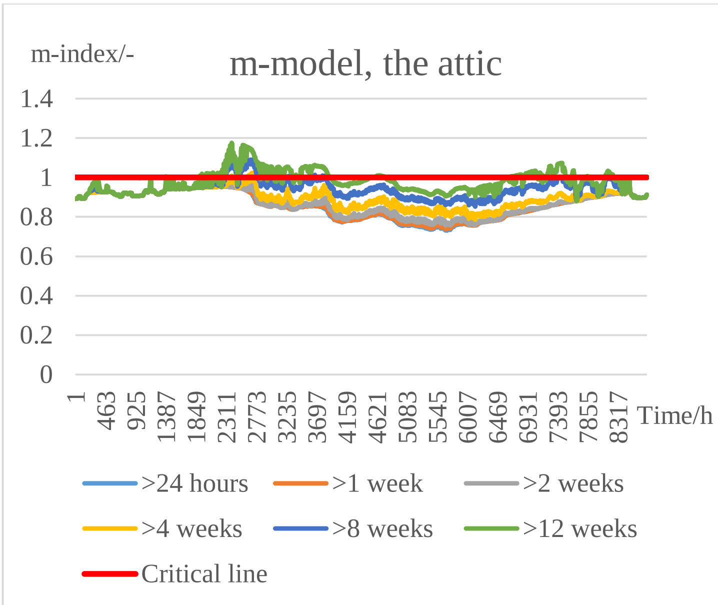

Figure 4.15 m-model results for attic in Lund.

VTT- & MRD-model

The results from both the VTT and MRD model are shown in Figure 4.16. The cathedral roof is assessed to be at risk by the MRD pine model. It exceeds the critical line mainly at the beginning of December and reaches up to an index of 1.27. The maximum index is 0.90 for MRD spruce and 0.61 for the VTT model.

The attic is not assessed as at risk for any of these models. The maximum index is 0.93 for MRD pine, 0.69 for MRD spruce and 0.39 for the VTT model.

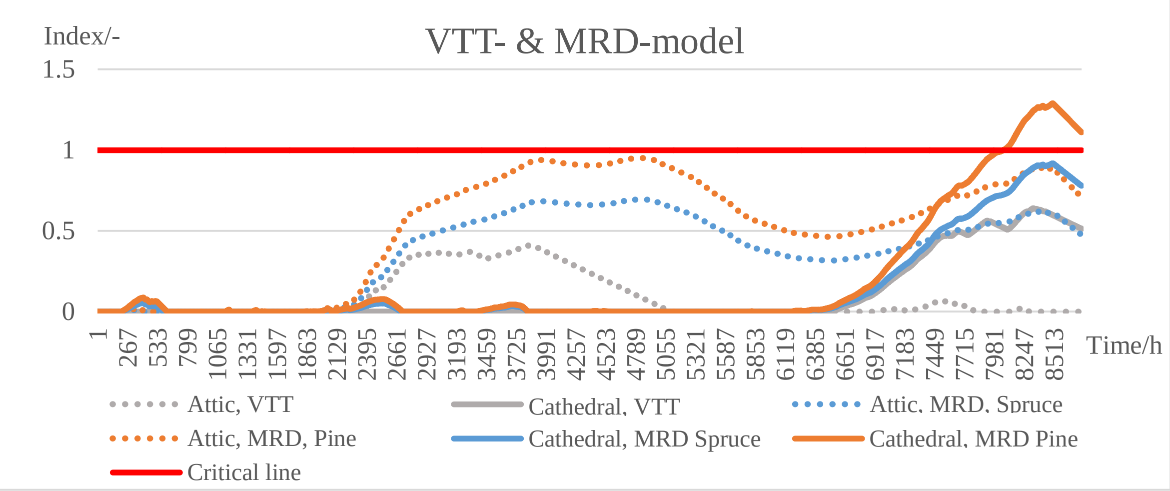

Figure 4.16 Combined graph for the VTT- and MRD-models in Lund.

4.2.1.2 Stockholm

WUFI-bio

According to WUFI-bio the cathedral roof does not indicate any risk throughout the chosen year. The maximum mould growth reaches 10 *mm/year*. The attic on the other hand exceeds the critical line in April, and reaches a maximum mould growth of 60 *mm/year*.

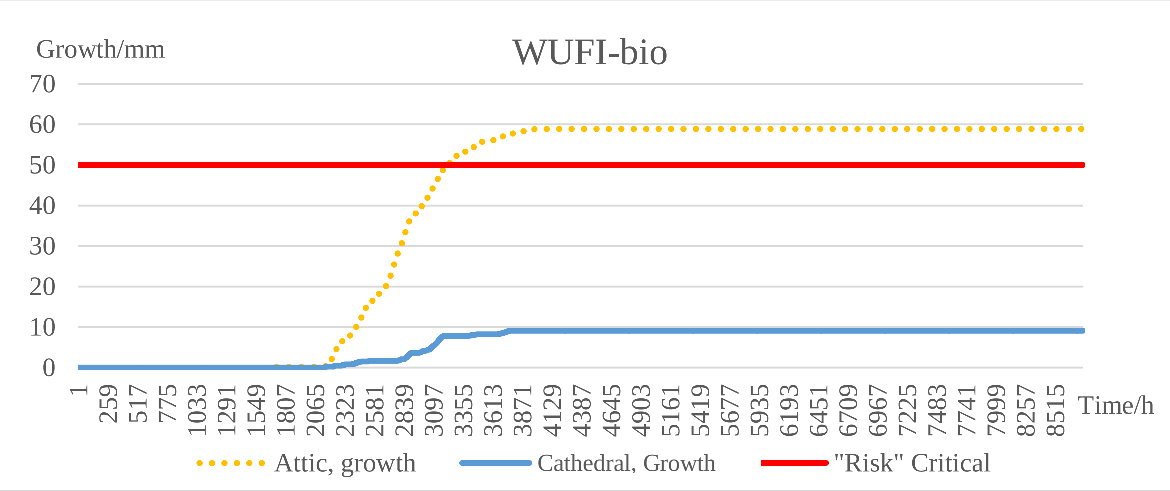

Figure 4.17 WUFI-bio results for attic and cathedral roof in Stockholm. Note that the critical line corresponds the growth, not the index.

M-model

The >12 and >8 weeks duration lines exceeds the critical line for the cathedral roof. It is assessed to be at *low risk* for the >12 weeks duration line and *low risk* for the >8 weeks duration line. Both lines exceeds the critical threshold mainly during autumn and winter. No other duration lines indicates any risk. The overall assessment for the cathedral roof is at *low risk*.

The >12 and >8 weeks duration lines exceeds the critical line for the attic. It is assessed to be at *low risk* for the >12 weeks duration line and *low risk* for the >8 weeks duration line. Both lines exceed the critical threshold mainly during spring. No other duration lines indicates any risk. The overall assessment for the attic is at *low risk*.

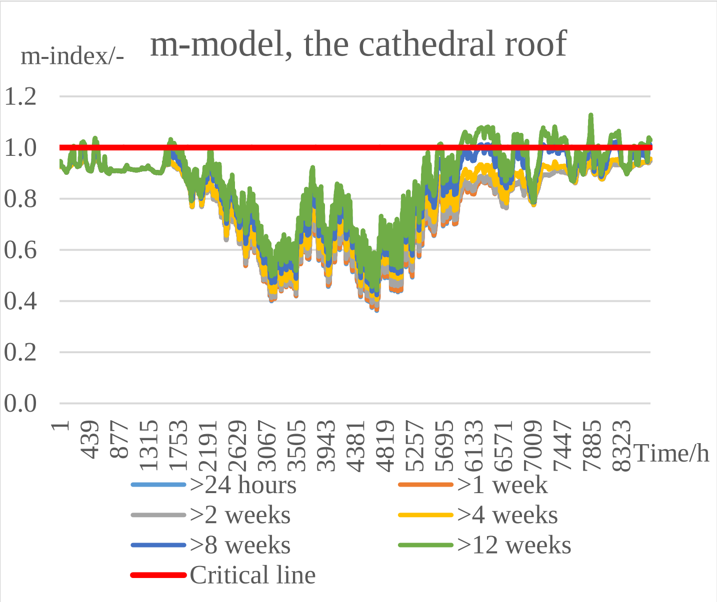

Figure 4.18 m-model results for cathedral roof in Stockholm.

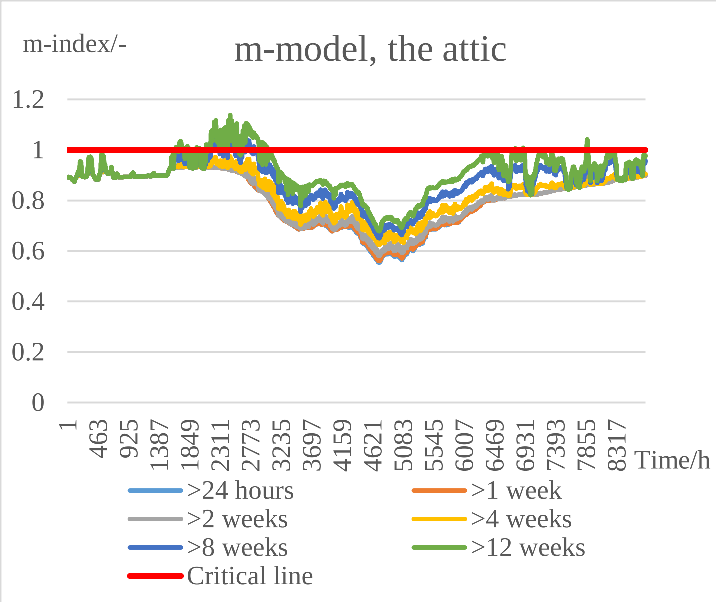

Figure 4.19 m-model results for attic in Stockholm.

VTT- & MRD-model

The results from both the VTT and MRD model are shown in Figure 4.20. The cathedral roof does not cross the critical threshold for any of the models. The maximum index is 0.6 for MRD pine, 0.4 for MRD spruce and 0.2 for the VTT model.

Neither the attic crosses the critical threshold in any of these models. The maximum index is 0.6 for MRD pine, 0.4 for MRD spruce and 0.2 for the VTT model.

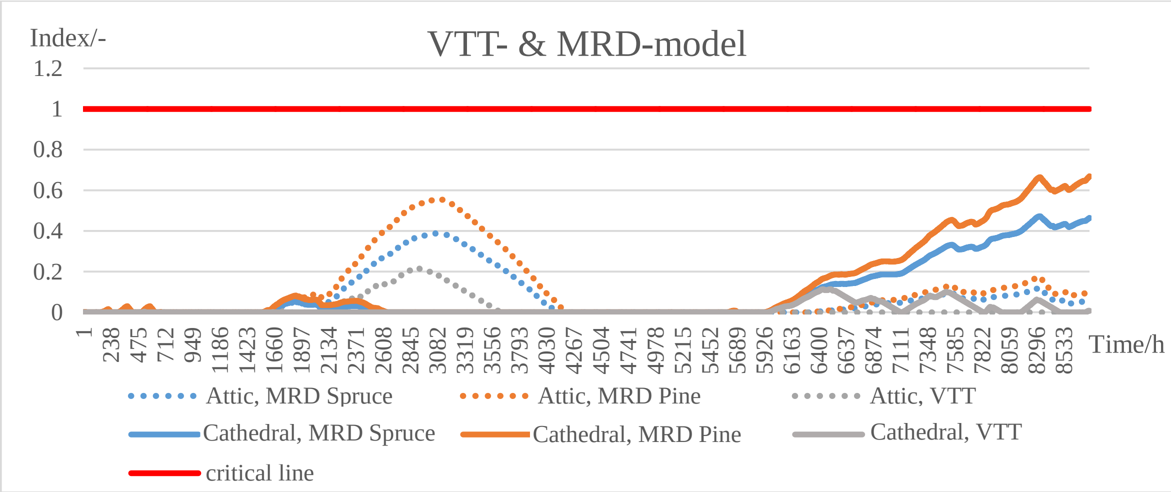

Figure 4.20 Combined graph for the VTT- and MRD-models in Stockholm.

4.2.1.3 Borlänge

WUFI-bio

According to WUFI-bio none of the structures have risks to mould growth in this chosen year. The cathedral roof reaches a maximum mould growth of 5 *mm/year*. The attic reaches a maximum mould growth of 45 *mm/year*.

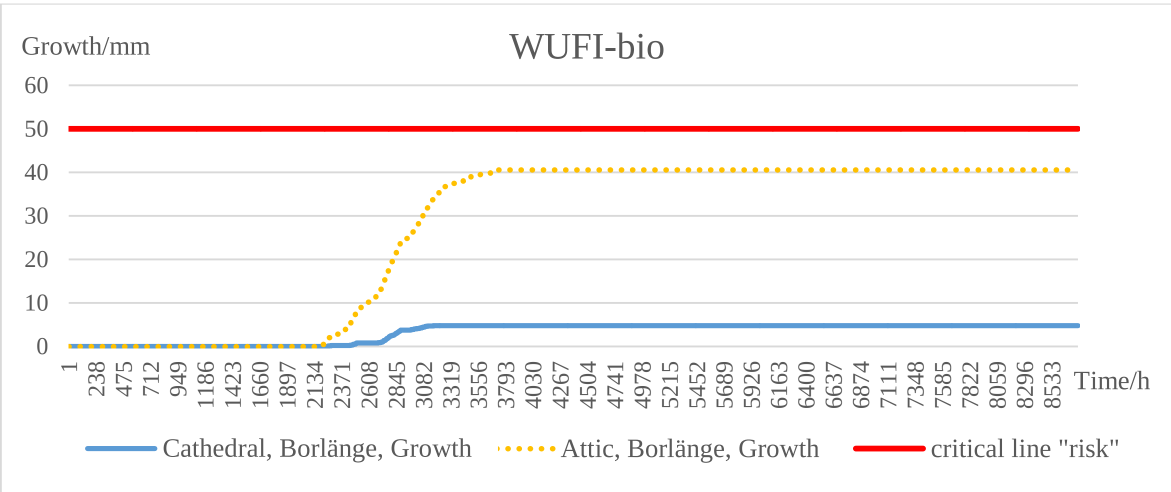

Figure 4.21 WUFI-bio results for attic and cathedral roof in Borlänge. Note that the critical line corresponds the growth, not the index.

M-model

The >12 and >8 weeks duration lines exceeds the critical line for the cathedral roof. It is assessed to be at *low risk* for the >12 weeks duration line and *low risk* for the >8 weeks duration line. Both lines exceeds the critical threshold mainly during autumn and winter. No other duration lines indicates any risk. The overall assessment for the cathedral roof is at *low risk.*

The >12 and >8 weeks duration lines exceeds the critical line for the attic. It is assessed to be at *low risk* for the >12 weeks duration line and *low risk* for the >8 weeks duration line. Both exceeds the critical threshold mainly during spring. No other duration lines indicates any risk. The overall assessment for the attic is at *low risk*.

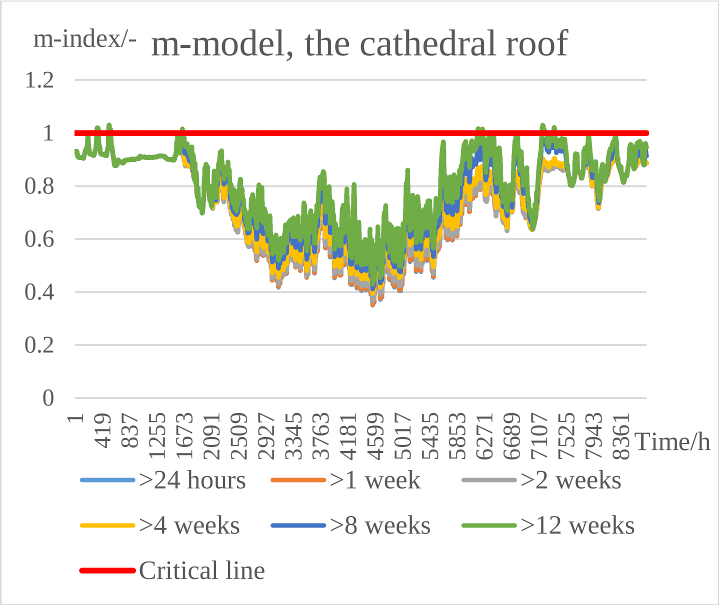

Figure 4.22 m-model results for cathedral roof in Borlänge.

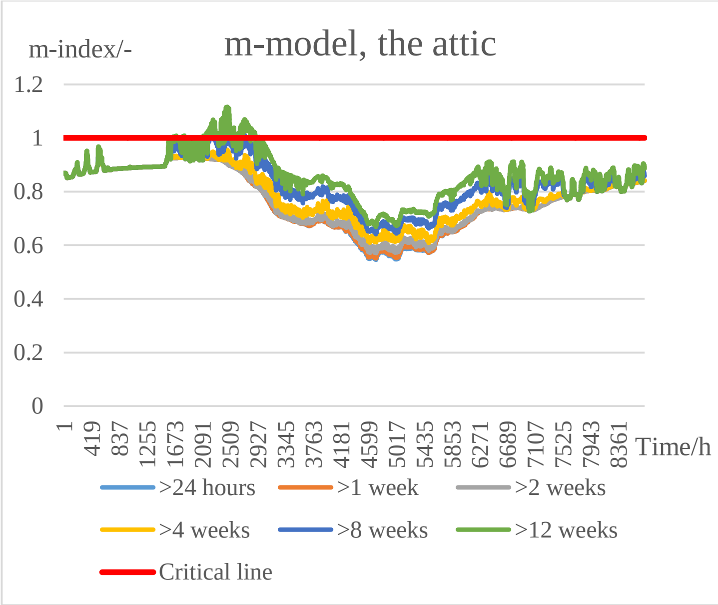

Figure 4.23 m-model results for attic in Borlänge.

VTT- & MRD-model

The results from both the VTT- and MRD-model are shown in Figure 4.24. The cathedral roof does not cross the critical threshold for any of the models. The maximum index is 0.1 for MRD-pine, 0.07 for MRD-spruce and 0.01 for the VTT-model.

Neither the attic cross the critical threshold in any of these models. The maximum index is 0.32 for MRD-pine, 0.22 for MRD-spruce and 0.05 for the VTT-model.

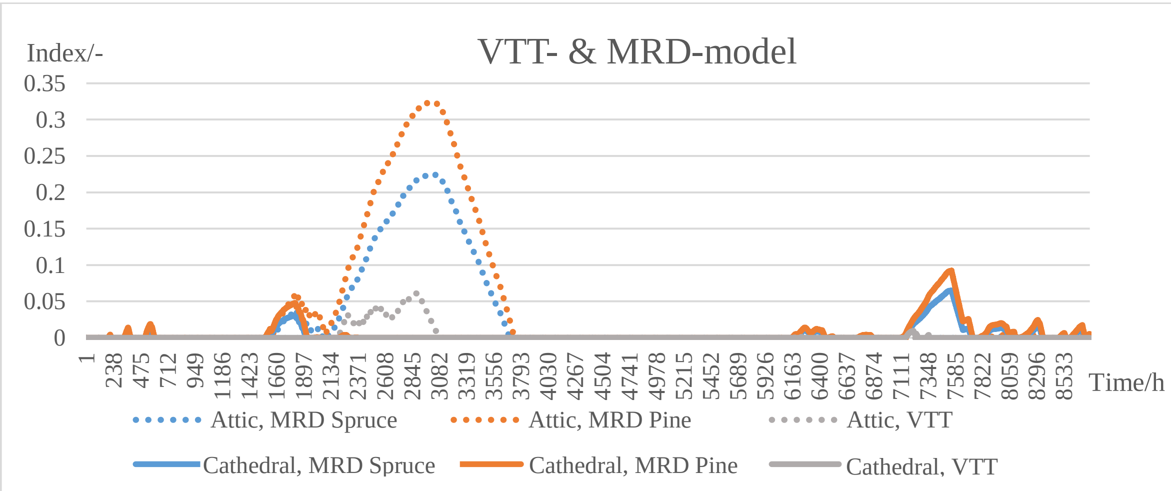

Figure 4.24 Combined graph for the VTT- and MRD-models in Borlänge (Note that the critical line is not visible in this graph)

4.2.1.4 Luleå

WUFI-bio

According to WUFI-bio the cathedral roof does not indicate any risk throughout the chosen year. The maximum mould growth reaches 10 *mm/year*. The attic on the other hand exceeds the critical line in April, and reaches a maximum mould growth of 82 *mm/year*

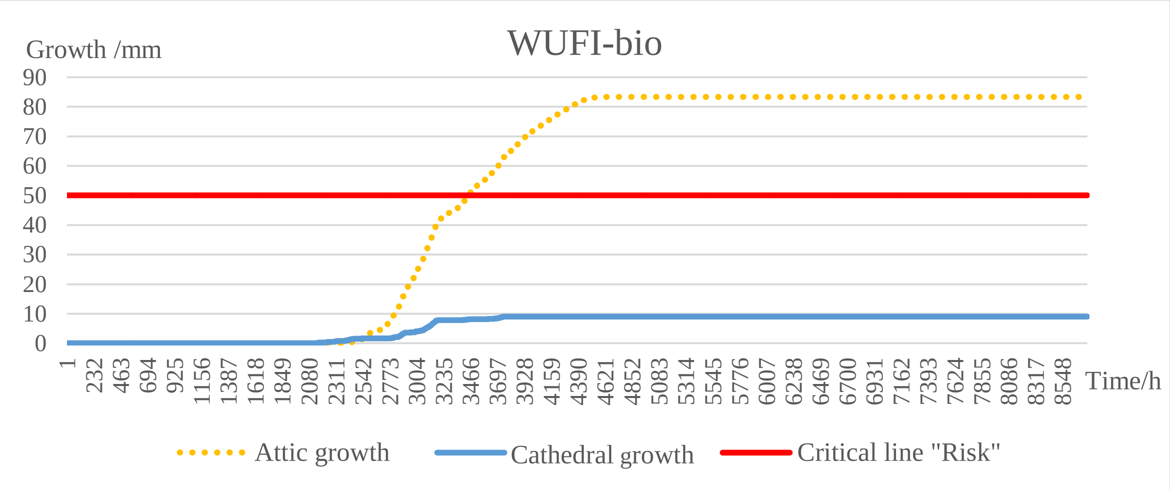

Figure 4.25 WUFI-bio results for attic and cathedral roof in Luleå. Note that the critical line corresponds the growth, not the index.

M-model

The >12 and >8 weeks duration lines exceeds the critical line for the cathedral roof. It is assessed to be at *low risk* for the >12 weeks duration line and *low risk* for the >8 weeks duration line. Both lines exceed the critical threshold mainly during spring. No other duration lines indicate any risk. The overall assessment for the cathedral roof is at *low risk*.

The >12 and >8 weeks duration lines exceeds the critical line for the attic. It is assessed to be at *low risk* for the >12 weeks duration line and *low risk* for the >8 weeks duration line. Both lines exceed the critical threshold mainly during spring. No other duration lines indicates any risk. The overall assessment for the attic is at *low risk*.

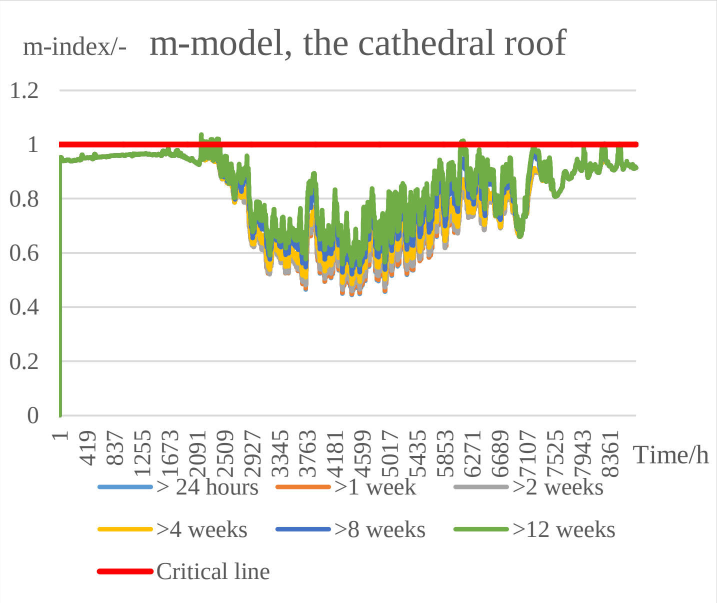

Figure 4.26 m-model results for cathedral roof in Luleå

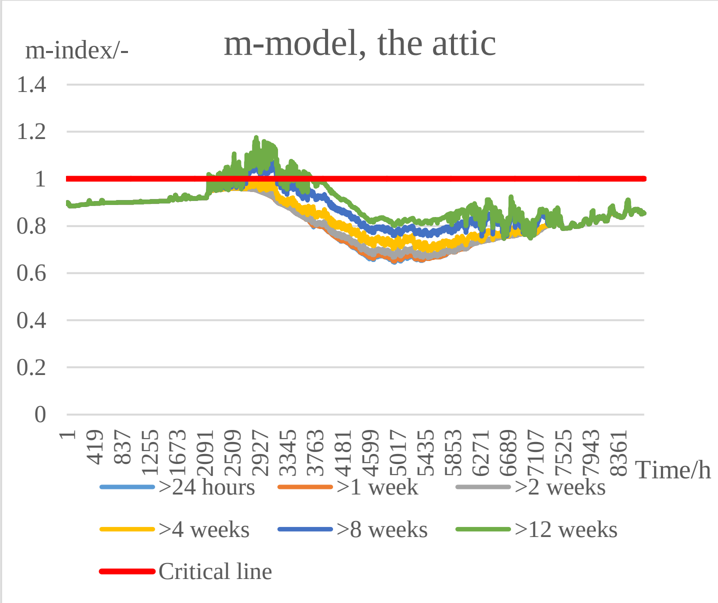

Figure 4.27 m-model results for attic in Luleå

VTT- & MRD-model

The results from both the VTT- and MRD-model are shown in Figure 4.28. The cathedral roof does not cross the critical threshold for any of the models. The maximum index is 0.07 for MRD-pine, 0.05 for MRD-spruce and 0.01 for the VTT-model.

Neither the attic cross the critical threshold in any of these models. The maximum index is 0.81 for MRD-pine, 0.57 for MRD-spruce and 0.33 for the VTT-model.

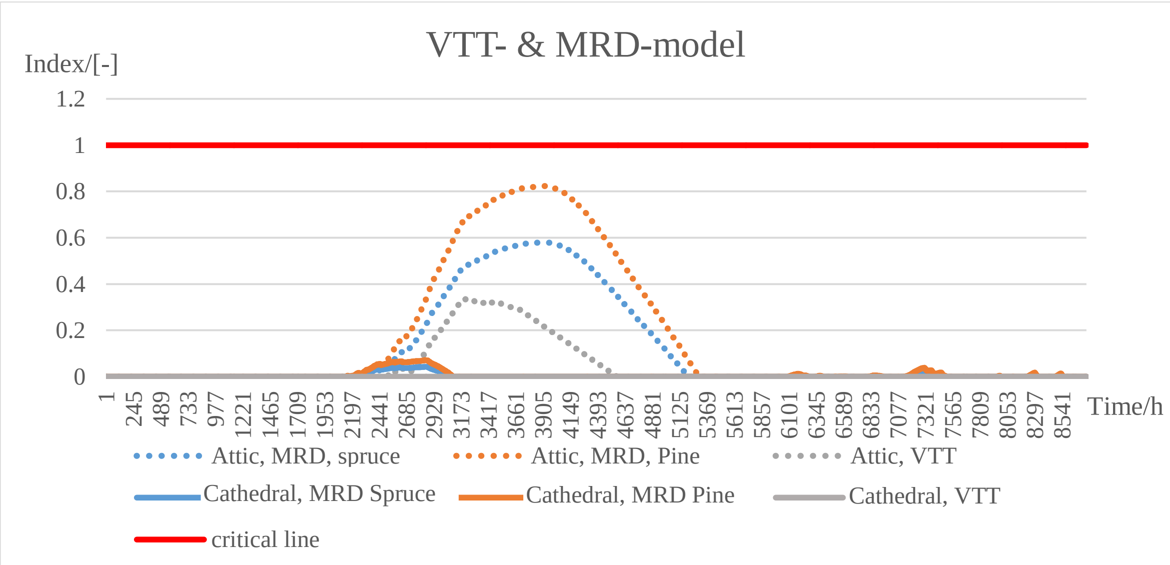

Figure 4.28 Combined graph for the VTT- and MRD-models in Luleå

4.2.2 Future climate

Following results are derived from the calculations using modified climate data, which represents a future climate for Stockholm, Lund, Luleå and Borlänge.

4.2.2.1 Lund

WUFI-Bio

According to WUFI-bio both types of roof structures have risks to mould growth in this chosen year. The cathedral roof exceeds the critical line in September and reaches a maximum mould growth of 143 *mm/year*. The attic exceeds the critical line in Mars and reaches a maximum mould growth of 173 *mm/year*.

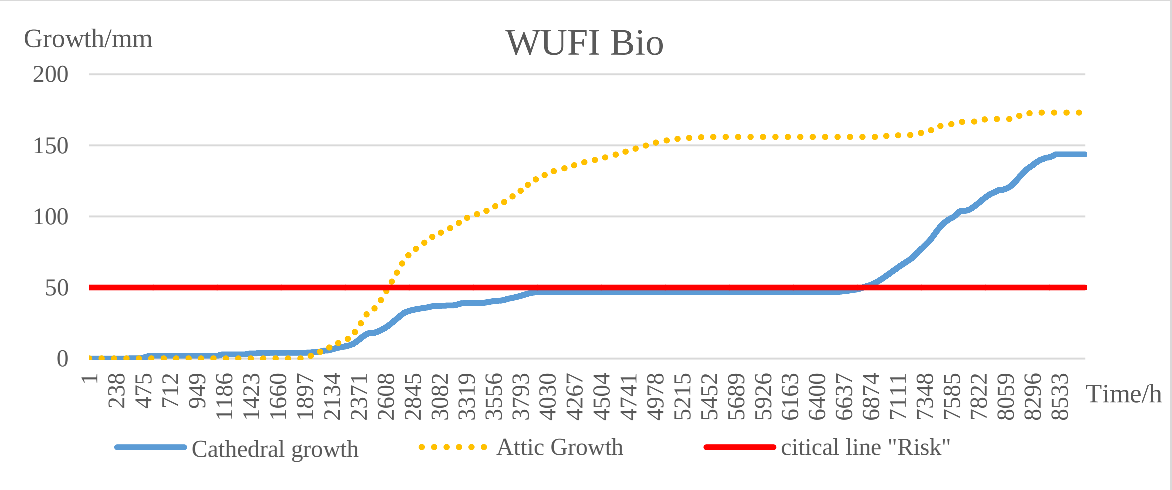

Figure 4.29 WUFI-Bio, a comparison between the cathedral roof and the attic using future climates in Lund. Observe that the critical line is referred to the growth and not the index in WUFI-Bio.

M-model

The >12, >8 and >4 weeks duration lines exceeds the critical line for the cathedral roof. It is assessed to be at *high risk* for the >12 weeks duration line, *high risk* for the >8 weeks duration line and *low risk* for >4 weeks duration line. All lines exceeds the critical threshold mainly during autumn and winter. No other duration lines indicates any risk. The overall assessment for the cathedral roof is *high risk*.

The >12, >8 and >4 weeks duration lines exceeds the critical line for the attic. It is assessed to be at *high risk* for the >12 weeks duration line, *high risk* for the >8 weeks duration line and *low risk* for the >4 weeks duration line. All lines exceed the critical threshold mainly during spring and autumn. No other duration lines is indicates any risk. The overall assessment for the attic is at *high risk*.

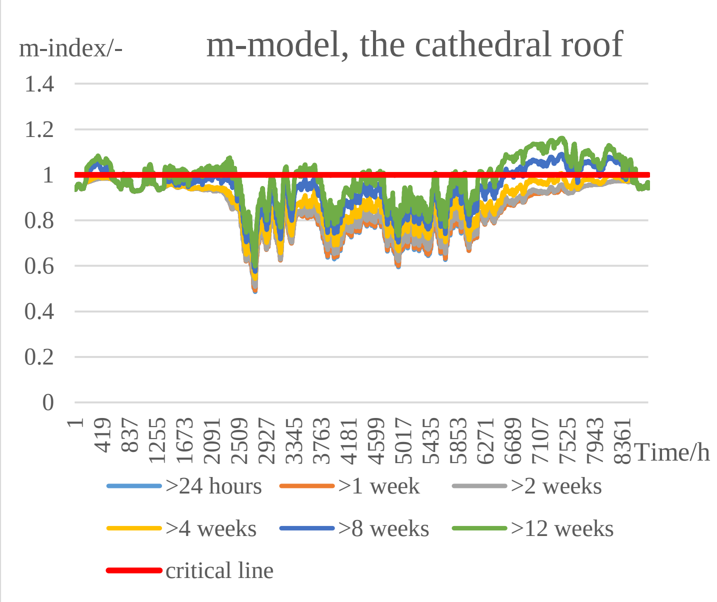

Figure 4.30 M-model, results from the cathedral roof using future climates in Lund

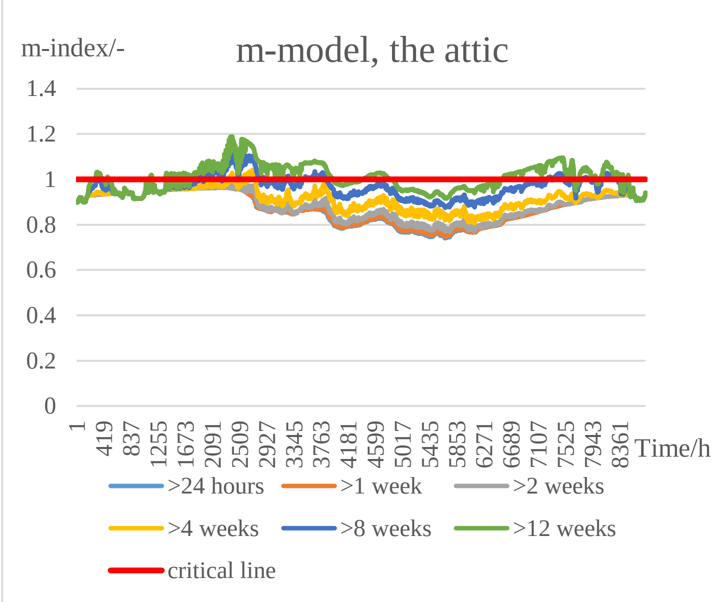

Figure 4.31 M-model, results from the attic using future climates in Lund

VTT- & MRD-model

The results from both the VTT- and MRD-model are shown in Figure 4.32. The cathedral roof is assessed to be at risk by both models. The MRD-pine exceeds the critical line in October and reaches up to an index of 1.84. The MRD-spruce exceeds the critical line in December and reaches up to an index of 1.34. The VTT-model also exceeds the critical line in December and reaches up to an index of 1.11.

The attic is assessed to be at risk by the MRD-pine and MRD-spruce model. The MRD-pine line exceeds the critical line in mars and reaches up to an index of 2.13. The MRD-spruce line exceeds the critical line in April and reaches up to an index of 1.51. The VTT-model reaches a maximum index of 0.80.

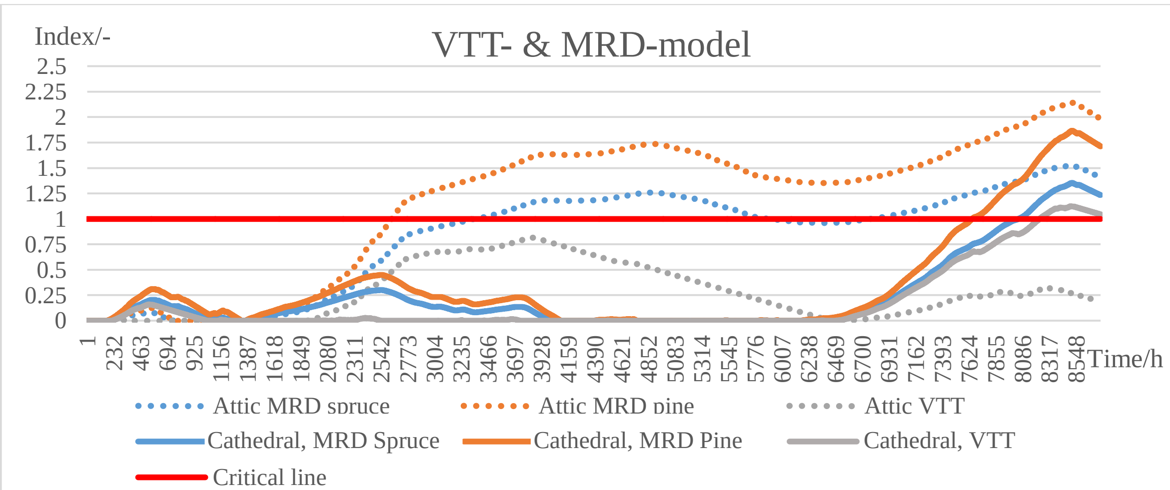

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Figure 4.32 VTT- & MRD-model, a comparison between the cathedral roof and the attic using future climates in Lund

4.2.2.2 Stockholm

WUFI-Bio

According to WUFI-bio both types of roof structures have risks to mould growth in this chosen year. The cathedral roof exceeds the critical line in December and reaches a maximum mould growth of 55 *mm/year*. The attic exceeds the critical line in Mars and reaches a maximum mould growth of 95 *mm/year*.

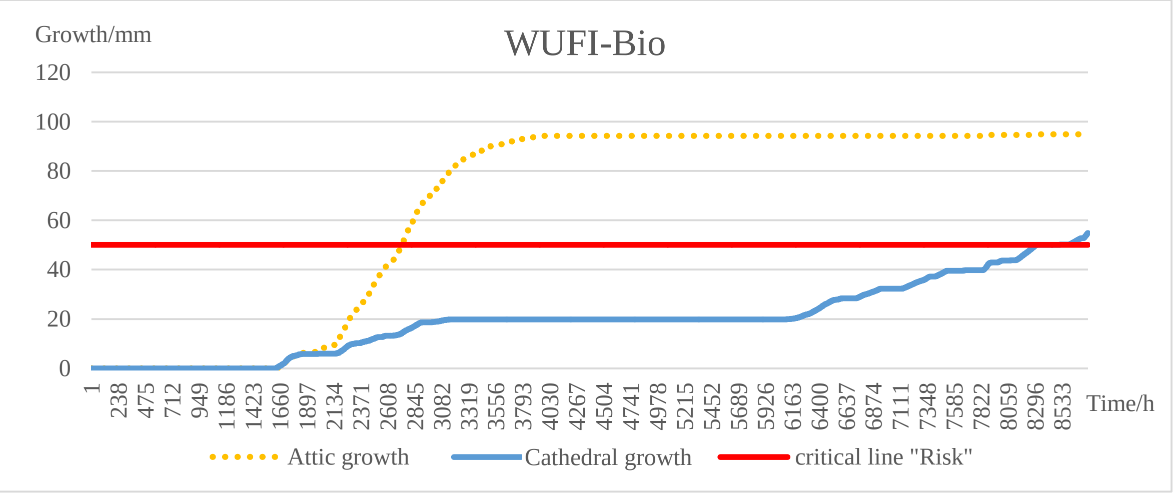

Figure 4.33 WUFI-Bio, a comparison between the cathedral roof and the attic using future climates in Stockholm

M-model

The >12 and >8 weeks duration lines exceeds the critical line for the cathedral roof. It is assessed to be at *risk* for the >12 weeks duration line and *risk* for the >8 weeks duration line. Both lines exceeds the critical line mainly during autumn and winter. No other duration lines indicates any risk. The overall assessment for the cathedral roof is at *risk*.

The >12 and >8 weeks duration lines exceeds the critical line for the attic. It is assessed to be at *risk* for the >12 weeks duration line and *risk* for the >8 weeks duration line. Both lines exceed the critical threshold mainly during spring. No other duration lines indicates any risk. The overall assessment for the attic is at *risk*.

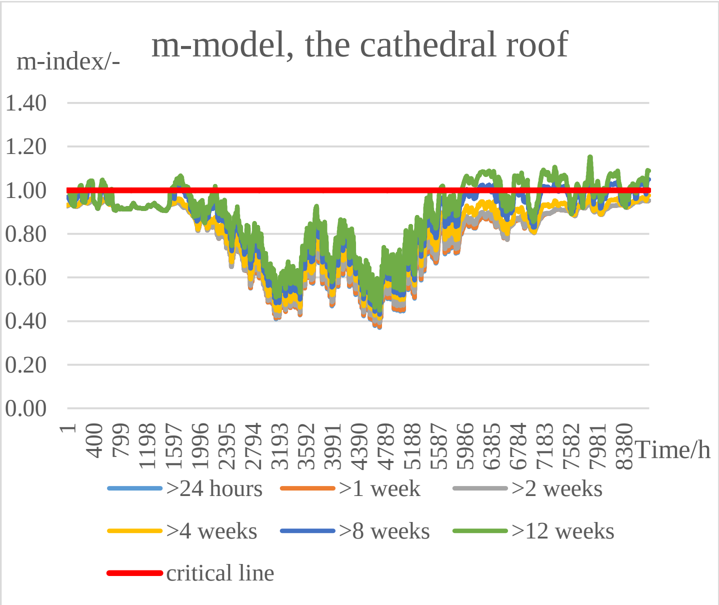

Figure 4.34 M-model, results from the cathedral roof using future climates in Stockholm

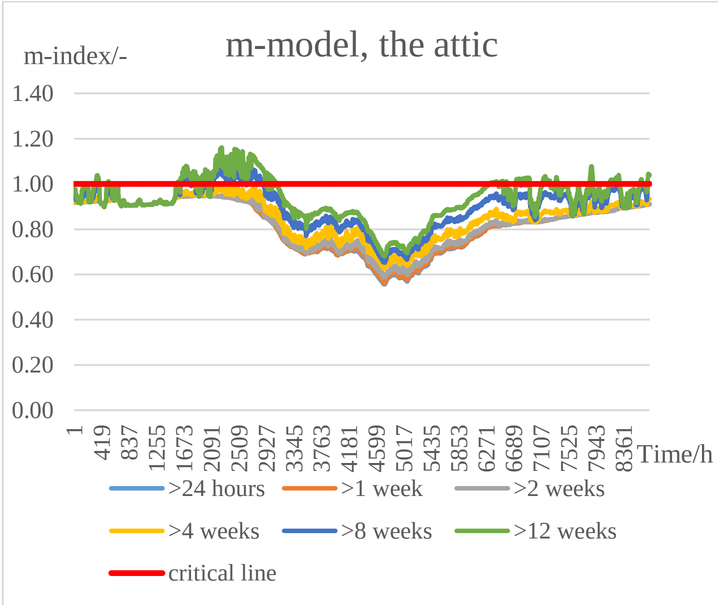

Figure 4.35 M-model, results from the attic using future climates in Stockholm

VTT- & MRD-model

The results from both the VTT- and MRD -model are shown in Figure 4.36. The cathedral roof is assessed to be at risk by the MRD-pine model. It exceeds the critical line mainly at the beginning of December and reaches up to an index of 1.11. The maximum index is 0.79 for MRD spruce and 0.28 for the VTT-model.

The attic does not cross the critical threshold for any of the models. The maximum index is 0.97 for MRD-pine, 0.70 for MRD-spruce and 0.48 for the VTT-model.

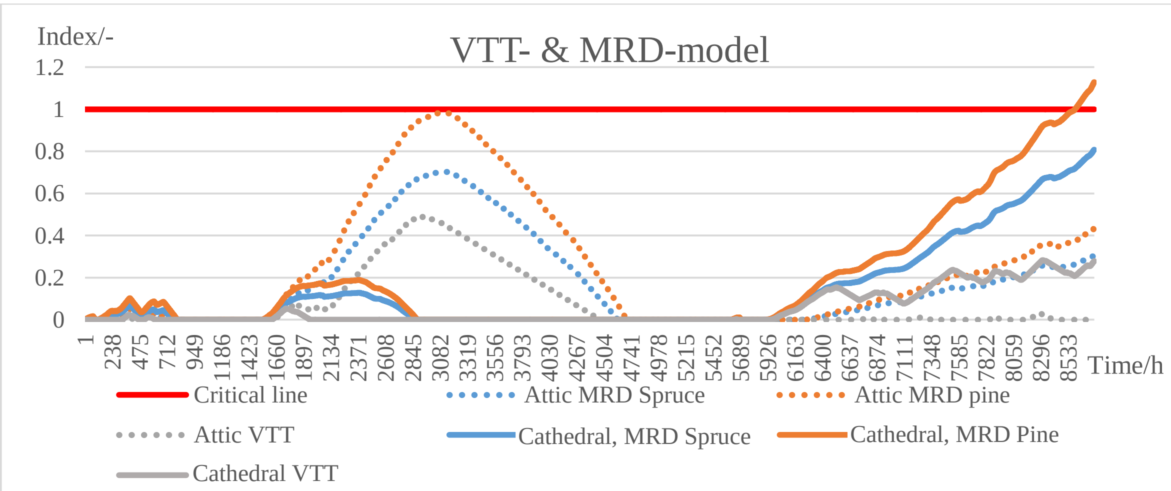

Figure 4.36 VTT- & MRD-model, a comparison between the cathedral roof and the attic using future climates in Stockholm

4.2.2.3 Borlänge

WUFI-Bio

According to WUFI-bio the cathedral roof does not indicate any risk throughout the chosen year. The maximum mould growth reaches 12 *mm/year*. The attic on the other hand exceeds the critical line in April, and reaches a maximum mould growth of 68 *mm/year*.

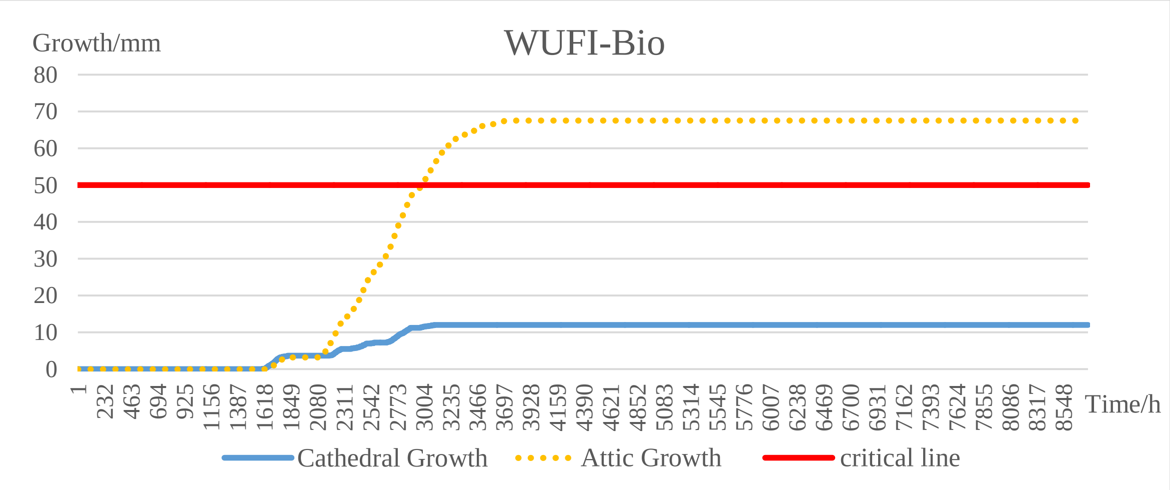

Figure 4.37 WUFI-Bio, a comparison between the cathedral roof and the attic using future climates in Borlänge

M-model

The >12 and >8 weeks duration lines exceeds the critical line for the cathedral roof. It is assessed to be at *low risk* for the >12 weeks duration line and *low risk* for the >8 weeks duration line. Both lines exceeds the critical threshold mainly during autumn and winter. No other duration lines indicates any risk. The overall assessment for the cathedral roof is at *low risk*.

The >12 and >8 weeks duration lines exceeds the critical line for the attic. It is assessed to be at *low risk* for the >12 weeks duration line and *low risk* for the >8 weeks duration line. It exceed the critical threshold mainly during spring. No other duration lines indicates any risk. The overall assessment for the attic is at *low risk*.

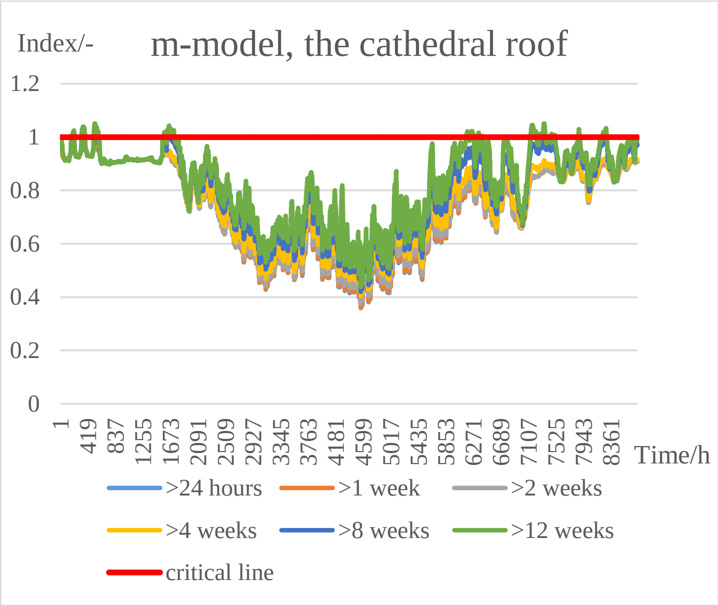

Figure 4.38 M-model, results from the cathedral roof using future climates in Borlänge

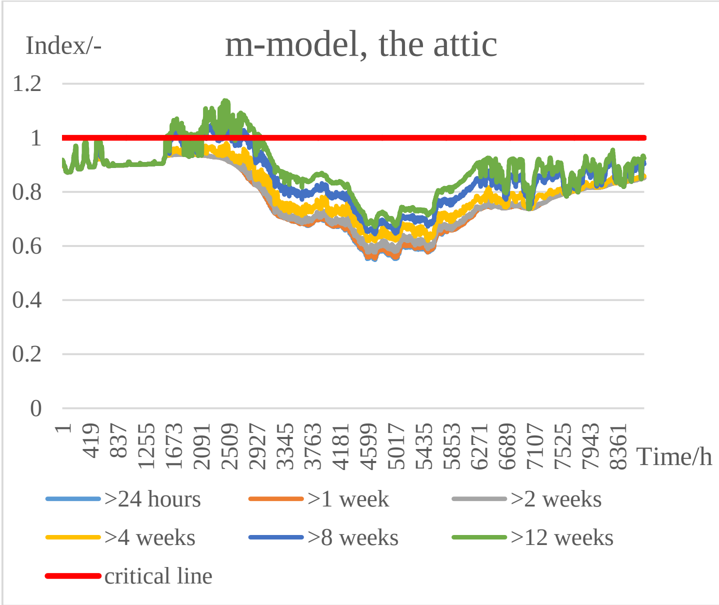

Figure 4.39 M-model, results from the attic using future climates in Borlänge

VTT- & MRD-model

The results from both the VTT- and MRD-model are shown in Figure 4.40. The cathedral roof does not cross the critical threshold for any of the models. The maximum index is 0.20 for MRD-pine, 0.12 for MRD-spruce and 0.01 for the VTT-model.

Neither the attic cross the critical threshold in any of these models. The maximum index is 0.66 for MRD-pine, 0.47 for MRD-spruce and 0.24 for the VTT-model

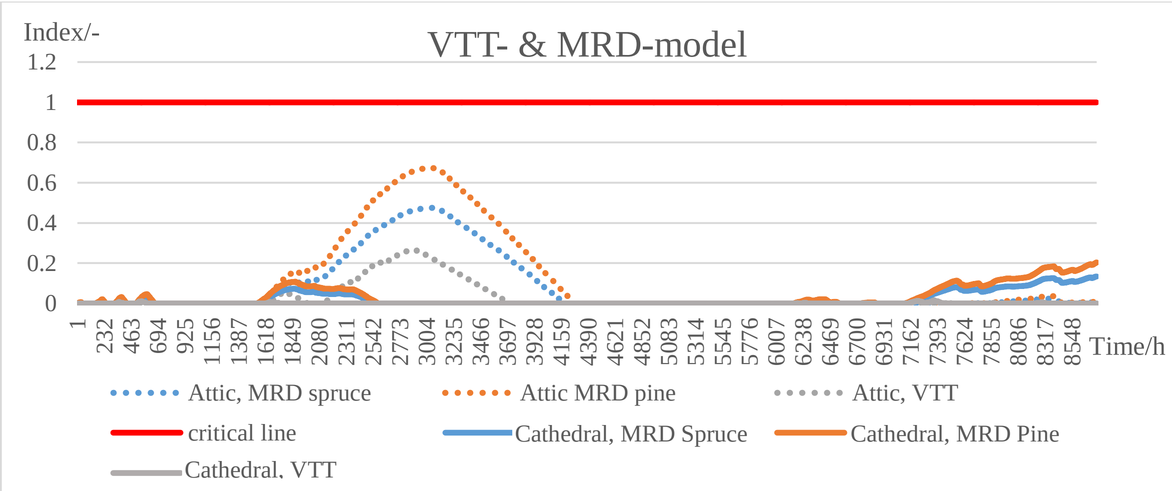

Figure 4.40 VTT- & MRD-model, a comparison between the cathedral roof and the attic using future climates in Borlänge

4.2.2.4 Luleå

WUFI-Bio

According to WUFI-bio both types of roof structures have risks to mould growth in this chosen year. The cathedral roof exceeds the critical line in Mars and reaches a maximum mould growth of 87 *mm/year*. The attic also exceeds the critical line in Mars, and reaches a maximum mould growth of 145 *mm/year*.

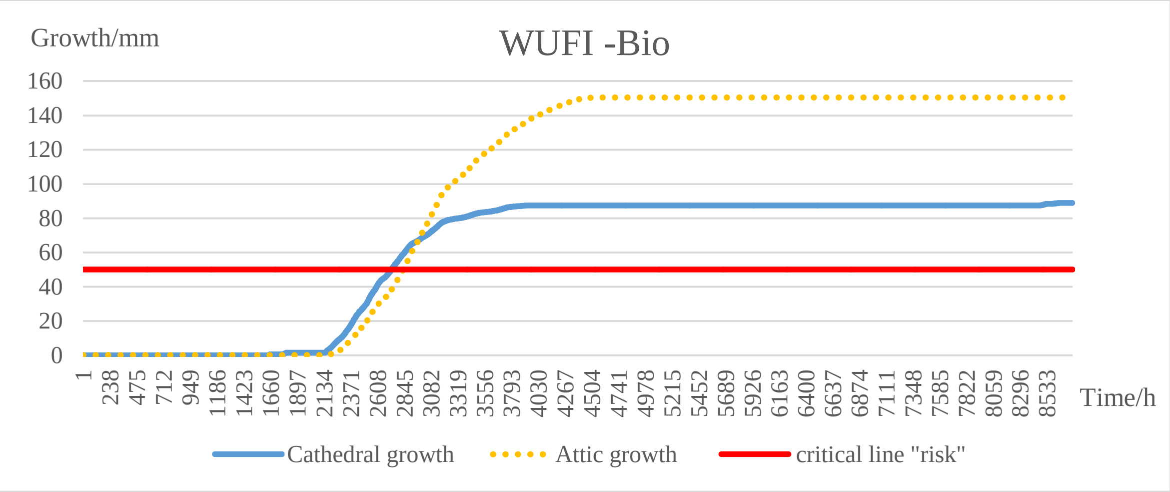

Figure 4.41 WUFI-Bio, a comparison between the cathedral roof and the attic using future climates in Luleå

M-model

The >12, >8, >4, >2, >1 weeks and >24 hours duration lines exceeds the critical line for the cathedral roof. It is assessed to be at *low risk* for the >12 weeks duration line, *risk* for the >8 weeks duration line, *high risk* for >4 weeks duration line, *high risk* for >2 weeks duration line, *high risk* for >1 week duration line and *high risk* for >24 hours duration line. All lines exceed the critical threshold mainly during spring. The overall assessment for the cathedral roof is at *high risk*.

The >12, >8 and >4 weeks duration lines exceeds the critical line for the attic. It is assessed to be at *risk* for the >12 weeks duration line, *risk* for the >8 weeks duration line and *risk* for >4 weeks duration line. All lines exceed the critical threshold mainly during spring. No other duration lines indicates any risk. The overall assessment for the attic roof is at *high risk*.

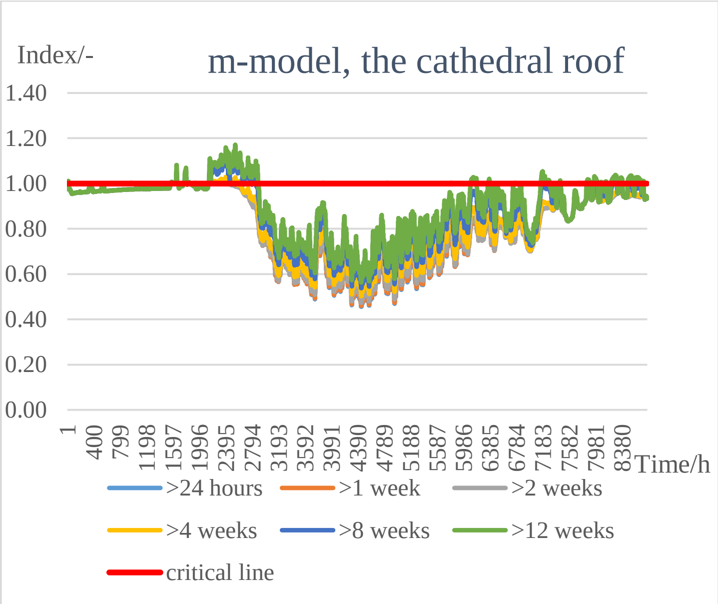

Figure 4.42 M-model, results from the cathedral roof using future climates in Luleå

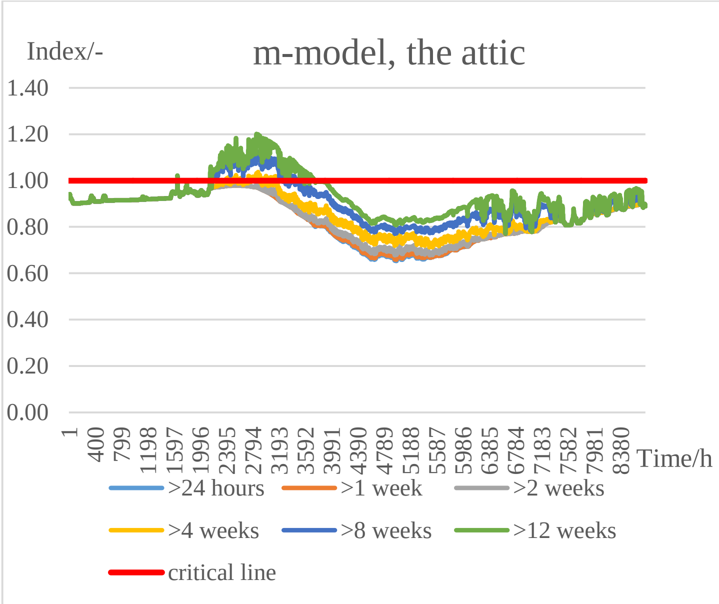

Figure 4.43 M-model, results from the attic using future climates in Luleå

VTT- & MRD-model

The results from both the VTT- and MRD-model are shown in Figure 4.44. The cathedral roof does not cross the critical threshold for any of the models. The maximum index is 0.90 for MRD pine, 0.62 for MRD-spruce and 0.51 for the VTT-model.

The attic is assessed to be at risk by the MRD-pine and MRD-spruce model. MRD-pine exceeds the critical line at the beginning of April and reaches up to an index of 1.69. MRD-spruce exceeds the critical line in April and reaches a maximum index is 1.23. The VTT-model reaches a maximum index of 0.99.

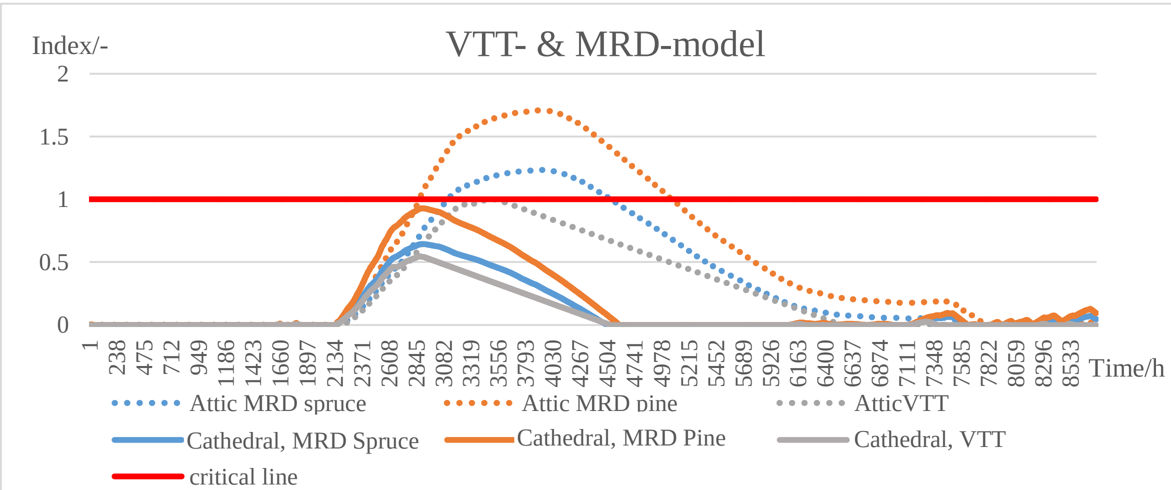

Figure 4.44 VTT- & MRD-model, a comparison between the cathedral roof and the attic using future climates in Luleå

4.2.3 Results summarized

Both the m-model and WUFI-bio asses the results using three classifications. High risk, Risk and low risk. Table 4.5 summaries the results from the mould models into these classifications. The VTT- and MRD-models only classifies as risk or no risk. This study interprets a crossing of the critical line for these models as *high risk*. Under the current climate situation, both the cathedral roof and attic structure are at risk in Lund, but at little risk in Borlänge. Stockholm and Luleå displays similar *risk*, where the attic according to WUFI-bio is the structure at *risk*. Generally, the future climates have generated higher temperatures and higher humidity in all locations. See Table 4.6. According to the four mould models, both the cathedral roof and the attic will be at high risk in Lund. The risk has also increased for both structures in Stockholm and Luleå, where the attic in Luleå show big potential mould growth. Borlänge seems not to have any big issues in future climate compared to the existing.

Table 4.5 Summarizing table of mould model assessments of the cathedral roof and attic structures under current climate.

	WUFI-bio		**m-model**		**MRD spruce**		**MRD pine**		**VTT**	
	Cathe.	Attic	Cathe.	Attic	Cathe.	Attic	Cathe.	Attic	Cathe.	Attic
Lund	Risk	Risk	High risk	Risk	Low risk	Low risk	High risk	Low risk	Low risk	Low risk
Stockholm	Low risk	Risk	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Borlänge	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Luleå	Low risk	Risk	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk

Table 4.6 Summarizing table of mould model assessments for future climate.

	WUFI-bio		m-model		MRD spruce		MRD pine		VTT	
	Cathe.	Attic	Cathe.	Attic	Cathe.	Attic	Cathe.	Attic	Cathe.	Attic
Lund	Risk	Risk	High risk	High Risk	High risk	High risk	High risk	High risk	High risk	Low risk
Stockholm	Risk	Risk	Risk	Risk	Low risk	Low risk	High risk	Low risk	Low risk	Low risk
Borlänge	Low risk	Risk	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Luleå	Low risk	Risk	High risk	Risk	Low risk	High risk	Low risk	High risk	Low risk	High risk

5 Discussion

This chapter is divided into subchapters to easily distinguish what part is discussed.

5.1 Discussion mould models

Predication of mould growth is an uncomplicated and at the same time, complicated process. The uncomplicated part is the correlation between temperature and RH that all models are considering to determine the mould growth. Basically, at a certain temperature and RH, there is an agreement between all models that mould growth will develop. The complicated part on the other hand, is how they handle boundary conditions, conditions where mould growth may or may not occur. Another factor besides RH and temperature needs to be accounted for is time. The laboratory work, which the models are based on, has a time limit and cannot account for a buildings total lifetime. There might be mould growth during, what seem to be, unfavourable conditions from a temperature and RH point of view, but the growth is very slow and not detectable for many years. Another important factor that involves time and boundary conditions, is regression of growth. Mould dies, or ages, during unfavourable conditions. WUFI-bio is the only model in this study that does not consider regression at all. Instead it pauses growth during unfavourable conditions and therefore constantly accumulate the mould growth over the simulated time period. Consequently WUFI-bio assess risk in 10/16 simulations, more than any other mould model. See Table 4.5 and Table 4.6.

There are many more factors that determine mould growth in reality, such as fluctuating climate, roughness of materials surface, interaction between mould species, previous exposure to mould spores etc. It is important to be aware about the models limitations and not see the assessment as truths, but as indications. They are most useful as a comparison tool to assess different structures between each other. All models are deterministic models, an improvement could be to develop prediction models which include a spread in germination time and growth rate.

Another factor that can explain the varying results is the critical threshold for when the estimated mould growth is considered to be too extensive. The MRD-model defines one *dose* as a 2 in Johanssons scale, which stretches from 1-4. The VTT-model uses Viitanens scale which stretches from 1-6, where >1 is set as the critical threshold. 2 in Johansson´s scale and 1 in Viitanens scale are considered to be the same, even though they are developed independently and the definition of the steps are slightly different. Furthermore, mould growth is hardly detectable and the outcome from the analyses of the samples are partly dependent on the equipment, such as positioning light and type of microscope, and also the individual skill of the researcher. All these subjective factors could create a difference in the design of the critical threshold, which in practice is considered to be equal. WUFI-bio determines the critical growth levels using mm growth which is fundamentally different from the other models. Where the critical definition in Viitanen and Johanssons scale is just a few hyphae, detectable on microscopic level, WUFI-bio critical level is 50 mm growth / year. According to the other mould models, this value would crush the top limit of their scales.

Today there are many materials that are being used in the building industry, and for a few of them, the critical moisture levels have been determined. The VTT- (original) and the MRD-models handles this by looking at two materials which are commonly used in buildings in Sweden, and evaluate theirs critical moisture levels thoroughly. This allows the models to be very material specific. For example, the VTT-model allows the user to consider the surface quality of spruce and pine. WUFI-bio and the m-model are instead separating materials into substrate categories. This gives the user responsibility to estimate in what category a material belongs, according to each substrate category definition. This opens up to an extended use of the mould model, but at cost of accuracy.

The MRD- and the VTT-model can give assessments based on several years of data, while WUFI-Bio and the m-model are limited to one year. In order to understand how mould develop in reality and to get reliable results, an assessment time of more than one year is obviously more appropriate since a buildings lifetime is more than 1 year. Although, to achieve comparable conditions they were all given one year to asses. This excludes the possibility to see if any of the structures may perform better in the long run. The cathedral roof showed generally unfavourable mould growth conditions throughout the year, but exhibited strong peaks which exceeded the critical line in the end of the year. In a multiyear analysis, the cathedral roof might have performed better due to significant regression during most of the year. The attic generally exhibited more mould growth throughout the year but did not necessarily cross the critical line. During a multiyear analysis the mould growth could potentially cause an accumulated growth in the attic. In that sense, the cathedral roof could be a better option than the attic from a longer perspective.

5.2 WUFI - hygrothermal discussion

All the graphs show basically the same pattern for each roof structure. The attic generally shows a higher overall mould growth potential throughout the year, especially during late spring and summer, but not necessarily crosses the critical line. The cathedral roofs mould potential is generally low until it quickly increases at the end of the year. The explanation for this lays in the hygrothermal properties of the two structures. The cathedral roof has generally a significantly lower RH during summer, about 10-15% lower and higher RH during winter, about 0-3% higher than the attic. The main reason is the difference in air change rates in the air gap. The ACH in the cathedral roof is set to 30. This allows the air gap to be dried out rather quickly from any excess moisture. This works as an advantage during the dry summer, the excess moisture which comes from the indoors is ventilated out and replaced with dry, warm air from the outdoors. While for the attic, 3 ACH does not allow all the excess moisture to be removed from the attic space at a desirable rate. For Stockholm, Borlänge and Luleå the mould growth risk increase begins earlier than in Lund. This can be explained by the difference in temperature between daytime and night-time and the influence of night sky radiation during spring. Warm dry air enters the attic during the day, when the temperature falls during night, and under influence of night sky radiation, the temperature decreases in the attic, and the RH rises. The air change rate in the attic is not sufficient to remove the extra moisture.

In the winter on the other hand, the conditions are different. The outdoor climate is more humid and the positive effect with a high ACH is now reversed. Any heat that escapes from the indoors that would have decreased the RH in the air gap, is quickly removed and replaced with moist outdoor air. The air gap is now more humid than outdoors, but the outdoor airs moisture storage capacity is very low, and apparently not enough to remove the free water caused by condensation and the excess moisture. This pattern can be detected in all locations in the hygrothermal results. The effect can also be seen in the mould models results, especially in the MRD- VTT- and m-model graphs for Lund. Compare to the other locations, it shows a significant increase of mould growth at the end of the year, this is due to the relatively higher temperatures (which triggers mould growth) in Lund.

When applying future climate the conditions are getting worse in all models and positions examined. The modified parameters in the climate data considers temperature, wind speed and rain, and consequently, higher temperature will not result in decreased relative humidity. Same RH with higher temperatures give more favourable conditions for mould growth. Furthermore, the increased rain will increase the moisture load penetrating the structures.

A representative, static ACH is difficult to assign in WUFI. Although blind evaluations between measurements and simulations have proven to give reasonable results, inserting a static air change rate seem more or less inappropriate since the conditions in the air gap fluctuates greatly. This is however, the only way of actually consider this factor. The ventilation rate in an air gap is connected to the size of the air gap and thus the total dimensions of the specific attic. For the attic an ACH of 3 was assigned accordingly to the basic conditions and recommendations in RäknaF, at the same time, the size of the attic space was set to 160 mm as it is impossible to assign different heights for the air gap in WUFI. This gives a rather low ventilation rate in terms of L/m^3. In reality an attic space can be several m^3 in volume, and a higher ventilation rate would therefore be expected. Further, in reality an attic space is not ventilated evenly throughout the whole space. The ventilation rate is higher close to the openings and slower in places far from the vents. This difference could create different moisture loads in the construction and thus different susceptibility for mould growth within the attic space. This phenomena is not as significant in the cathedral roof as the openings in many real cases are as wide as the air gap.

Safety margins have been considered and included throughout this report by applying worse case scenarios in many of the performed steps; from developing the constructions, to picking the appropriate climate etc. Assigning parameters from a worse case perspective could lead to misleading results and should be treated carefully and with great awareness. Potentially, it could lead to results that are too far from reality which could result in higher material costs etc. The effects of changing different parameters, that have been concluded to have great effect on the hygrothermal performance e.g. ACH, have been studied. The influence of shading was taken into consideration by simulating the structures to the north, which is the orientation with the least solar radiation and thereby highest RH. A south orientation would presumably give lower RH values and higher temperature but in a design phase the north orientation is to be consider the worst case scenario, and therefore deterministic for the whole construction. Another safety factor is that the worst year was chosen from the WUFI-results.

This moisture conditions could therefore be considered extreme, as the other nine years had lower RH. However, the difference between the years were very small which means that the worst year is still considered to be representative for the whole simulated time period. To use the results as a benchmark for moisture safety design it should consequently not be deemed excessive, but realistic.

5.3 Lund

It is hard to determine which structure that is the most favourable in Lund. The results fluctuates widely depending on which mould model that is used. However, the cathedral roof is the only structure with a *high risk* verdict on two of the models (m-model and MRD-pine). On this basis the attic is the better option. Both structures are performing poorly in the future climate. The increased temperatures and rain fall makes a bad situation worse. The attic was considered a better alternative in existing climate, and since both structures performs equally bad in the future climate, the attic must be considered the better option overall. But in any case, actions to ensure the structures moisture integrity is probably needed. One example of this could be a forced ventilation system which ventilates the attic when the outdoor air is drier than in the attic space.

The difference in results for the MRD-model for spruce versus pine is quite significant. The cathedral roof would, according to this model, be at risk if it is made out of pine. This shows how it can be advantageous to be able compare similar, but different, materials.

5.4 Stockholm

Generally the conditions seem to be less favourable for mould growth than Lund.

The cathedral roof seems to be the better option in Stockholm. None of the mould models predict any risk. Also the attic show good results, with WUFI-bio as the only model prediction *risk*. However, the attic has one great advantage over the cathedral roof, and that is accessibility. If mould growth would appear in any of the structures it is much more likely to be detected in an attic space where people may visit once in a while. The only obvious reason to enter the air gap in a cathedral roof would be during renovation of the roof cover, and it is therefore less likely to detect any mould growth tendencies in the cathedral roof comparing to the attic. The recommendation is, on this basis, to build an attic. The results from future climate enhances the attic as best choice, especially since the MRD-pine model asses the cathedral roof as *high risk*. Furthermore, the other models assessment is similar between the structures, and the most logical choice is therefore the accessible attic.

5.5 Borlänge

Borlänge show very little mould growth potential for both structures. This is due to the location inland which to some extent resembles a continental climate, which is characterized by dry weather and big yearly temperature differences. The structure choice is irrelevant from a mould growth perspective, but should instead be based on personal preferences. WUFI-bio shows an increased risk assessment for the attic in the future climate compare to existing climate, but it is negligible, partly since it the expected mould growth is relatively low, and partly since no other models demonstrate any risk.

5.6 Luleå

In existing climate Luleå is a rather safe location for any of the structures. During spring and summer all models show a quite significant mould growth, but the cold temperatures during autumn and winter demonstrates a significant decline of mould. Except for WUFI-bio, which is the only mould model without a function to calculate regression and hence maintains a high mould growth potential throughout the year. When ruling out WUFI-bio, the preferred structure can be based on factors outside this study. For the future climate on the other hand, the attic displays big problems compared to the cathedral roof. By analysing the graphs, the problem seems not be an increased winter temperature, but increased spring temperature which give a prolonged period of favourable conditions for mould growth. The overall recommendation for Luleå is therefore to use cathedral roof, which show better performance for the future.

Remark

The results for the m-model for the cathedral roof in Luleå in future climate, show a significant difference pattern compare to the other models, and also other m-models. See appendix D. The critical duration quote for the > 24 hour duration line seems suspiciously high (26.7), compare to the *high risk* criteria which is 1. The second highest m-model result is 1.36 for attic, in Lund for future climate, and the others differs ±0.3 from 1. This rises the suspicion of an error from either WUFI or in the m-model file. After several investigations with new WUFI-results, testing with other years and conducting analysis with other m-model files there were no difference in in results. However, when the period that gave the abnormal results was isolated (24/2-18-4) a pattern could be detected. When RH is above 98%, temperature must be below -2°C to not indicate a massive mould growth. E.g. 98% and -2.5°C show no indication of mould growth, while 98% RH and -1.5 °C displays high risk. When changing the safety factor from 0.98 to 1, i.e. ignoring the safety factor, the results changed drastically and were more similar to the other models assessments. The <24 hour duration line were now 0 and also the other duration lines showed a more reasonable results, similar to the other m-models. The safety factor were changed to 1 in the other m-models, to observe if the results would show a similar drastic difference, but this pattern could not be detected.

6 Conclusions

- The cathedral roof can contribute to a more moisture safe environment in some climates. It is s better choice in the two most northern locations, Borlänge and Luleå, and generally show a lower mould growth throughout the year compared to the attic in Lund and Stockholm. However, for the two latter locations it displays significant mould growth potential at the end of the year, due to warmer winters than the other locations.
- Not all models predicts the same mould growth, even for each location with the same climate data. One way to handle the uncertainties about growth, hibernation and regression would be to develop a stochastic mould model with a probability distribution pattern (spread of results) instead of a deterministic result. Until then, use of several mould models is recommended.
- The future climate exacerbates the moisture safety for both structures in Lund and Stockholm. In Borlänge, the future climate does not have a big impact on mould growth potential on either structures, while in Luleå the attic displays much worse results compared to the cathedral roof in the future climate.
- Differences in air change rate gives significantly different RH curves, and thus different mould growth curves. A cathedral roof (high ACH) is generally a better choice in locations with long periods below freezing temperatures. The opposite goes for the attic (low ACH).
- The outcome from mould models should be seen as indications, not as truths since mould growth is a biological process that includes many different factors such as type of mould species, contamination, surface structure etc.

7 Suggestion for further research

- Investigate the leakages through the vapour barrier in roof structures from several real cases in order to find a general value.
- Examine how ACH in building parts change during yearly seasons by conducting real measurements. Study the hydrothermal and mould growth potential based on these measurement by changing ACH season by season.

Bibliography

Adan, C. G. Olaf. 1994. *On the fungal defacement on interior finishes.* Eindhoven : Eindhoven University of Technology, 1994. ISBN 9038601948.

Ahrenens, C and E, Borglund. 2007. *Fukt på kallvindar.* Göteborg : Chalmers, Building Physics, 2007.

Ayanbimpe, Grace Mebi, Danjuma, Wapwera Samuel and Okolo, Mark Ojogba. 2012. Relationship between fungal contamination of indoor air and health problems of some residents in Jos. [ed.] Sunil Kumar and Rakesh Kuma. *Air Quality - monitoring and modeling.* Jos : InTech, 2012, pp. 1-7.

Berggren, Björn, Togerö, Åse and Tengberg, Charlotte Svensson. 2010. Fuktsäkerhet och isolering i välisolerade hus - hur kan takkonstruktioner optimeras? *Bygg & Teknik.* Växjö : Grafiska punkten, 2010.

Boverket. 2009. *Så mår våra hus.* Karlskrona : Boverket, 2009. ss. 16-40. ISBN 978-91-86342-29-6.

Boverkets byggregler, 18. 2011. *Boverkets byggregler, BFS 2011:26.* Karlskrona : BBR, Boverket, 2011. pp. 92-93. ISBN 978-91-86045-02-9.

Cooley, J Danny, et al. 1998. *Correlation between the prevalence of certain fungi and sick building syndrome.* Lubbock : Department of Microbiology and immunology, Texas Tech University Health Science Centre, 1998. ISSN 1743-3541.

Falk, Jörgen. 2014. *Rendered rainscreen walls - Cavity vantilation rates, ventilation drying and moisture-induced cladding deformation.* Lund : Media-Tryck, Lund University, 2014. ISBN 978-91-7473-746-2.

Hagentoft, Carl-Erik, et al. 2012. *Riskanalyser för ventilerade kallvindskonstruktioner SBUF-projekt 12438, Formas-BIC 11.* Borås : SBUF, 2012.

Hens, Hugo L. S. C. 2009. Moisture Control In Buildings. [bokförf.] Dejan Mumovic & Mat Santamouris. *A Handbook of Sustainable Building Design & Engineering - An integrated approach to energy, health and operational performance.* Abingdon : Earthscan, 2009, ss. 211-213.

IBP, Fraunhofer. 2013. Creating Weather files. *Fraunhofer IBP.* [Online] 29 October 2013. [Cited: 5 April 2015.] http://www.wufi.de/frame_en_wetterdaten.html.

Ikeda, Kenichi, et al. 2012. *The role of the Extracellular Matrix (ECM) in Phytopathogenic Fungi: A Potential target for Diseases Control.* Japan : Kobe University, 2012. ISBN 978-953-51-0489-6.

Johansson, Pernilla. 2014. *Determination of the critical moisture level for mould growth on building materials.* Lund : Avdelning för Byggnadsfysik, LTH, 2014. pp. 11-37. ISBN 978-91-88722-42-3.

Johansson, Pernilla, et al. 2005. *Kritiskt fukttillstånd för mikrobiell tillväxt på byggnadsmaterial - Kunskapssammanfattning.* Borås : SP, 2005. p. 2. ISBN 91-85303-442-9.

Kalagasidis and Sasic, Angela. 2007. *Simulations as the way of bridging the gaps between desired and actual hygothermal performance of buildings.* Gothenburg : Department of Building Technology, Chalmers University of Technology, 2007.

Lacey, J., o.a. 1986. The influence of water and temperature on moulding and mycotoxin production. *Proceedings of the fourth international working conference on stored-productio protection.* Tel Aviv : Maor-Wallach Press, 1986, ss. 63-76.

Li, Yujing. 2007. *Mould on building materials, A calorimetric study of fungal activity as a function of environmental factors.* Lund : Lund institute of technology, Lund University, 2007. ISBN 978-91-628-7239-7.

Lidgren, Persson, Camilla. 2010. *Bygg fuktsäkra takkonstruktioner.* Malmö : Skanska Sverige AB, Teknik och projektledning, 2010.

Martin, Krus, Nouidui, Thierry and Klaus, Sedlbauer. 2009. *Application of software tools for moisture protection of buildings in different climate zones.* Germany : Fraunhofer Institute for Building Physics, 2009. pp. 2-7.

Mundt-Petersen, S. Olof. 2013. *Comparison of hygrothermal measurements and calculations in a single, family wooden house on the west coast of Sweden.* Lund : Building Physics, LTH, 2013. ISBN 978-91-88722-45-4.

Mundt-Petersén, S. Olof. 2015. *Moisture Safety in Wood Frame Buildings - Blind evaluation of the hygrothermal calculation tool WUFI using field measurements and determination of factors affecting the moisture safety.* Lund : Department of Building Physics, Lund University, 2015. ISBN 978-91-88722-57-7.

Nevander, Lars Erik och Elmarsson, Bengt. 1994. *Fukthandboken.* Stockholm : Svensk byggtjänst, 1994.

Nielsen, Kristian Fog. 2002. *Mould growth on building materials; secondary metabolites, mycotoxins and biomarkers.* Lyngby : Biocentrum-DTU Technical Unversity of Denmark, 2002. pp. 3-8. ISBN 87-88584-65-8 .

Parra, R. and Magan, N. 2004. *Modelling the effect of temperature and water activity on growth of Aspergillus niger strains and applications for food spoilage moulds.* Applied mycology group, Insitute of Bioscience and technology, Cranfield University, Silsoe : Bedford, 2004. ISBN 9781424438075.

Samuelson, Ingvar and Hägerhed, Engman, Linda. 2006. Kalla vindar-problem och förbättringar. *Bygg & Teknik.* Växjö : Grafiska punkten, 2006, Vol. 98.

Sandin, Kenneth. 2004. *Praktisk husbyggnadsteknik.* Lund : Studentlitteratur, 2004. pp. 76-77. ISBN 9789144048796.

SBUF. 2013. *SBUF Informerar om effekter på funktion och kostnad av styrd ventilation av kallvindar.* SBUF productions, 2013.

Sedlbauer, Claus. 2001. *Prediction of mould fungus formation on the surface.* Stuttgart : Fraunhofer Institute for Building Physics, 2001.

Sedlbauer; Martin; Breuer. 2003. *Mould Growth Prediction with a New Biohygrothermal Method and its Application in Practice.* Lodz : Fraunhofer-Institute, 2003. pp. 594-601. ISBN 83-88499-09-2.

SMHI. 2011. Om analysen. *Klimatscenarier.* [Online] SMHI, 1 January 2011. [Cited: 8 May 2015.] http://www.smhi.se/klimatdata/framtidens-klimat/klimatscenarier/haag.html#us.

SP, Sveriges Tekniska Forskningsinstitut. 2010. Kurser och seminarium. *Fönstermontage.* [Online] 1 January 2010. [Cited: 2 April 2015.] http://www.sp.se/sv/training/international/Documents/Tr%C3%A4teknik%20och%20tr%C3%A4byggande/L%C3%A4ckage_i_f%C3%B6nster_-_SP_Energiteknik,_B%C3%B6rje_Gustavsson.pdf.

SP, Sveriges Tekniska Forskningsinstitut. 2013. Parallelltak - fuktteknisk bedömning. *Fuktsäkerhet.* [Online] SP, 1 November 2013. [Cited: 2 February 2015.] http://www.fuktsakerhet.se/sv/delar/tak/parallell/fukttek_bedomning/Sidor/default.aspx.

Thelandersson, Sven and Isaksson, Tord. 2012. *Mould resistance design (MRD) model for evaluation of risk for microbial growth under varying climate conditions.* Lund : Division of Structural Engineering - Lund University, 2012. ISSN 0360-1323.

Thelandersson, Sven, Isaksson, Tord and Niklewski, Jonas. 2014. *Fuktsäker utformning av klimatskiljande byggnadsdelar med fuktkänsliga material - Vägledning för projekt och riskvärdering.* Lund : Lunds Tekniska Högskola - Int. för bygg- och Miljöteknologi, 2014. ISBN 978-91-979543-6-5.

Togerö, Åse, Tengberg, Charlotte Svensson and Bengtsson, Bengt. 2011. The m-model: a method to assess the risk for mould growth in wood structures with fluctuating hygrothermal conditions. *NSB 2011 - 9th Nordic Symposium on Building Physics.* [Online] 29 May 2011. [Cited: 3 February 2015.] http://webhotel2.tut.fi/nsb2011/sites/webhotel2.tut.fi.nsb2011/files/b10_04_ase_togero2.pdf.

Tuomo, Ojanen, et al. 2011. *Mold growth modeling of building structures using sensitivity classes of materials.* Tampere : ASHRAE, 2011.

U.S. Environmental Protection Agency, Office of Air and Radiation, Indoor Environments Division. 2010. A Brief Guide to Mold, Moisture and Your Home. *EPA United States Environmental Protection Agency.* [Online] 1 September 2010. [Cited: 9 February 2015.] http://www.epa.gov/mold/pdfs/moldguide.pdf.

Walker, I.S and Forrester, T.W. 1995. Building and environment. *Field measurement of ventilation rates in Attic.* London : Elsevier, 1995, pp. 334-346.

Wallentén, Petter, et al. 2015. *Utkast Räkna F.* Lund : LTH, 2015.

Verekeen, Evy and Roels, Staf. 2012. Review of mould models and their influence on mould risk evaluation. [book auth.] Qingyan Chen. *Building and Environment 51.* Bremen : Elsevier, 2012, pp. 296-310.

Viitanen, Hannu. 1996. *Factors affecting the development of mould and brown rot decay in wooden material and wooden structures.* Uppsala : The Swedish University of Agricultural Sciences, Department of Forest Production, 1996. pp. 8-15. ISBN. 9157651159.

Viitanen, Hannu, et al. 1998. *Development of an improved model for mould growth: Modelling.* Finland : Technical Reserch Centre of Finland, Department of Civil Engineering (Tampere University of Technology), 1998.

Wiklund, Lotten. 2015. Varning för mirakelkur mot sjuka hus. *Forskning & Framsteg.* 1, 2015, Vol. 1, 1.

Zirkelbach, D., et al. 2013. *WUFI Pro 5 manual.* Germany : Fraunhofer Institute fur Bauphysik, 2013. pp. 22-35.

8 Appendix A – Material properties in WUFI

Following table displays the materials picked in WUFI and their properties

Materials & Properties	Bulk Density [kg/m3]	Porosity [m3/m3]	Specific Heat Capacity [J/kgK]	Thermal conductivity of dry material [W/mK]	Water Vapour Diffusion Resistance Factor of Dry Material [µ-value]	Initial Moisture Conditions [kg/m3]	Source
Tiles (red solid brick, extruded)	1650	0,41	850	0,6	9,5	100	Fraunhofer-IBP - Holzkirchen
Air layer (70mm)	1,3	0,999	1000	0,4	0,23	0	Generic Materials
Roof Membrane (roof membrane V13)	2400	0,001	1000	0,5	100000	0	Generic Materials
Wood Board (massive wood-radial, spruce)	455	0,73	1500	0,09	130	80	Fraunhofer-IBP - Holzkirchen
Air Layer (2*2mm+46mm)	1,3	0,999	1000	0,047 & 0,23	0,79 & 0,38	0	Generic Materials
Attic Space, Air Layer (2*5mm+150mm)	1,3	0,999	1000	0,047 & 0,94	0,79 & 0,07	0	Generic Materials
Insulation Retaining Board (wood fibre board)	300	0,8	1500	0,05	12,5	10	Fraunhofer-IBP - Holzkirchen
Insulation Material (mineral wool, heat cond. 0,04W/mK)	60	0,95	850	0,04	1,3	0	Fraunhofer-IBP - Holzkirchen
Vapour Barrier (vapour retarder)	130	0,001	2300	2,3	100000	0	Fraunhofer-IBP - Holzkirchen
Air Gap (without additional moisture capacity, 25mm)	1,3	0,999	1000	0,155	0,51	0	Generic Materials
Gypsum Board	850	0,65	850	0,2	8,3	8	Fraunhofer-IBP - Holzkirchen

9 Appendix B – Future climate settings

Following table presents the correction factors used.

	Lund			Stockholm			Borlänge			Luleå		
	Temp [°C]	**Rain [%]**	**Wind [w/s]**	**Temp [°C]**	**Rain [%]**	**Wind [w/s]**	**Temp [°C]**	**Rain [%]**	**Wind [w/s]**	**Temp [°C]**	**Rain [%]**	**Wind [w/s]**
1	2.12	1.15	-0.70	3.38	1.167	-0.15	2.77	1.14	0.99	3.38	1.167	-0.15
2	2.17	1.15	0.52	3.24	1.185	-0.69	2.74	1.13	0.61	3.24	1.185	-0.69
3	2.04	1.09	0.25	3.42	1.166	0.06	2.67	1.17	0.41	3.42	1.166	0.06
4	2.00	1.17	0.51	3.00	1.194	-0.72	2.46	1.18	-0.38	3.00	1.194	-0.72
5	1.43	1.03	0.54	2.99	1.153	-0.86	2.09	1.04	0.15	2.99	1.153	-0.86
6	1.78	1.09	-0.48	3.21	1.118	-0.50	2.36	1.14	-0.35	3.21	1.118	-0.50
7	2.11	1.17	0.10	3.45	1.207	-0.30	2.68	1.16	-0.07	3.45	1.207	-0.30
8	1.56	1.08	0.58	3.25	1.099	0.49	2.35	1.08	0.62	3.25	1.099	0.49
9	1.53	1.06	0.63	3.08	1.108	-0.57	2.03	1.09	-0.18	3.08	1.108	-0.57
10	2.04	1.07	-0.39	3.55	1.155	-0.47	2.65	1.14	-0.16	3.55	1.155	-0.47

10 Appendix C - Moisture flow calculations

Pressure drop and moisture flow calculations

The protecting vapor barrier should be completely tight, however due to carelessness during building phase or installations in the ceiling during user phase there is a risk of holes in the vapor tight membrane. This is accounted for by introducing a 3 mm hole /m2 in the vapor barrier. This represents a nail penetration or bad fittings / joints. Following equations are from Fukthandboken (Nevander, o.a., 1994).

Pressure drops:

$$\Delta P_{tot} = \Delta P_{wind} + \Delta P_{thermal} + \Delta P_{ventilation}$$

$\boldsymbol{\Delta P_{wind}}$

$$\Delta P_{wind} = (\mu_{outside} - \mu_{inside}) * \frac{\rho * u_0^2}{2}$$

Where:

μ= is form factor (-). Outside: -0.5 for 30°, Inside: 0.2 (the most unfavorable).

ρ= air density (kg/m³), 1.25

u_0=wind speed (m/s). Hourly from climate files.

$\boldsymbol{\Delta P_{thermal}}$

$$\Delta P_{thermal} = g_g * (\rho_{out} - \rho_{inside}) * h$$

Where:

g_g=9.81m/s²

h= max building height, 8 m

ρ (20°)=1.20255 kg/m³

Correlation between density and temperature:

Air density at 0°C (273.15°K) and 50 % RH= 1.2906 kg/m³

$$\rho_{out} = 1.2906 * \frac{273.15}{273.15 + T_{out}}$$

T_{out}=Hourly temperature from climate file.

$\boldsymbol{\Delta P_{vent}}$

The house is considered to be well insulated, consequently the pressure difference due to ventilation is zero.

$$\Delta P = \frac{32*\eta*L}{d^2} * \left(\frac{R}{A}\right) + \xi * \frac{\rho}{2} * \left(\frac{R}{A}\right)^2,$$

$$0 = \frac{32 * \eta * L * A * 2 * r}{d^2 * \xi * \rho} - \frac{\Delta P * 2 * A^2}{\xi * \rho} + R^2$$

Where:

η=dynamic viscosity, 0.00001808 Ns/m²

L=Vapor barrier thickness, 0.001 m

d=diameter of hole, 0.003m

R=the air flow

A=area hole, 0.00000707 m²

ξ=loss factor, 1.8 (-)

R is solved for using the pq formula where

$$R = -\frac{32 * \eta * L * A}{d^2 * \xi * \rho} \pm \sqrt{(\frac{32 * \eta * L * A}{d^2 * \xi * \rho})^2 + \frac{\Delta P * 2 * A^2}{\xi * \rho}}$$

Only positive flows are accounted for, it is one R-value per hour and it is inserted in the following formula:

$$G = R * (v_{indoors} - v_{mineral\ wool})$$

$v_{indoors}$=hourly data extracted from WUFI.

$v_{mineral\ wool} = v_m$

$v_m = v_s(T_m) * \varphi_m$

Where: $v_s(T_m) = p_s(T_m) * \frac{M_v}{R_k * (273.15 + T_m)}$

$p_s(T_m) = a * (b + \frac{T_m}{100})^2$

Factor a and b are dependent on the temperature according to:

0°C $\leq T_m \leq 30$, a=288.68 Pa, b=1.098 and n=8.02

M_v=18.02 kg/kmol

R_k=8314.3 J/kmol*K

The moisture flows are inserted into WUFI by the vapor barrier and considered to influence 100% of the mineral wool layer. Any negative flows which indicates drying out are set to 0 to ensure a worst case scenario.

(Nevander, o.a., 1994)

11 Appendix D – m-model tables

Future climate results in red.

Lund

Attic Lund	**>24 hours**	**>1 week**	**>2 weeks**	**>4 weeks**	**>8 weeks**	**>12 weeks**
Max duration (period M>1 [h])	0	0	0	95 / 284	591 / 1439	1670 / 2737
Risk assessment	Low Risk	Low Risk	Low Risk	Low Risk/ Low risk	Low Risk / High risk	Risk / High risk
Critical duration quote (max/critical)	0.00	0.00	0.00	0.14 / 0.42	0.44 / 1.07	0.83 / 1.36

Cathedral Lund	**>24 hours**	**>1 week**	**>2 weeks**	**>4 weeks**	**>8 weeks**	**>12 weeks**
Max duration (period M>1 [h])	0	0	0	0 / 55	1389 / 1884	1985 / 2300
Risk assessment	Low Risk	Low Risk	Low Risk	Low Risk/ Low risk	High risk/ High risk	Risk / High risk
Critical duration quote (max/critical)	0.00	0.00	0.00	0.00/ 0.82	1.03 / 1.04	0.98 / 1.14

Stockholm

Attic Stockholm	**>24 hours**	**>1 week**	**>2 weeks**	**>4 weeks**	**>8 weeks**	**>12 weeks**
Max duration (period M>1 [h])	0	0	0	0	614 / 1097	1114 / 1426
Risk assessment	Low Risk	Low Risk	Low Risk	Low Risk	Low risk/ Risk	Low Risk / Risk
Critical duration quote (max/critical)	0.00	0.00	0.00	0.00	0.46 / 0.81	0.55 / 0.71

Cathedral Stockholm	>24 hours	>1 week	>2 weeks	>4 weeks	>8 weeks	>12 weeks
Max duration (period M>1 [h])	0	0	0	0	362 / 1152	922 / 1730
Risk assessment	Low Risk	Low Risk	Low Risk	Low Risk	Low risk/ Risk	Low Risk / Risk
Critical duration quote (max/critical)	0.00	0.00	0.00	0.00	0.27 / 0.86	0.46 / 0.86

Borlänge

Attic Borlänge	>24 hours	>1 week	>2 weeks	>4 weeks	>8 weeks	>12 weeks
Max duration (period M>1 [h])	0	0	0	0	204 / 761	710 / 1253
Risk assessment	Low Risk	Low Risk	Low Risk	Low Risk	Low risk/ Low Risk	Low Risk / Low Risk
Critical duration quote (max/critical)	0.00	0.00	0.00	0.00	0.15 / 0.57	0.36 / 0.62

Cathedral Borlänge	>24 hours	>1 week	>2 weeks	>4 weeks	>8 weeks	>12 weeks
Max duration (period M>1 [h])	0	0	0	0	12 / 88	100 / 317
Risk assessment	Low Risk	Low Risk	Low Risk	Low Risk	Low risk/ Low Risk	Low Risk / Low Risk
Critical duration quote (max/critical)	0.00	0.00	0.00	0.00	0.01 / 0.07	0.05 / 0.16

Luleå

Attic Luleå	>24 hours	>1 week	>2 weeks	>4 weeks	>8 weeks	>12 weeks
Max duration (period M>1 [h])	0	0	0	8 / 547	675 / 1260	1230 / 1707
Risk assessment	Low Risk	Low Risk	Low Risk	Low Risk / Risk	Low risk/ Risk	Low Risk / Risk
Critical duration quote (max/critical)	0.00	0.00	0.00	0.01 / 0.81	0.50 / 0.94	0.61 / 0.85

Cathedral Luleå	**>24 hours**	**>1 week**	**>2 weeks**	**>4 weeks**	**>8 weeks**	**>12 weeks**
Max duration (period M>1 [h])	0 / 628	0 / 631	0 / 631	0 / 775	11 / 1025	150 / 1044
Risk assessment	Low Risk / High risk	Low Risk / High risk	Low Risk / High risk	Low Risk / High risk	Low risk/ Risk	Low Risk / Low Risk
Critical duration quote (max/critical)	0.00 / 26.7	0.00 / 3.76	0.00 / 1.89	0.00 / 1.15	0.01 / 0.76	0.07 / 0.52

12 Appendix E – Sensitivity analysis, ACH

Following tables display the RH and the effects of changing air change rates in the cathedral roof and the attic in Lund.