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Hygrothermal performance of sarking roof structure

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The main objective of this thesis was to study the suitability of a new roof type, sarking roof in Finland. The sarking roof is used in the Southern Europe, but the climatic conditions in Finland are different. The Finnish cold climate has high humidity in the outside air. The air flowing through the sarking roof, could cause condensation and moisture could be trapped in the roof components causing decay and mold growth. This study of the hygrothermal behavior of the sarking roof is aimed at establishing whether such risk is real.

To study the hygrothermal behavior of the sarking roof, simulations of moisture and heat flow through various points of roof structure in various roof types were conducted with WUFI 2D. Highly accurate data of moisture and heat flows inside the various roof structures were obtained. The simulation results were analyzed and compared with the graphs of a mold growth experiment.

The study of simulation cases showed that there are no risks of mold and structural decay inside a sarking roof. It was established that an addition of sarking insulation improves the thermal performance of a roof and prevents thermal bridges through wooden rafters. Furthermore, the thesis showed that a board can be installed between the insulation materials without any moisture accumulation inside, which could damage the roof. The findings can open a new solution for roof insulation in Finland. Thus, this thesis can be used as a reference document for further research into a similar subject.

Keywords	Isover, sarking, moisture, mold, decay, WUFI 2D

Contents

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Nirmal Magarati Magar
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Helsinki, Finland

1 Introduction

Finland is a Northern European country. Winter is the most prolonged season in Finland and summer is short. The average temperature is 10°C during summer and -3°C during winter [1]. The average humidity during winter is above 80% [2]. Since the outside temperature is usually low and humidity is higher, the roofs, floors and lower parts of building components are vulnerable to excess moisture. The excess of moisture can cause condensation, which is a common problem in Finland. Condensation can cause surface dampness and increase the risk of mold growth. This can affect the thermal performance of building components, cause health problems for the occupants and even result in the structural decay.

The demand for energy efficient buildings and better indoor air quality are increasing in the construction industry. To meet that demand, it is very important to make buildings air tight and minimize the heat loss. The thickness of insulation can be increased to improve the thermal performance of a building. However, other innovative solutions should be studied as well. It is good to study the hygrothermal behaviour of new structures. Sometimes building components can be damaged by moisture that is trapped inside due to various reasons. To avoid such damages, it is very important to study moisture and heat flow in building components like the roof and walls. This thesis investigates the hygrothermal performance of roof structures and the potential damages caused by an excess of moisture in building components.

The building structure studied in this thesis is a sarking roof model which is not yet introduced in Finland. It is a roof structure where a sarking insulation is installed above the main insulation layer. It is very important to investigate the effects of a cold and long winter on the new roof model. The thesis aims to find if the new roof model can be introduced in Finland and help to improve thermal performance of roof.

According to Saint-Gobain Isover, the sarking roof structure studied is commonly used in southern and central European countries. The company wanted to see if the structure would cause any moisture risk in the roof components if the sarking roofs were used in Finland. If the roof model is found to be suitable for the Finnish climate, Saint-Gobain Isover can launch it in the market.

1.1 Outline

This thesis is commissioned by Saint-Gobain Isover. It is a supplier of sustainable insulation solutions operating in the whole world. Isover products are used in both residential and non-residential buildings. The final year project studied the heat and moisture flow in a sarking roof structure after installation of board material between the main insulation and sarking insulation. If the roof model is shown to be free from moisture damage like condensation, mold and structural decay, the roof structure shall be considered suitable for Finland.

The heat and moisture flow is investigated with WUFI 2D software. The software provides information about heat and moisture conditions on building elements during different times of the year. For the preparation of this thesis different books, e-journals, research publications and interviews were used as references and sources.

1.2 Constraints

Since this research on the sarking roof structure is the first of its kind in Northern Europe, there was a lack of articles and case studies about the structure. As this final year project is based on an analysis of a WUFI 2D simulation results, the limited availability of functions in the student version of WUFI 2D became another constraint because there were not enough material data. Besides that, to find the thermal conductivity, density and water diffusion factors for some of the materials was challenging.

2 Background

A building is an assembly of different components like walls, windows, roof, columns, slabs and many other components. The purpose of construction of building is to protect the people from harsh natural weather like rain, snow, wind, fire, heat and many other harmful agents. A building consists of different components and structures and among those components some are exposed to the outside weather and environment every day. The everyday exposure to outside environment can cause wear and tear in the building elements due to natural actions. Sometimes the damage can be such that it can increase the risk of damage in the internal components of the building as well.

Among the components of a building, the roof is a very important component as it protects other structures. It is exposed to the weather, and therefore natural actions like rain, heat, wind, snow and other agents can cause decay and deterioration. Therefore, any damage to the roof can cause severe damage on the roof structure itself and the elements below it as well. Thus, the protection and construction of the roof should be well planned from the design state. Also, the selection of material is an important factor for better performance of a roof. [3.]

A roof is an integrated component of building envelope system and plays a very important role in the energy efficiency of the building. The influence of the roof in the energy efficiency of a building is sometimes ignored. As seen in figure 1 below, the roof alone is responsible for 25% of conductive heat loss. This is because of poorly insulated attics, offering the heat a way to escape. [4.]

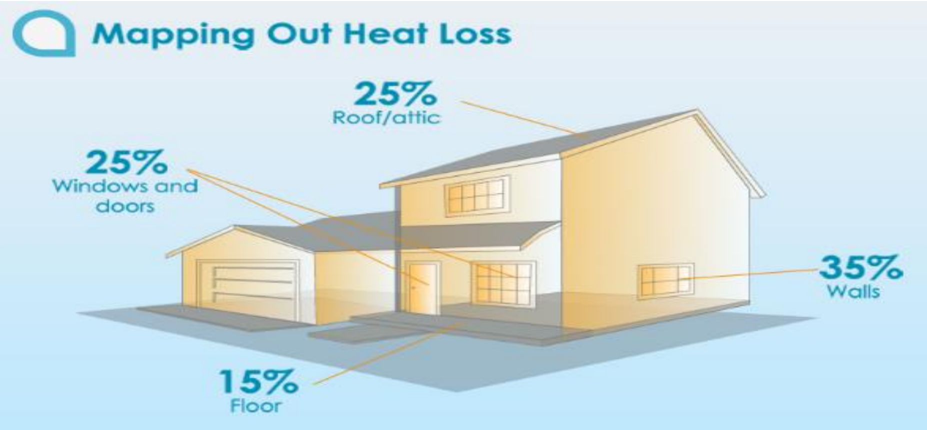


Figure 1. Heat loss through building components [4].

A building should be like an airtight box for better thermal and energy performance. Just like a small hole in an air tight box can affect the air, temperature, and pressure inside the box, a small leakage in the roof structure can allow heat to escape through it. This can degrade the thermal performance of insulation, resulting in more need of energy for heating.

The insulation material used in the roof structure helps to limit the heat flow between the building interior and the outdoors through the roof. Therefore, the selection of roof insulation material is very important for energy efficiency [3]. The air entering through a leakage could have moisture. The moisture accumulation on the internal components of a roof could lead to mold formation and even structural decay in some cases. The mold formation affects the indoor environment and well-being of occupants. Thus, it is necessary to study the effect of moisture on a roof structure. [3.]

3 Sarking roof

In general, a sarking roof is a pitched roof structure with a continuous insulation layer over the load bearing rafters. The insulation acts as an integral part of the roof and helps in preventing heat loss. [5.] As seen in the picture 2 below, there are insulation (yellow substance) both between and above the rafters. They are separated by a board material. The board material can be gypsum, plywood or fibreboard. The insulation material above the board is known as sarking insulation.

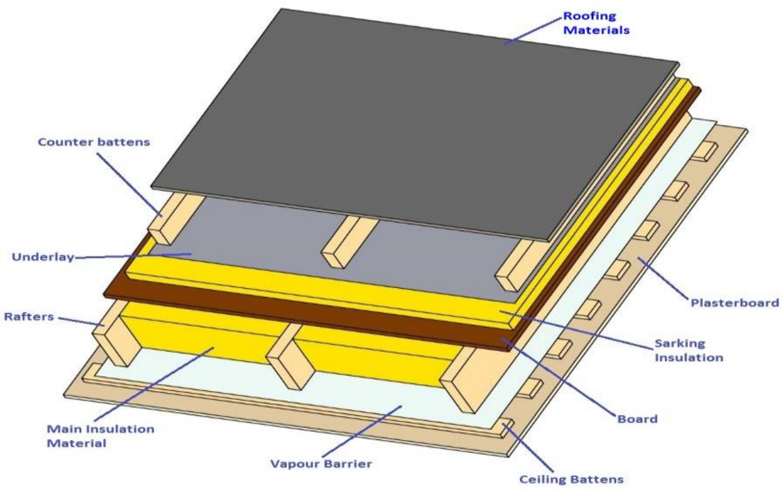


Figure 2. Sarking Roof Structure.

According to Ari Karhunen [Product development Engineer, 8 December 2016, personal communication], this kind of a roof is not currently used in Finland but a similar roof structure is used in some Southern European countries. This roofing solution is used in Switzerland as Isover solution product.

A sarking solution has many benefits over a traditional roof. Sarking roof is easy to install. It allows the outflow of moisture, which helps in keeping the surface dry and prevents mold formation and structural decay. It conserves heat and is thermally efficient. [5.] According to Ari Karhunen, when an additional insulation layer is installed between wooden rafters and counter battens, it improves the acoustic and thermal properties of the roof.

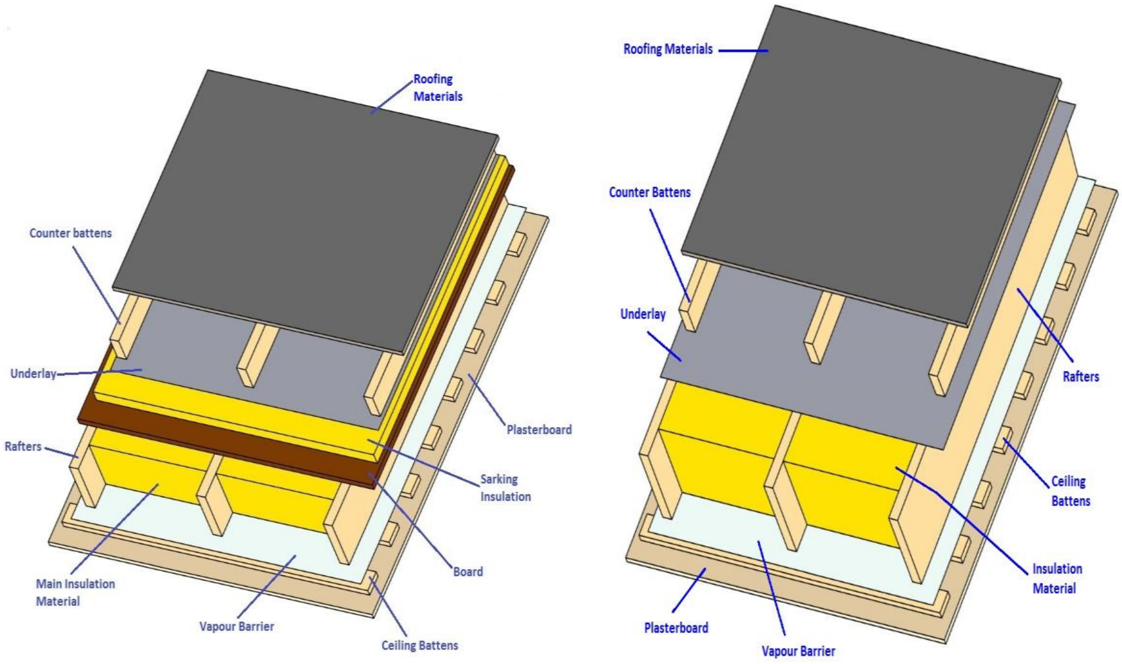


Figure 3. Sarking roof (Left) and reference roof (Right).

Figure 3 above shows the differences between a sarking roof and a reference (traditional) roof. The roof on the right in figure 3 is used in Finland at present. The sarking roof has additional sarking insulation over the main insulation layer. This helps to improve the thermal and acoustical performance of the roof. In the reference roof model, there is a possible thermal bridge through the wooden rafters. However, these problems can be minimised if sarking insulation is added above the main insulation layer and wooden rafters.

While installing sarking insulation above the main insulation, there could be a risk of workers falling while stepping on the insulation material. Thus, the addition of a board material below could enhance the strength of the roof as well as safety for worker. The installation of the board between the insulation layer could affect the structure, if moisture cannot pass through the board material. The main objective of this thesis is to find out if there will be a moisture accumulation on the board and if that can cause mold and structural decay risks.

4 Moisture transfer

The transfer of moisture between building components has significant impacts on the health and comfort of occupants, the durability of building components, and the energy efficiency of the building. To investigate the hygrothermal activity in a building component, it is important to know about moisture flow.

The most damaging form of moisture transfer is when rainwater, ground water or snow penetrates the building structure through holes and transfers in liquid form. [6.]

Another way that moisture can move through structures is capillary action. Although the building structure is damaged slowly, as the capillary needs a porous medium for water transfer, the damage to the building can be severe. The damage cannot be seen in its initial stage as it usually begins in a dark crawlspace and when the damage starts being visible, it may be significant and requires quick response. [6.]

Moisture can also flow through air in the form of water vapour. When moist air passes through a building envelope, it condensates when it passes through any surface that has temperature below the dew point. The condensed water makes the surface damp creating an environment for mold to flourish and even cause decay of the building components in the long term. Although the quantity can be small, moisture can pass through building envelopes even without a leakage. This process where water vapour passes through permeable materials due to a difference in vapour pressure or temperature difference is called vapour diffusion. [6.]

5 Moisture damage in building

A building structure can be deteriorated through use and age. The damage can be worse if exposed to external chemical, physical and biological agents. An excess of moisture in building materials can increase the threat of bio deterioration like fungus germination, structural damage and decay, and infestation. It is impossible to have a 100% microorganism free building because microorganisms are always present one way or another. The moisture conditions, temperature and the exposure time of the material are the main factors for the evolvement of molds that can also lead to structural damage. [7.]

Moisture is one of the most dangerous threats to the durability and performance of a building. The presence of excess moisture in a building can damage the building structure by infestation and structural decay on one hand and pollute the indoor air and affect the health of occupants on the other. [1;8]

When moist air gets in contact with a cold surface, it can condensate and form a liquid which can collect in building structures and cause structural damage. However, if the moisture condensates inside the building components like walls and ceilings, it is difficult to notice. There can be mold and mildew formation inside the structure. The damages of moisture can be seen when the infection spreads in a large area. The moisture can lead to different types of damages in the building structures, described below. [6.]

5.1 Thermal performance of building

When there is a moisture leakage in a roof structure, the moisture accumulates in the insulation layer and other interior building components. It takes a long time to notice the damage while the moisture penetrates the insulation layer and starts appearing on interior surface. By the time the moisture effect is identified on the internal surfaces of building, the insulation layer is damaged and its thermal performance can be reduced.

When the insulation layer gets wet because of excess moisture, it lowers the R- value of the insulation. Consequently, the insulation cannot protect the interior of the building from extreme outdoor temperatures during winter. The damage can reduce the thermal performance of the structure and can cause an increase in energy consumption. [9.]

5.2 Formation of blisters

Moisture trapped inside the roof structure can further damage the roof. When the moisture gets into the roofing structure, it turns either into water within the insulation layer or into vapour.

Then again, if the vapour does not find a way to escape, it rises to a blister within the roof structure. When the pressure of the vapour rises, it escapes through a weak part of the blister, creating a hole that offers a way for water to enter the structure. [9.] Figure 4 is an example of blistering.

Figure 4. Blistering on roof surface [10].

5.3 Condensation risk

Condensation is one of the most common reasons for dampness in a building. It occurs when moist air gets in contact with a colder surface. The air is cooled and water condenses at the dew critical point. This usually happens during winter. If the surface is impervious like glass, water may collect on its surface, but if the surface is permeable like wallpaper and plasters, the surface will be damp because of water absorption by plasters and wallpaper. [10.]

Condensation can cause mold growth and structural decay. It can corrode a metal structure through a chemical reaction of water and the metal. There is a risk of shrinkage or swelling of wooden components, which can cause deformation of building structures when the condensed water is absorbed by the materials. A leakage or an absence of any underlay membrane can give an easy entrance for water. Moisture saturation of insulation can affect the thermal performance of the material and result in heat loss of the building. The unseen mold growth inside the roof and ceiling structures can cause allergic reactions to people living in the house. Condensation can be avoided by using an improved heating and ventilation system that extracts the moist internal air and replace it with outdoor air. It is good to insulate cold surfaces to avoid condensation. [10.]

5.4 Mold risk

Excess moisture is the main reason for mold formation. When a water leakage or moisture condensation make a structure surface damp, the fungii gets a favorable environment for growth. The development and expansion of mold depends upon the humidity, temperature and the exposure time of the material. The critical relative humidity (RH) for mold growth is above 75 - 80%. But the mold growth also depends upon the temperature and the time duration of moist surface. [7.]

Table 1 below indicates the mold index according to visual appearance of mold. As seen in the figure, mold index 0 means there is no mold growth on the surface. Mold index 1 is the initial stage of mold development. The molds are visual through microscope when mold index is 3. At mold index 3, less than 50% of mold infection is seen on the surface. When more than 10% of the mold infection is visible to the eye, the mold index 4. At indexes 5 and 6, the surface is heavily infected. [7.]

Table 1 Mold index according to visual appearance [7.]

Index	Description of the growth rate
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10 % coverage, or, **< 50 % coverage of mould (microscope)**
4	Visual findings of mould on surface, 10 - 50 % coverage, or, **>50 % coverage of mould (microscope)**
5	Plenty of growth on surface, > 50 % coverage (visual)
6	Heavy and tight growth, coverage about 100 %

Sometimes, the mold index can be decreased due to too dry conditions. If there is a drop in the humidity to below 75% for a long period for instance 10 weeks, this helps in reducing the mold growth rate and even decreases the mold index. This happens because mold does not get nutrients in low humidity and its expansion stops. [7;8]

Figure 5 below shows the sensitivity of different building materials to mold growth at 97% relative humidity (RH) and 22°C temperature. The growth of mold depends upon the type of building materials used. Some materials, like pine wood are sensitive to mold growth while concrete and glass wool are more resistant to mold formation. [7.]

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

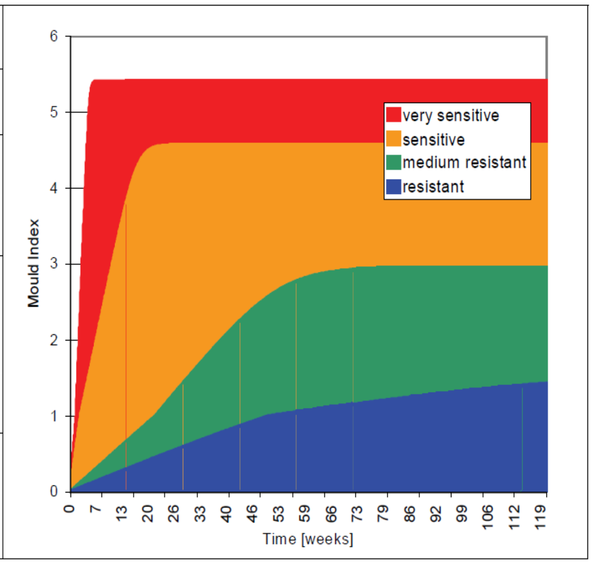


Figure 5 Mold growth sensitivity in different materials at 97% RH and 22°C [585;7.].

For instance, a pine sap wood is very sensitive to mold growth. If the humidity is above 97% at 22°C temperature, fungus starts to develop on pine wood surface in one week and have mold index 1. Fungii cover more than 50% of the damp surface on pine wood within 7 weeks and reach mold index 5. As seen in figure 6, glued wooden boards and spruce take more exposure time for fungus to develop. Concrete and mineral wool are more resistant to mold growth. Those materials take more than 13 weeks for mold growth at mold index 1. Thus, the mold formation can be affected by the materials also. If the material can resist mold then it takes longer time for mold formation. [7.]

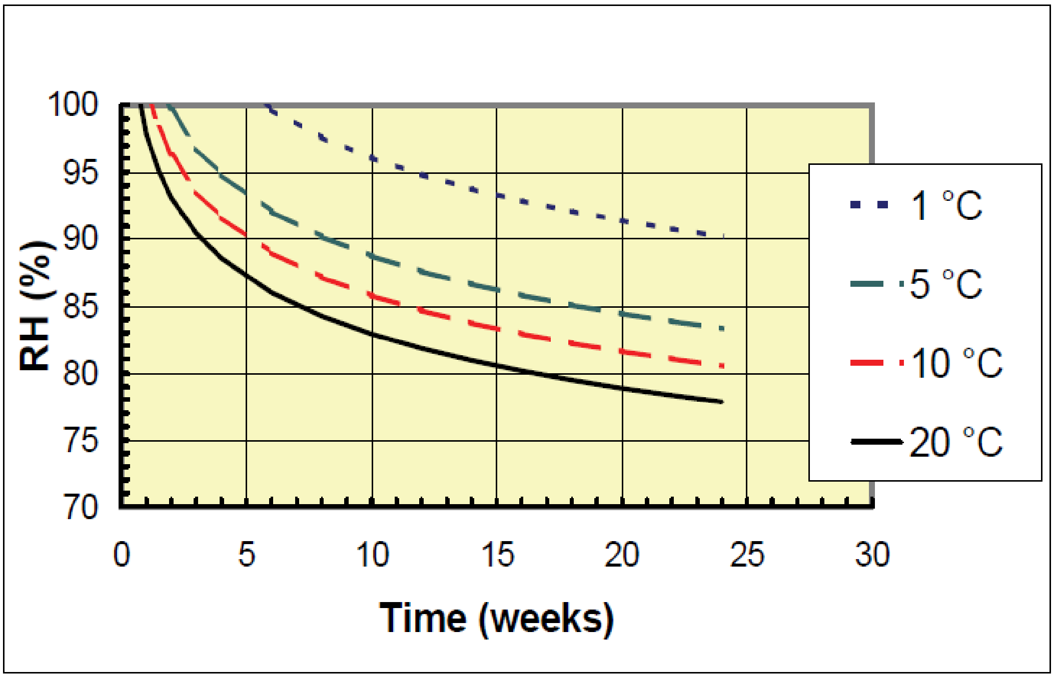


Figure 6. Mold growth probable condition on pine sapwood [582; 7.].

Figure 6 above shows the duration for mold growth according to humidity and temperature conditions in pine sap wood. Pine wood is considered a very sensitive material for mold growth. The mold growth experiment was conducted by Hannu Viitanen. The above result of the sap pinewood experiment is one of the references for mold growth analysis in this thesis. [7.]

According to Viitanen's experiment, if the RH is 80% at 20°C, the condition should remain same for 15 weeks for mold to develop. If the RH increases during that time, this will provide better environment for mold and can escalate the time for the mold development. Also, if the RH is above 90% but the temperature is only 1°C, the mold formation time will be more than 20 weeks. The surface at this condition will be very cold for mold to develop in comparison to temperature at 20°C. This cold temperature does not allow the mold to develop quickly although the RH is above 90%. The mold formation will be very slow at 1°C because of cold surface and it stops if the temperature goes below 0°C. [7.]

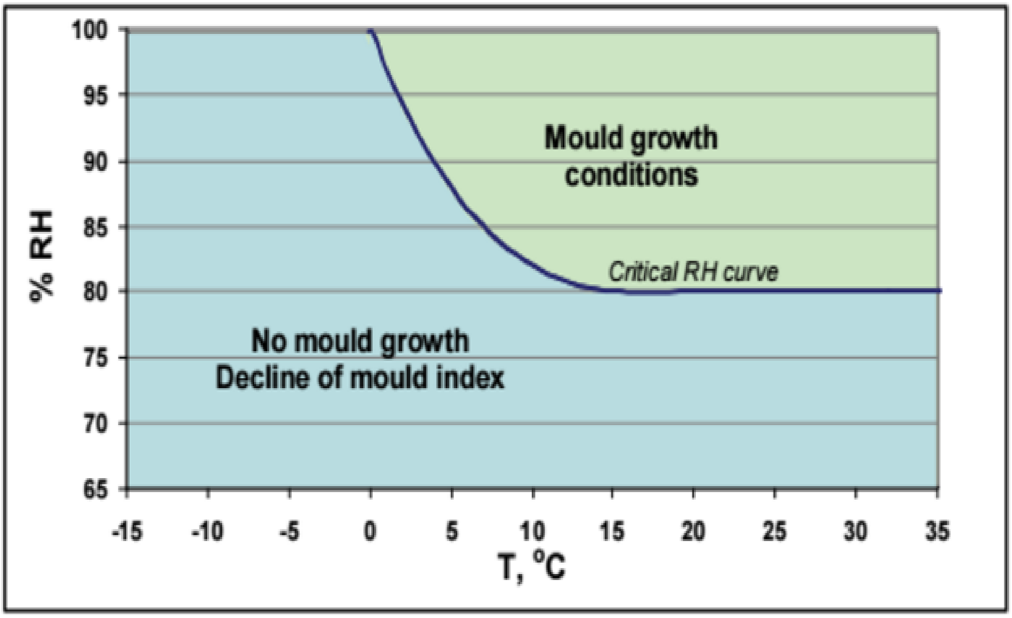


Figure 7 Mold growth condition according to humidity and temperature [586; 7.].

Figure 7 above shows the mold growth condition based on the humidity and the temperature. The mold cannot grow if the temperature is under 0°C even if the RH is above 80%. This happens because the frost condition is not favorable for mold survival. If the humidity is 80% and higher at a temperature above 0°C, such conditions give more chances for mold growth. [7].

When the humidity is under 80%, the mold growth stops because the surface starts to dry and becomes unfavourable for the mold. If the humidity remains below 80% for longer period for instance like eight weeks, the mold stops to develop because of lack of nutrients that is needed for mold to expand. This dry condition could make the mold index to decrease because when there will be lack of nutrients the mold starts to vanish. This shows that humidity and temperature plays very important role in mold formation. [7.]

5.5 Structural decay

Structural decay is caused by excessive moisture content in a material or building component. Structural decay is a serious consequence of exposing wooden materials to high RH for a longer period.

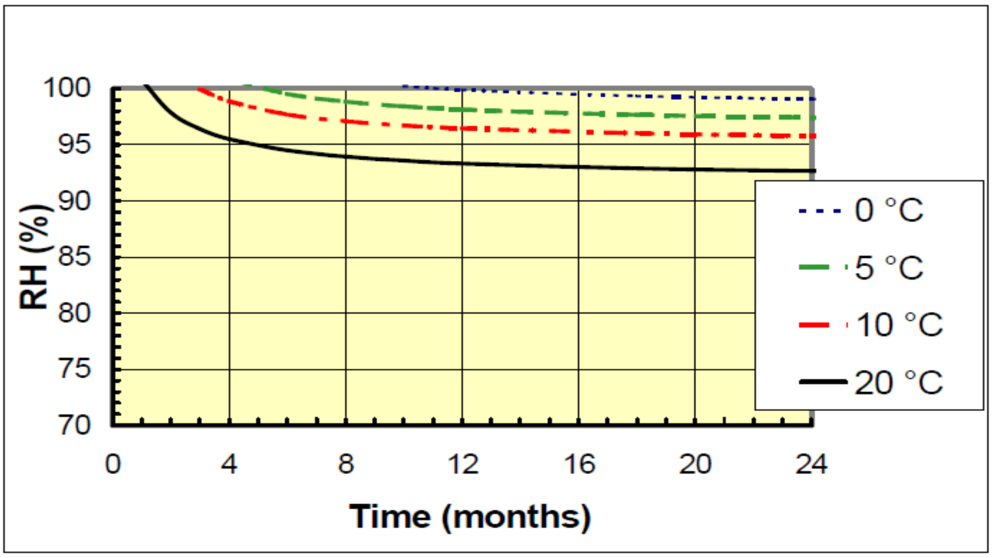


Figure 8. Wood Decay condition [8;11].

According to the experiment by Viitanen [7] on pine sapwood, the critical RH should be above 90% and moisture content in wood above 25% for several weeks for decay to start. Figure 8 above shows the result of Viitanen's experiment. Looking at the 20°C temperature line on the figure 8 above if the RH is 95% and the temperature between 10-20°C, it takes about 4 months for the material to decay. [11.]

Decay of a structure depends upon the temperature and exposure duration of a material to the environment also. If the RH is 95% for 2 weeks and it decreases to 75% for 4 weeks, there will not be any structural decay risk because of the fluctuation of humidity. This sapwood decay information is used as a baseline when the decay of material is investigated in this study. [11.]

6 Materials

In this final year project, common materials used in roof structure were used to obtain comparable data for new structure. For the thermal conductivity values for most materials the information in the WUFI 2D database were used. The data needed for materials that are not listed in the WUFI database were obtained from the material manufacturer websites and product data sheets. In this study, plywood and bitumen are used as roofing material but these materials can be replaced by any kind of roofing materials that are suitable for a pitched roof.

6.1 Isover KL-37 insulation material

Isover KL- 37 by Saint Gobain is a rot proof insulation material. It is the main insulation material used in both the sarking and reference roof models in this study. It is a non-organic, soft and unfazed glass wool board. It is odourless, and its chemical neutral properties have no negative impact on the indoor air quality and occupants' health. It fulfils the building material emission class M1 and has A1 Euro class in fire resistance. It is available in various thickness and sizes. [12.]

Isover KL- 37 can be used as an insulation layer on roofs, floors, walls and ceilings. It can be used as insulation in wood, metal and even concrete structures. In addition to offering good thermal insulation, it is also a very good sound insulation. Its thermal conductivity value is 0,037 W/mK and water vapor diffusion factor is 1. More information about the installation, and a declaration of performance can be found on the of Isover website. [12.]

6.2 Isover sarking insulation

Isover sarking insulation is a rigid insulation material. It is made of inorganic and chemically neutral materials, which do not have an adverse effect on the quality of indoor air or occupant's health. Similarly, to Isover KL 37, this product does not have any corrosive substances and is rot proof as well. It is coated with glass fibre tissue on one side and has grooved edges on the long side of the board. It belongs to the building material emission class M1. It has A2 s1, d0 – Euro class fire resistance properties. It is available in various thickness and sizes.

Isover sarking insulation is used on structures when good insulation and compressive strength is required. Its high compressive strength of 60Kpa helps it to withstand loads on the roof and prevents it from sagging. Its thermal conductivity value is 0,037 W/mK and water vapor diffusion factor is 1. IN this final year project, a sarking insulation of 30 mm and 50 mm thickness is used to study the effect of various thickness in insulation on moisture conditions. Since no public data was available for citation, the data for this material was obtained from Isover.

6.3 Isover Isoprotect fibreboard

Isoprotect fibreboard is a strong and pressure resistant wooden fibreboard. It is weatherproof and can be sued in roofs and walls. It can be found in various thickness from 35 – 100mm. [13.]

If the thickness of an isoprotect board is from 35- 80 mm, its thermal conductivity is 0,044 W/mK and water vapor diffusion factor is 3. For my final year project, isoprotect fibreboard of 35 mm is used. The additional information about this product can be found on the Isover website. [13.]

6.4 Isover Vario Xtra

Isover vario xtra by Saint Gobain is a vapour barrier, which prevent moisture. It is easy to install and has high performance on air tightness and moisture control ensures better protection from moisture. It can be used in pitched roof, flat roofs and timber frame walls. [14.]

The S_d value of isover vario xtra ranges from 0,3 – 25m depending on the relative humidity around it. During normal moisture conditions, it works as a common vapour barrier but when the RH increases inside roof structures, the water permeability factor of the material changes and allows the humidity to enter back to the indoor air. This way Isover

Vario Xtra prevents accumulation of moisture inside roof structure. The additional info and DoP about this product can be found in the manufacturer website. [14.]

6.5 Gyproc GN 13 gypsum board

Gyproc GN 13 gypsum board is selected from Gyproc product range. It is Saint-Gobain brand as well. It is durable and easy to install. It is used for ceiling and wall surfaces. It is used between the main insulation layer and the sarking insulation to prevent accident of workers during installation. [15.].

It has a thermal conductivity value of 0,25 W/mK and water vapor diffusion factor is 10. The additional info about this product can be found in the material manufacturer website [15.].

6.6 Bowcraft roofing underlay

An underlay is a very important membrane that acts as a secondary roof. It is installed under the primary roof structurer and above the insulation layer. It helps to protect the thermal insulation and building structure from precipitation, rain and condensation. [16.]

In this final year project, the underlay has a S_d value of 0,04 m. This membrane has low diffusion resistance. Thus, water vapour can penetrate it easily but liquid water cannot pass through it. [16.]

6.7 Laminated veneer lumber (LVL)

Laminated veneer lumber (LVL) is a high-strength engineered wooden product used for structural applications. It is manufactured by bonding together thin wooden chips with a type A adhesive under heat and pressure to get waterproof and solid bond. The thin wooden slices are usually 3 mm thick, dried and sorted by their properties before laminating. [17.]

LVL is durable and has less risk of shrinkage. It can be manufactured of any length. It can be used as rafters and joists, lintels, beams, framing structures, I-beams, portal frames and truss chords. [17.]

6.8 Plywood

Plywood is one of the most common material used as building material. It is a composite material made by gluing thin laminated veneer lumbers (LVL) or piles of softwood or hard wood. The grains of each layer are perpendicular to the adjacent layer. This increases the strength of plywood. [18.]

Plywood can be used in wall partitions, ceilings, formwork or external walls, as well as for flooring and furniture. It can be found in different thickness and sizes. The strength of plywood is the same as that of wood and its moisture and chemical resistance properties are better. [18.]

6.9 Soft wood

Softwood is widely used in building components. About 80% of timbers are softwood. It is used to make furniture, windows and doors as well. In this study, softwood is used as counter battens to forms a ventilation gap between underlay and roofing materials.

The thermal conductivity value and other characteristic value of soft wood is taken from WUFI 2D. Softwood like pine wood and spruce are commonly used as roof counter battens in Finland. [19.]

7 Methodology

The invention of modern software and technologies which can be used during the building design phase, has made building design, planning and construction a lot easier. There are many kinds of BIM software which give information about how the construction materials or certain building components react depending on the local environment and climate.

For the study of hygrothermal behaviour of the sarking roof in this final year project, a building simulation software called WUFI 2D is used. WUFI 2D gives the information about the heat and moisture flow conditions in the building components and helps to analyse the potential threats caused by moisture on building structures. It helps to analyse the mold risk also.

For the study of the moisture and heat flow through the sarking roof, a sample roof model was created in WUFI 2D and set for a certain time and then simulation was done. The simulation result showed the heat and moisture flow on different surfaces of the roof structure. The results obtained from WUFI 2D simulation were then compared with the Viitanen's mold growth results which are on page 10,11,12 and 13 of this project. The comparison analysis was done to study the risk of mold formation and structural decay caused due to moisture accumulation inside the roof structure. Such risks can be avoided by adopting precautions at the designing phase.

8 Boundary conditions

The sarking roof model and reference roof were simulated in WUFI 2D to study their hygrothermal performance. To perform the simulation in WUFI 2D, the boundary conditions were set according to the Finnish requirements. The thermal transmission coefficient (U) value of a sarking roof was set at 0.09 W/m^{2}K which is according to NBC C3. With U-value as 0.09 W/m^2 K, the thickness of main insulation material was calculated. The U-value calculation can be found in appendix. The surface heat transfer coefficient for an exterior surface where the heat flow is vertical up or down was used as 0.04m^{2}K/W

(NBC C4, page 24). Therefore, the heat transfer coefficient for an exterior surface is 25 $W/m^2 K$. Similarly, for an internal surface, it is 10 $W/m^2 K$.

The roof structures in the simulations were considered ideal and air tight. No construction damages and ventilation leakages were considered at any point of the study. The roof was assumed to be inclined at 18° and had well ventilated air gap. The spacing of the wooden rafters was 600mm center to center.

The analysis focuses on the condensation, frost problems, mold risks and structural decay problems which could occur due to the presence of excess moisture inside the roof structure. Since the weather data for the next five years are collected from WUFI 2D weather database, the climate change could change the weather in the future or the real humidity and temperature data could be slightly different from the WUFI 2D data. The climatic boundary conditions of the exterior and interior surface of the roof is shown in figure 9 below. The boundary conditions are similar in all roof models.

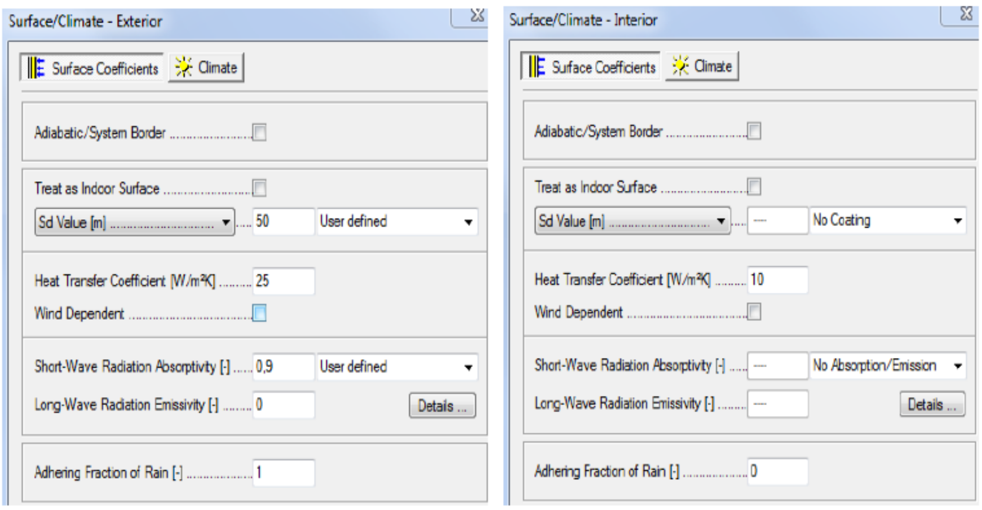


Figure 9. Exterior and interior surface boundary conditions

In figure 9 above, the picture on the left shows the boundary condition for the exterior surface and the picture on the right shows the boundary condition for the interior surface of the roof.

9 Simulation case study

In the final year project, there are six sarking roof models. They are divided into two groups as per the thickness of the sarking insulation. In each group, there are three roof models for testing three different kinds of board materials. The first group consists of a 30mm thick sarking insulation roof structure. It has three sub groups with three board types used. The second group includes a 50mm thick sarking insulation. It has also three sub groups.

The graph result obtained from the WUFI 2D simulation represents a whole year in which each column represents 12 months. Although the time for the simulation was five years, the third year is used to investigate the outcomes. This is because the WUFI 2D analysis showed a constant curve from the second year of simulation onwards. An example of a five year WUFI 2D simulation is shown in figure 10 below. The result is filtered to one year for a precise study of moisture and heat conditions over the whole year. As can be seen the RH curve is constant from the second year onwards. It was seen that using just one year from this result gives precise RH and temperature conditions.

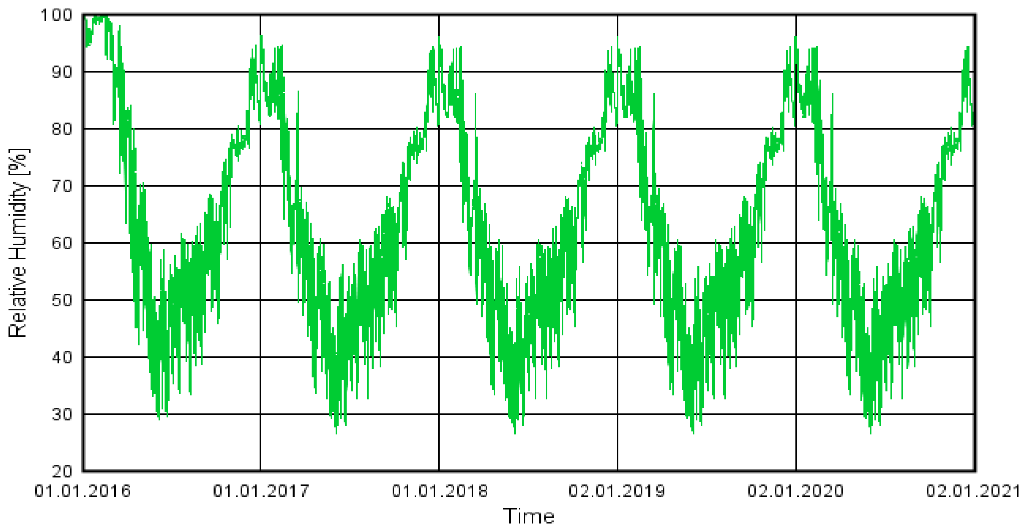


Figure 10. WUFI 2D simulation result for RH.

10 Reference roof model

The reference roof structure was provided by Isover. A case study had been done by Wahlfors on the reference roof model. According to Wahlfors, the reference roof model was considered to be suitable to be used in Finland. The reference roof is similar to the sarking roof but there is no sarking insulation and board material above the main insulation. The U-value calculation of the reference roof model is available in appendix 13.

Figure 11 below is the section view of the reference roof structure. The red points denote the critical points in the roof structure that are taken into consideration in this study. These critical points were chosen based on a discussion with Ari Karhunen, Isover Design Engineer and the thesis advisor and Kari Suvanto, my supervisor and Senior Lecturer. The same critical points were selected for the sarking model also. Those points were selected to study the moisture accumulation possibilities on the surface of those points and if that could lead to risks caused by excess of moisture on the materials.

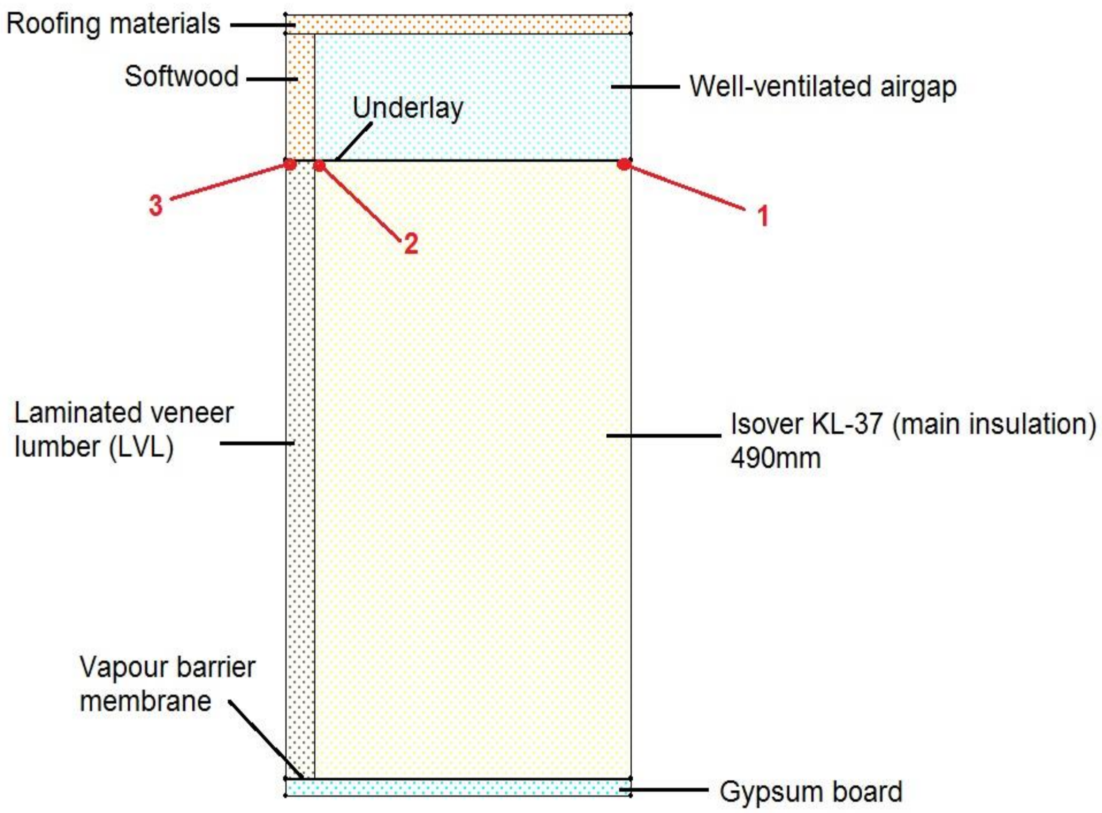


Figure 11. Reference roof model and the three critical points.

The materials used and their thickness for the reference roof model are listed in table 2 below. For the simulation case studies in this thesis, plywood and bitumen are used as roofing materials. Nevertheless, other roofing materials that are suitable for a pitched roof can replace them.

Table 2 Material data used on reference roof.

	Materials (From rooftop)	Thickness (mm)	Thermal conductivity W/mK
1	Plywood and Roofing materials (s_d= 50)	15	0.13
2	Underlay - weather resistant barrier (s_d= 0.04)	1	2.3
3	Counter battens -Soft wood	50*100	0.09
4	Air gap- Air layer 100mm without additional moisture capacity	100	0.59
5	Mineral wool - Isover KL-37	490	0.037
6	Laminated LVL Lumber	50*490	0.14
7	Vapor barrier- Isover Vario Xtra	1	2.3
8	Gypsum plaster board	13	0.25

The above materials and thickness of materials were provided by Saint Gobain Isover. The results of the WUFI 2D simulations were studied and analysed for the hygrothermal behaviour on the surfaces marked with the critical points indicated in figure 11. Also, the simulation results were compared with the mold growth conditions of Viitanen’s experiment to analyse the mold and decay risk inside the roof structure.

10.1 Critical point 1- Isover KL-37 insulation

The graphs below show the results of the moisture accumulation on the surface of the critical point 1, which is marked as 1 in figure 11. The graphs in figure 12 show the RH and temperature on the surface of the Isover KL-37 beneath the underlay.

According to the result obtained from the WUFI 2D, the RH is close to 100% during the winter because this surface comes directly in contact with the outside air. The condensation risk is higher in the winter. The RH is more than 90% for about 3 months but it is fluctuating to 80% at the same time. This shows there will not be any condensation risk.

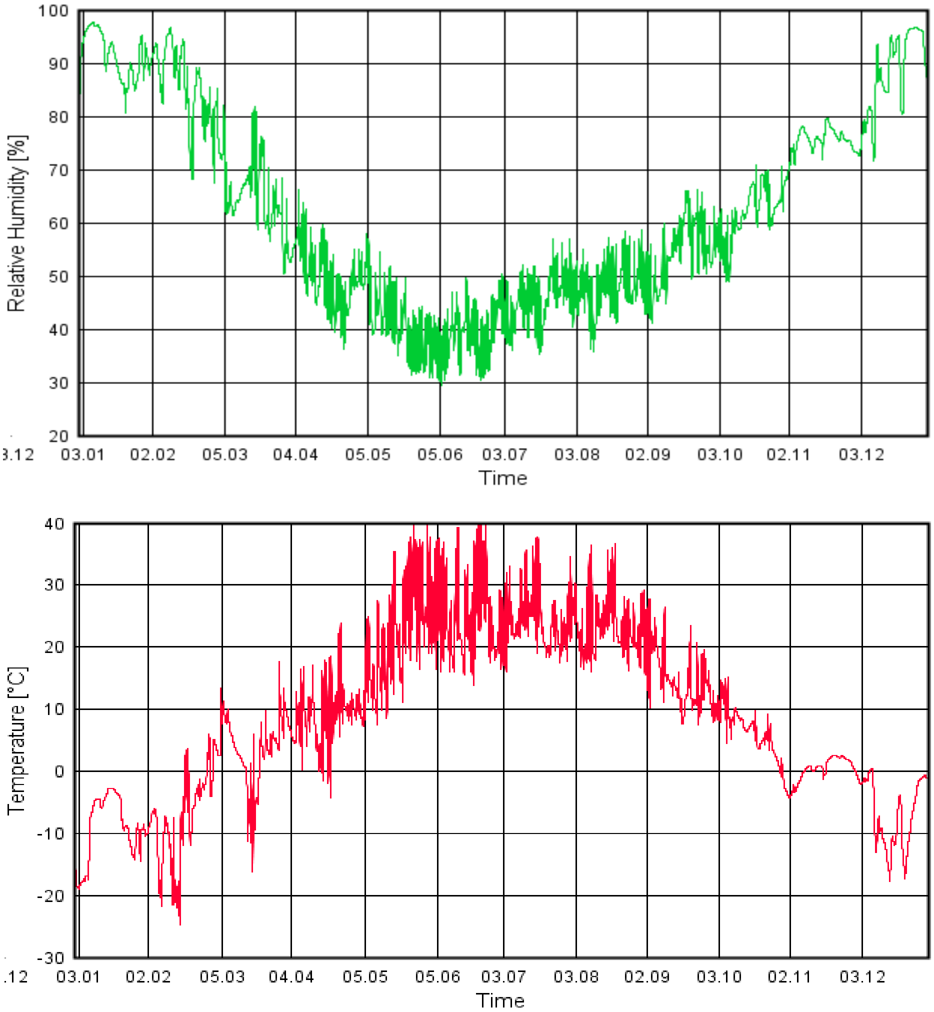


Figure 12. RH and Temperature at critical point 1 of reference model.

An observation of the RH and temperature values shows that there is no risk of infestation. As seen from the temperature graph, when the RH is above 80%, during December and January, the surface temperature is below 0°C, which is too cold for fungus growth. From the month of February, the temperature increases but at the same time the RH also decreases and remains below 75% for more than six months. When the surface temperature increases during spring, the RH is falling making the surface conditions too dry for mold growth. As the RH increases during autumn, the temperature falls to the freezing point, which stops mold development. Thus, there is no risk of mold formation and structural decay.

10.2 Critical point 2- Between LVL, main insulation and softwood

The graphs in figure 13 below display the RH at the corner surface point with laminated LVL, insulation layer and soft wood. It is marked as the critical point 2 in the reference model in figure 11.

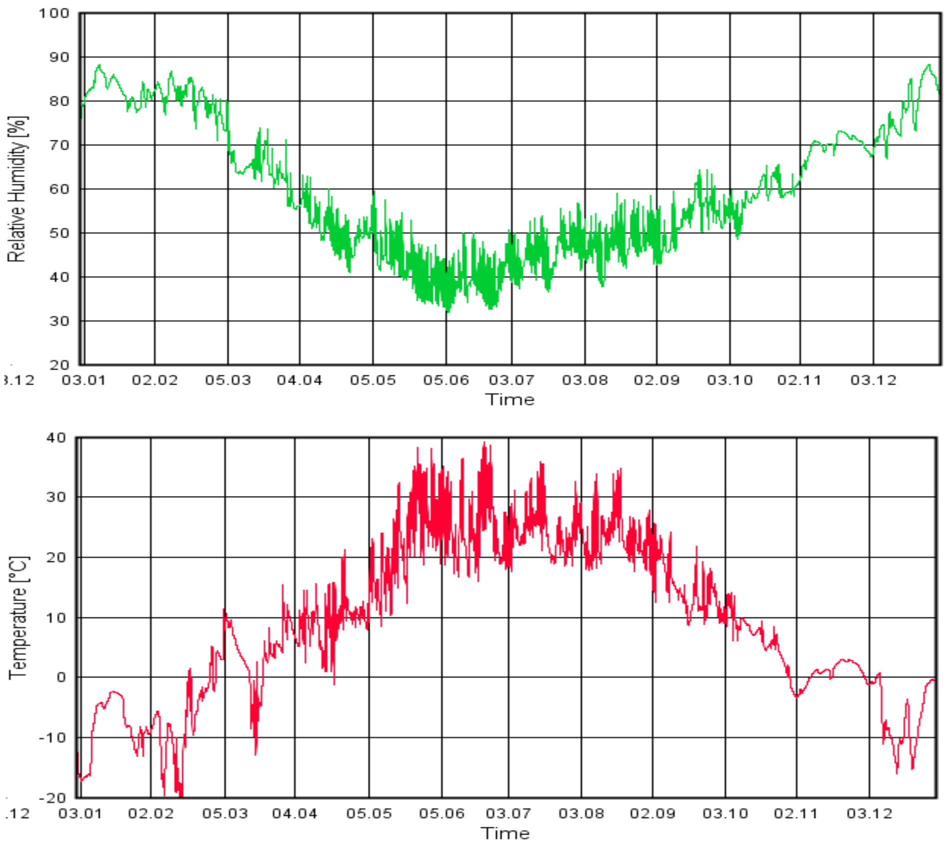


Figure 13. RH outcome at critical point 2.

The RH at the critical point 2 is below 90% during winter. It shows that there is no risk of water formation and structural decay at this point. When the temperature is below 0°C, there cannot be decay problem.

The temperature graph is almost identical to the one for the previous surface in figure 13. The humidity is above 80% from December to February but the temperature remains below zero. There cannot be mold formation on such cold surfaces. The temperature is slightly above 5°C at the end of February but the humidity is decreasing at that time, and it drops below 70% making the surface dry. Thus, there is no mold risk or structural decay problem.

10.3 Critical point 3 – Between LVL and softwood

Figure 14 below shows the humidity conditions at the critical point 3. The critical point is marked in figure 11 as 3. The temperature outline is not included at this point because the RH is below 70% for almost the whole year which shows that the surface has dry conditions.

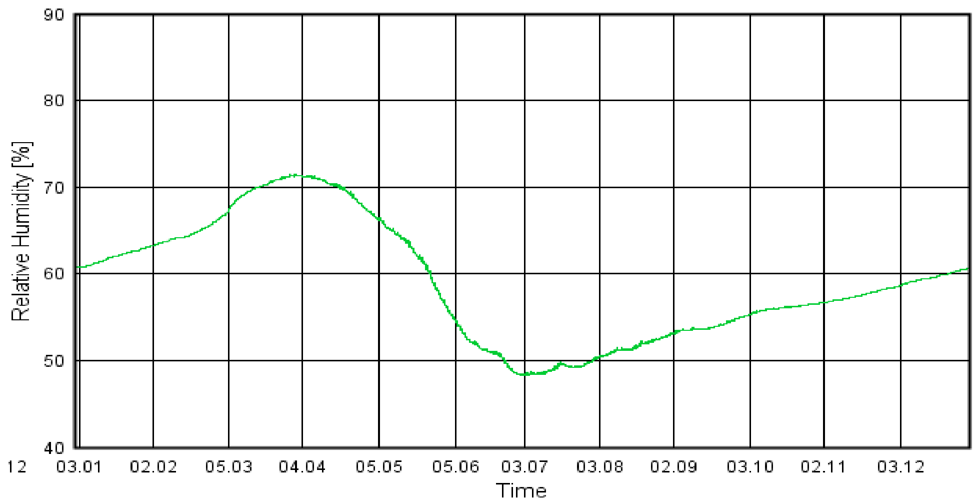


Figure 14. RH between LVL and Softwood at critical point 3.

The humidity conditions on this surface shows that there is no problem of mold formation and structural decay due to the moisture accumulation. When the RH is below 70%, fungus cannot get enough nutrients to expand even if the temperature remains favourable.

The temperature graph of this surface is not included because at the RH level below 70%, there will not be any mold and decay problems. Thus, there will be no problem of mold and structural decay in such dry conditions.

The further simulation studies and analysis were conducted on the sarking roofs. The sarking roofs are similar to the reference roof but slightly modified with the addition of sarking insulation above the main insulation material. A wooden board is used between the insulation and the sarking insulation which could give support for the insulation installer. The strength of the board material is not studied in this final year project. However, a different study of the strength of the board material for the worker's safety can be done in future.

11 Sarking roof models with 30mm sarking insulation

The sarking roof models in this study are mainly divided into two simulation cases according to the thickness of the sarking insulation. In the first group, there are 3 sarking roof models with 30 mm thick sarking insulation and 400mm thick main insulation. The main insulation layer and sarking insulation are separated by three types of wooden boards in each model. The technical data of the materials were gathered from the material manufacturers' websites and WUFI 2D. The U-value calculation of the sarking roof model is available in appendix 14.

The case studies intend to investigate the moisture conditions, when a board material is added between the main insulation and sarking insulation. The board has a higher water vapour resistance factor, which could prevent moisture flow out of the structure. That is why the critical points were chosen around the board material. The critical points are shown in figure 15. The results of the simulation on the critical points are interpreted in this final year project.

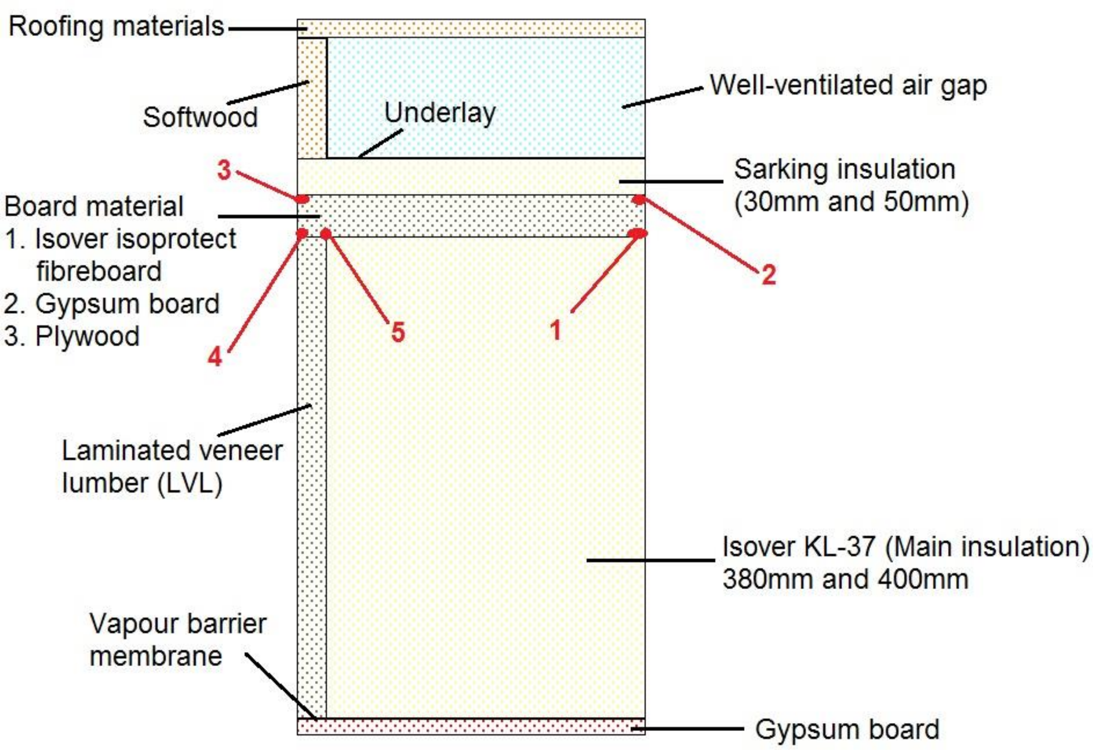


Figure 15. Sarking Roof model with the five critical points.

The materials used, their dimensions and thermal conductivity for this group are shown in table 3 below. For the final year project, plywood and bitumen are used as roofing materials. Nevertheless, other roofing materials suitable for a pitched roof can replace them.

Table 3 Material data for sarking roof model

	Materials (From rooftop)	Thickness (mm)	Thermal conductivity W/mK
1	Plywood and roofing materials (s_d= 50)	15	0.13
2	Underlay - weather resistant barrier (s_d= 0.04)	1	2.3
3	Counter battens -Soft wood	50*100	0.09
4	Air gap- Air layer 100mm without additional moisture capacity	100	0.59
5	Sarking insulation	30	0,037
6	Board A. Isoprotect Fibreboard B. Gyproc gypsum Board C. Plywood	 35 13 15	 0.044 0.25 0.13
7	Mineral wool - Isover KL-37	400	0.037
8	Laminated LVL Lumber	50*400	0.14
9	Vapor barrier- Isover Vario Xtra	1	2.3
10	Gyproc Gypsum board	13	0.25

The results of the simulation cases are studied and analysed for the hygrothermal performance on the surfaces marked with the critical points indicated in figure 15. The simulation shows the humidity and temperature conditions of the surfaces at the critical points. The simulation results are then analysed by comparing with the Viitanen's mold growth experiment in figure 6-8 on page 10 - 13.

12 Simulation case 1 - Sarking roof with 30mm sarking and Isoprotect

The first simulation case study of sarking roof model consist of a structure with 30mm thick sarking insulation. It is installed above board as seen in figure 15. Between the insulation materials, there is a 35mm thick Isover Isoprotect fibreboard. The WUFI 2D simulation results are analyzed below.

12.1 Critical point 1- Between Isover KL 37 insulation – Isoprotect fibreboard

The graphs in figure 16 below represent the RH and temperature on the surface between the Isover KL 37 and Isoprotect fibreboard. It is tagged as critical point 1 in figure 15. The RH reaches its highest level just above 70% in the winter. The lowest humidity condition for mold growth is above 80 % if the temperature and exposure period are suitable for fungus survival, as shown in the figure 7 on page 12.

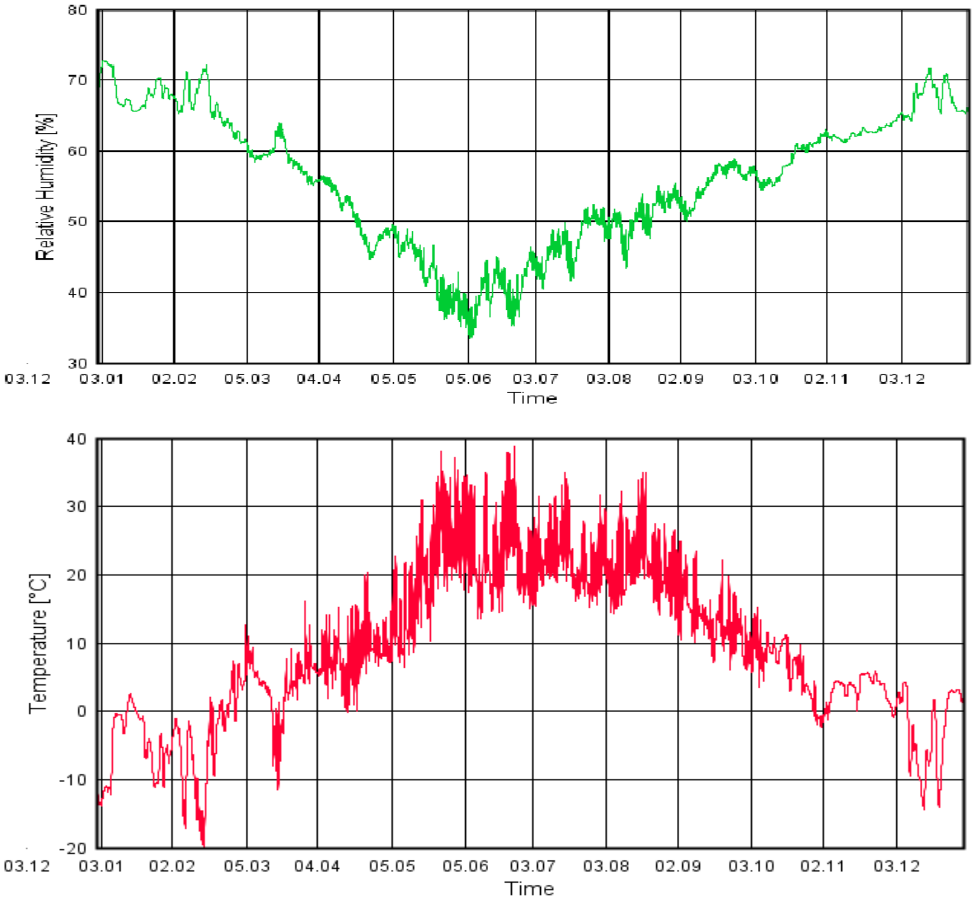


Figure 16 RH and Temperature readings on critical point 1.

According to the green graph on figure 16, which represents the RH level on the surface of the critical point 1, the surface remains dry throughout the year. The surface is free from structural decay because the RH level is very low for the surface to decay. When the RH level of this simulation case is compared with the RH level of material decay graph of figure 8 on the page 13, the RH level is not enough for structural decay

According to figure 7 on the page 12, the critical RH for mold formation should be above 80%. Since the RH at the critical point 1 in the simulation is below 70% for most of the year, there is no excess moisture to allow mold formation and decay development.

12.2 Critical point 2 - Between Isoprotect board and sarking insulation

The graphs in figure 17 below represent the RH and temperature level throughout a year at the critical point 2. It is marked as point 2 in figure 15. The critical point 2 is the surface between Isoprotect fibreboard and sarking insulation. The green graph below represents the RH condition at the critical point 2. The RH is above 70% for about three months from the month of December to February but stayed under 80% throughout the year. It could be considered critical conditions if the RH were stable above 75%. However, the RH fluctuates and never crossed 80%.

Furthermore, the temperature during December to February is around the freezing point which does not support fungus growth. Although the temperature rises to over 5°C at the end of February while the RH is above 70%, the surface conditions are still considered to be dry because the RH is still below 80%, as seen in figure 6-7 on page 11-12.

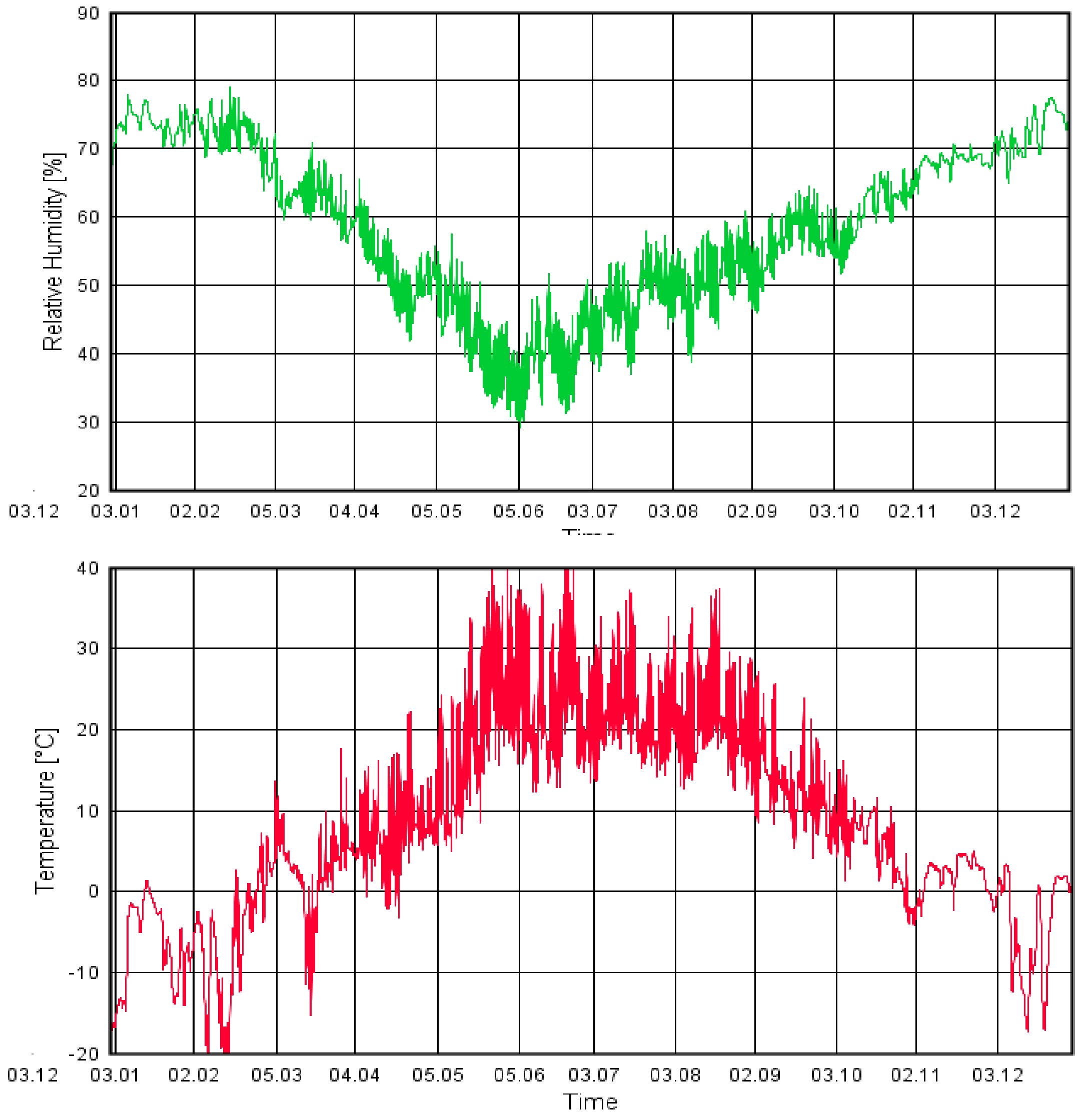


Figure 17. RH and Temperature readings on critical point 2 surface.

Although the temperature is more than 1°C in some cases when the RH is above 70% the humidity is not enough for mold formation at that temperature. Furthermore, the duration was only some days which is another hindrance for fungus germination. It can be said that this surface is invulnerable to any damage caused by moisture.

12.3 Critical point 3 – Between sarking insulation and Isoprotect board

The graph in figure 18 below shows the humidity conditions throughout the year on the surface of the critical point 3. The temperature outline is not included at the critical point 3 because the RH is below 70% for almost the whole year which indicates a dry surface at the critical point 3. Therefore, fungus cannot get nutrients to expand even if the temperature remains favourable.

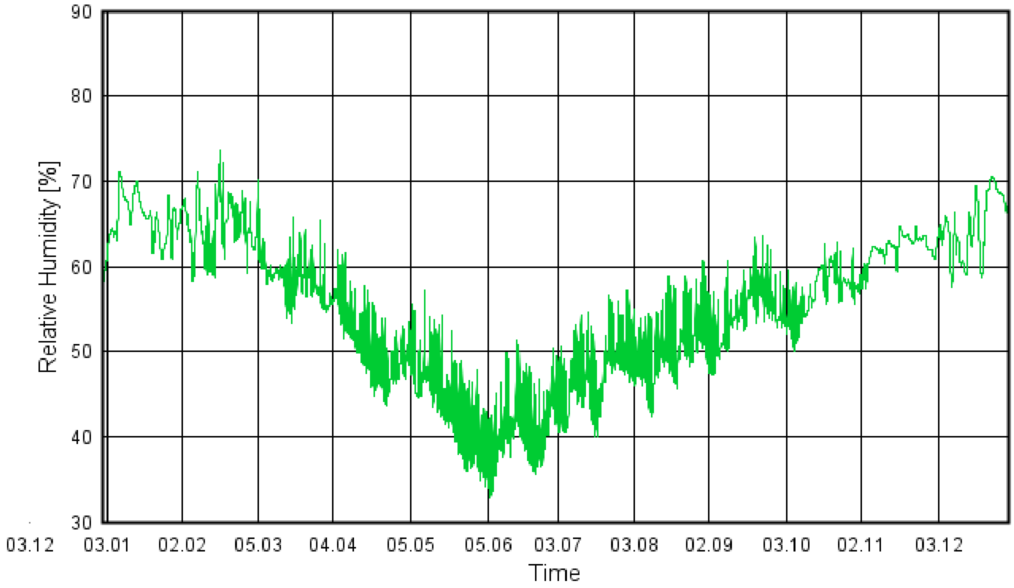


Figure 18. RH at critical point 3.

The critical point 3 is on the same level as the critical point 2 but the critical point 3 has less humidity percentage. The LVL material below the sarking insulation plays an important role on reducing the humidity percentage of the critical point 3. The LVL has higher heat transmittance than the insulation material which is why the heat escapes quickly through LVL but heat flows slowly through the insulation material. The heat escaping through the LVL reaches the surface of the critical point 3 faster than through the insulation material making the Isoprotect fibreboard surface warmer at the critical point 3. Thus, this increase in temperature at the critical point 3 helps to reduce the RH level on the critical point 3.

12.4 Critical point 4 - Between Isoprotect board and LVL

The graph in figure 19 below represents the RH conditions achieved from the simulation at the critical point 4. This critical point is the surface layer between the fibreboard and LVL. If the humidity is 60%, the mold growth stops as seen from figure 7 on page 12. Thus, the green graph below shows that there is no moisture related problem as the RH is below 60% for all the time.

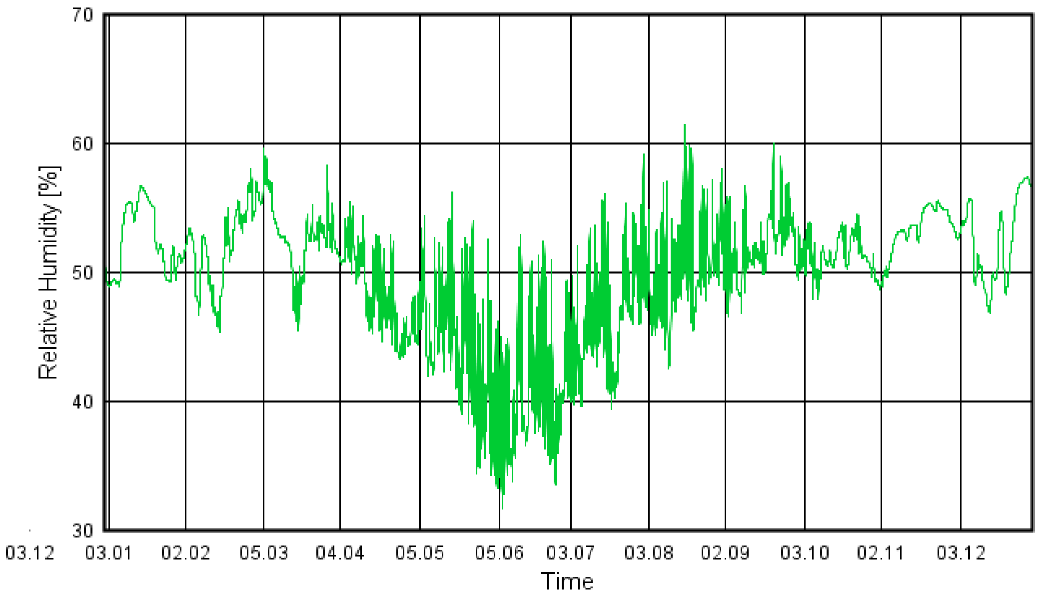


Figure 19. RH on surface critical point 4.

The temperature graph of the critical point 4 is not included because the RH is below 60% throughout the year which is safe for mold and decay risk. The critical point 4 is on the surface of LVL. The heat transmittance is faster in LVL because of it has high thermal conductivity. When the heat escapes from inside to outwards through the LVL, the heat transmittance is fast which has higher temperature when it reaches the critical point 4. This higher temperature results in lower RH at that surface even if the moisture content is same. Therefore, the critical point 4 has lower humidity level which is unfavourable for mold formation.

12.5 Critical point 5 - Between LVL, Isover KL 37 and Isoprotect board Corner

Figure 20 below shows the humidity conditions at the critical point 5. The RH in the surface layer is below 60% throughout the year. As mentioned earlier, the ideal RH for mold germination is above 75%. When comparing the below simulation result and mold formation conditions in figure 6-8 on page 11-13, it can be concluded that the surface is protected from being moist and the material will be safe from rot and blight.

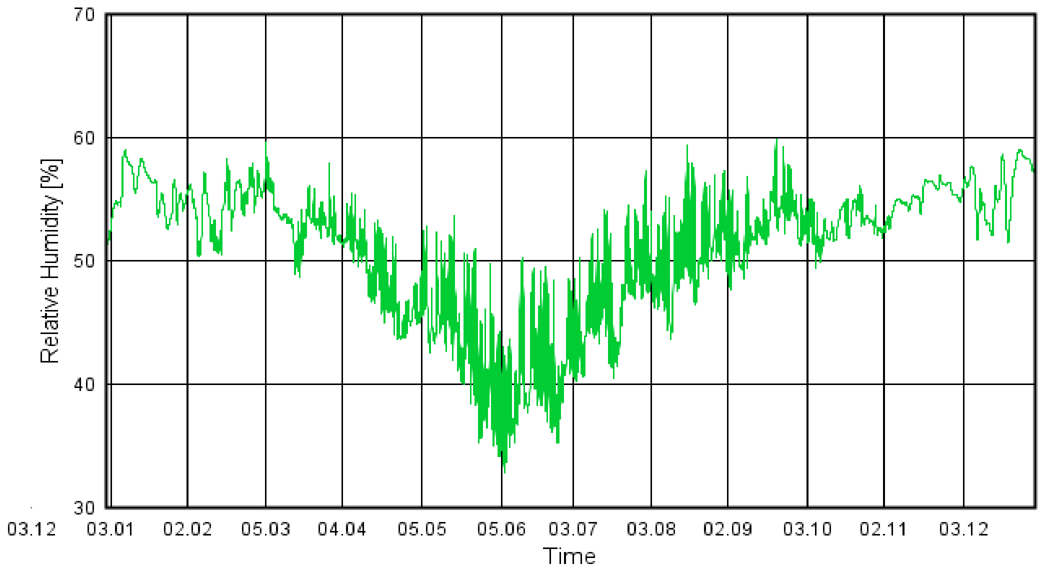


Figure 20. RH on surface critical point 5.

The critical point 5 is at the corner between the LVL, Isover KL 37 insulation and Isoprotect board. The heat transmittance is faster in LVL than in insulation material. As mentioned in the critical point 4, the heat which escapes outward through the LVL helps to increase the temperature on the surface of the critical point 5. Therefore, the critical point 5 has the lower humidity in comparison to the critical point 1 which is on same level (see figure 15 on page 27).

In the next Simulation case study, the Isoprotect board is replaced by a gypsum board. The results of this first simulation case study showed that the surface with RH below 70% is safe from moisture damage. A lower RH for longer time will result in a decline in the mold index [8, 7].

13 Simulation case 2 - Sarking roof with 30mm sarking and gypsum board

The second roof model is similar to the previous sarking model apart from the board used between the insulation layers. In this model, Gyproc GN 13 board is used. The aim of this study is to explore if there are any differences in the moisture and heat flow when a different board material is used. Gypsum has higher thermal conductivity and water diffusion resistance factor than the Isoprotect fibreboard. This could block the moisture passing through the board resulting in moisture accumulation on the board surface.

Simulation case 1 showed that the critical points 4 and 5 had RH below 70%. When the RH is below 70%, there is no risk of water condensation, mold formation or structural decay. Therefore, only the outcomes that have RH above 70% are shown and analyzed in the upcoming Simulation case studies.

The critical points which have RH lower than 70% are not analysed in detail because they are safe from mold or structural decay. However, the graph of those critical points can be found in the appendices.

13.1 Critical point 1 - Between gypsum board and Isover KL-37 insulation

The graph in figure 21 below shows the RH conditions on the surface at the critical point 1. It is tagged as point 1 in figure 15.

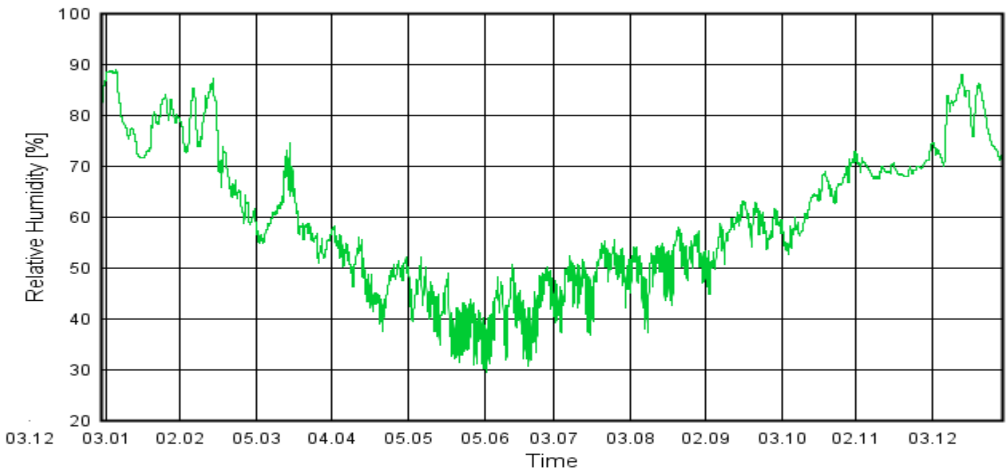


Figure 21. RH on surface critical point 1.

As illustrated on the graph above, the RH fluctuates between 30 and 90% throughout the year. It reaches near to 90% during the winter. The RH should be above 90% for building material to decay. There will be no decay development as the RH is below 90%. Furthermore, the temperature is around zero which is not favorable for decay as well.

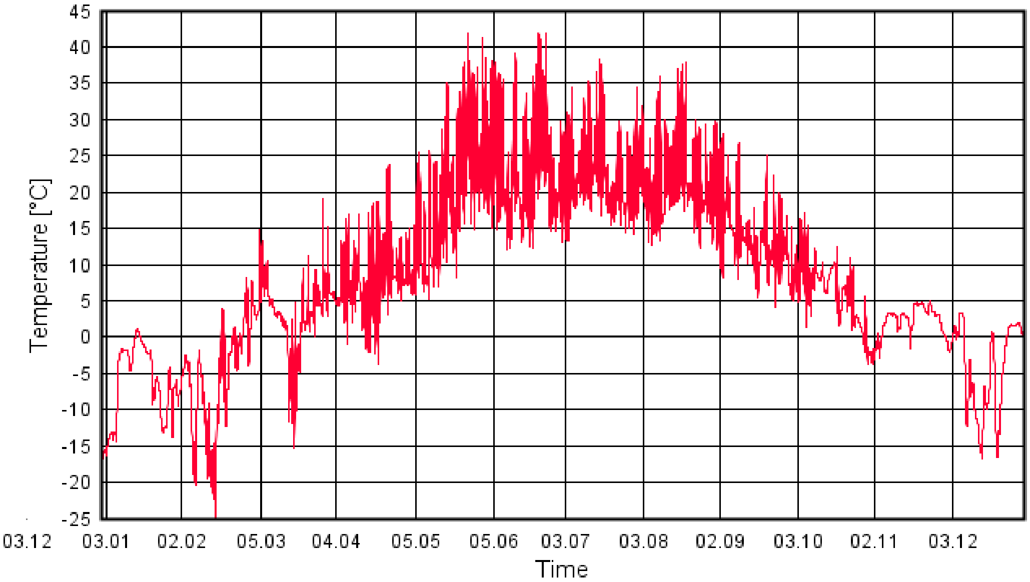


Figure 22. Temperature on surface critical point 1.

The second graph in figure 22 represents the temperature of the same surface. The temperature is around 0°C when the RH is above 75%. At this temperature, even if the RH is above the critical percentage, fungus germination is not possible due to cold temperature. When the temperature is favourable for mold, the surface is dry due to a decrease in the RH. The RH remains below 70% for more than six months. It is as low as 30% during warm days. This shows that the surface becomes too dry and is unharmed from infestation.

13.2 Critical point 2 - Between gypsum board and sarking insulation

The graph below shows the RH on the surface layer between the gypsum board and sarking insulation at critical point 2 in figure 15 on page 24. The RH in figure 23 below is fluctuating from above 80% to around 70% in the same month. Even in the highest RH percentage, there is no material decay problem because the RH is still not above 90%, which is minimum condition for structural damage.

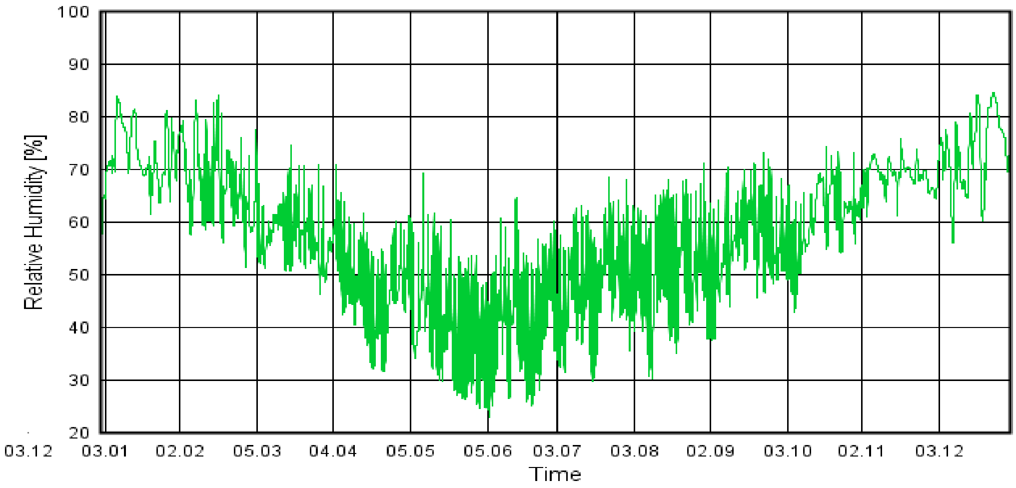


Figure 23. RH at critical point 2.

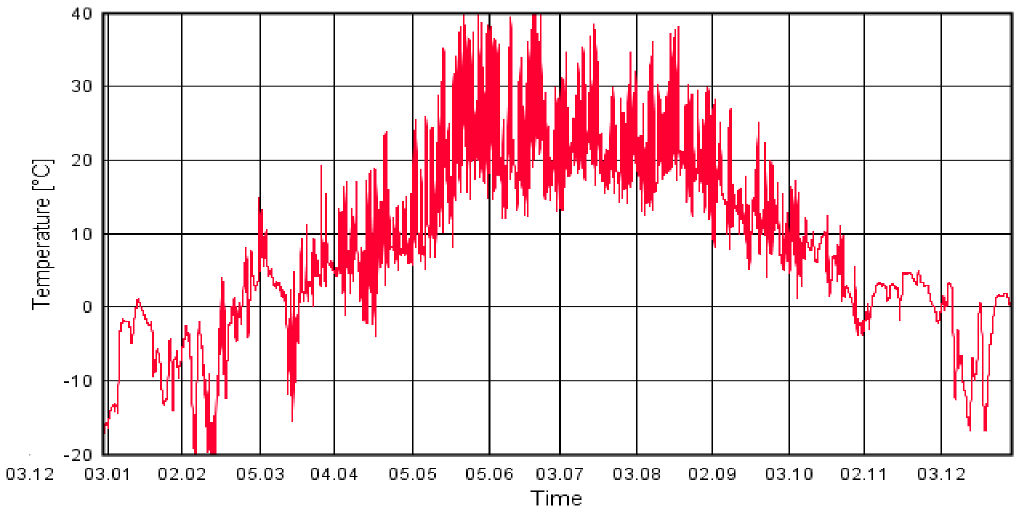


Figure 24. Temperature at critical point 2.

Although the RH in some time is above 80% which is deemed as appropriate condition for the fungus formation, the temperature is around freezing point during the same periods. Furthermore, the exposure period is also very short. As seen in figure 6 on page 11, the fastest mold formation, when RH is above 80% is 15 weeks but the temperature should be 20°C. In this case, the temperature is usually around freezing point. That means it is too cold for fungus development. Moreover, if the RH drops to around 70%

which is dry conditions, the mold development stops [8, 7]. Therefore, there is no any mold risk.

13.3 Critical point 3 - Between Sarking insulation and gypsum board

Figure 25 below shows humudity conditions on the critical point 3 on the same surface as the critical point 2 between the sarking insulation and gypsum board, but in different location. The point can be seen in figure 15 on page 27.

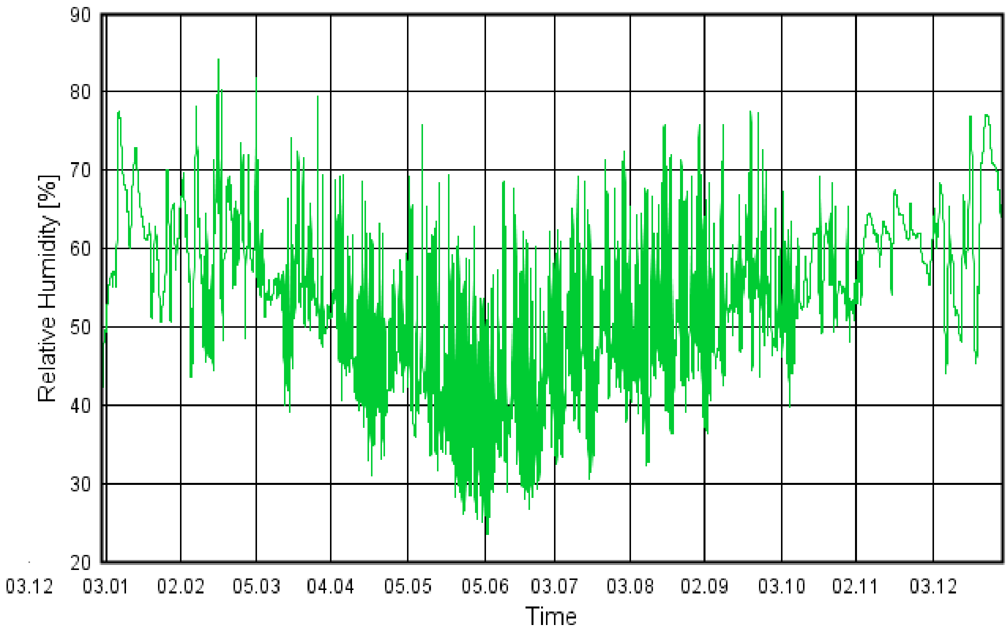


Figure 25. RH at critical point 3.

The RH at the critical point 2 reaches above 80% during the winter, but the RH is below 80% during the same time on the surface of the critical point 3. The RH level in the critical point 3 fluctuates from 75% to below 60%. The RH level reaches above 80% during February but does not stay long. When compared the above graph with the figure 8 on page 13, there is no risk of decay development because the RH level should be above 90% for decay to develop in a material.

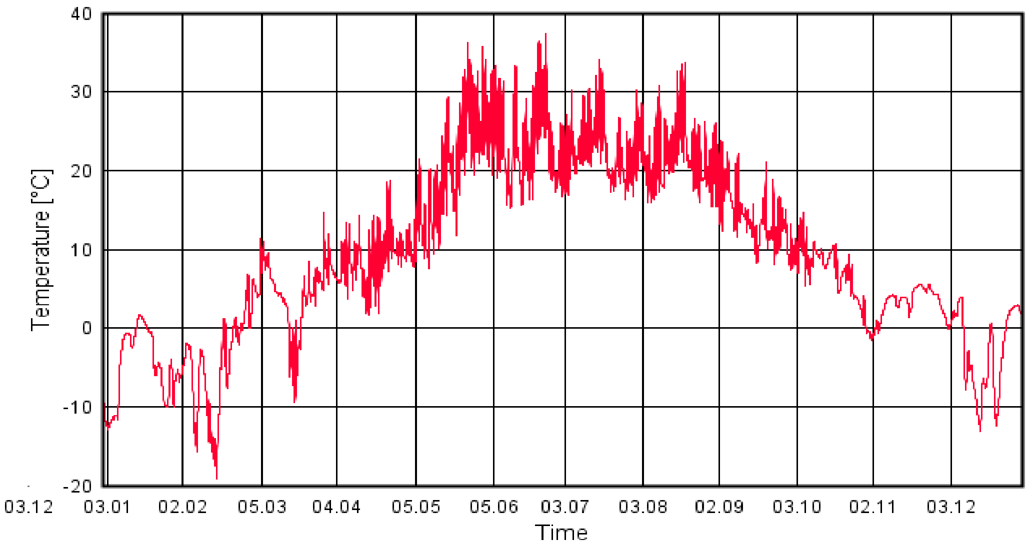


Figure 26. RH and temperature at critical point 3.

The graph on figure 26 is the temperature graph at the critical point 3. The average RH is about 70% for the whole year. It goes above 75% sometime, but drops instantly. For mold development, the humidity should remain above 80% so that surface could get damp. The dampness should then remain for a long time to lead to mold germination. When the RH falls, the surface gets time to dry out.

According to the simulation results presented above, the humidity is above 80% once during February, but the RH does not remain at that level and falls below 70% instantly. The fluctuation of the RH does not give time for mold to be active. The RH remains below 70% for more than a week which allows surface to dry and decrease the mold index rather than increasing it (as can be seen in mold index at table 1 on page 9). Thus, the critical point 3 is free from fungus development.

The analysis and simulation graphs of the critical points 4 and 5 are discussed above because the RH remained below 70% on those surfaces. Therefore, they are not critical to mold and decay risk. The graphs of simulation on the critical points 4 and 5 can be found in appendices 1 and 2.

14 Simulation case 3 - Sarking roof with 30mm sarking and plywood

The simulation case 3 has sarking roof model with plywood board used instead of fibre-board and gypsum board. The objective of changing the board is to see the effect on the moisture performance of various boards. The analysis of the findings at the critical points marked in figure 15 are presented below.

14.1 Critical point 1 - Between Isover KL 37 insulation and plywood

The graph below in figure 27 shows the RH is the surface between the main insulation material and plywood at the critical point 1 in figure 15 on page 27. The RH is above 75% from December to February as seen in the green graph. It is below 90%, so there is no liquid formation problem, which could lead to structural decay.

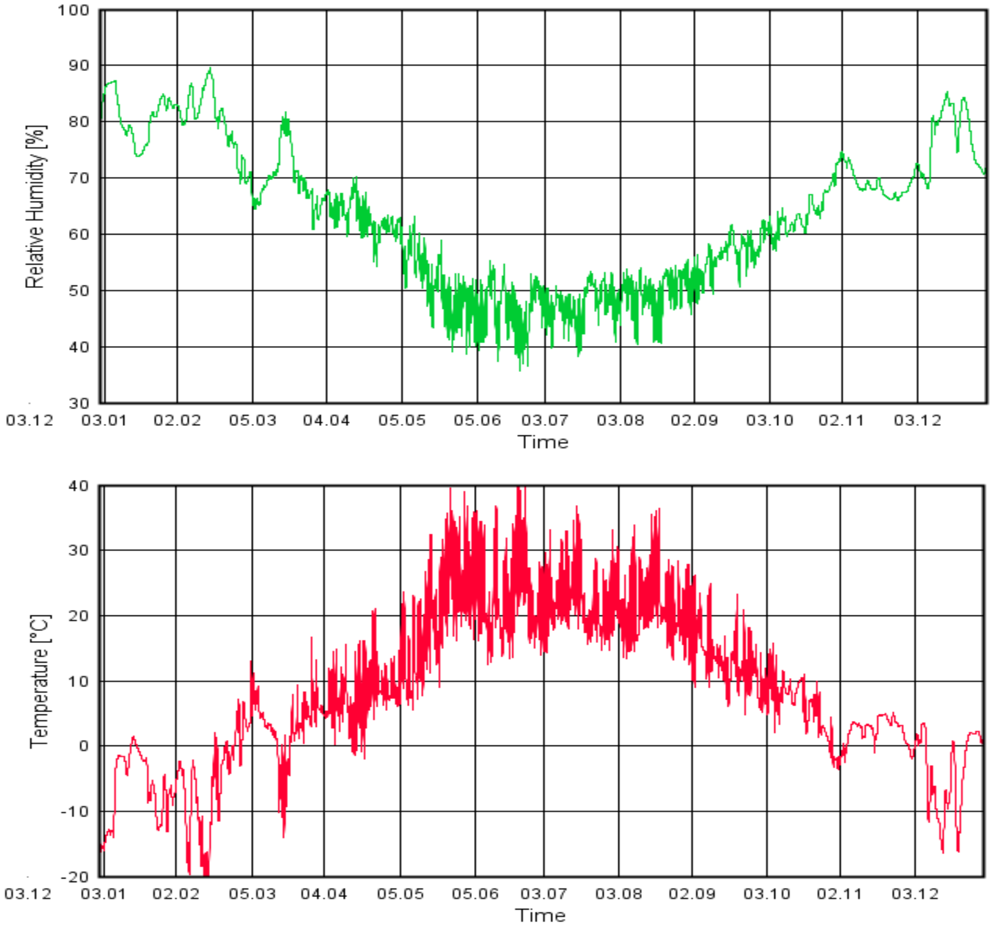


Figure 27. RH and temperature at critical point 1.

The red graph in figure 27 shows the temperature on the same surface. The temperature is around 0°C whenever the RH is more than 80%. At this temperature, the fungus activity is null due to the cold temperature. There are some rare occurrences when the RH is above 80% and the temperature above 0°C. This could be risky, but the RH falls in few days. This time duration is not long enough for mold progression. When the temperature is suitable for mold, the RH is lower than 70% for more than half a year. This dry conditions prevent the mold formation on the critical point 1.

14.2 Critical point 2 - Between plywood and sarking insulation

The graph in figure 28 below shows the RH on the top surface of plywood in contact with the sarking insulation. This surface is marked as critical point 2 in figure 15.

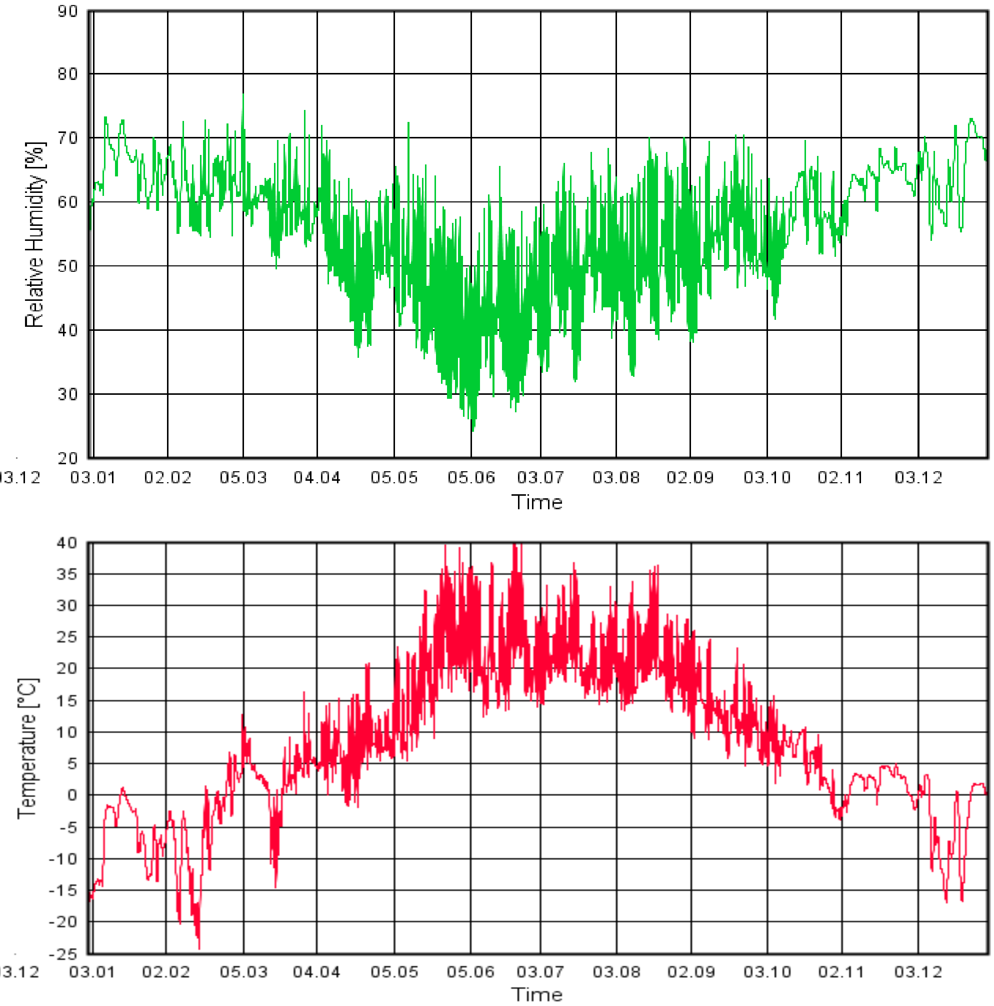


Figure 28. RH and temperature on surface at critical point 2.

The surface at this critical point is also free from structural decay risk. When the simulation graphs are compared with mold conditions in figure 6-8 on page 11-13, the surface is too dry for fungus formation. The time when the humidity is above 70% is shorter than the time when the humidity remains below 70%. It allows the surface to dry and prevent risks caused by moisture.

14.3 Critical point 3 – Between sarking insulation and plywood above LVL

The outline in figure 29 below shows that the RH on the surface of the critical point 3 is below the critical level for mold formation. The critical point is marked as 3 in figure 15 on page 27. The RH is above 70% sometime, but does not remain for a long time and falls below 70%. The RH level remains below 70% for a longer time. This longer time of lower humidity helps the surface to dry out. In such conditions when the RH is below 70% throughout the year, the surface at the critical point 3 becomes too dry for mold formation. Thus, can be concluded that the surface at the critical point 3 is safe from mold and decay because of its dry conditions, which do not provide sufficient nutrients for mold to expand.

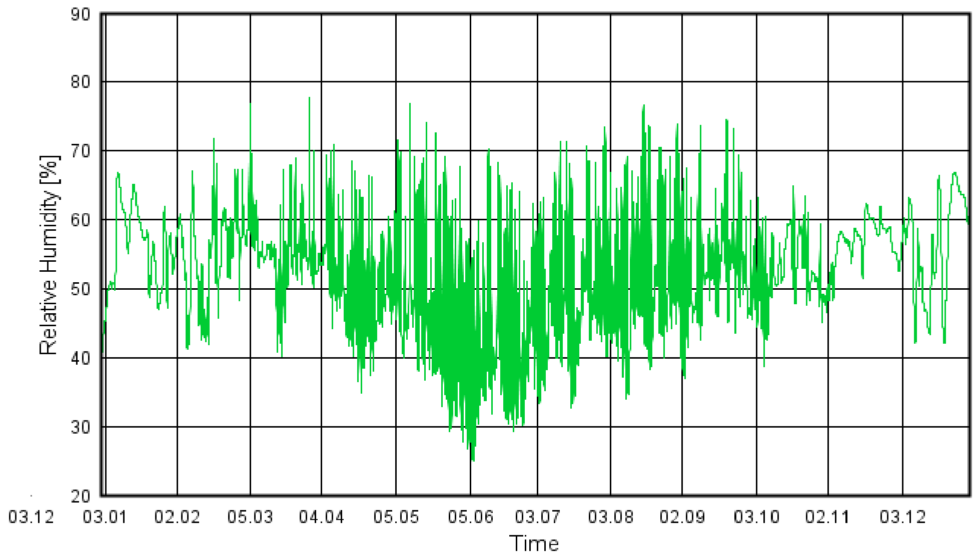


Figure 29. RH at critical point 3.

The temperature graph of the critical point 3 obtained from the simulation is not included because the RH is below 70% for almost the whole year. Therefore, it is not necessary to compare the temperature with the humidity for mold risk.

The RH of the surface at critical points 4 and 5 is below 70% most of the year. Sometimes it rises above 70% for a week during winter. However, the temperature at the time is sub-zero. Fungus development is not possible in such conditions because of cold. Since critical points 4 and 5 were not problematic, the simulation results were not discussed in the analysis below but can be found in appendices 3 and 4.

15 Discussion of sarking model with 30mm sarking insulation

The effect of heat and moisture flow in a roof structure is an important issue to be investigated. A moisture damage cannot be seen in its initial stage but when the damage is visible, it will have caused a lot of structural damage and the repair will be expensive.

In the reference roof model, there are chances of condensation due to the high RH but mold formation is not possible because the surface is cold when the RH is above 80%. During other times of the year, the RH is below 70% for more than 6 months, which allows the surface to dry. Although there is no mold or decay risk in the reference model, the thermal properties of the roof are not efficient. The risk of heat escaping through the roof is higher than it would be in sarking roof. The thermal bridge through the wooden rafter may be another problem.

The sarking roof model simulations showed that the moisture condition inside the roof materials depends upon the type of board materials used and their thermal transmittance values. For instance, if the board used between the insulation layer and sarking layer has low thermal conductivity, the RH is relatively low.

In addition, the RH level is low along the surfaces which are located above materials with a high thermal transmittance value. For instance, the RH is higher at the critical point 2 than in the critical point 3 (see figure 15) because of the high thermal transmittance value of LVL. The heat escapes faster through LVL than through insulation. This transmitted heat increases the temperature of the surface at critical point 3, but at critical point 2, due to the lower thermal conductivity of the insulation, the heat transmittance is slow and when the air reaches at the critical point 2, it might not be as warm as at critical point 3. Thus, the RH is higher at the critical point 2 than at critical point 3.

The analysis of the critical points in all simulation cases showed that critical points 1 and 2 in the sarking models are more critical than the other critical points in term of risks caused by moisture accumulation. The reason for high moisture accumulation at the critical points 1 and 2 are the low diffusion resistance of mineral wool. The moisture passes through wool easily but when it reaches the critical point 1, the board material with higher diffusion resistance resist the passage of vapour through it. This initiates the increase in moisture accumulation at this critical point.

There is no risk of the roofing material being decayed due to moisture in any of the sarking roof models. There are some simulation cases where RH is higher than 80% which could encourage mold formation. However, the RH instantly falls thus allowing the surface to dry. In many simulation cases, the RH are below risk levels.

Comparing the surface at critical point 1 in the reference model and sarking models, the humidity is higher in the reference model above 90%. However, the RH is below 90% at the same Critical Point when a sarking insulation is used. This shows the impact of sarking insulation on the roof.

There are no conditions that helps fungi formation. Although the critical RH is above 75% for about 3 months on some surfaces, the temperature during that time is around freezing point and the RH also fluctuates. When the temperature is at zero, mold development is not possible. Similarly, higher humidity does not mean risk of mold because mold needs water, oxygen, time and a favorable temperature for expansion. A lack of enough exposure time and suitable temperature even if the humidity is above 80% are the situation in most of the simulation cases, making mold expansion difficult.

The following simulation cases are done with a similar sarking model but the thickness of insulation material and sarking insulation are changed.

16 Sarking roof models with 50mm sarking insulation

In this group, there are three sarking roof models. The thickness of the sarking insulation is increased to 50 mm while the thickness of the main insulation is decreased to 380mm. However, the U-value remains at 0.09 $W/m^2 K$. The materials and boundary conditions are similar to those of the previous simulation cases. The purpose of the simulation is to determine if the moisture behavior changes at all with the change in the thickness of the sarking insulation. The U-value calculation for the sarking roof models are available in appendix 15.

The critical points on surface studied are similar to previous simulation cases as shown in figure 15. The previous simulation case studies of the sarking roof models with the 30mm sarking insulations showed that the RH is higher at critical point 2 than in critical point 3 in all simulations. Therefore, critical point 3 is not discussed in detail, but the RH and temperature results can be found in the appendices. Likewise, the surfaces with the RH below 70%, are not included in the analysis below because they are safe from any moisture damage. However, their outcomes are attached in the appendices.

The materials used, their thickness and thermal conductivity are shown in table 4 below. For the simulation studies in this thesis, plywood and bitumen are used as roofing materials. Nevertheless, they can be replaced by other roofing materials, which are suitable for pitched roofs.

Table 4 Material data for sarking roof with 50 mm sarking insulation.

	Materials (From rooftop)	Thickness (mm)	Thermal conductivity W/mK
1	Plywood and roofing materials (s_d= 50)	15	0.13
2	Underlay - weather resistant barrier (s_d= 0.04)	1	2.3
3	Counter battens -Soft wood	100*50	0.09
4	Air gap- Air layer 100mm without additional moisture capacity	100	0.59
5	Sarking insulation	50	0,037
6	Board A. Isoprotect Fibreboard B. Gyproc gypsum Board C. Plywood	 35 13 15	 0.044 0.25 0.13
7	Mineral wool - Isover KL-37	380	0.037
8	Laminated LVL Lumber	380*50	0.13
9	Vapor barrier- Isover Vario Xtra	1	2.3
10	Gyproc Gypsum board	13	0.25

The results of the simulation are studied and analysed for the hygrothermal performance on the surfaces marked with critical points indicated in figure 15. The simulation shows the humidity and temperature condition of the surface at the critical points and the mold risk is analysed by comparing the simulation outcomes with Viitanen's mold growth experiment from figure 5-9 on page 11-13.

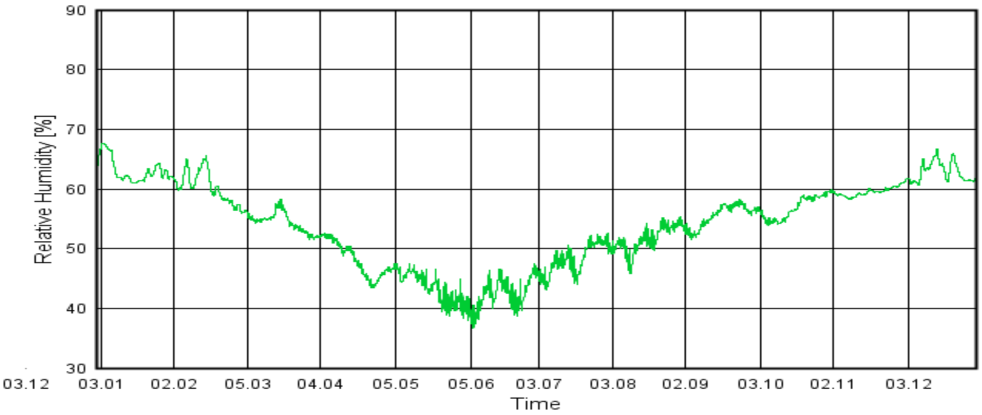
17 Simulation case 4 - Sarking roof with 50mm sarking and Isoprotect board

The sarking roof model in this simulation case has similar materials to previous sarking models. However, the sarking insulation is increased to 50mm while the main insulation is decreased to 380mm. Between the insulation materials, there is a 35mm thick Isoprotect fibreboard. The WUFI 2D simulation resulted in graphs are analysed below.

The goal is to investigate if the difference in thickness of the sarking insulation can have any effect in moisture accumulation on the critical points of figure 15 on page 27.

17.1 Critical point 1 – Between Isover KL-37 - Isoprotect board

Figure 30 below outlines the outcomes on critical point 1 when Isoprotect board is used between the insulation layers. The RH and temperature at critical point 1 seems to be almost similar to the Simulation case 1 (on page 29) at the same surface but RH is lower in this model. It is because of the increase in the thickness of the sarking insulation and the decrease in the thickness of the main insulation.



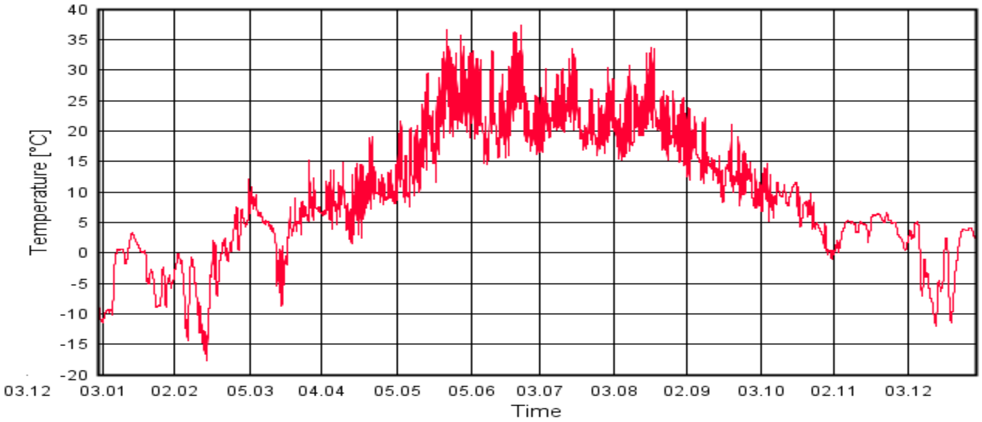


Figure 30. RH and temperature at critical point 1.

The heat flowing outward reaches the surface on the critical point 1 faster because of the decrease in the thickness of the main insulation. Also, the increase in the thickness of the sarking insulation increases the thermal condition of the saking insulation’s inner surface. Because of this the RH is lower than in simulation case 1. Since the condensation can not occur in such condition, the surface is free from decay. Comparing the above simulation results with figure 6-8 on page 11-13, the conditions are too dry for mold formation.

17.2 Critical point 2 – Between Isoprotect board and sarking insulation

The graphs below in figure 31 shows the RH and temperature level throughout a year on the critical point 2. The RH is higher than in critical point 1. When the air flows from the critical point 1 to critical point 2, the air losses some heat. Thus, the loss of heat results in low temperature on the surface of the critical point 2 than in the critical point 1 and the RH level increases in comparison to the critical point 1.

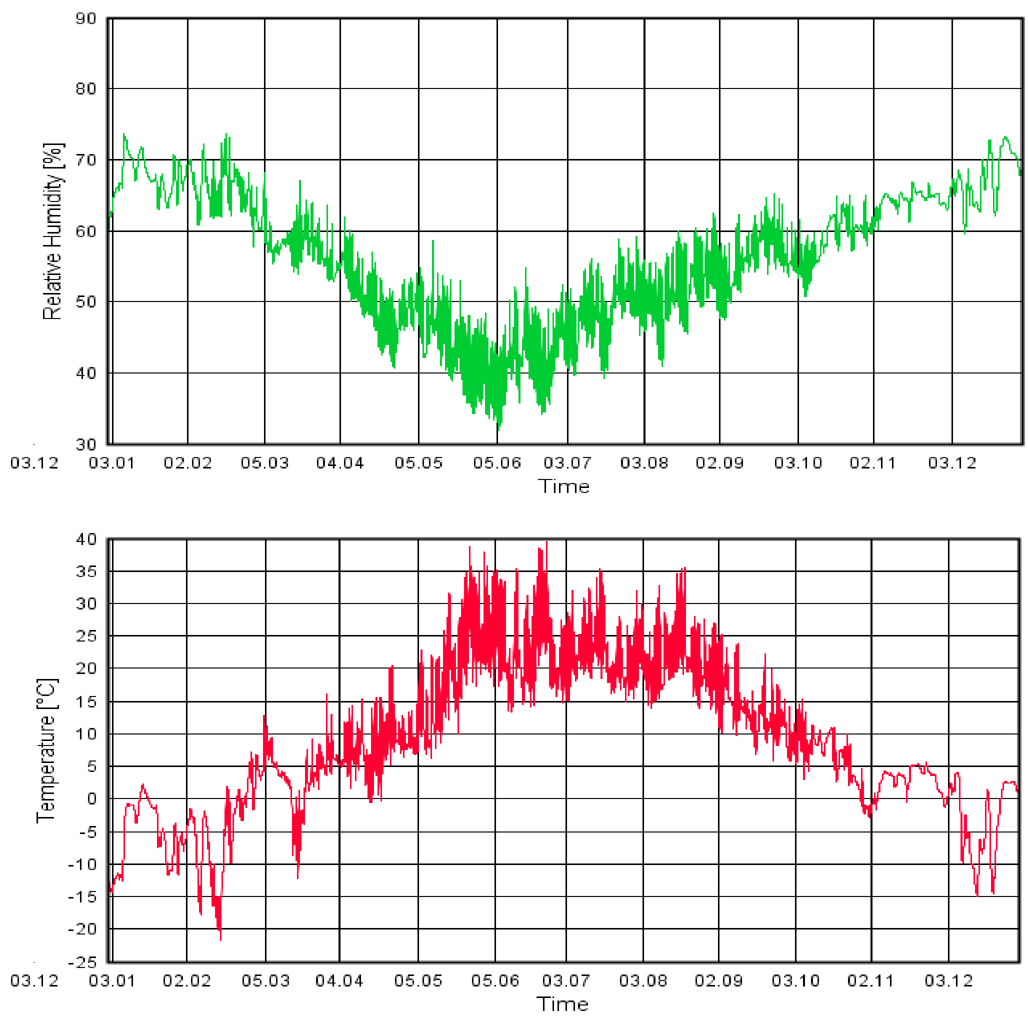


Figure 31. RH and temperature on critical point 2.

The RH remains above 70% very rarely. According to the simulation graphs, the RH level is below 75%. When this RH level is compared with the Viitanen's mold formation graph on page 11-13 with figure 6-8, this conditions can be considered as unfavorable condition for mold growth. Therefore, there is no risk of mold formation in such dry conditions.

The humidity percentage in other critical points 3, 4 and 5 are below 70% throughout the year. The water moisture content on the wooden material is below 16% in such case which makes it safe and strong against structural damage. Mold needs suitable RH, temperature and exposure time to develop. Without one of them, mold cannot expand. Since the RH is below 70% throughout the year, the humidity level is considered as dry condition and fungus cannot germinate on those surfaces. The graphical simulation results of the surfaces are enclosed in appendices 5, 6 and 7.

18 Simulation case 5 - Sarking roof with 50mm sarking and gypsum board

In the sarking model in case 5 with 50mm sarking insulation and gypsum board, Gyproc GN 13 board is used between the insulation materials. The objective of studying this model is to determine if there will be any change in the moisture and heat flow conditions if the board is changed. The thermal conductivity and diffusion factor of gypsum are higher than those of the Isoprotect fibreboard. Thus, the gypsum board could resist more moisture in comparison to the Isover Isoprotect fibreboard.

After the simulation of simulation case 5, it was found that the surfaces at the critical points 3, 4 and 5 have RH content below 70% throughout the year. Fungus development is not possible in such conditions because mold does not get sufficient nutrients. Since the critical points 3,4 and 5 were not the critical ones for mold risk, their heat and moisture performance are not explained below but can be found in appendices 8 and 9.

18.1 Critical point 1 - Between main insulation and gypsum board

The graph below in figure 32 represents the RH on surface of the critical point 1. The simulation graphs below are compared with the mold growth and structural decay graph from figure 6-8 on page 11-13.

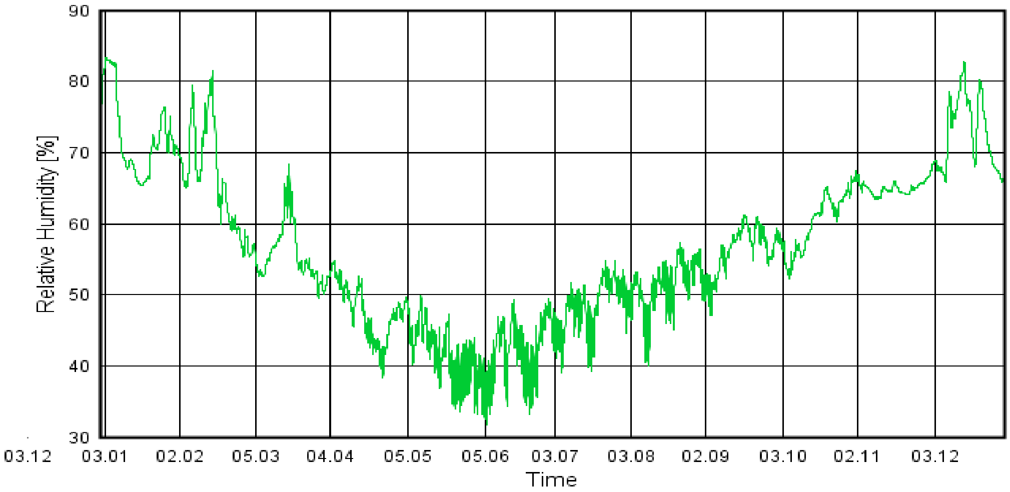


Figure 32. RH at critical point 1.

The RH exceeds the critical level for mold growth during a couple of months in the winter, but the RH does not remain above 75% for a long time. Comparing this graph with figure 8 on page 13, the structural decay cannot occur because of the low humidity and moisture content.

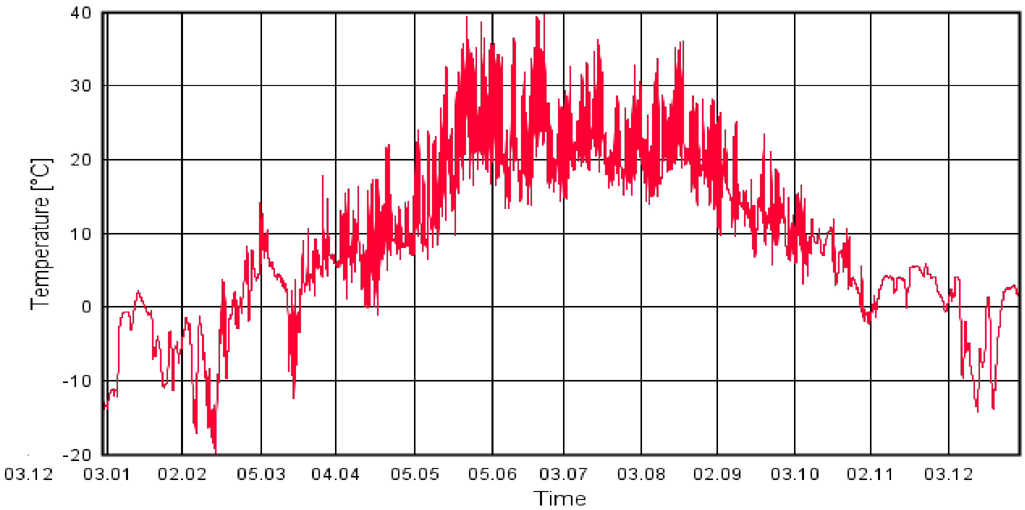


Figure 33. Temperature at critical point 1.

As can be seen in figure 33, when the RH is above 75%, the temperature is around freezing point. Therefore, the conditions are not favorable for mold infestation. Even during the winter, the fluctuation in humidity allows the surface to dry when humidity is falling. The RH remains below 70% for more than eight months. Thus, there is no risk due to excess moisture.

18.2 Critical point 2 – Between sarking insulation and gypsum board

As seen in figure 34 below, there is no risk of structural decay and mildew formation on surface of critical point 2 because the RH is not above 80% when the temperature is above +0°C. The RH is about 80% during February for a couple of days when the temperature is above 5°C. The surface is only exposed to such high humidity for a very short time, so there is no time for fungus to develop.

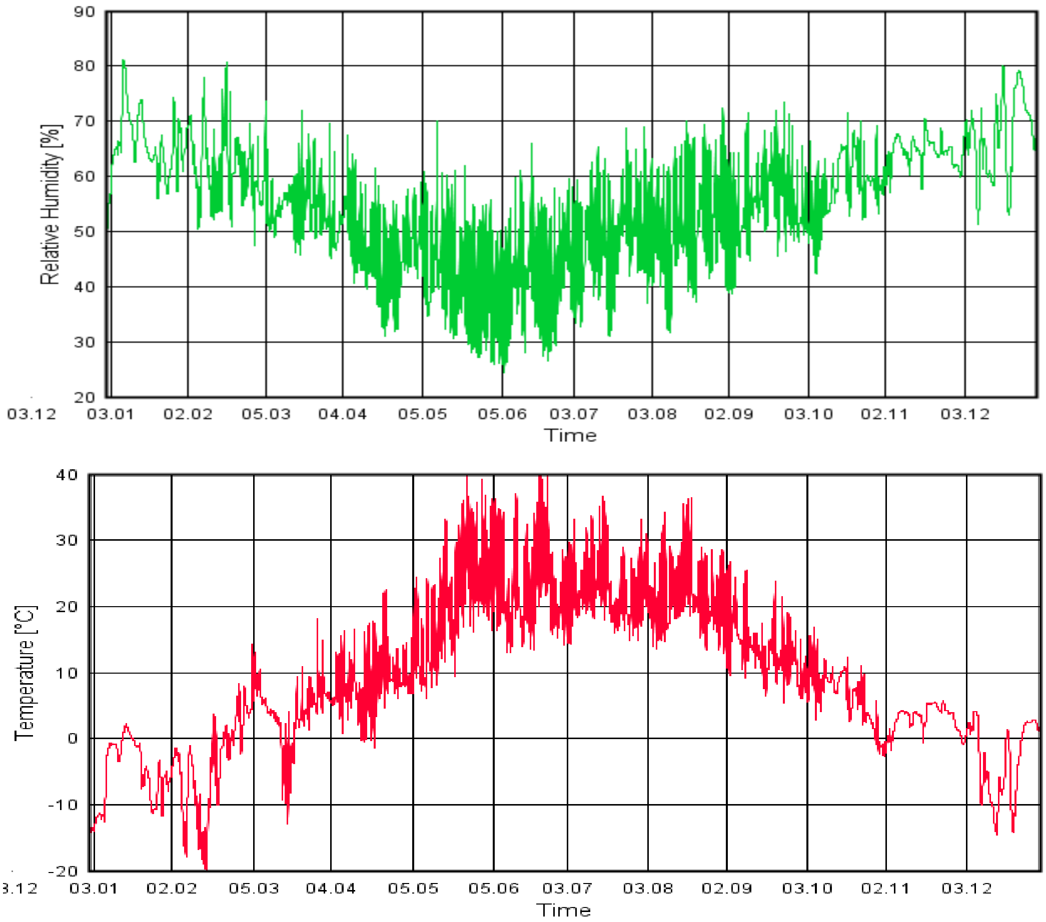


Figure 34. RH and temperature at critical point 2.

The humidity drops below 70% and the conditions remain dry for almost 9 months continously. The surface temperature should be over 10°C with the RH above 75% and it should last for more than 15 weeks for mold to develop. But according to simulation results, the temperature and exposure duration are not sufficient for mold expansion. Undeniably, there is no structural damage if there is no mold risk.

18.3 Critical point 3 – Between sarking insulation and gypsum board

The graphs in figure 35 below displays the RH and the temperature conditions on the surface at the critical point 3 (see figure 15 on page 27). The surface at the critical point 3 can be considered dry and cold during the winter because the RH is below 70% and, at the same time, the temperature is around subzero.

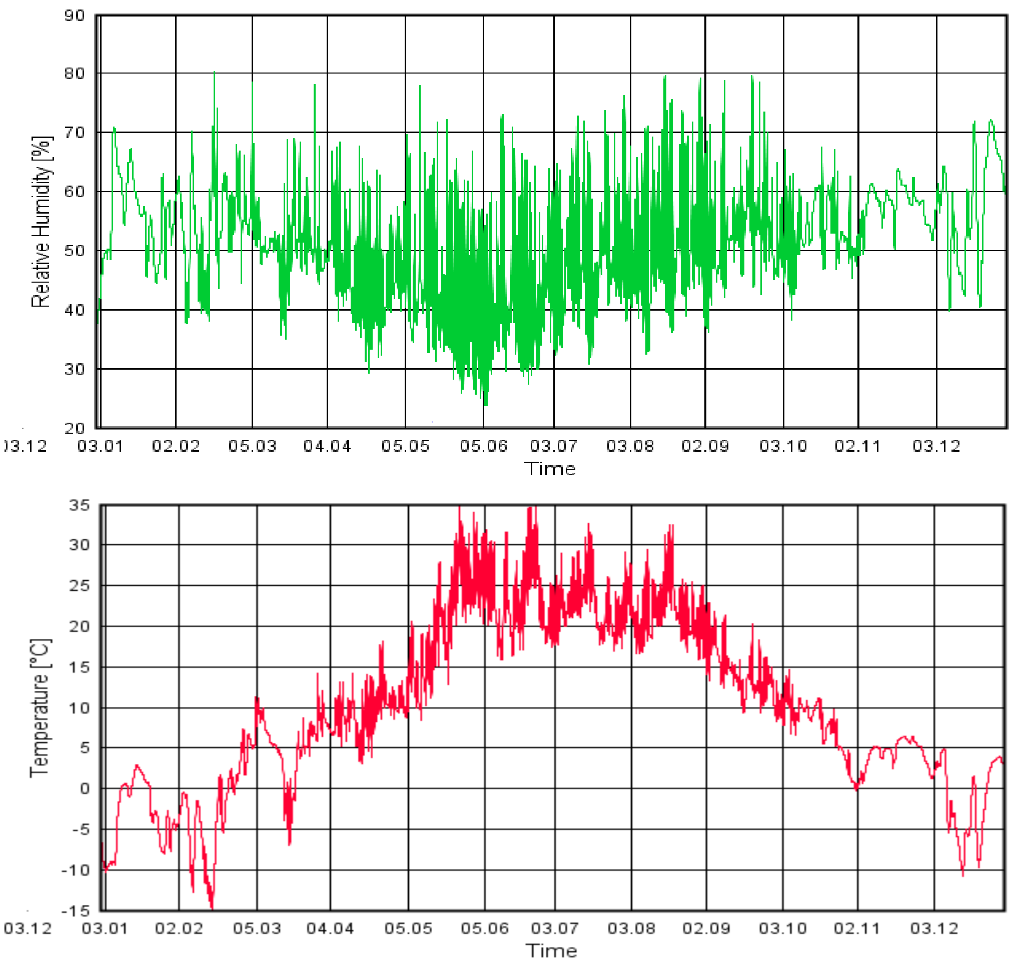


Figure 35. RH and temperature at critical point 3.

The RH rises to almost 80% sometime, but it drops instantly. For instance, the RH is 80% during September when the temperature is 20°C. In such condition, the RH should remain above 80% for 15 weeks for mold to develop. But according to the simulation result, the RH drops to below 70% instantly and remain below 70% for almost two weeks. So, the mold cannot develop in just couple of days when the RH is above 80%. Thus, such fluctuation in RH will not support mold growth.

The humidity remains below 70% for a longer period than it remains above 75%. This allows the surface to dry. This fluctuation does not support any mold development. Since the humidity falls shortly, there will be no mold expansion risk or decay problem.

19 Simulation case 6 - Sarking roof with 50mm sarking and plywood

Another simulation case consists of a plywood as the board material between the insulation materials. The roof structure, thickness of the materials and their properties and the U-value of the roof are similar to those of the previous sarking models except for the board material used between the insulation layers.

The purpose of studying this simulation case is to discover if there are any differences in moisture transport if a different board is used. The roof was modelled in WUFI 2D with boundary conditions similar to the other simulation cases. The relative humidity was analysed in different critical points as shown in figure 15 on page 27.

19.1 Critical point 1 – Between Isover KL-37 insulation and plywood

According to the graph on figure 36, the surface at critical point 1 seem to be vulnerable to mold growth during winter because the RH is above 75% for more than three months. Nevertheless, the RH also falls below 70% during those months. The results for this surface are almost similar to those of the previous model with same materials but a 30 mm sarking insulation. Although the RH is suitable for fungus infestation, the RH level is not dangerous for structural damage.

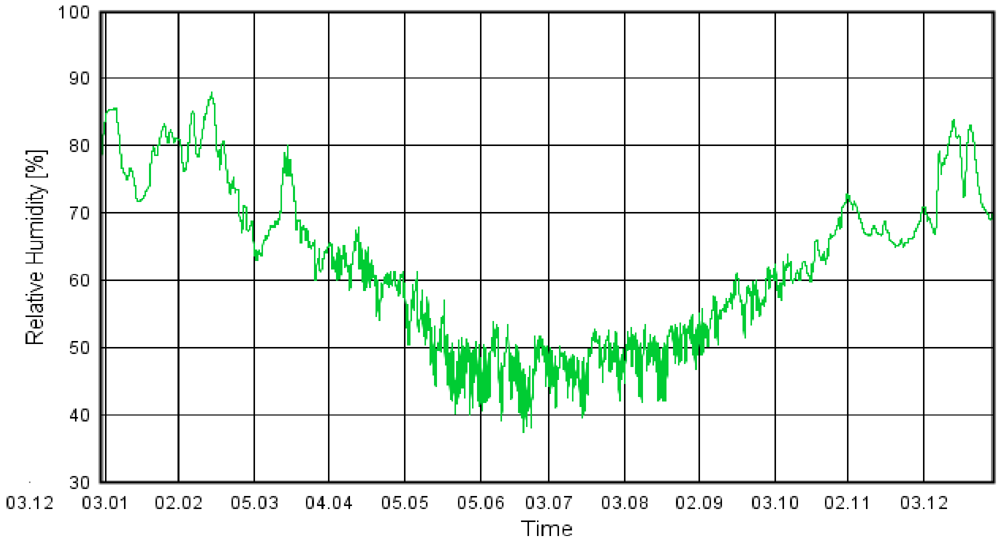


Figure 36. RH and temperature at critical point 1.

A comparison of the RH graph to the temperature changes in figure 37 below indicates that it is difficult for mold to grow in such conditions. When the temperature rises to conditions favourable for mold, the RH drops below 75%. As mentioned by Viitanen, mold cannot develop in frost or dry conditions. Moreover, when the RH decreases continuously, this low humidity for a longer period can make mold growth impossible [8, 7].

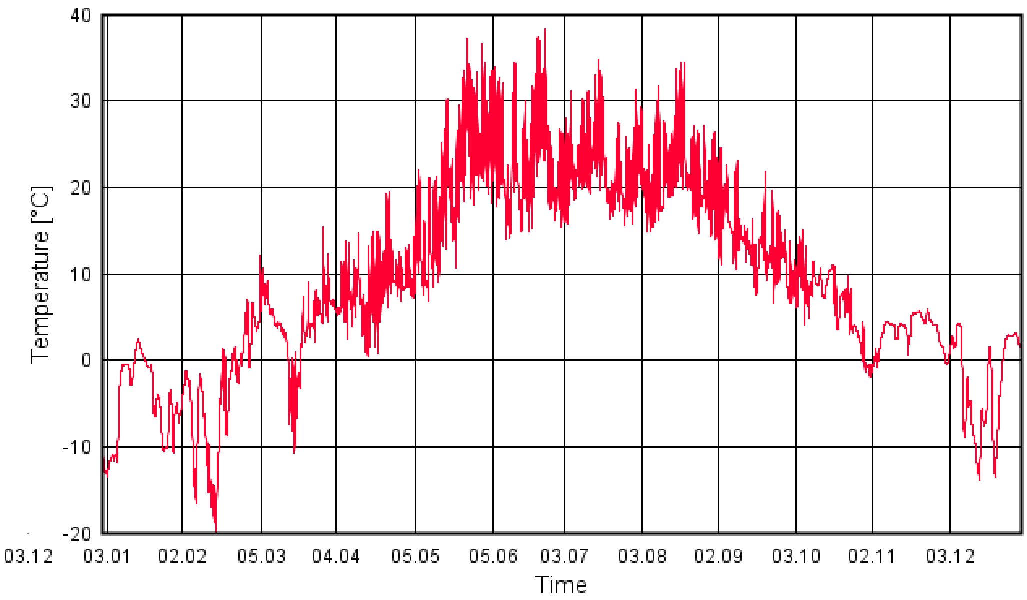


Figure 37. RH and temperature at critical point 1.

19.2 Critical point 3 – Between sarking insulation and plywood

The graphs below in figure 38 are the RH and the temperature conditions at the surface of critical point 3. The critical point 3 is the surface between the sarking insulation and the plywood board. According to the simulation result, the RH is below 70% almost throughout the year.

However, the RH is around 75% sometimes. Although, this condition cannot be classified as critical for moisture damage because the RH hardly reaches 75% and it drops down rapidly in short time. For mold development at this temperature the RH should be above 75% for more than 12 weeks, Since the RH plunges promptly, the time needed for mold to germinate increases. Thus, there is no hazard of blight growth.

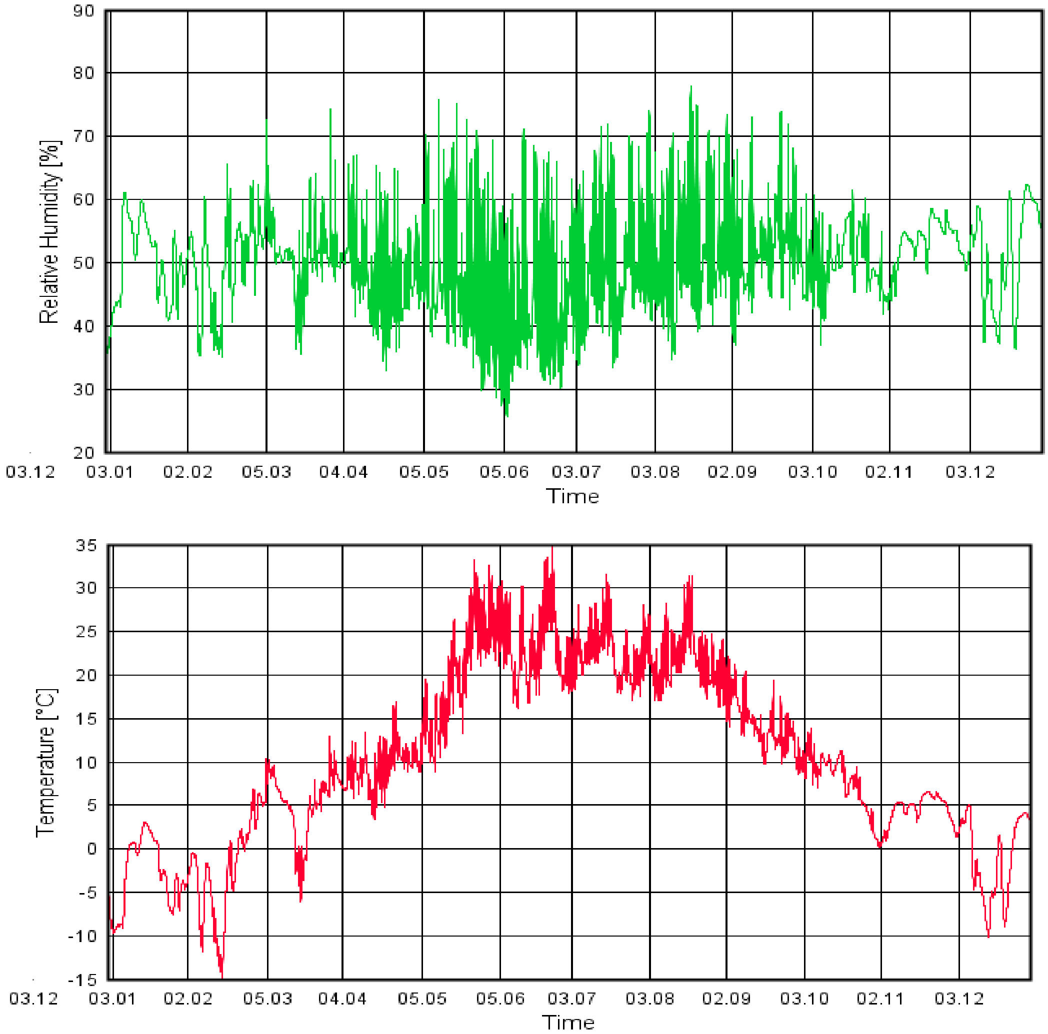


Figure 38. RH and temperature at critical point 3.

When the result of this model is compared to the simulation case 3 where a similar board was used, but the sarking insulation was only 30mm thick, the result is almost similar. The RH level in this model seem to be lower than in case 3. This can be because of the increase in the thickness of the sarking insulation which produces more barrier for heat flow outwards. Also, the decrease in thickness of main insulation layer, helps to absorb more heat from inside which means warmer surface than in Simulation case 3.

The surface at critical points 2, 4 and 5 (refer to figure 15 on page 27) seem to be safe from structural decay and mold formation. The RH is below 70% throughout the year on those surfaces. This means the conditions are too dry for mold flourish because of a lack of nutrients. The results for the critical points are available in appendices 10, 11 and 12.

20 Discussion of sarking model with 50mm sarking insulation

The critical points, materials used and boundary lines used in the simulations for a sarking roof with 50mm sarking insulation were similar to the simulation case studies with sarking roof models with 30mm sarking insulation. The main objective of simulation was to investigate if the thickness of insulation layers has any effect on the performance of the roof structures.

The study of the moisture and temperature effect on the critical points in all simulation cases with 50mm sarking insulation showed that there are no hazards which an excess of moisture could cause. The RH was usually below 70% when the temperature was above zero. The RH was above 75% during cold times, but the surface temperature was below freezing point at the same time. There were some simulation cases where the RH was higher than 80% but the RH did not remain at that level for a long time. The length of the time when the RH remains above 75% was shorter than the time when the humidity was below 70%. The RH dropped quickly and remained below 70% for more than half a year, thus giving time for the surface to dry up. According to Viitanen, mold needs a longer time to develop if there will be fluctuation in the RH and temperature.

Usually, mold formation is the first step leading to structural decay. For fungus to sustain, it needs nutrients, oxygen and a moist surface with a favorable temperature above zero. The expansion of mildew depends upon the length of exposure to these favorable conditions. If the surface is not damp for a long period, fungus cannot get enough nutrients and cannot expand.

In the study, no surface had critical conditions with the RH above 75% and the temperature above subzero for more than one week. Mold can develop in one week if the surface humidity is above 95% and the surface temperature of 20°C. At 10°C temperature, mold takes more than two weeks to develop at the same humidity level. This shows that mold formation can also be affected by the surface temperature. On none of the simulation cases the RH remained above 75% for more than one week constantly with a suitable temperature. There was always fluctuation in the RH and the temperature which affected the favorable condition for the mold formation. Hence, making the mold growth difficult.

21 Comparison between sarking roof models with reference model

Jyväskylä was selected for the simulation in this final year project, because it is situated in the middle of Finland. The weather data of Jyväskylä was used as average data for Finland. Figure 39 below represents the average humidity and temperature conditions in Jyväskylä throughout the year [20].

As seen in figure 39, during the winter, the RH is above 80% in Finland. However, it is not close to 100%. Thus, the problem of structural decay does not exist although there is risk of mold formation. Furthermore, when the RH is high, the temperature is below 5°C. In such conditions mold growth takes more than 20 weeks.

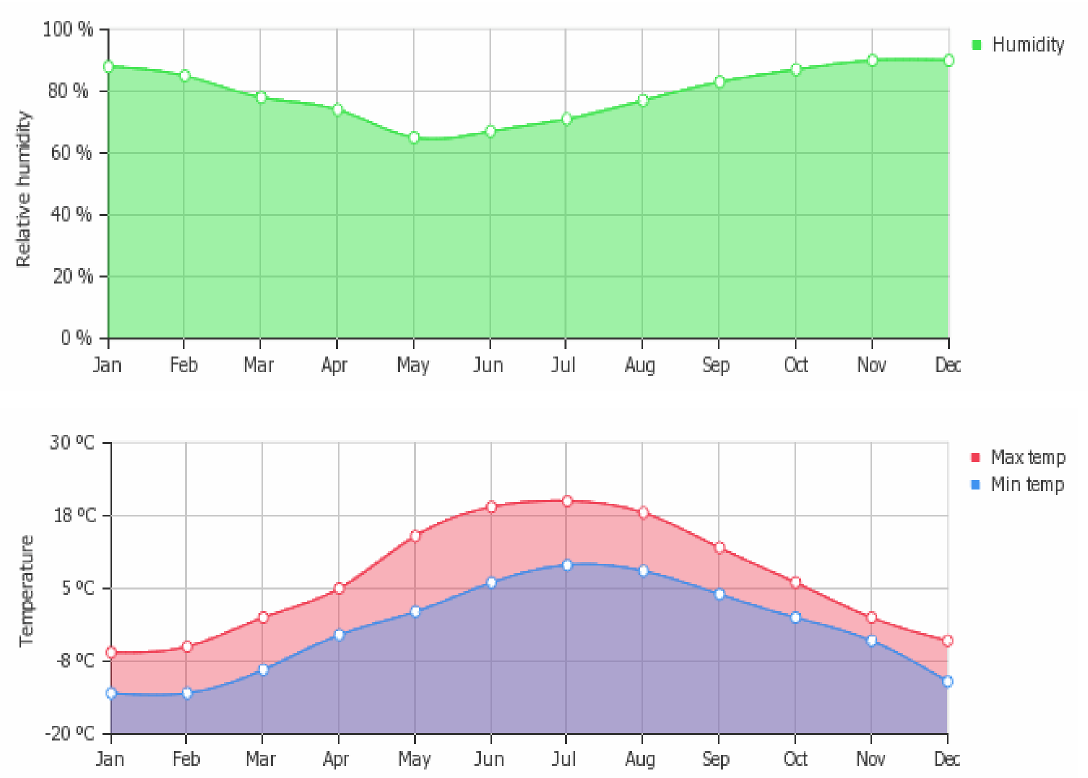


Figure 39. Average humidity (top) and temperature (bottom) of Jyväskylä. [20.]

According to the simulation results of reference roof model, there were no risk of condensation and mold formation in reference roof model. The RH was above 90% during winter and there was possibility of frost formation due to very low temperature. During other times of the year, the RH was below 70% for more than 6 months, which could allow the surface to dry. Although there was no mold and decay risk in the reference model, the risk of heat escaping through the roof is higher than in the sarking roof. The thermal bridge through a wooden rafter could be a big problem.

In sarking roofs, when the sarking insulation was added, it improved the thermal performance of the roof by preventing outward heat flow. The sarking insulation helped to prevent thermal bridges through wooden rafters because it was installed over the rafters. The results for a sarking model with a 30mm and 50mm sarking insulation were almost similar. However, the sarking models with a 50mm sarking insulation had better thermal performance and RH level was lower at the critical points in comparison to sarking roof model with 30mm sarking insulation.

In the sarking model with a 30mm thick sarking insulation, the maximum humidity was about 90% when plywood was used but only around 70% when an Isover Isoprotect board was used. This is because of the difference in the thermal conductivity and diffusion resistance factors of the board materials. The humidity exceeded the critical level during the winter in the sarking models, but at the same time the temperature of the surfaces were at freezing point and not favorable for the mold growth.

There were some simulation cases during spring and autumn when the humidity level was around the critical point when the temperature was above subzero but the exposure time was very short for mold development. The conditions were similar with the sarking roof model with a 50 mm sarking insulation, but the humidity was lower with the increase in the sarking insulation thickness. Thus, there is no risk of condensation, frost, mold and decay on the sarking roof structure.

22 Comparison between sarking roof with 30mm and 50mm sarking insulations

The simulation results of the sarking roof models showed that the sarking models are free from condensation, mold and structural decay risks. Nevertheless, the moisture accumulation on a roof structure varied upon the thickness of the sarking insulation and the board used between them. The RH and the temperature conditions on the five critical points were different for each board that was simulated. When the board material with a lower thermal conductivity and lower water diffusion factor was used, the RH was below the critical level at all the critical points.

The differences in the hygrothermal performance of the sarking roof models caused by the change in the board materials and the thickness of sarking insulation are discussed below.

22.1 Change in the thickness of insulation layers

The difference in the hygrothermal behaviour of sarking roof due to the change in the thickness of insulation layers are explained below. Figure 40 below shows the difference in the RH between the sarking models with 30mm and 50mm thickness on the surface of the critical point 1 with the same board but different thickness of the sarking insulation.

The graph on the left shows the results of the sarking model with a gypsum board. It has a sarking insulation of 30mm thickness and a 400mm main insulation. The graph on the right has the same materials, but the thickness of the sarking insulation is increased to 50mm and the main insulation is decreased to 380mm. Thus, the overall thickness of the insulation materials were 430mm in both sarking roof models.

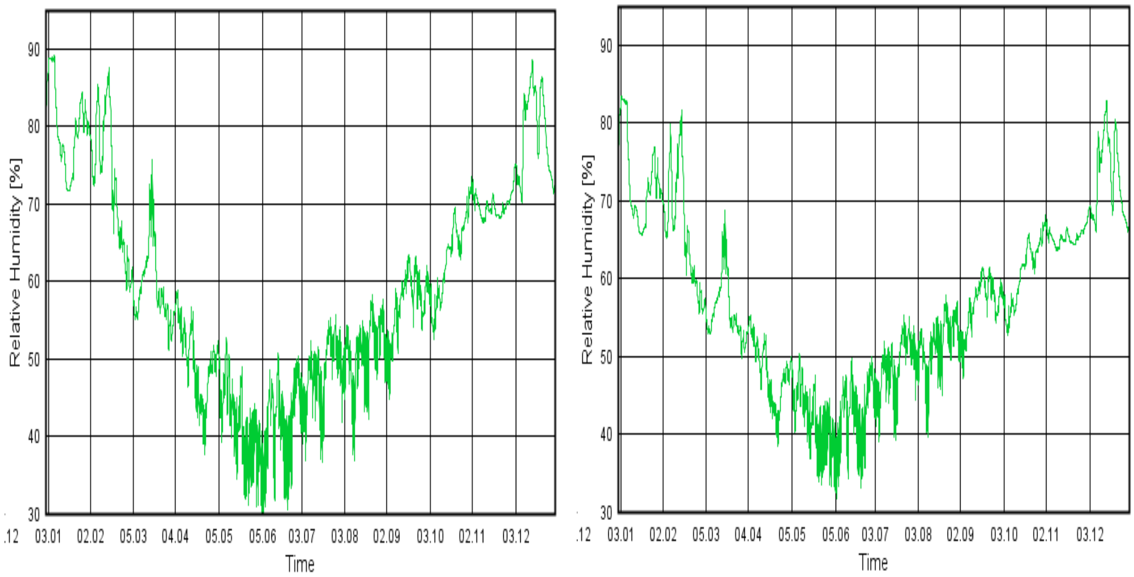


Figure 40. RH with 30mm sarking (Left) and RH with 50mm sarking insulation (Right).

As the graphs in figure 40 show the RH fluctuates in almost the same way in both simulation cases, but the RH level on the right picture with a 50mm sarking insulation is lower than the RH on the left with a 30mm sarking insulation.

The reason for the RH level to be lower in sarking roof with 50mm sarking insulation is when the inside air flows through the main insulation, the air takes less time to reach the critical point 1 because the thickness of main insulation layer is only 380mm instead of 400mm. Thus, when the air reaches at the critical point 1, the air is warmer which results in increase in the temperature at the surface of the critical point 1 and that decreases the RH level.

Likewise, the increase in the thickness of the sarking insulation slows the heat escaping process through it and making the surface of the critical point 1 warmer. This also results in the rise of the temperature at that surface and lowering the RH level.

22.2 Change in the board materials

Figure 41 below shows the dissimilarities in the moisture flow conditions when the different board materials were tested. The thickness of the insulation layer and sarking insulation were same in both simulation cases. For this comparison, a sarking model with an Isoprotect fibreboard (Simulation case 1) and a gypsum board (Simulation case 2) were studied. The sarking insulation was 30mm thick in both simulation cases.

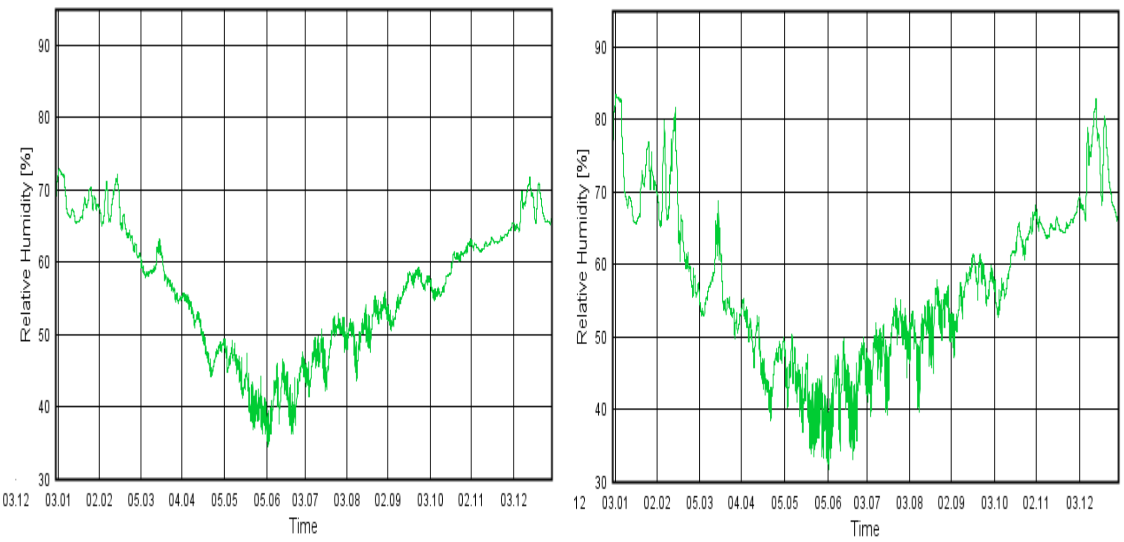


Figure 41. RH with Isoprotect board [left] and with Gypsum Board [Right].

In figure 41, the graph on the left is the sarking model with the Isoprotect board. The second graph is the same sarking model but the gypsum board is used between the insulation layers. The graphs show the RH levels on the surface of the critical point 1 of both sarking models.

The graphs show that the RH level is comparatively low when the Isoprotect fibreboard was used. The RH was just above 70%. The RH level when gypsum board was used was above 80% at the same point on same time. The sarking roof model with the Isoprotect fibreboard has lower RH than gypsum board because the Isoprotect fibreboard has lower thermal conductivity and water diffusion factor.

When the air passes through the Isoprotect board, the heat escaping is slow because of lower thermal conductivity of the Isoprotect board. Also, the moisture can easily pass through the Isoprotect board in comparison to the gypsum board because of lower water diffusion factor of the Isoprotect board. Thus, the sarking roof with the Isoprotect fibre-board has lower RH level.

23 Exceptions

The study of sarking roof models were not limited to the thickness of insulation layers and the board materials. Additional studies were done by changing the air exchange rate and the vapour barrier to study the effect on the sarking models. The analysis of the simulations are discussed below.

23.1 Change in air exchange rate

An additional analysis was done in simulation case 2 which is a sarking roof model with gypsum board and a 30mm sarking insulation. When the air exchange source was increased to 20 [1/h], it was found that the humidity at all surfaces was increased by a small amount. The aim of this simulation was to find the effect of air exchange rate on the hygrothermal performance of the sarking roof.

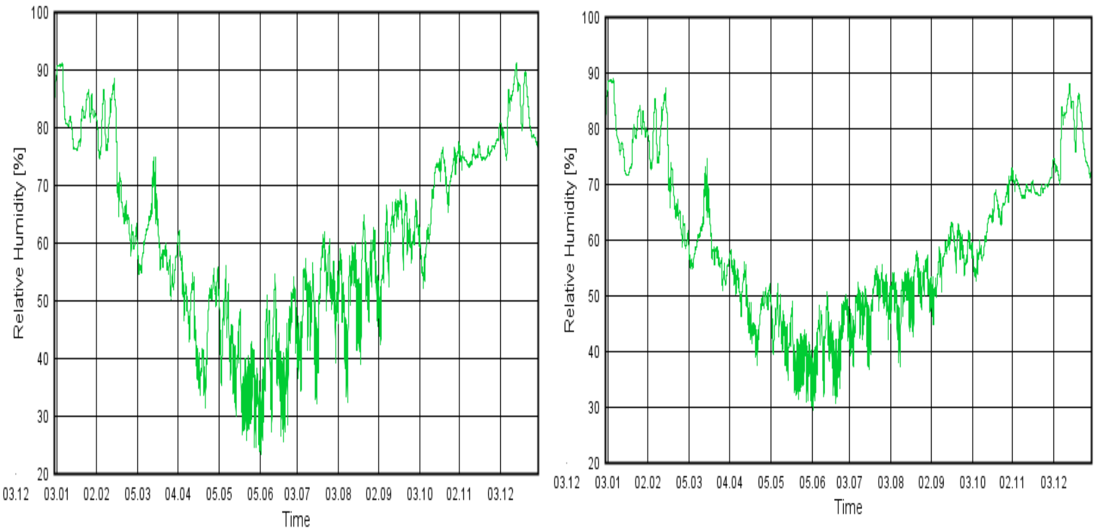


Figure 42. Humidity when air exchange 20 [1/h] (Left) and air exchange 5 [1/h] (right).

Figure 42 above shows the RH conditions on the surface at the critical point 1 on the sarking structure when the air exchange rate was changed. The graph on the left was the humidity level when the air exchange rate was increased to 20 [1/h] and the graph on the right was the RH level when air exchange rate was kept 5 [1/h].

When the two simulation are compared, it can be clearly said that, the air exchange rate can have a small impact on hygrothermal performance on the sarking roof. When the air exchange rate is increased by four times, the rise in RH is barely 4%. When the air exchange rate was increased, the cool air from outside replaced the inside warm air faster. The cool air decreases the temperature of the air inside. When this air flows outward and reaches to the critical point 1, the RH level is high due to the low temperature. Thus, the RH percentage increases with the decrease in the air temperature although if the moisture content remains the same in the air.

23.2 Change in vapour barrier

The sarking roof with the gypsum board and 30mm sarking insulation from the simulation case 2 was further inspected by changing the vapour barrier membrane. The Isover Vario Xtra vapour barrier was replaced by a traditional PE foil Isover VapoBlock vapour barrier. The goal was to study if the change in the vapour barrier can have a significant effect on moisture accumulation on the board surface.

The graph on the left in figure 43 represents the simulation with Isover VapoBlock and the graph on the right the Isover Vario Xtra vapour barrier. Figure 43 below shows moisture flow at the critical point 1 when different vapour barriers are used in the sarking structure.

The simulation result showed that there was not such visible impact of vapour barrier on moisture flow. As seen from the two graphs below in figure 43, it is very difficult to distinguish the results. This shows that the change in vapor barrier has no impact on the moisture flow.

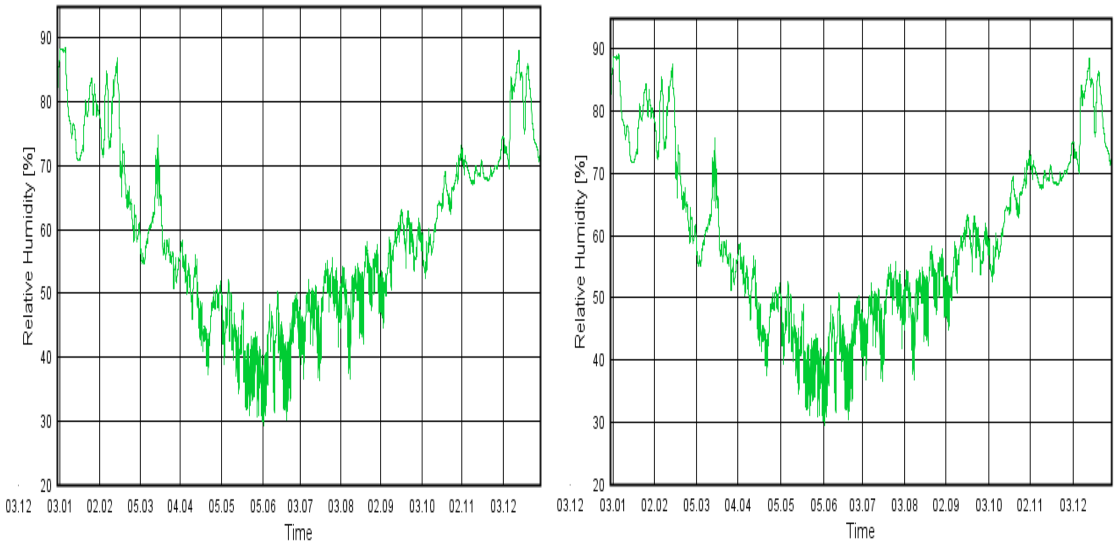


Figure 43. RH with Isover VapoBlock (left) ; RH with Isover Vario Xtra(right).

Isover Vario Xtra is an intelligent membrane which can change its diffusion resistance property according to the moisture conditions. It acts as a moisture tight membrane in dry conditions. However when the RH increases, Isover Vario Xtra allows excess moisture to pass back to the indoor air, thus reducing the excess moisture accumulation on roofing components. The humidity conditions are not at a critical level because the RH is fluctuating from about 90% to 70% in a short time. When the RH falls, such condition help the surface to dry out. Thus, there is no risk of mold formation.

If the RH was above 90% without falling to 70%, such conditions could make the surface at the critical point 1 damp and help in mold growth. But if the Isover Vario Xtra is used, the excess moisture could be passed back to the indoor air allowing the critical point 1 to dry out. In the graphs above, the humidity conditions are not at the critical level which makes the Isover Vario Xtra to function as tight membrane like VapoBlock. That is why the results are similar.

24 U-value comparisons

The thickness of the main insulation layer in the reference roof structure was 490mm. According to the calculations done with DOF Lämpö software, the U-value of the reference roof is 0,084 W/m^{2}K. Since there is no continuous insulation layer, there can be a cold bridge through the wooden rafters of the roof. According to the EN 6946 standard, in such cases 0.01 W/m^{2}K should be added as a correction value. Thus, the final U-value of the reference roof model is 0,094 W/m^{2}K. The calculation can be found in appendix 13.

A new U-value was calculated for the reference roof model by adding a sarking insulation on it. In this case, the total thickness with the main insulation and the sarking insulation was the same as in the reference model, i.e. 490mm, but the main insulation layer was reduced to 460mm and a 30mm sarking insulation was added to make 490mm. The U – value of the reference roof model with 30mm sarking insulation addition was 0.083 W/m^{2}K. The calculation can be found in appendix 16.

Another U-value was calculated for the reference roof with a 440mm main insulation and a 50 mm sarking insulation. The U-value was 0.082 W/m^{2}K. In this case, the total thickness of the insulation material was kept at 490mm as well. In neither of the sarking simulation cases 0,01 W/m^{2}K correction value was used as correction value because the insulation layer was continuous. The U-value calculations are found in appendix 17.

When the U-values of the original reference roof model and the reference roof model with a 30 mm sarking insulation were compared, the U-value was 10% lower when the sarking insulation was added. Thus, with the same thickness of the insulation layer, the thermal performance of the roof can be improved, if a sarking insulation is added.

The calculation result showed that the addition of sarking insulation helps to improve the U-value of the roof structure because the addition of sarking insulation prevents the thermal bridges through the wooden rafters, hence minimizing the heat escape and improving the thermal performance of the roof structure.

25 Conclusion

In Finland, buildings need more energy for heating than elsewhere in Southern and Central Europe because of the cold climate. The new Finnish building regulations requires for energy efficient buildings. Thus, Isover decided to introduce the sarking roof in Finland. Although this roof is widely used in some European countries, the climatic conditions are different from those in Finland. More insulation is needed in Finland to overcome the cold. A board is added between the main insulation and the sarking insulation to ensure the safety of workers while doing roof work. The installation of a board could increase the strength of the roof, but it also has an effect on moisture and heat flows because the heat and moisture flow properties of the board used are different from those of insulation materials. The simulation studies done in this thesis aimed at investigating the hygrothermal performance when a board is used between the insulation layers.

When comparing the surfaces at the critical point 1 in the reference model and the sarking models, the reference model has higher RH while the humidity decreases with the addition of a sarking insulation at the same critical point in the sarking roof. Furthermore, the increase in the thickness of the sarking insulation lowered the RH level. The use of a sarking insulation in the reference model improved the U-value of the reference roof structure. This shows that the addition of a sarking insulation can prevent heat escaping and improve the thermal performance of a roof and minimize damages caused by an excess moisture.

In some simulation cases, the RH rose above 75%. However, this usually happened during the winter when the temperature was below freezing point. Also, the critical humidity time was very short for the mold growth. In addition, the RH was below 75% for the majority period of the year. The RH above 75% does not mean that there are chances of mold and structural decay development, the temperature and the time of exposure play an important role for damages as well. For a structure to be infested by mold, a material should be exposed to high humidity for a long period at above sub-zero temperatures. If one of those conditions is not met, the mold growth is not possible. In none of the simulation cases, there was a case of the RH, temperature and exposure time that would have been favourable for mold expansion.

The simulation cases showed that a board can be installed between the main insulation layer and the sarking insulation which could give support for a worker during installation. There will be no moisture accumulation inside the roof structure despite the use of the board. However, for the analysis of the strength of the board to ensure the safety of roof installer, a different study on the strength of board material should be conducted.

The analysis of the simulation cases showed that there is no moisture accumulation on the critical points which could cause mold formation or structural decay inside. According to the simulation results, the humidity conditions and moisture flow on those critical points vary according to the boards used. For instance, with the Isover Isoprotect fibreboard, the RH is 70% at the critical point 1 whereas with the plywood the RH is over 80% on the same critical point at the same time. This is due to the difference in the thermal properties and the diffusion resistance variation of the board materials. The Isoprotect board has a lower thermal conductivity and lower diffusion factor than the plywood. Thus, the lower thermal conductivity helps the Isoprotect fibreboard to prevent heat escaping while the lower diffusion resistance allows the moisture to pass through the board. Although there was such variation in the RH content on the critical points, if the outcomes are compared with Viitanen's experiment for mold growth conditions which are in figure 6-8 on page 11-13, the structure is still free from mold and structural decay development.

By the observation of the hygrothermal performance of the boards, it is found that Isover Isoprotect fibreboard has least humidity and moisture content among all three boards simulated. The weather can be unpredictable and the weather data calculated by the software cannot be 100% accurate. Naturally, in reality, the humidity conditions can be somewhat different. Considering the risk, if the humidity was 10% higher than the WUFI 2D data, the Isover Isoprotect would still be a suitable board to be used between the insulation and the sarking insulations. Although the Isover Isoprotect fibreboard was found to be most preferred in these simulation cases, the simulation results also showed that sarking roof models with all the tested boards are suitable for Finnish climate.

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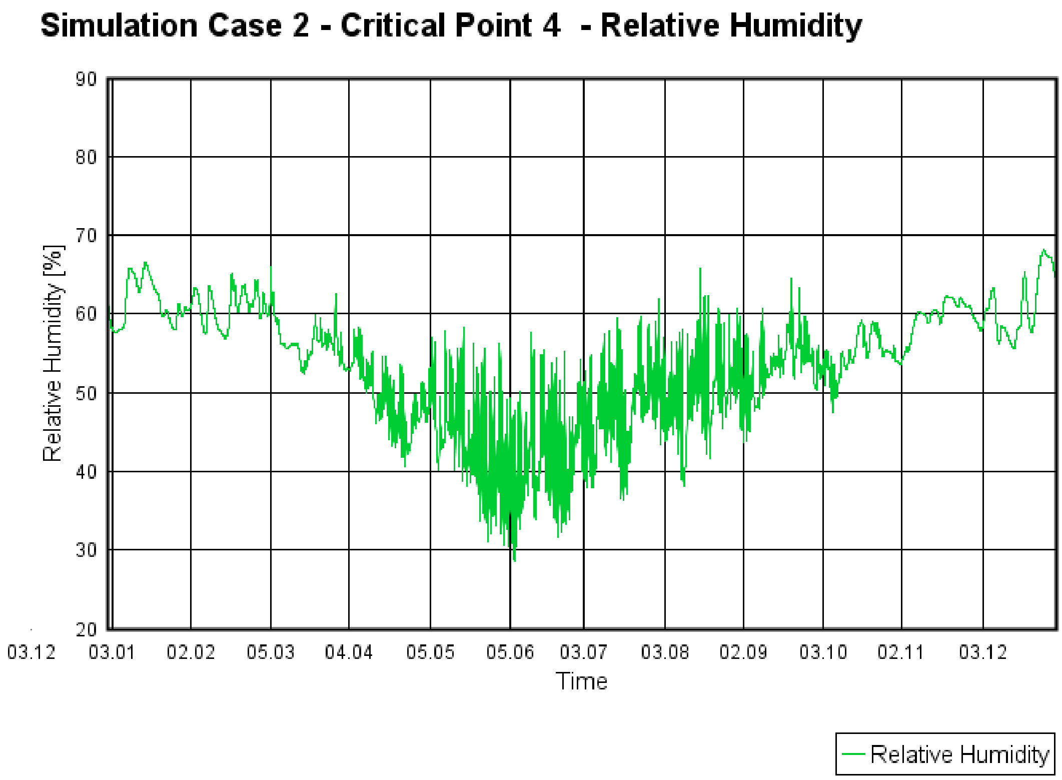
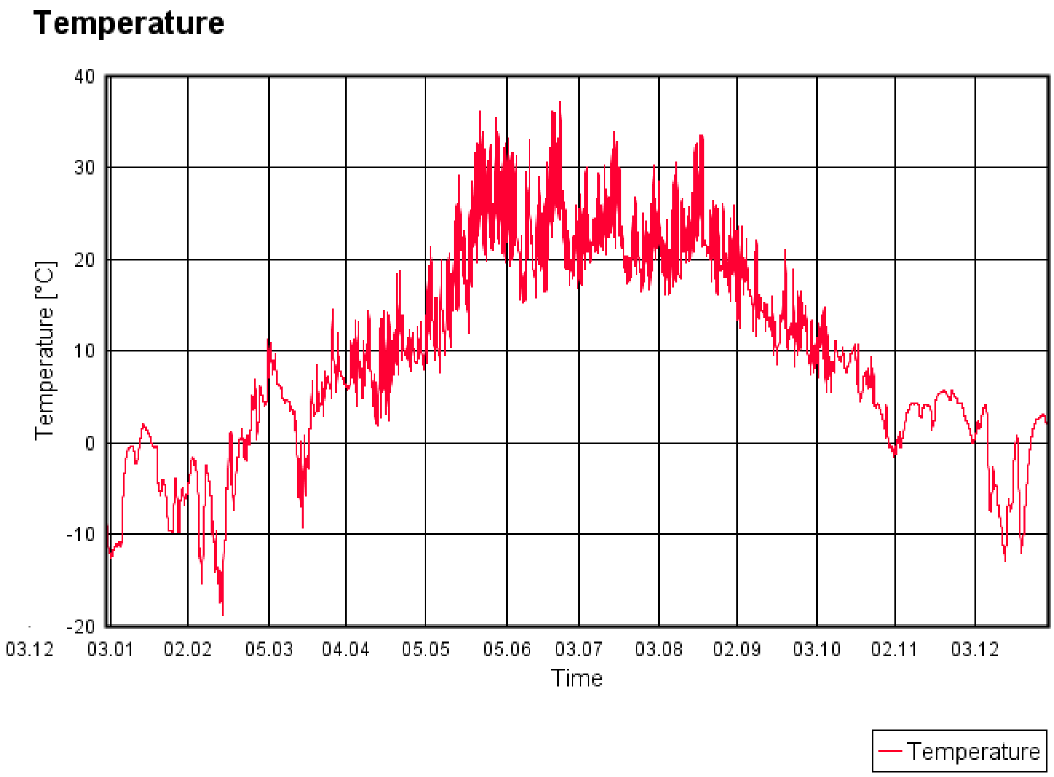
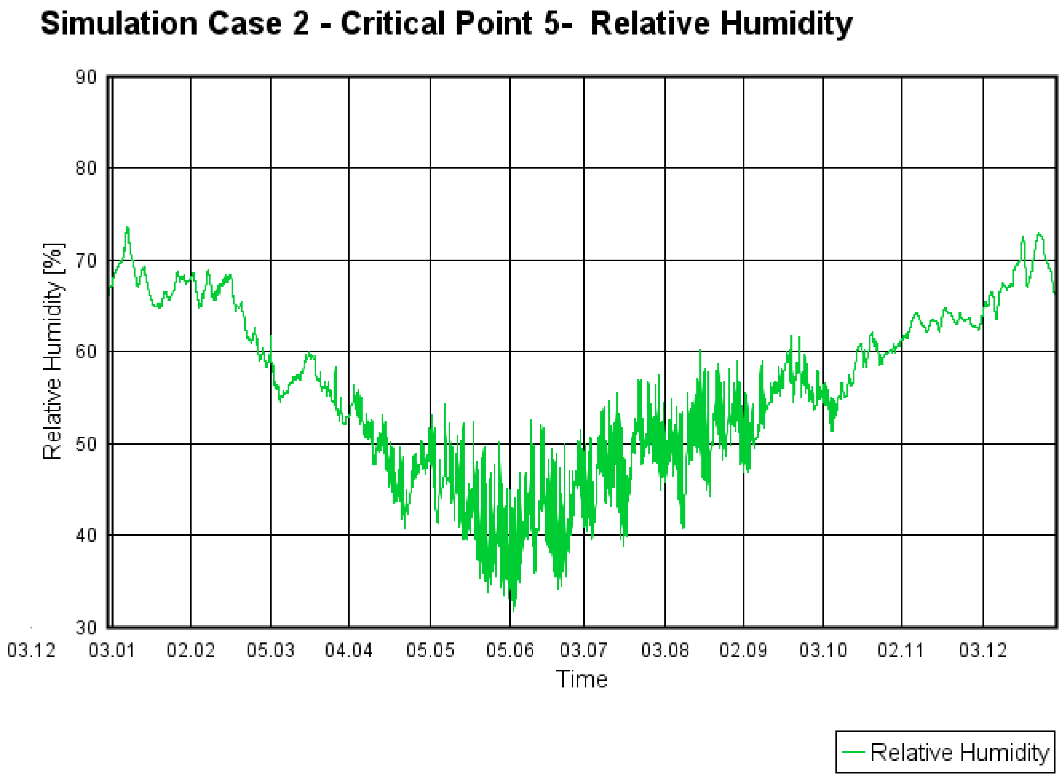
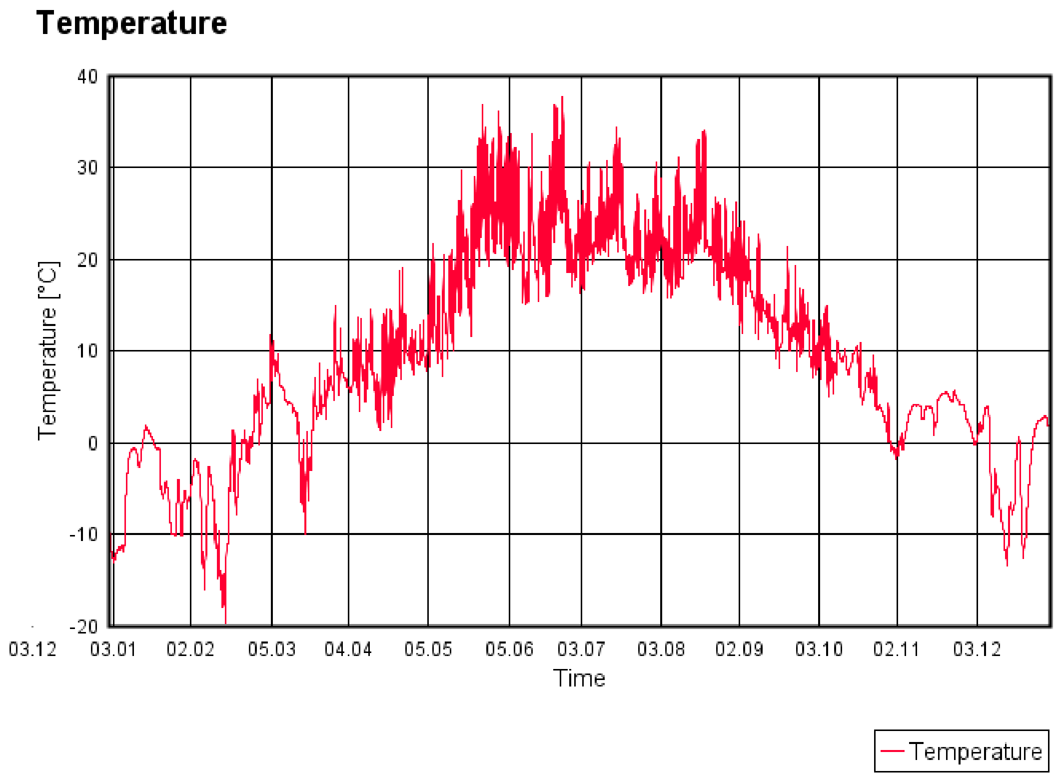




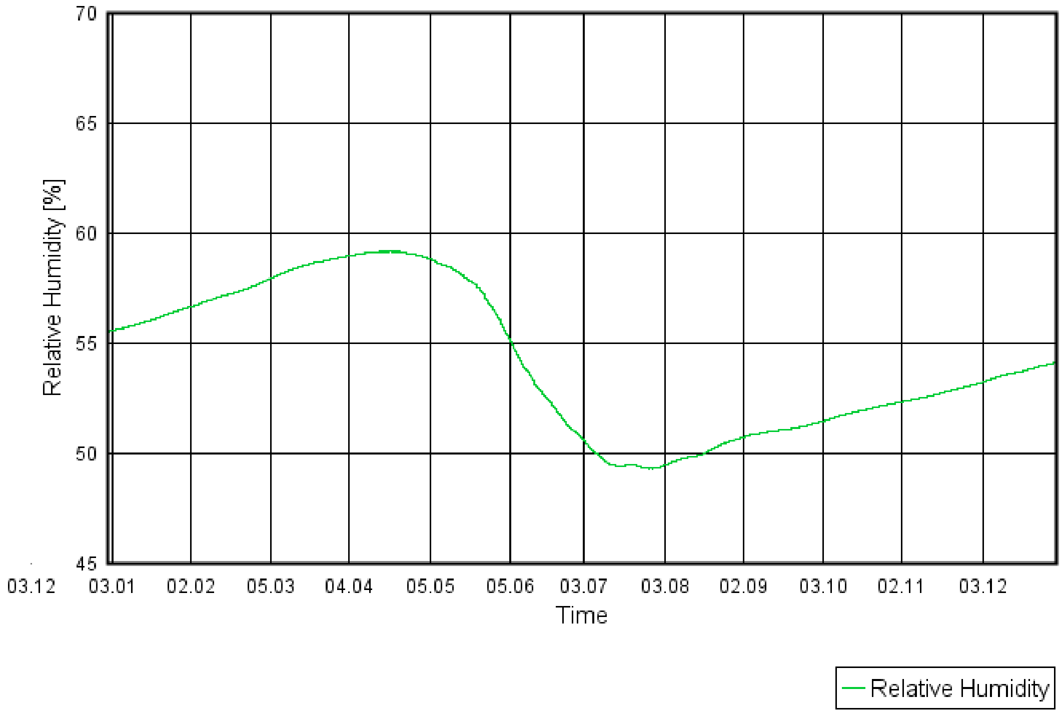
Appendix 1 Critical point between LVL and gypsum board.



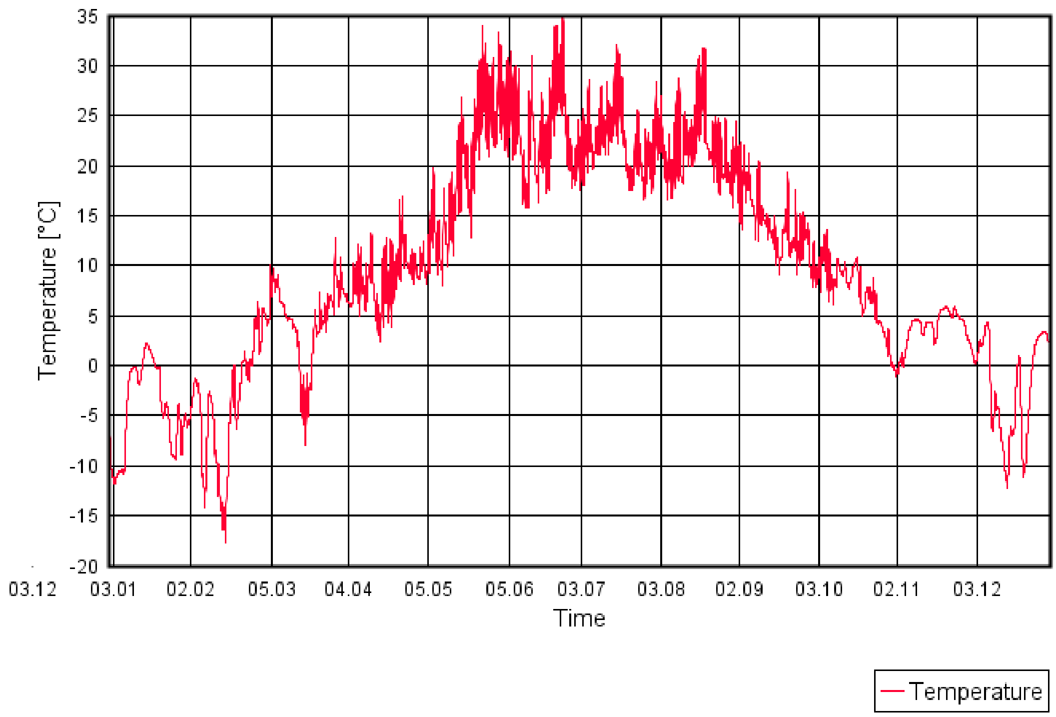


Appendix 2 Critical point between LVL, main insulation and gypsum board.

Simulation Case 3 Critical Point 4 - Relative Humidity

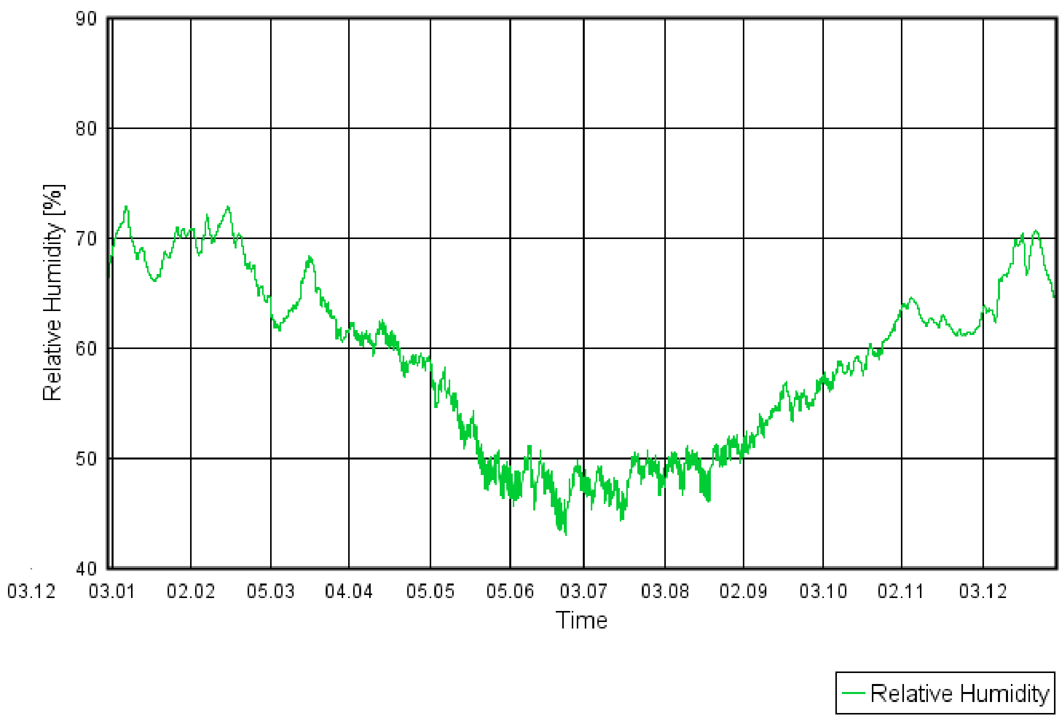


Temperature

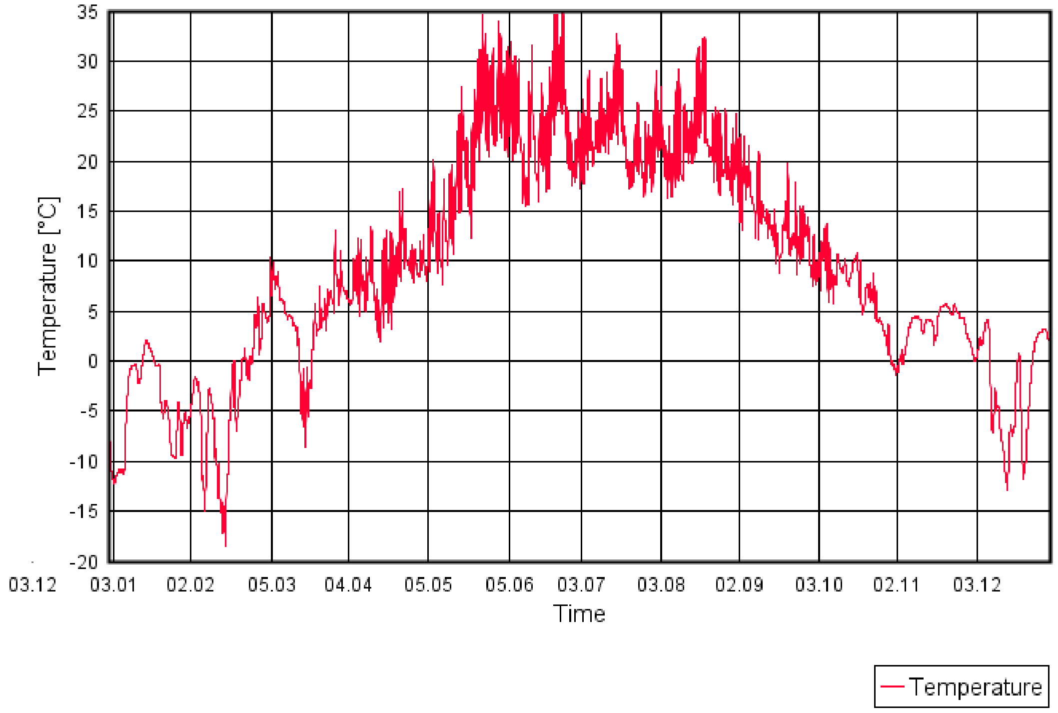


Appendix 3 Critical point between LVL and plywood board.

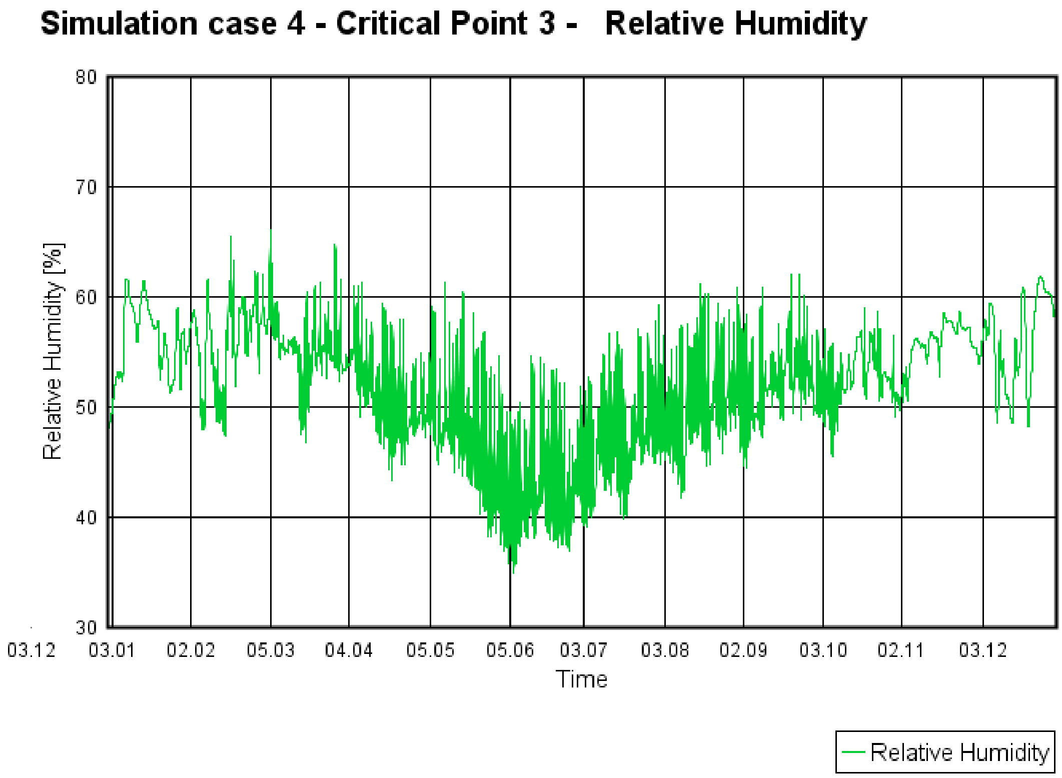
Simulation Case 3 Critical Point 5- Relative Humidity

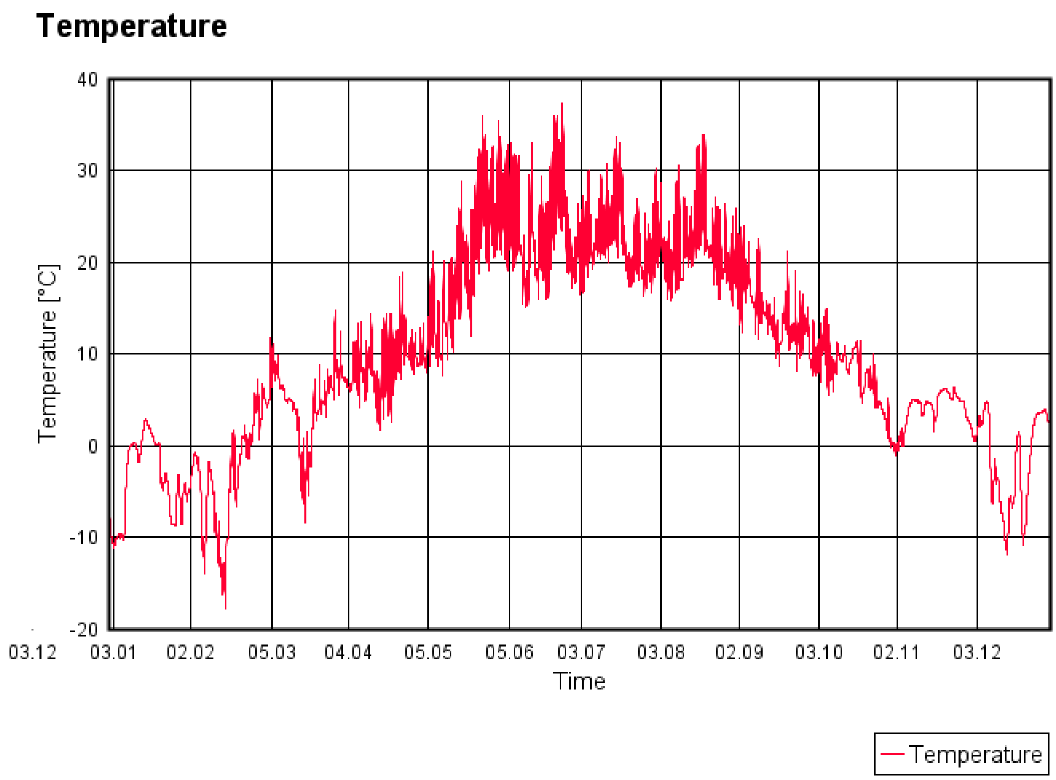


Temperature

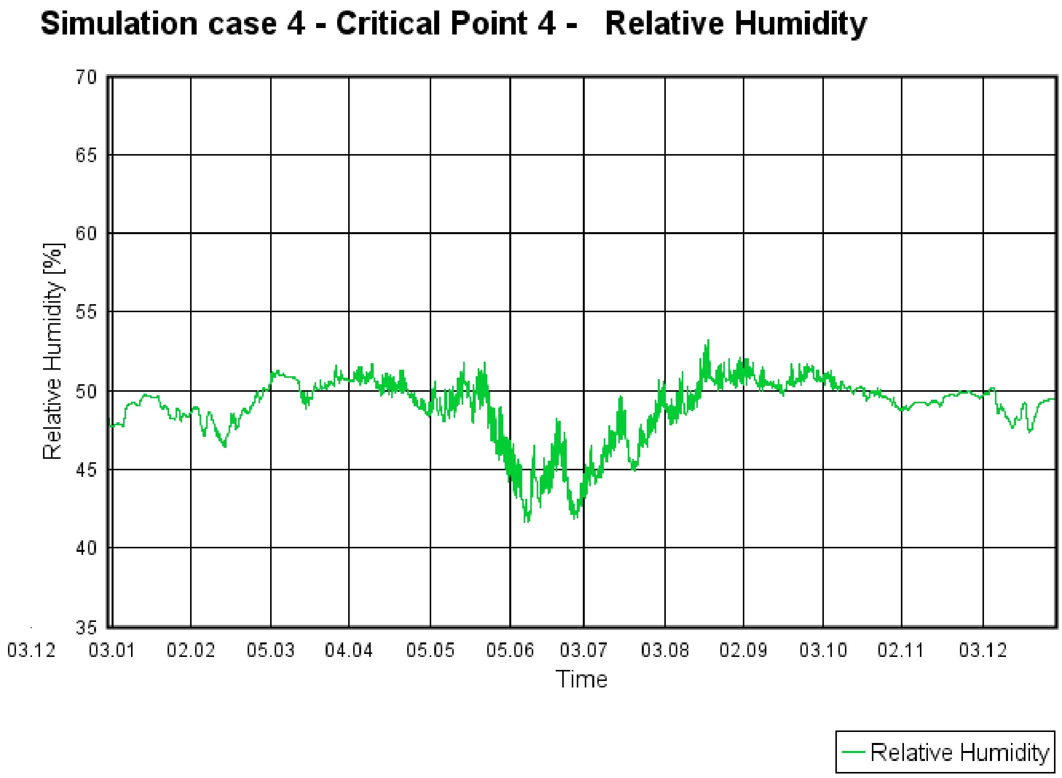


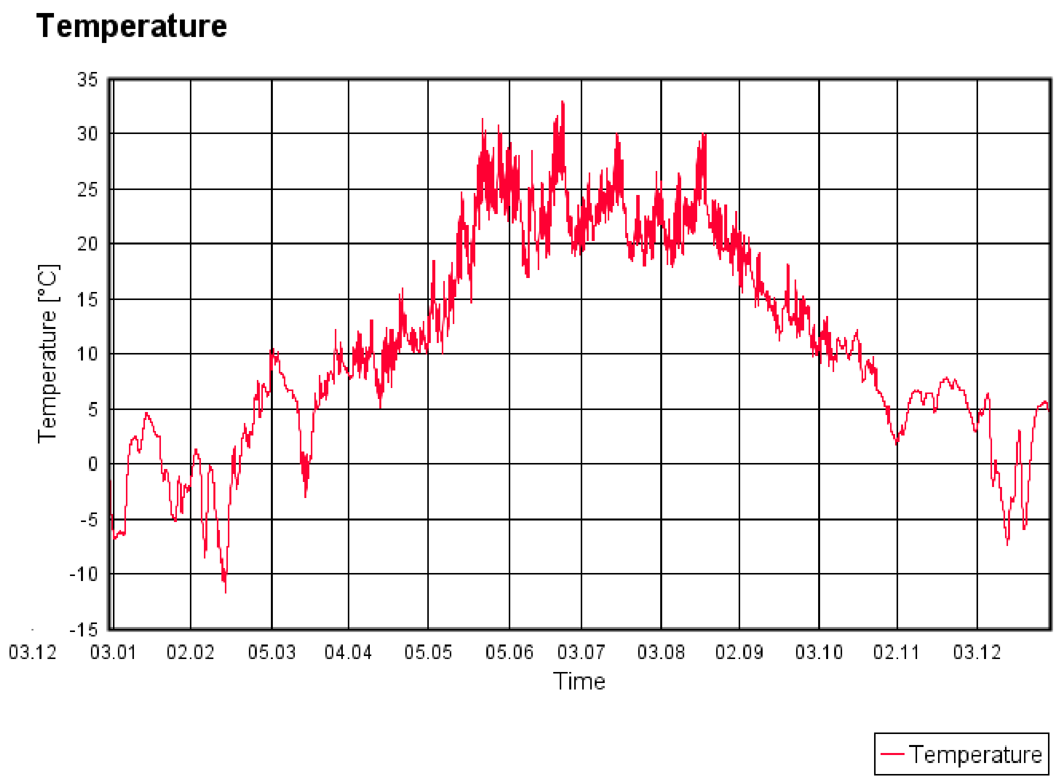
Appendix 4 Critical point between LVL, main insulation and plywood board.



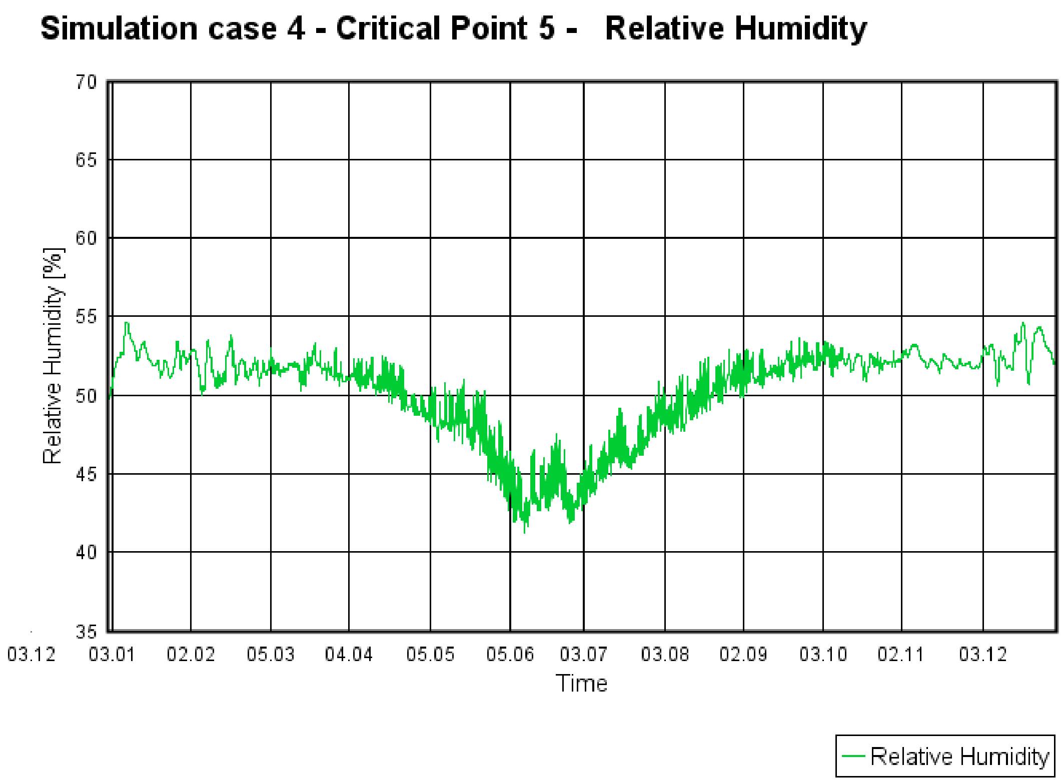


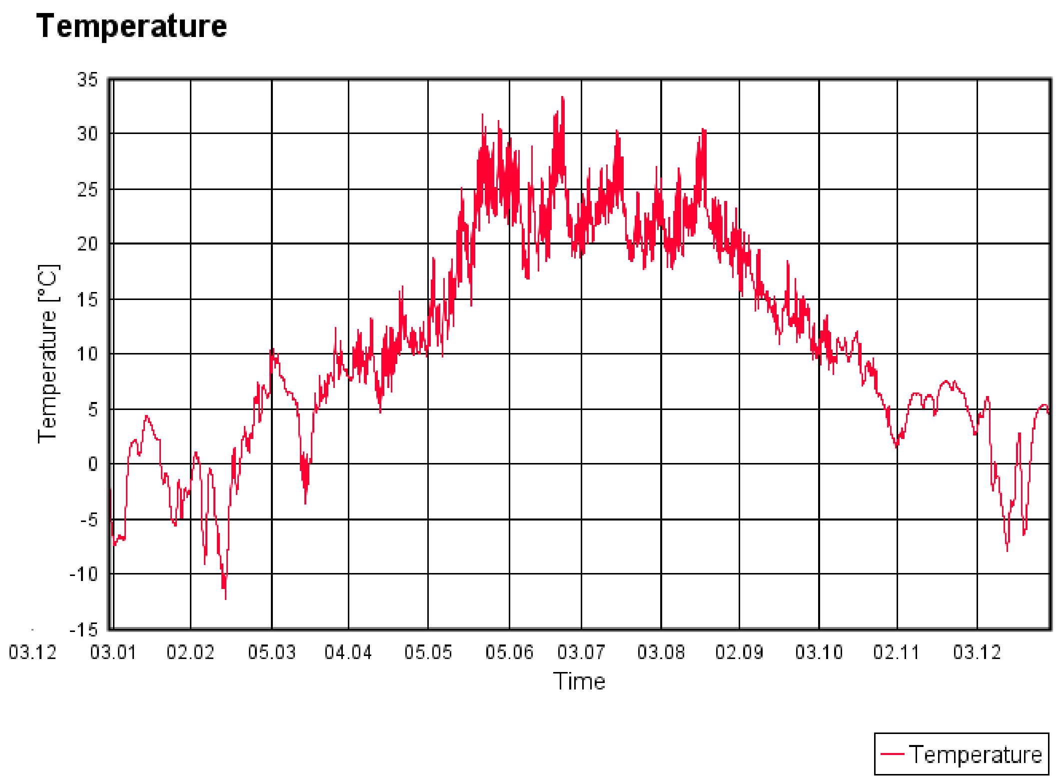
Appendix 5 Critical point between Isoprotect board and 50 mm sarking insulation.



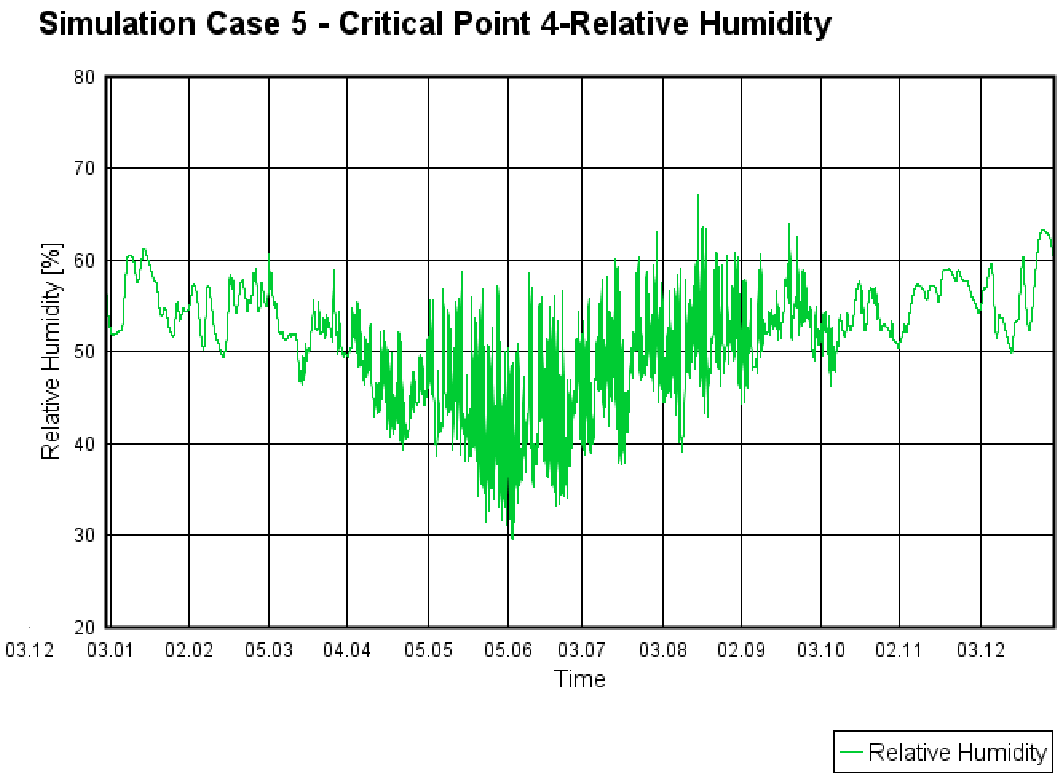


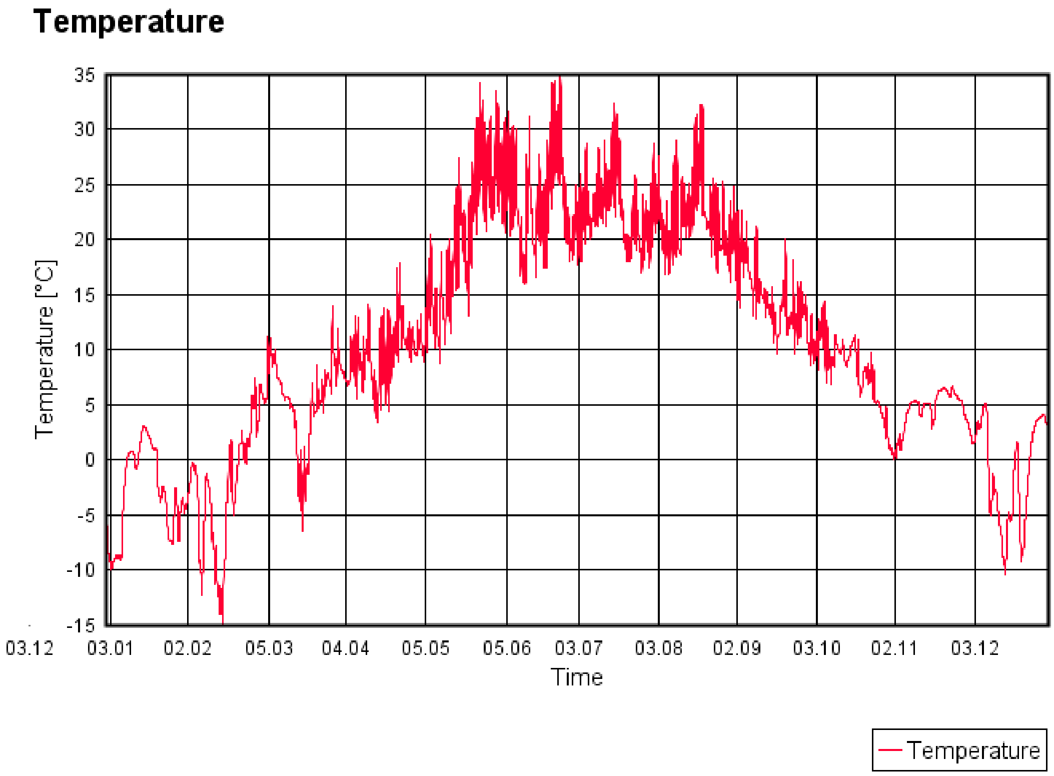
Appendix 6 Critical point between Isoprotect board and LVL.





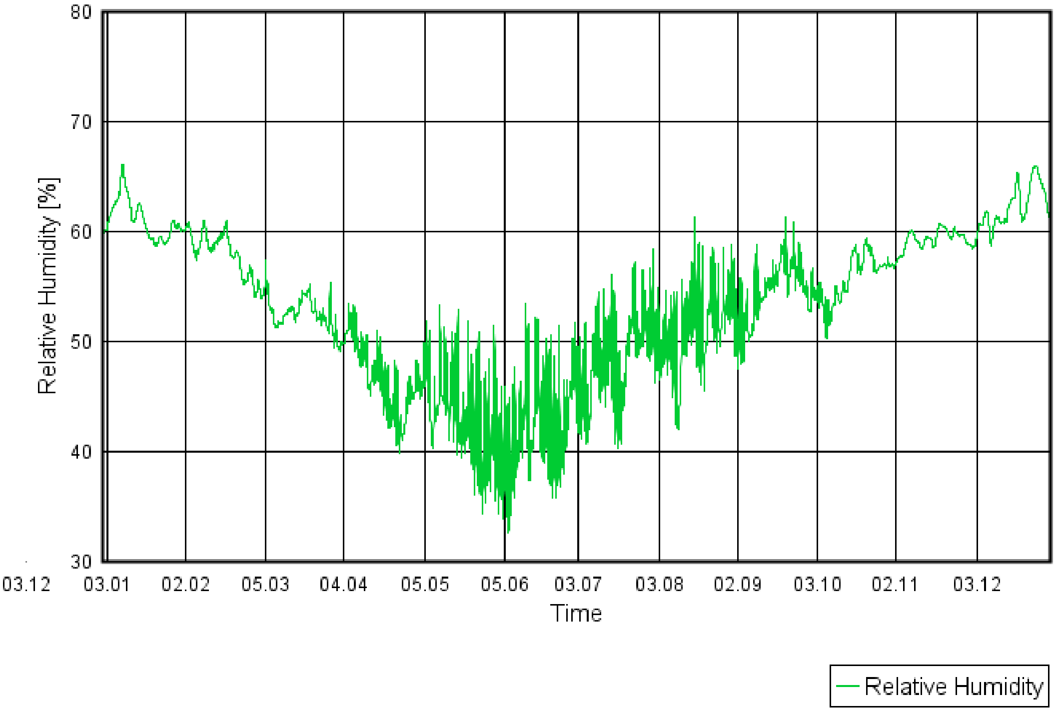
Appendix 7 Critical point between Isoprotect board, main insulation and LVL.



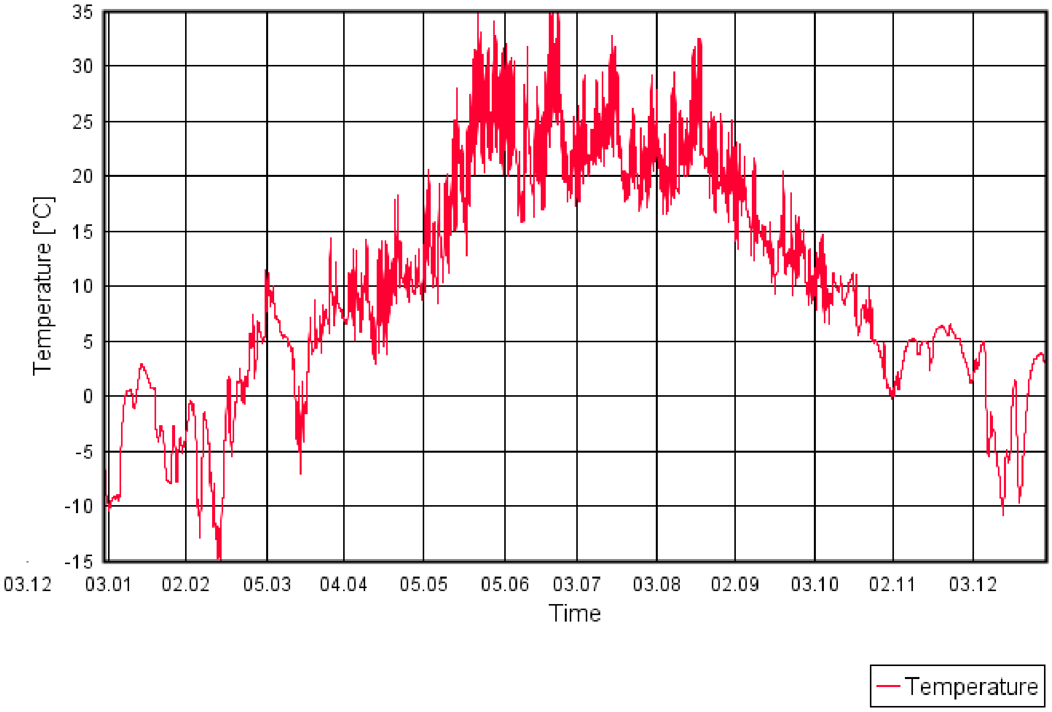


Appendix 8 Critical point between LVL and gypsum board.

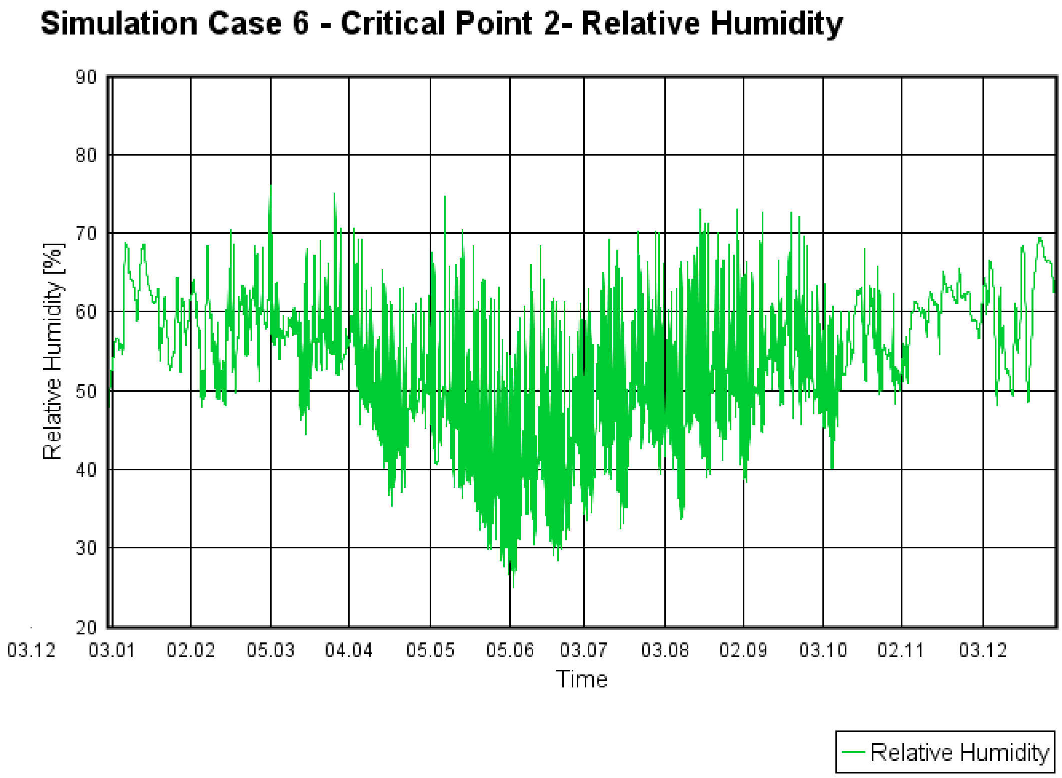
Simulation Case 5 - Critical Point 5- Relative Humidity

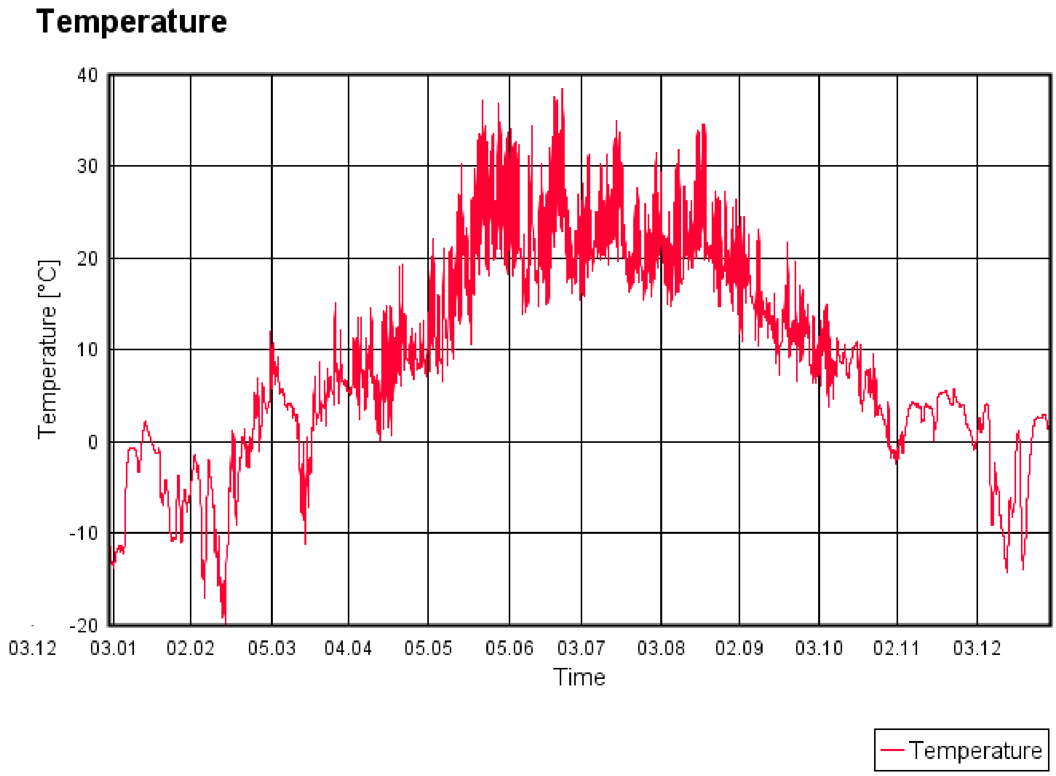


Temperature

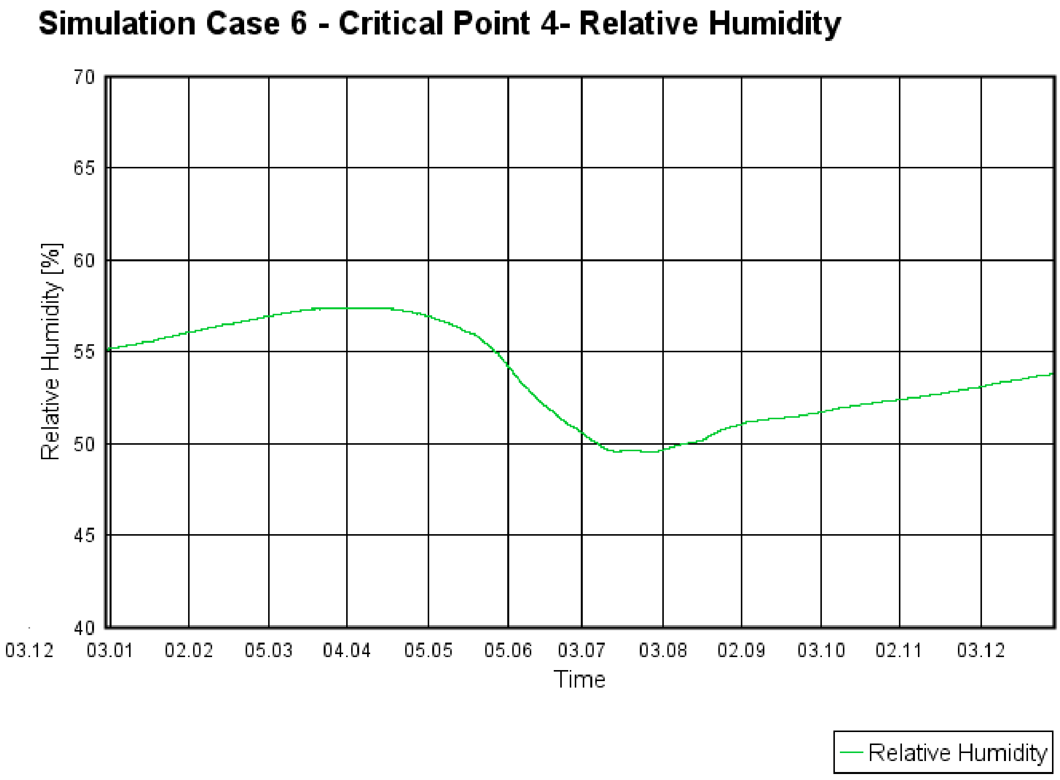


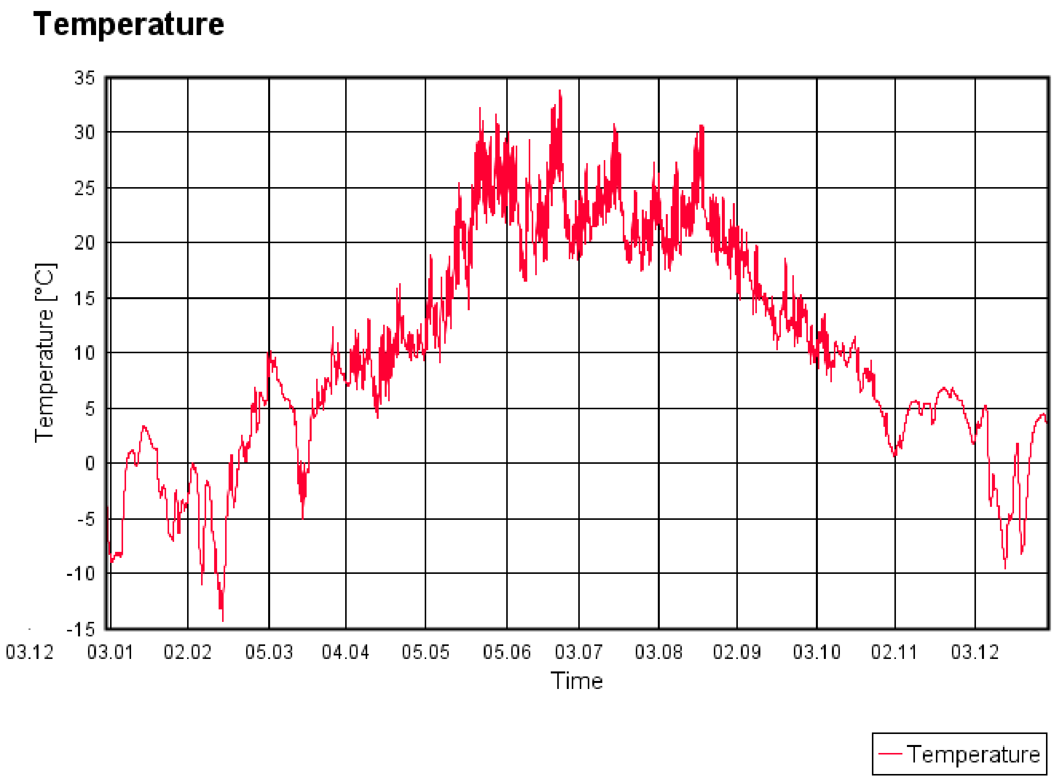
Appendix 9 Critical point between gypsum board, main insulation and LVL.



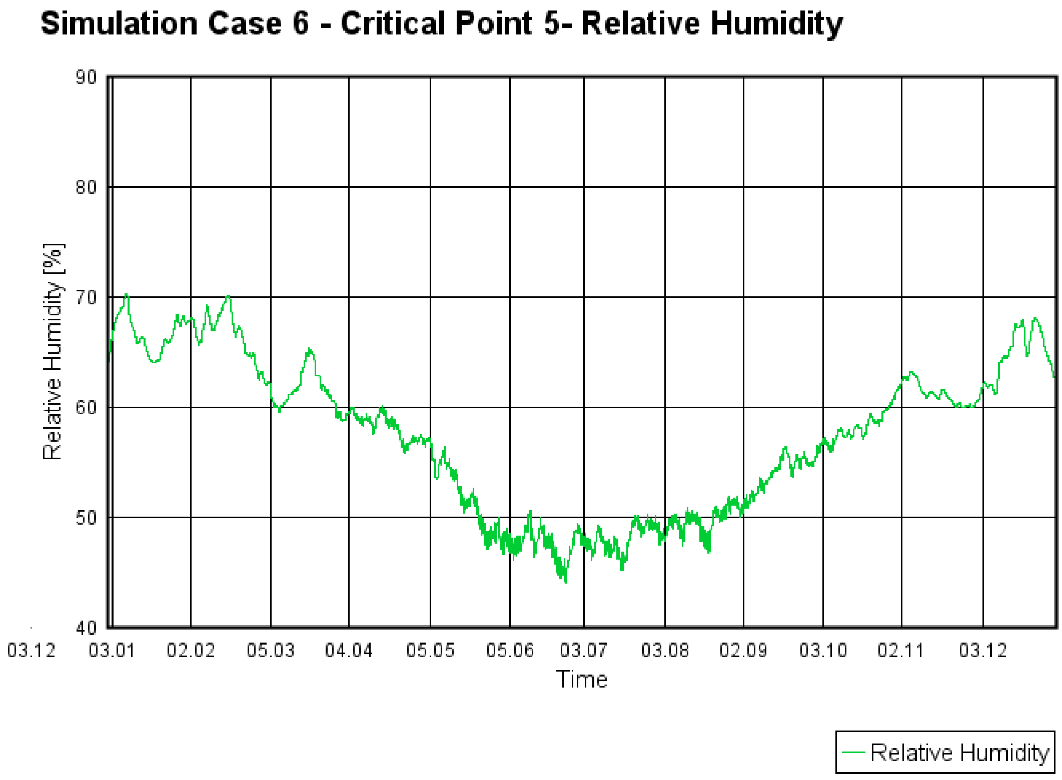


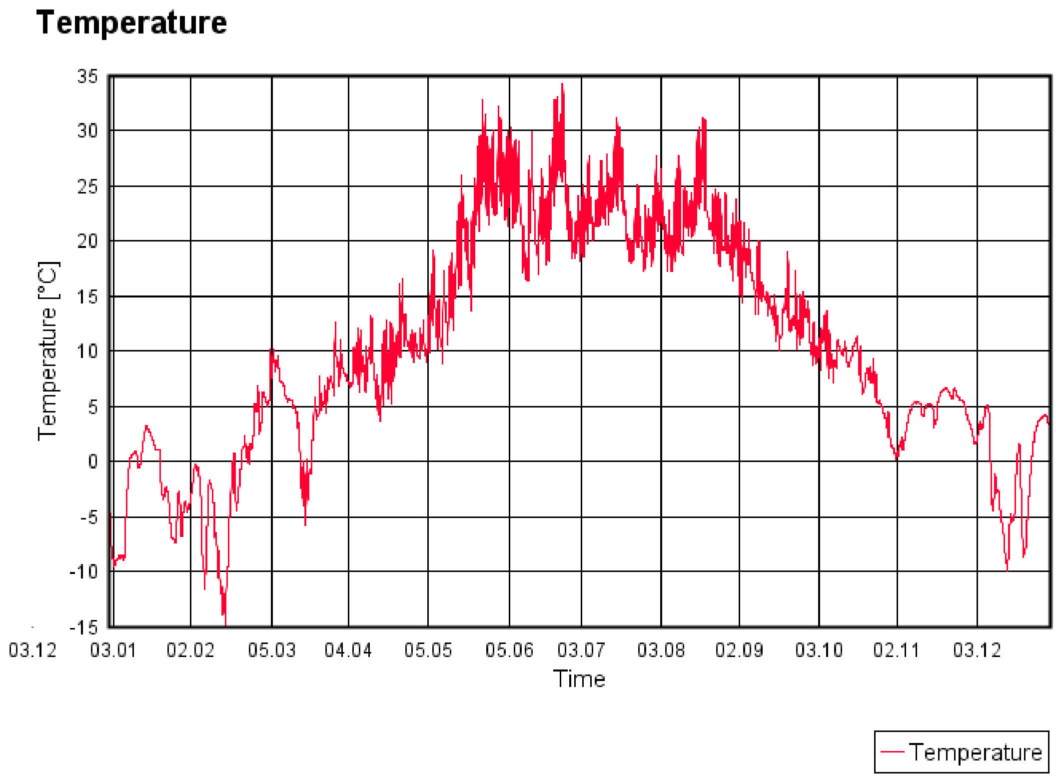
Appendix 10 Critical point between 50mm sarking insulation and plywood.





Appendix 11 Critical point between LVL and plywood.



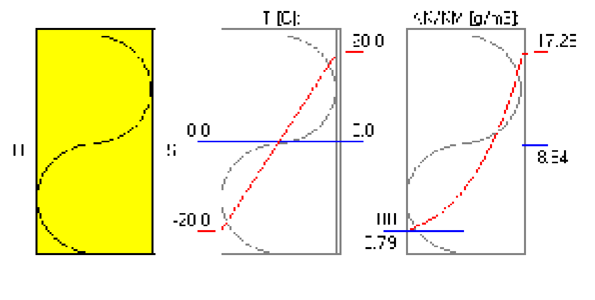


Appendix 12 Critical point between plywood board, main insulation and LVL.

Rakennuskohde:	Sisältö:	
ISOVER - Rakennekirjasto	Lämpimän tilan yläpohja	
Suunnittelija:	Päiväys:	Tunnus:
ISOVER	10/7/2016	Reference st

Rakenteen päätiedot:

U-arvo:	0.094 W/m2K
Paksuus:	504.200 mm
Pinta-ala:	1.00 m2
Paino:	9.01 kg
Hinta:	0.00 euro
Vesihöyryn vastus:	7.086e+04 m2hPa/g
Vesih. läpäisykerroin:	1.411e-05 g/m2hPa
Lämmönvastus:	10.637 m2K/W
Pintavastus, ulko:	0.100 m2K/W
Pintavastus, sisä:	0.100 m2K/W
Kulma (0-90):	15.000



Rakenteen kerrostiedot: Kerrokset ulkoa (U) sisälle (S)

	KERROS:	T [mm]:	LJ [W/mK]:	VHV [m]	Hinta [e/m3]:	Paino [kg/m3]:
1	Underlay	1.00	1.0000	2.000000e-01	0.00	0.00
2	ISOVER KL-37	490.00	0.0370	6.857143e-01	0.00	0.00
3	Vapour barrier	0.20	1.0000	5.000000e+01	0.00	0.00
4	Gypsum board	13.00	0.2500	1.300000e-01	0.00	693.00

	KYLMÄSILTA:	LJ [W/mK]:	SPA [%]:	Hinta [e/m3]:	Paino [kg/m3]:	LK [W/K](kpl):
2	LVL beam cc900	0.1300	5.6	0.00	0.00	---

T = Paksuus, LJ = Lämmönjohtavuus, VHL = Vesihöyryn läpäisevyys, SPA=Suht. pinta-ala, LK = Lisäkonduktanssi

Lämpötilat ja kosteudet: **3:n päivän kylmin (0.0 h)**

Piste:	T [C]:	KK [g/m3]:	KM [g/m3]:	SK [%]:	C [g/m2]:
U	-20.00	0.88	0.79	90.0	0.00
1	-19.70	0.90	0.79	87.6	0.00
2	-19.70	0.90	0.82	90.9	0.00
3	19.55	16.84	0.93	5.5	0.00
4	19.55	16.84	8.62	51.2	0.00
5	19.70	16.99	8.64	50.9	0.00
S	20.00	17.29	8.64	50.0	0.00

T=Lämpötila, KK=Kyllästymiskosteus, KM=Kosteusmäärä, SK=Suhteellinen kosteus

Lisätiedot:

U-arvossa mukana korjaustermi:
Ei yhtenäistä kylmäsillan katkaisevaa eristekerrosta = 0.010 W/m2K
Tässä rakenteessa on kantava kertopuurunko, joka on koko kattorakenteen korkuinen.

Rakenneosan sisä- ja ulkopuolinen lämmönvastus; Rsi=Rse=0,10 m2K/W. Rakennekerrokset rajoittuvat ulkopinnaltaan hyvin tuulettuvaan ilmakerrokseen.

U-arvon vertailuarvo lämpimän tilan yläpohjalle (RakMK C3 2010): 0,09 W/m2K.

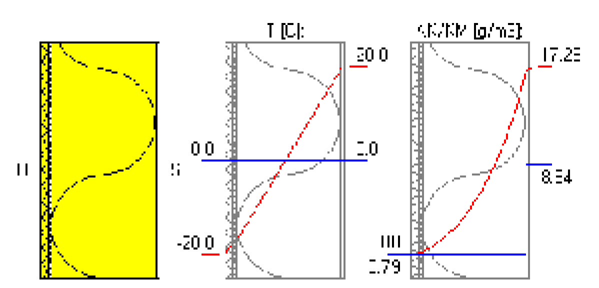
C:\Users\A0380196\Documents\Tuotekehitys\Kattotuotteet\Sarking Board\Opinnäytetyö\Rakenteet\Reference structure.LAM

Appendix 13 U - value calculation of reference roof model.

Rakennuskohde:	Sisältö:	
ISOVER - Rakennekirjasto	Lämpimän tilan yläpohja	
Suunnittelija:	Päiväys:	Tunnus:
ISOVER	10/7/2016	30+400 sarki

Rakenteen päätiedot:

U-arvo:	0.094 W/m2K
Paksuus:	455.200 mm
Pinta-ala:	1.00 m2
Paino:	15.01 kg
Hinta:	0.00 euro
Vesihöyryn vastus:	7.071e+04 m2hPa/g
Vesih. läpäisykerroin:	1.414e-05 g/m2hPa
Lämmönvastus:	10.652 m2K/W
Pintavastus, ulko:	0.100 m2K/W
Pintavastus, sisä:	0.100 m2K/W
Kulma (0-90):	15.000



Rakenteen kerrostiedot: Kerrokset ulkoa (U) sisälle (S)

	KERROS:	T [mm]:	LJ [W/mK]:	VHV [m]	Hinta [e/m3]:	Paino [kg/m3]:
1	Sarking insulation	30.00	0.0370	9.523810e-02	0.00	0.00
2	Plywood	12.00	---	---	0.00	500.00
3	ISOVER KL-37	400.00	0.0370	6.857143e-01	0.00	0.00
4	Vapour barrier	0.20	1.0000	5.000000e+01	0.00	0.00
5	Gypsum board	13.00	0.2500	1.300000e-01	0.00	693.00

	KYLMÄSILTA:	LJ [W/mK]:	SPA [%]:	Hinta [e/m3]:	Paino [kg/m3]:	LK [W/K](kpl):
3	LVL beam cc900	0.1300	5.6	0.00	0.00	---

T = Paksuus, LJ = Lämmönjohtavuus, VHL = Vesihöyryn läpäisevyys, SPA=Suht. pinta-ala, LK = Lisäkonduktanssi

Lämpötilat ja kosteudet: **3:n päivän kylmin (0.0 h)**

Piste:	T [C]:	KK [g/m3]:	KM [g/m3]:	SK [%]:	C [g/m2]:
U	-20.00	0.88	0.79	90.0	0.00
1	-19.66	0.91	0.79	87.2	0.00
2	-16.93	1.16	0.81	69.3	0.00
3	-16.93	1.16	0.81	69.3	0.00
4	19.49	16.77	0.91	5.4	0.00
5	19.49	16.78	8.62	51.4	0.00
6	19.66	16.95	8.64	51.0	0.00
S	20.00	17.29	8.64	50.0	0.00

T=Lämpötila, KK=Kyllästymiskosteus, KM=Kosteusmäärä, SK=Suhteellinen kosteus

Lisätiedot:

Tässä rakenteessa on kantava kertopuurunko, joka on koko kattorakenteen korkuinen.

Rakenneosan sisä- ja ulkopuolinen lämmönvastus; Rsi=Rse=0,10 m2K/W. Rakennekerrokset rajoittuvat ulkopinnaltaan hyvin tuulettuvaan ilmakerrokseen.

U-arvon vertailuarvo lämpimän tilan yläpohjalle (RakMK C3 2010): 0,09 W/m2K.

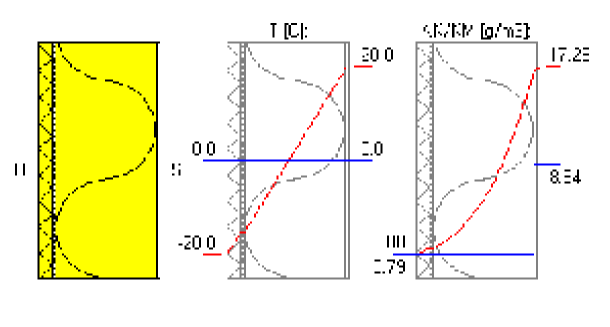
C:\Users\A0380196\Documents\Tuotekehitys\Kattotuotteet\Sarking Board\Opinnäytetyö\Rakenteet\Sarking insulation 30mm.LAM

Appendix 14 - value calculation of sarking roof model with 30 mm sarking insulation and 400mm main insulation.

Rakennuskohde:	Sisältö:	
ISOVER - Rakennekirjasto	Lämpimän tilan yläpohja	
Suunnittelija:	Päiväys:	Tunnus:
ISOVER	10/7/2016	50+380 sarki

Rakenteen päätiedot:

U-arvo:	0.093 W/m2K
Paksuus:	455.200 mm
Pinta-ala:	1.00 m2
Paino:	15.01 kg
Hinta:	0.00 euro
Vesihöyryn vastus:	7.071e+04 m2hPa/g
Vesih. läpäisykerroin:	1.414e-05 g/m2hPa
Lämmönvastus:	10.753 m2K/W
Pintavastus, ulko:	0.100 m2K/W
Pintavastus, sisä:	0.100 m2K/W
Kulma (0-90):	15.000



Rakenteen kerrostiedot: Kerrokset ulkoa (U) sisälle (S)

	KERROS:	T [mm]:	LJ [W/mK]:	VHV [m]	Hinta [e/m3]:	Paino [kg/m3]:
1	Sarking insulation	50.00	0.0370	9.523810e-02	0.00	0.00
2	Plywood	12.00	---	---	0.00	500.00
3	ISOVER KL-37	380.00	0.0370	6.857143e-01	0.00	0.00
4	Vapour barrier	0.20	1.0000	5.000000e+01	0.00	0.00
5	Gypsum board	13.00	0.2500	1.300000e-01	0.00	693.00

	KYLMÄSILTA:	LJ [W/mK]:	SPA [%]:	Hinta [e/m3]:	Paino [kg/m3]:	LK [W/K](kpl):
3	LVL beam cc900	0.1300	5.6	0.00	0.00	---

T = Paksuus, LJ = Lämmönjohtavuus, VHL = Vesihöyryn läpäisevyys, SPA=Suht. pinta-ala, LK = Lisäkonduktanssi

Lämpötilat ja kosteudet: **3:n päivän kylmin (0.0 h)**

Piste:	T [C]:	KK [g/m3]:	KM [g/m3]:	SK [%]:	C [g/m2]:
U	-20.00	0.88	0.79	90.0	0.00
1	-19.66	0.91	0.79	87.2	0.00
2	-15.11	1.37	0.81	58.9	0.00
3	-15.11	1.37	0.81	58.9	0.00
4	19.49	16.77	0.91	5.4	0.00
5	19.49	16.78	8.62	51.4	0.00
6	19.66	16.95	8.64	51.0	0.00
S	20.00	17.29	8.64	50.0	0.00

T=Lämpötila, KK=Kyllästymiskosteus, KM=Kosteusmäärä, SK=Suhteellinen kosteus

Lisätiedot:

Tässä rakenteessa on kantava kertopuurunko, joka on koko kattorakenteen korkuinen.

Rakenneosan sisä- ja ulkopuolinen lämmönvastus; Rsi=Rse=0,10 m2K/W. Rakennekerrokset rajoittuvat ulkopinnaltaan hyvin tuulettuvaan ilmakerrokseen.

U-arvon vertailuarvo lämpimän tilan yläpohjalle (RakMK C3 2010): 0,09 W/m2K.

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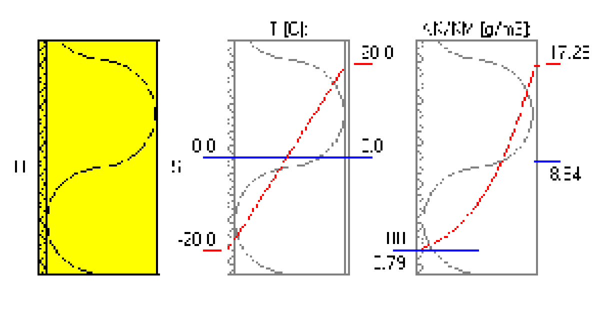
Appendix 15 U-value calculation of sarking roof model with 50mm sarking insulation and 380mm main insulation.

Rakennuskohde: ISOVER	Sisältö:	
Suunnittelija: ISOVER	Päiväys: 1/24/2017	Tunnus: 30+460 sarki

Rakenteen päätiedot:

U-arvo:	0.083 W/m2K
Paksuus:	504.200 mm
Pinta-ala:	1.00 m2
Paino:	9.01 kg
Hinta:	0.00 euro
Vesihöyryn vastus:	7.099e+04 m2hPa/g
Vesih. läpäisykerroin:	1.409e-05 g/m2hPa
Lämmönvastus:	12.080 m2K/W
Pintavastus, ulko:	0.100 m2K/W
Pintavastus, sisä:	0.100 m2K/W
Kulma (0-90):	15.000



Rakenteen kerrostiedot: Kerrokset ulkoa (U) sisälle (S)

	KERROS:	T [mm]:	LJ [W/mK]:	VHV [m]	Hinta [e/m3]:	Paino [kg/m3]:
1	Underlay	1.00	1.0000	2.000000e-01	0.00	0.00
2	Sarking insulation	30.00	0.0370	9.523810e-02	0.00	0.00
3	ISOVER KL-37	460.00	0.0370	6.857143e-01	0.00	0.00
4	Vapour barrier	0.20	1.0000	5.000000e+01	0.00	0.00
5	Gypsum board	13.00	0.2500	1.300000e-01	0.00	693.00

	KYLMÄSILTA:	LJ [W/mK]:	SPA [%]:	Hinta [e/m3]:	Paino [kg/m3]:	LK [W/K](kpl):
3	LVL beam cc900	0.1300	5.6	0.00	0.00	---

T = Paksuus, LJ = Lämmönjohtavuus, VHL = Vesihöyryn läpäisevyys, SPA=Suht. pinta-ala, LK = Lisäkonduktanssi

Lämpötilat ja kosteudet: **3:n päivän kylmin (0.0 h)**

Piste:	T [C]:	KK [g/m3]:	KM [g/m3]:	SK [%]:	C [g/m2]:
U	-20.00	0.88	0.79	90.0	0.00
1	-19.70	0.90	0.79	87.6	0.00
2	-19.70	0.90	0.82	90.9	0.00
3	-17.30	1.13	0.84	74.3	0.00
4	19.55	16.84	0.94	5.6	0.00
5	19.55	16.84	8.62	51.2	0.00
6	19.70	16.99	8.64	50.9	0.00
S	20.00	17.29	8.64	50.0	0.00

T=Lämpötila, KK=Kyllästymiskosteus, KM=Kosteusmäärä, SK=Suhteellinen kosteus

Lisätiedot:

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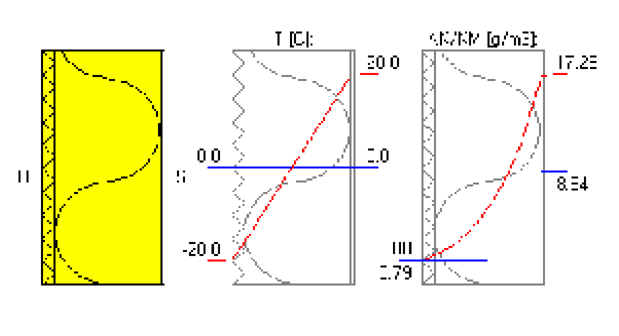
Appendix 16 U-value calculation after addition of 30mm sarking insulation on reference roof model.

Rakennuskohde: ISOVER	Sisältö:	
Suunnittelija: ISOVER	Päiväys: 1/24/2017	Tunnus: 50+440 sarki

Rakenteen päätiedot:

U-arvo:	0.082 W/m2K
Paksuus:	504.200 mm
Pinta-ala:	1.00 m2
Paino:	9.01 kg
Hinta:	0.00 euro
Vesihöyryn vastus:	7.099e+04 m2hPa/g
Vesih. läpäisykerroin:	1.409e-05 g/m2hPa
Lämmönvastus:	12.183 m2K/W
Pintavastus, ulko:	0.100 m2K/W
Pintavastus, sisä:	0.100 m2K/W
Kulma (0-90):	15.000



Rakenteen kerrostiedot: Kerrokset ulkoa (U) sisälle (S)

	KERROS:	T [mm]:	LJ [W/mK]:	VHV [m]	Hinta [e/m3]:	Paino [kg/m3]:
1	Underlay	1.00	1.0000	2.000000e-01	0.00	0.00
2	Sarking insulation	50.00	0.0370	9.523810e-02	0.00	0.00
3	ISOVER KL-37	440.00	0.0370	6.857143e-01	0.00	0.00
4	Vapour barrier	0.20	1.0000	5.000000e+01	0.00	0.00
5	Gypsum board	13.00	0.2500	1.300000e-01	0.00	693.00

	KYLMÄSILTA:	LJ [W/mK]:	SPA [%]:	Hinta [e/m3]:	Paino [kg/m3]:	LK [W/K](kpl):
3	LVL beam cc900	0.1300	5.6	0.00	0.00	---

T = Paksuus, LJ = Lämmönjohtavuus, VHL = Vesihöyryn läpäisevyys, SPA=Suht. pinta-ala, LK = Lisäkonduktanssi

Lämpötilat ja kosteudet: **3:n päivän kylmin (0.0 h)**

Piste:	T [C]:	KK [g/m3]:	KM [g/m3]:	SK [%]:	C [g/m2]:
U	-20.00	0.88	0.79	90.0	0.00
1	-19.70	0.90	0.79	87.6	0.00
2	-19.70	0.90	0.82	90.9	0.00
3	-15.70	1.30	0.84	64.4	0.00
4	19.55	16.84	0.94	5.6	0.00
5	19.55	16.84	8.62	51.2	0.00
6	19.70	16.99	8.64	50.9	0.00
S	20.00	17.29	8.64	50.0	0.00

T=Lämpötila, KK=Kyllästymiskosteus, KM=Kosteusmäärä, SK=Suhteellinen kosteus

Lisätiedot:

C:\Users\A0380196\Documents\Tuotekehitys\Kattotuotteet\Sarking Board\Opinnäytetyö\24.1.2017\440_50 sarking.LAM

Appendix 17 U-value calculation after addition of 50mm sarking insulation on reference roof model.