MASTER

Hygrothermal risk assessment after insulating ground floors using whole building simulation

Donkervoort, Roger

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Roger Donkervoort (0887242)

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Supervisors:

Dr. ir. H. L. Schellen

Dr. ir. L. C. Havinga

Dr. ir. T. A. J. van Hooff

Dr. F. Gauvin

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Abstract

In order to limit global warming, greenhouse gas emissions should be reduced. The building sector is responsible for a large portion of the global energy-related CO_2 emissions. Most of these emissions are caused by heating, cooling, and ventilating buildings. Heat demand is the most prominent. Roughly 12.5% of the heat losses occur through the floor. Suspended ground floor constructions with a crawl space are common throughout Europe. Currently, While the insulation status of these floors is poorly recorded, it is estimated that there are still millions of uninsulated ground floors throughout Europe. Insulating the uninsulated floors is likely to lead to a large carbon emission reduction. However, insulating constructions might introduce hygrothermal risks to constructions and could cause health risks for their occupants for example in the form of mould.

To get insight into the risks that come with insulating ground floors, a case study was conducted in which the crawl space conditions of a dwelling were simulated through whole building simulation and compared to real-world measurements obtaining very similar results. The comparison was then used to validate the model used to simulate the crawl space conditions.

The model was then used to simulate different insulation strategies. With this model the effect of the insulation strategies on the crawl space conditions was predicted. These different strategies include bottom insulation compared to ground floor insulation underneath a wooden floor. Furthermore, the effect of vapour tight ground covers and ventilation were simulated. The results from the variant study showed less hygrothermal risk in the variants with bottom insulation due to a lower relative humidity (RH) due to higher temperatures. However, these variants showed only little energy savings with a maximum of 3% compared to an uninsulated variant.

A higher RH has the potential to cause hygrothermal issues like wood rot and mould growth, especially in construction joints. Ground floor insulation showed to yield more energy savings (roughly 11%). However, ground floor insulation results in a higher RH in crawl spaces. Even higher if it is done without a vapour tight ground cover. During the summer when the air outside contains more moisture, the RH was at its highest in most cases.

Contents

Chapter 1: Introduction

1.1. Background

Back in the year 2015, the Paris agreement was adopted. In the Paris agreement, 196 countries agreed on limiting global warming to a maximum of 2°C compared to pre-industrial conditions (UNFCCC, 2020). To achieve this temperature goal, countries should reduce their greenhouse gas emissions.

The residential buildings alone account for 17% of all the global energy-related CO_2 emissions and 22% of the global primary energy usage (GlobalABC, 2020). This energy is mostly used to condition the interior climate by heating, cooling, and ventilation (Jones, 2011). At this moment, building heat demands account for a significant part of the total energy use in Europe (Persson et al., 2015). Therefore, thermally retrofitting the existing buildings seems to be a good solution to improve the environmental performance of the building sector (Far et al., 2018).

The total heat loss of a building consists of more than 81% of heat losses through the building envelope, the remaining part is accounted for by ventilation heat loss (Najjar, 2019). This 81% can be divided into four categories: Floor, exterior walls, roof, and openings. They account for 15.75%, 19.87%, 12.88%, and 51.50% of the heat loss through the building envelope (Najjar, 2019).

Nowadays, there is a lot of research being conducted related to building energy savings and the hygrothermal risks that are introduced when adding insulation to buildings. However, these studies focus almost entirely on exterior walls while the heat loss caused by the floor is only slightly lower. Therefore, this study will focus on ground floor insulation and the hygrothermal risks that come with it.

In Europe, Suspended timber ground floor constructions used to be the most common ground floor construction for family dwellings. However, they have nowadays been replaced by solid concrete floors as the most common ground floor construction (Westoby, 1958). Nevertheless, suspended timber ground floor constructions are common throughout Europe (Pelsmakers et al., 2019). This is due to the long lifespan of buildings. For example, in the UK alone there are an estimated 10 million uninsulated suspended timber ground floors (Power, 2008; Dowson et al., 2012).

In 2009 a study was conducted to assess the insulation status among western European countries. A total of eight countries were included in this research. These countries are Austria, Finland, France, Germany, The Netherlands, Sweden, Switzerland, and the UK. In the Netherlands, only 43% of the ground floors are insulated. Similarly, in Austria, this percentage lies somewhere between 30% and 60% (Meijer et al., 2009). While in Finland the number is somewhere between 50 and 100% and in Sweden, it is stated that a "high" percentage of the floors are insulated (Meijer et al., 2009). From the other countries, there is no data available on the ground floors.

It can be stated that the number of insulated and uninsulated floors in many regions is not well recorded at this moment (Meijer et al., 2009). Many of the insulation percentages in the studies are obtained through estimations by experts. Furthermore, it should also be noted that the quality of insulation is not included in these data (Meijer et al., 2009).

Insulating the previously mentioned millions of uninsulated suspended timber floors is likely to lead to a significant reduction in carbon emissions (Shorrock et al., 2005). Additionally, occupant thermal comfort of the building might be improved by insulating floors (Pelsmakers, 2016; HE, 2010).

Furthermore, when adding insulation, ventilation paths might be altered. Adding insulating materials might improve the airtightness of the construction by filling gaps and cracks and thus reduce airflow from the crawl space to the living areas above it (Pelsmakers, 2016; HE, 2010). This is a positive side effect since argon gas (and potential mould particles) finds more resistance to enter the living environment.

Despite these advantages, adding insulation materials to a ground floor is not completely without risk. Insulation of ground floors can lead to moisture-related problems such as mould growth or wood decay. Mould growth in the crawl space can affect occupant health because mould spores could travel to the living area above the crawl space (Airaksinen et al., 2003).

Obstructing or reducing crawl space ventilation might lead to moisture problems in the crawl space (Rickaby, 2014; EST, 2006). Reduced crawl space ventilation can occur when blocking, or partially blocking, airbricks or air ducts with insulating material. This is sometimes done intentionally, to limit heat losses, or unintentionally due to poor placement of the insulation material.

Finally, insulating ground floors leads to reduced heat loss to the crawl space, which in return leads to higher relative humidity (RH) due to a lower temperature in the crawl space. This could result in moisture problems during the summer due to the crawl spaces being colder (Kurnitski, 2000). A common problem that could be avoided by insulating the bottom of your crawl space instead of the ground floor itself.

Due to the variety of risks and benefits previously mentioned that come with insulating ground floors (and the necessity to do so to reduce energy usage and limit carbon emissions), it is important to be able to predict the post-insulated hygrothermal conditions in a crawl space (Pelsmakers et al., 2019). This can be done using whole building simulation software (Vanhoutteghem et al., 2017). However further work on validating such simulations should be conducted.

Therefore, in this study, further validation work is done on the case study of Vanhoutteghem (Vanhoutteghem et al., 2017). However, EnergyPlus with the HAMT module will be used as a whole building simulation model instead of the Bsim simulation model which was used by Vanhoutteghem. This is because HAMT EnergyPlus has great modelling potential and is open-source software (Simon Pallin, 2017).

Besides performing further validation work, this study will also perform a variant study. The goal of the variant study is to gain insight into which insulation strategies cause the least hygrothermal issues. There is a variety of ways to insulate ground floors. For example, the bottom of a crawl space itself can be insulated. Alternatively, insulation materials might be added to the floor construction. In addition to this, there is a wide range of insulation materials that can be used. Lastly, vapour tight ground covers can be used in combination with insulation.

A validated whole building model can be used to give insight into the hygrothermal risks that come with the variety of different insulation methods. "Knowledge of the pre- and post-insulated hygrothermal floor void conditions is of great importance to avoid structural damage and health issues" (Pelsmakers et al., 2019). Therefore, in this study, a variety of different insulation strategies are simulated using a whole building simulation model.

1.2. Research aims and objectives

Insulating the existing building stock will lead to a large reduction in energy usage and therefore a reduction in carbon emissions. Despite the focus on the insulation of uninsulated buildings, there has not been a paid lot of attention to the insulation of ground floors in terms of hygrothermal risks. In the current literature, the main focus is on the insulation of facades and walls. This study aims to determine if ground floor conditions can be simulated with a whole building simulation model. Then use the model to gain an understanding of which ground floor insulation strategies yield the lowest hygrothermal risks. For the sake of clarity, the research objectives are summed up below.

- To answer if whole building simulation can be used for hygrothermal simulations EnergyPlus and DesignBuilder were used to develop a model of a case study. This will then be compared to real-world measurements to validate the model.

- The model will provide different output variables. These contain among others temperature, RH, absolute humidity, air changes per hour (ach), energy consumption, temperature, and the moisture content of the ground floor. These variables are analyzed to assess the hygrothermal risks. Literature was consulted to provide methods to do so.

- Furthermore, a variant study will be conducted to investigate the hygrothermal risks that come with different insulation strategies. The variant study will use the EnergyPlus model. In this variant study, the effect of vapour tight ground covers, ventilation reduction, soil moisture content, and bottom insulation compared to insulation underneath the ground floor will be taken into account. This will be done in order to determine which insulation strategy has the lowest hygrothermal risk. The hygrothermal risks will be evaluated using the methods that will be covered in the section about what hygrothermal risks there are.

In order to be able to answer the various problems, the aim and objectives are translated into one research question with four sub-research questions.

Research question

- Can we simulate the influence of different floor insulation strategies to determine which strategy leads to the lowest hygrothermal risks using whole building simulations?

Research sub-questions

- Is whole building simulation an accurate way to simulate the crawl space hygrothermal conditions for ground floors?
- What different types of hygrothermal risks are of main concern for ground floors?
- How can we quantify these hygrothermal risks using whole building simulation?
- What are the effects of employing different insulation strategies on hygrothermal risks?

1.3. Methodology

There are four parts to the main research question. Firstly, we want to know whether or not it is possible to use whole building simulation to simulate the hygrothermal conditions of a ground floor with crawl space. This will be answered using measured data from a case study in comparison to our best efforts to simulate this case study using EnergyPlus. The second part is dedicated to what hygrothermal risks are of main concern to ground floors. The third part is about ways to quantify those risks. This should provide methods to analyse the hygrothermal risks. The fourth element of the question is: Which strategy leads to the lowest hygrothermal risk? This will be answered through a variant study.

in Chapter 2 an exploration of the available literature is provided. Chapter 2 will emphasize the purpose and relevance of this research.

Chapter 3 contains the case study. The case study should answer if it is possible to use whole building simulation to simulate the hygrothermal conditions of a ground floor. The objective is to compare the measured data with the simulated data and thus establish if this method is capable of performing these simulations.

Chapter 4 will cover the variant study. The variant study should answer which strategy would lead to the lowest hygrothermal risk. This will be done by simulation of different variants. Followed by an overview of which hygrothermal risks there are. Afterwards, methods that quantify those risks are presented

Chapter 5 will discuss the results derived from the case study and the variant study in the first paragraph. In the second paragraph, conclusions will be made to answer the research questions. Furthermore, some recommendations for future work will be done.

Chapter 2: Literature research

2.1. Literature study

Currently, there are many studies done in the area of building refurbishment and the hygrothermal risks that are introduced when adding insulation to buildings. However, a large amount of these studies specifically focus on walls or facades.

For example, 136 results are found when using the search engine Scopus with the search terms given in Table 1. Most of these studies have hygrothermal performance as their main research topic in relation to energy savings. However, some just include a brief mention of hygrothermal conditions. When the third category of search terms is stripped down to only "floor" and "crawl space", only twelve results show up of which five have the word wall or facade in the title. The remaining seven articles only mention hygrothermal performance or floors.

Table 1: search terms literature search

Category 1	Category 2	Category 3
hygrothermal	refurbish	roof
	retrofit	wall
	renovation	facade
	insula*	floor
		crawl space

It can also be observed that there is a rise in the amount of research conducted in the field of hygrothermal performance besides energy performance. From the aforementioned 136 results, almost all of the studies were done in the past 10 years. This is illustrated in Figure 1.

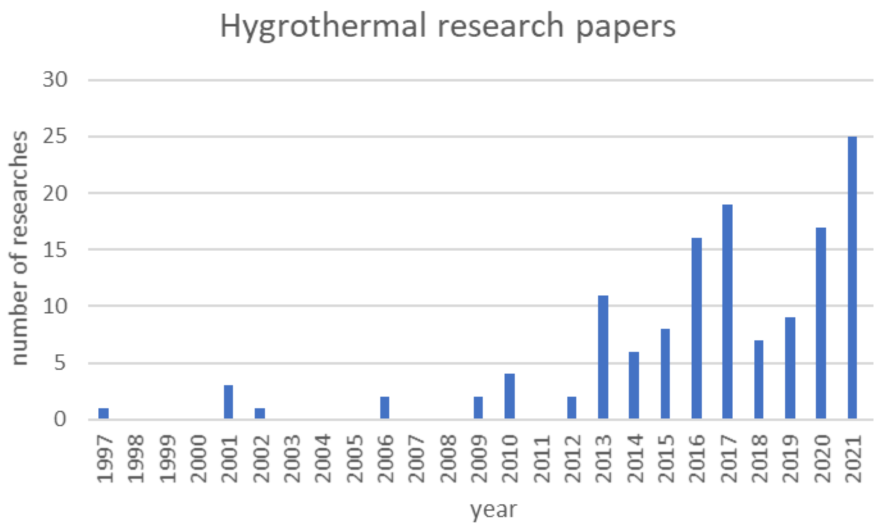

Figure 1: research output that mentions hygrothermal conditions (Using the search terms in Table 1)

It can be concluded that there is not a lot of research about the hygrothermal conditions of ground floors from the perspective of refurbishment or energy savings. Therefore, the search terms of category two from table 1 were taken out of the search query while category three was reduced to "floor" and "crawl space". This gave 103 search results out of which 24 results seem relevant. Those 24 results provided a good base for a literature search. Through means of snowballing and searches for often cited authors more research was found.

2.2. Literature results

It is not uncommon for hygrothermal problems to occur in buildings when they are insulated in a renovation process. Some studies keep an inventory of buildings in which insulation was added as part of a renovation project where mould growth is monitored. For example, in a recent study (Pelsmakers et al., 2019) fifteen ground floors were monitored, of which six were uninsulated and nine insulated. Most of the insulated floors exceed the critical thresholds for mould growth for significant periods (Pelsmakers et al., 2019).

Besides this, there is a rise in attention to the combination of hygrothermal research and energy savings. This is probably due to the variety of risks that come with insulating ground floors. Therefore, it is important to be able to predict the post-insulated hygrothermal conditions in a crawl space.

In literature, various research can be found by Matilainen (2003) and Kurnitski (2000) about the effects of ventilation and ground covers on a crawl space. For the variant study, it is important to understand the influence of certain changes. This can provide a way to understand if the model that is made for the case study also gives expected results in a variant study.

One of the best-known effects of outdoor ventilated crawl spaces is that in the summer moisture conditions can become a problem due to the crawl space remaining cold for a long time, because of the thermal mass of the ground. The outdoor air usually has a higher temperature and contains more moisture than the air in the crawl space. This causes moisture transport into the crawl space and can also potentially cause condensation (Matilainen & Kurnitski, 2003).

Furthermore, “Ground moisture evaporation has higher values in the winter than in the summer” (Matilainen & Kurnitski, 2003). Therefore, this effect might slightly mask the effect of the added moisture in the summer.

Ventilation of the crawl space to control RH is recommended (Kurnitski, 2000). “During the heating season an air change rate of 0.5–1.0 ach provided the driest conditions, but in the summer, it was necessary to use an air change rate of 2.0–5.0 ach to warm up the crawl space and to achieve acceptable conditions” (Kurnitski, 2000).

When focusing on the construction of the building, the location of the insulation on the base floor construction seems to have no effect on crawl space conditions. Placement of the insulation under or on top of the ground floor provided the same results (Matilainen & Kurnitski, 2003).

Furthermore, when looking at recommendations for insulation strategies for a crawl space, ground covers are recommended (Kurnitski, 2000). “The safest way to control moisture conditions in outdoor air-ventilated crawl spaces is to use highly insulating ground covers and a low air change rate” (Matilainen & Kurnitski, 2003).

Chapter 3: Case study

In this chapter, the first paragraph will describe the case study. In the second paragraph, the methodology of the case study will be explained. In the third paragraph, the settings and equations used will be presented. The fourth paragraph will show the results of the simulations. Finally, the fifth paragraph will show the validation of the results.

3.1. The building

For this case study, the measurement data from a suspended outdoor ventilated crawl space was used (Vanhoutteghem et al., 2017). Due to circumstances, it was not possible to conduct measurements ourselves. In the case study by Vanhoutteghem (2017), the temperature and humidity of a crawl space were monitored and later simulated, noting that further validation was necessary for their simulations.

The building in which the temperatures and RH were measured is located in Denmark near Annisse. In addition to this, it is important to mention that this building is located approximately 100 m distance from an inland lake. Therefore, the groundwater level is probably very high.

Besides the measured temperature and humidity in the crawl space, the weather data from a local weather station in Annisse was available. Therefore, this building was well suited to be used as a case study. In Figure 2 a floor plan of the ground floor is depicted. In Figure 3 a cross-section of the case study building is depicted.

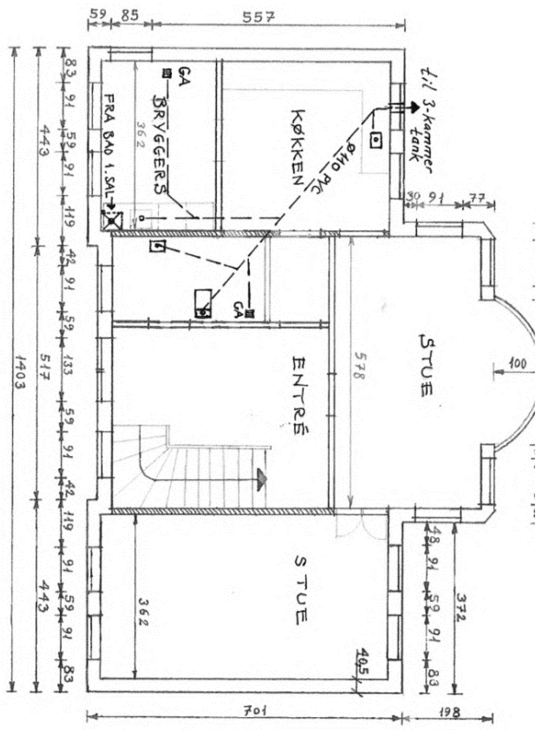

Figure 2: Floor plan Annisse building (Vanhoutteghem et al, 2017).

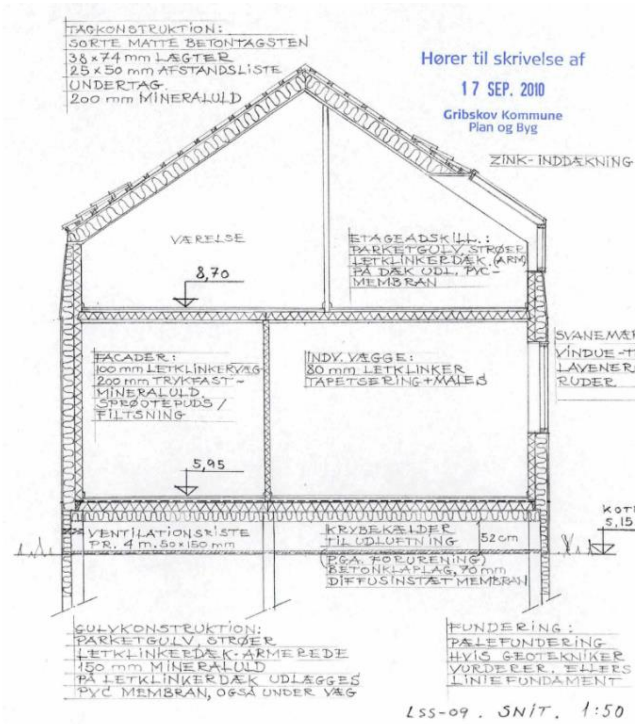

Figure 3: cross-section Annisse building (Vanhoutteghem et al, 2017).

3.2. Methodology

The goal of using this building as our case study is to build a model that is able to simulate the humidity and temperatures in the crawl space of this building. The model can then be compared to the real-world measurements provided by Vanhoutteghem (2017). This is to answer the first sub-research question: Is whole building simulation an accurate way to describe the crawl space conditions for ground floors? This methodology section describes the model, the calculation methods, and the software. Additionally, some uncertainties are discussed.

A general comparison between the measured data and the simulated data will later be provided in the results section. The inaccuracy of the resulting model will be measured and discussed in the validation section.

3.2.1. The schematization of HAM flows of the building

This section is dedicated to the description of the model. Figure 4 shows the simplified geometry used and the various HAM flows that were simulated. The materialization of the simplified geometry is added in appendix A1. When comparing the cross-section of the case study in Figure 3 with the schematization in Figure 4 it is apparent that the second floor is missing. The second floor was not simulated, because in the initial stage of this research certain information like the cross-section was not yet available. However, in this case, leaving the second floor out would have a neglectable impact on the simulation results of the temperature and humidity in the crawl space. Therefore, it is left out. The only reason to include it would be to get an accurate result of the energy usage of the building. But in order to get that, additional information about the heating system would have been required as well.

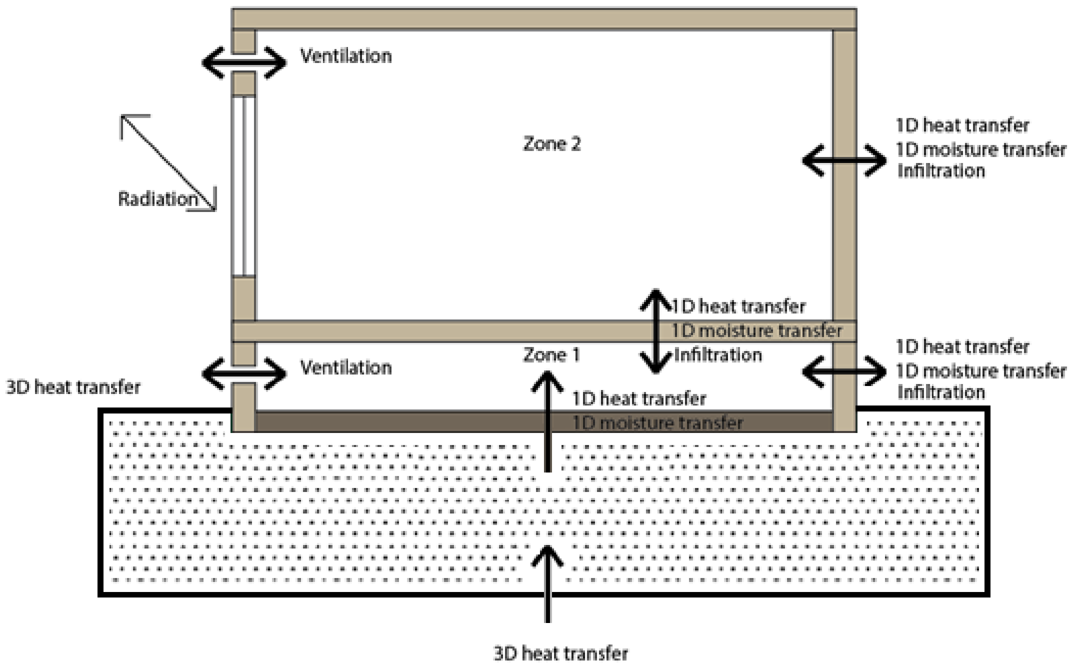

Figure 4: Schematization of the geometry in EnergyPlus and the HAMT flows through the building

The model contains two zones. Zone 1 is the crawl space and our main area of interest in this simulation. Zone 2 is the conditioned living space. The conditions are described in Table 2. In the floor between the zones, the infiltration that takes place through cracks is modelled using an airflow network (AFN). In this AFN the ventilation of both zones is also included. Zone 2 has mechanical ventilation whereas the crawl space in zone 1 is naturally ventilated. The HAMT module from EnergyPlus is used to simulate the heat and moisture flows through the facade and through the ground floor between the zones. In Section 3.2.2. the choice for the HAMT module is further explained. For the heat from the soil on the ground in the crawl space, a ground domain was used to calculate the surface temperatures. In Section 3.2.3. the usage of the ground domain will be further explained. In Section 3.2.4. the AFN will be explained.

Table 2: Conditioning zone 2

Settings	
Heating setpoint temperature	22 ^oC
Heating set back temperature	17 ^oC
Cooling setpoint temperature	24 ^oC
Cooling set back temperature	27 ^oC
Controlled minimum and maximum RH	0 – 100 %
Ventilation minimum	0.9 l/s per m^2 floor

3.2.2. Simulation software and solver methods

In the original case study from (Vanhoutteghem et al., 2017) the whole building simulation was done using Bsim. However, in this case study, EnergyPlus was used. EnergyPlus is the most used building performance simulation tool (Anh-Tuan Nguyen et al., 2014). Besides this, EnergyPlus contains four different solver methods of which two support moisture transfer. Furthermore, EnergyPlus is open-source which comes with certain advantages. One of these advantages is that there are third party programs that are attuned to EnergyPlus. One of these is DesignBuilder, a tool to design buildings. This was used to recreate the building. DesignBuilder was used because it has a clearer interface of the model settings than EnergyPlus itself. Afterwards, the simulations were done with EnergyPlus. The structure of how EnergyPlus and DesignBuilder work together is shown in appendix A2.

The four solver algorithms in EnergyPlus are a finite difference approach, a conduction transfer function (CTF), a combined heat and moisture finite element method (HAMT), and a moisture penetration depth conduction transfer function (EMPD).

CTFs calculate rapidly but do not calculate the coupled heat and moisture transfer inside the building envelopes (JunYang et al., 2015). Similarly, the default finite difference approach does not include moisture transfer. Therefore, these methods are not suitable for this research. A finite-element method like HAMT calculates the coupled heat and moisture transfer inside building envelopes and the interactions between the envelope and the environment. The only drawback is the longer computation time than simplified models (JunYang et al., 2015). EMPD is a compromise between the two methods. It is able to estimate moisture flows through a building with faster, but less accurate calculations (JunYang et al., 2015).

The HAMT module from EnergyPlus was eventually selected as the solver method for this research since accuracy is of high importance in this research. This solver method would also resemble Bsim the most.

3.2.3. Ground heat transfer

As previously stated, the ground temperatures are of great importance to the hygrothermal conditions of the crawl space. For the ground heat transfer, a ground domain is used which can be seen in Figure 5. The ground temperatures underneath the construction are calculated using the undisturbed ground temperature at a depth of ten meter. Furthermore, the outside weather conditions influence the temperatures inside the ground domain. These are included by simulating an area with a width of ten meters around the perimeter of the building.

"This model uses an implicit finite difference formulation to calculate the ground temperatures. The result is a stable simulation for all timesteps and grid sizes. However, an iteration loop is necessary to converge the temperatures in the ground domain for each timestep" (U.S. department of energy, 2022).

The final results of this 3D heat transfer calculation are the temperatures directly beneath the building. However, since these results are a temperature distribution located on a 2D plane (surface area of the crawl space), the average surface temperature is applied to the 1D HAMT module in the simulation.

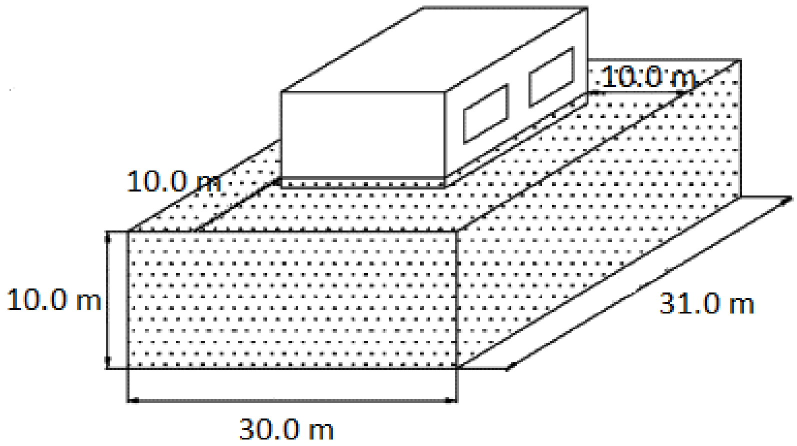

Figure 5: ground domain generated in DesignBuilder used in the EnergyPlus simulations

For the ground temperatures in the crawl space, the "Undisturbed Ground Temperature Model" developed by Xing was used. A ground domain in combination with Xing's method for calculating undisturbed ground temperatures was used because it is a relatively accurate ground-coupled heat transfer model with a low computational cost (Jia Yu. Et al, 2020). This model was developed using a numerical model for the estimations of ground temperatures (Xing et al, 2014). This model includes various aspects like soil freezing/thawing, snow accumulation, and melting at the ground surface.

Furthermore, this numerical model relies on general weather data which can be extracted from weather data files. With the weather data, a worldwide dataset of typical year ground temperatures was created by Xing (2014). The ground temperatures from the dataset are then used in the simplified design model using Equation 1. The specific data to enter per region is provided by Xing (Xing et al, 2014). Appendix A3 shows an example of some of this data. Appendix A4 shows the use of Equation 1 for two different locations.

$$T(z,t) = T_s - \sum_{n=1}^{2} \Delta T_{s,n} * e^{-z\sqrt{\frac{n\pi}{\alpha\tau}}} * cos\left[\frac{2\pi n}{\tau}(t-\theta_n) - z\sqrt{\frac{n\pi}{\alpha\tau}}\right] \quad (1)$$

T(z,t) is the undisturbed ground temperature as a function of time and depth, in ^{o}C

T_s is the average annual soil surface temperature, in ^{o}C

$\Delta T_{s,n}$ is the n-th amplitude of the soil temperature change throughout the year, in ^{o}C

θ_n is the n-th phase shift, or day of minimum surface temperature, in days

α is the thermal diffusivity of the ground, in m^2/day

τ is time constant, 365 days.

z is the depth, in m

3.2.4. Airflow network (AFN)

In literature, ventilation is often mentioned as one of the most important influencers of the crawl space condition (Kurnitski, 2000). It is even mentioned as one of the primary reasons for hygrothermal problems during the summer (Matilainen & Kurnitski, 2003). Often studies use various air change rates in their research. This is probably due to the difficulty of estimating ventilation rates.

In this case study, for example, 1.4 air changes per hour (ach) and 0.35 ach were used initially as a ventilation rate for the simulations in the summer and winter respectively. These air changes were adopted from earlier research on this case study by Vanhoutteghem (2017). These air changes were selected by Vanhoutteghem to best fit the simulated crawl space conditions with the measured conditions.

However, due to some temperature drops observed in the measured data, an AFN (airflow network) was considered, because this simulates the ventilation pressure dependent. It occurred that these rapid drops in crawl space temperatures coincided with moments of high wind speeds. These high wind speeds cause a larger pressure difference causing more ventilation of the crawl space with the air outside.

Using an AFN resulted in some drastically different air change rates for the crawl space. The ventilation rates are depicted in Figure 6. Figure 6 shows a comparison of the initial air changes taken from the earlier research and two variants of the air changes resulting from using an AFN. It can be observed that there is a difference between the AFN results and the ach adopted from earlier research. In the two AFN variants, the discharge coefficient of the vents is respectively 0.6 and 0.5. The discharge coefficient is a dimensionless factor of resistance used in EnergyPlus (see Equation 2).

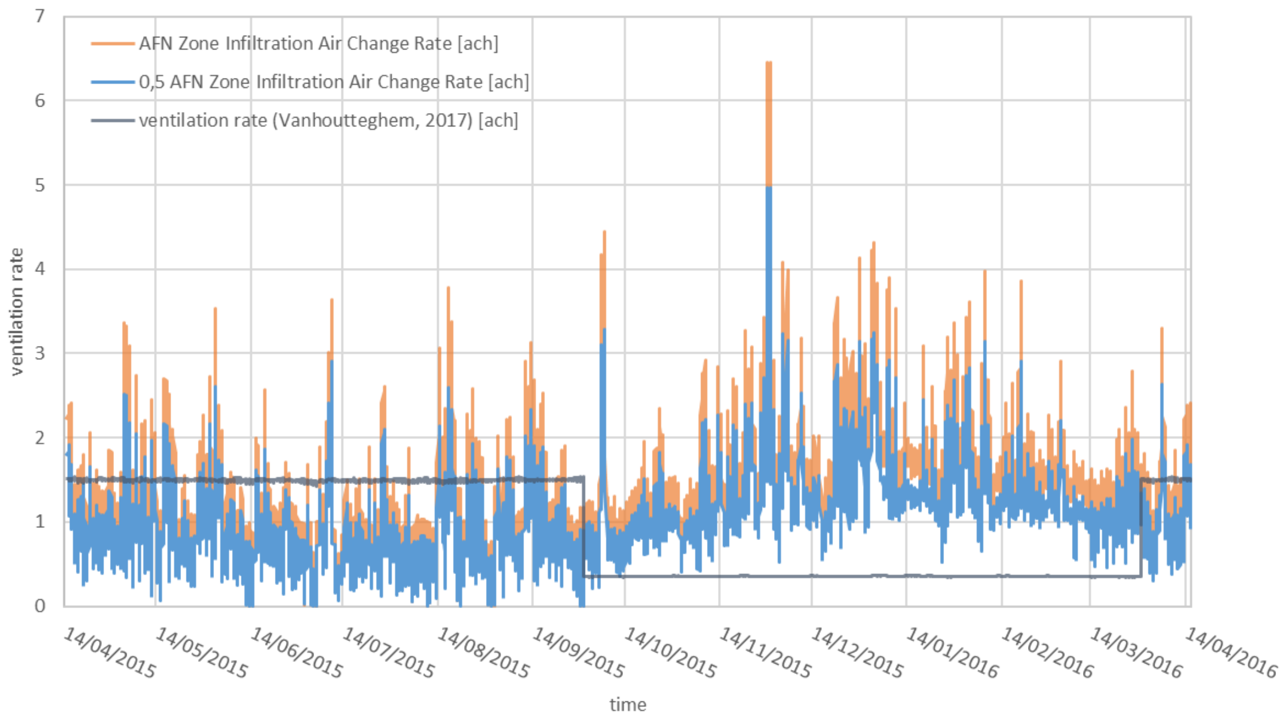

Figure 6: ventilation of the crawl crawl space [ach] using an AFN compared to adopted air change rates.

The AFN calculates the air changes based on infiltration (through cracks) and ventilation through vents, openable windows, and mechanical ventilation. An overview of the AFN flows is provided in Figure 7. This figure contains six nodes and various flows in between these nodes. For each zone, there is an inlet node, an outlet node, and a zone node. The flows are divided into three categories, Natural ventilation, infiltration, and mechanical ventilation. The infiltration takes place through cracks in the construction. The natural ventilation in the crawl space is through vents. The living spaces in zone 2 are conditioned mechanically. Note that there is no ventilation drawn through the window, this is because the window is set to be closed.

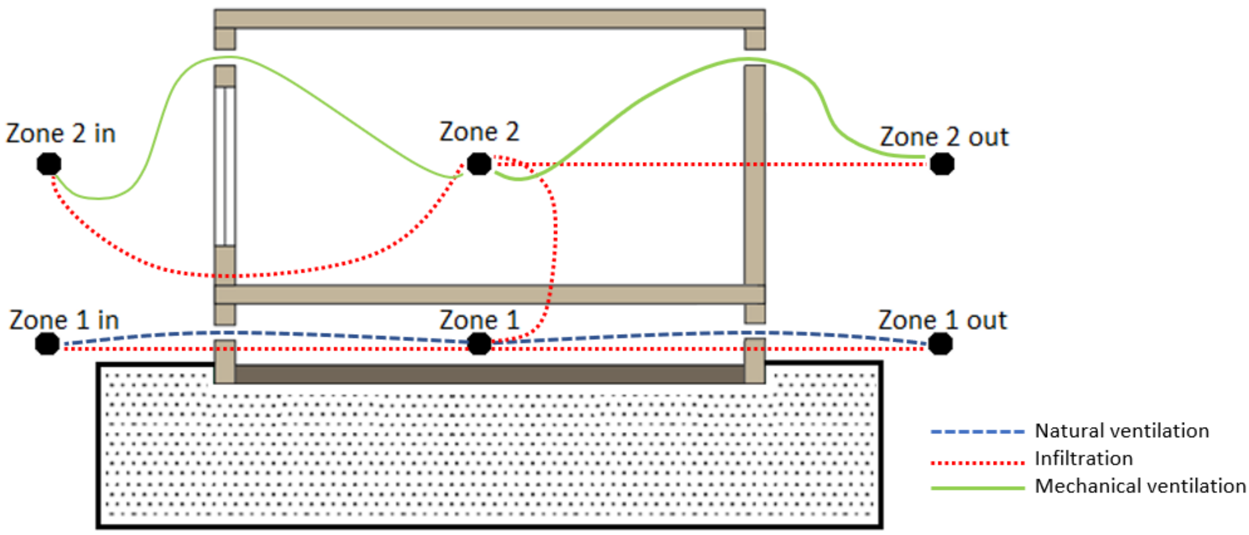

Figure 7: airflow network, an overview of ventilation flows

In the crawl space, there are four vents through which the airflow is calculated using Equation 2. The effective leakage area (ELA) is used to define surface air leakage.

$$\dot{m} = ELA * C_d \sqrt{2\rho} * (\Delta P_r)^{0.5-n} \ (\Delta P)^n \qquad (2)$$

Where:

$\dot{m}$ = Air mass flow rate [kg/s]

ELA= Effective leakage area [m^2]

ρ= Air density [kg/m^3]

ΔP_r = Reference pressure difference [Pa]

ΔP = Pressure difference across this component [Pa]

C_d= Discharge coefficient [dimensionless]

n= Air mass flow exponent [dimensionless]

Furthermore, there are four walls and a ceiling (the ground floor) in the crawl space through which infiltration takes place due to cracks in the construction. Additionally in the case that the vents would be closed there would also be infiltration through the cracks in the closed vent. This will be calculated using Equation 3.

$$Q = (Crack\ factor) * C_T * C_Q * \Delta P^n \qquad (3)$$

Where:

Q = air mass flow (kg/s)

(Crack Factor) = a crack factor can be added, however in EnergyPlus the crack factor is one

C_T = reference condition temperature correction factor (dimensionless) (see Equation 4)

C_Q = air mass flow coefficient (kg/s Pa^n @ 1 Pa)

ΔP = pressure difference across crack (Pa)

n = air flow exponent (dimensionless)

$$C_T = \left[\frac{\rho_o}{\rho}\right]^{n-1} \left[\frac{\nu_o}{\nu}\right]^{2n-1} \quad (4)$$

Where:

ρ = Air density at the specific air temperature and humidity ratio conditions [kg/m^3]

ν = Air kinetic viscosity at the specific air temperature condition [m^2/s]

ρ_o = Air density at air conditions of 20°C, 0.005 kg/kg and 101325 Pa [kg/m^3]

ν_o = Air kinetic viscosity at an air temperature of 20°C [m^2/s]

The C_Q can be set in EnergyPlus to certain fixed values. However, when using DesignBuilder it assigns values based on an indication of airtightness utilizing a crack template. In this crack template five levels of airtightness can be selected: "Very poor, poor, medium, good or excellent". When "medium" is selected, the air mass coefficient is the area of the wall is multiplied by 0.0001 kg/sPa per m^2. In the case of the floor construction, the area is multiplied by 0.0009 kg/sPa per m^2 when "medium" is selected. These numbers and formulas are based on research by Orme et al. (1998). The data was derived from a wide range of sources (Orme et al., 1998). Therefore, selecting medium seems representable since data about the airtightness of the building is not available. Table 3 provides an overview of the air mass coefficients for each construction element in the crawl space.

Table 3: air mass coefficient per construction element

Construction plane	Air mass flow coefficient (C_Q) kg/s per Pa
Ground floor (110.01 m^2) medium	0.0990086
Crawl space wall 1 (7,701 m^2) medium	0.0007701
Crawl space wall 2 (7,701 m^2) medium	0.0007661
This wall also includes vents	0.008 (per m crack length)
Crawl space wall 3 (7,000 m^2) medium	0.0007
Crawl space wall 4 (7,000 m^2) medium	0.0007

3.2.5. Uncertainties in DesignBuilder input

The goal of this study is to provide an accurate model to predict the temperature and relative humidity in the crawl space of the case study building. However, there are some uncertainties in the available information about the building.

Firstly, all the properties of the building materials have to be estimated. For example, when the cross-section indicates mineral wool insulation in the facade the properties can still vary slightly depending on the type and manufacturer of the mineral wool. Another example is the wide range of concrete densities, ranging from 2000 kg/m3 to 2600 kg/m3 according to EN 206. Materials can be selected from a material database in DesignBuilder. The attributes of the material data include conductivity, density, and heat capacity.

Additionally, when the HAMT module is selected, the box: "include moisture data" can be selected. This opens up a small database of around ten materials that includes moisture data for an EPMD or HAMT calculation. To get additional moisture data, the WUFI database was accessed. For the soil FSP, the insulation materials EPS, and spray PU foam the WUFI database was used. For the materialization in general, generic data was selected to make an accurate approach. The data of wood (generic spruce wood), generic concrete, and mineral wool were already in the Design builder database. It was also observed that the moisture content dependant conductivity in the moisture data will overwrite the previously entered conductivity.

Secondly, for the outdoor conditions a general weather file for Denmark, measured nearby Copenhagen, was combined with the measured weather conditions of a local weather station in Annisse overwriting the general weather file. The building in the case study is located at Annisse at a 40 km distance from Copenhagen. The weather file was edited so that the temperature, wet bulb temperature, relative humidity, wind speed, and wind direction would match those that are measured at a local weather station nearby the case study location during the measurements of the case study. The values for radiation and weather codes were taken from the general file since the radiation was not measured at the local weather station nor did the local weather station provide weather codes. This could potentially lead to the rain flag overwriting dry conditions in some cases.

Additionally, some natural phenomena cannot be simulated using the HAMT module from EnergyPlus. An important phenomenon that cannot be simulated using HAMT is the groundwater level and more importantly the precipitation in the ground (Simon Pallin et all, 2017). A complete list of phenomena HAMT is not able to cope with is provided in Appendix A5.

This however does not mean that when rain is flagged this is not included in the simulations. According to the documentation of EnergyPlus, in the case of rain, the convective heat losses are increased in order to simulate an increased convective heat loss from wet surfaces. Additionally, the temperature used for calculations is switched to the wet-bulb temperature. Finally, the coefficients for liquid water transport through materials are switched from a HAMT-SUCTION curve when wet to a HAMT-REDISTRIBUTION curve when rain is not flagged in the weather file.

However, since precipitation is not included in the modelling, the ground moisture content might be inaccurate. Due to this uncertainty, multiple simulations were conducted during the validation process using different ground moisture contents, varying the ground moisture content from 9.2 kg/m^3 to 370 kg/m^3. This can be translated to relative humidity using the sorption isotherm of the soil material. In Table 4 the moisture contents used in the simulations are listed.

Table 4: soil relative humidity to moisture content

Relative humidity of the soil [-]	Moisture content kg/m^3
0.80	9.20
0.85	12.9
0.90	20.1
0.95	40.0
1.00	370

The final uncertainties are energy-related and have no direct influence on the temperatures and humidity in the crawl space. The HVAC system installed in the case study is unknown. Therefore, a simple fan coil unit was selected in combination with an air-cooled chiller. These systems ensure that the temperatures and setback temperatures are maintained for occupied and unoccupied hours respectively.

3.3. Results.

We ran the whole building simulation for a duration of two years. The results from this simulation include various output data such as energy usage, indoor air temperatures, surface temperatures, and indoor relative humidity. From the indoor air temperature and the indoor air relative humidity, absolute humidity can be derived. The case study measured the relative humidity and the temperature in the crawl space. Later, these parameters will be used for the validation of the model and for the decision about which model fits best.

For comparison between the measurements and the simulations, we have three variables we compare. These are the temperature in the crawl space, the relative humidity in the crawl space, and the absolute humidity in the crawl space. In Figure 8, the resulting temperature of the simulations with the scheduled ventilation of 1.4 ach in the summer and 0.35 ach in the winter are shown. These simulations have various moisture contents. This may show how sensitive the results are to changes in the moisture content of the soil. In Figure 8, the measured temperature in the crawl space was added in red for comparison. Figure 8 shows that the simulations with lower moisture content have slightly lower temperatures.

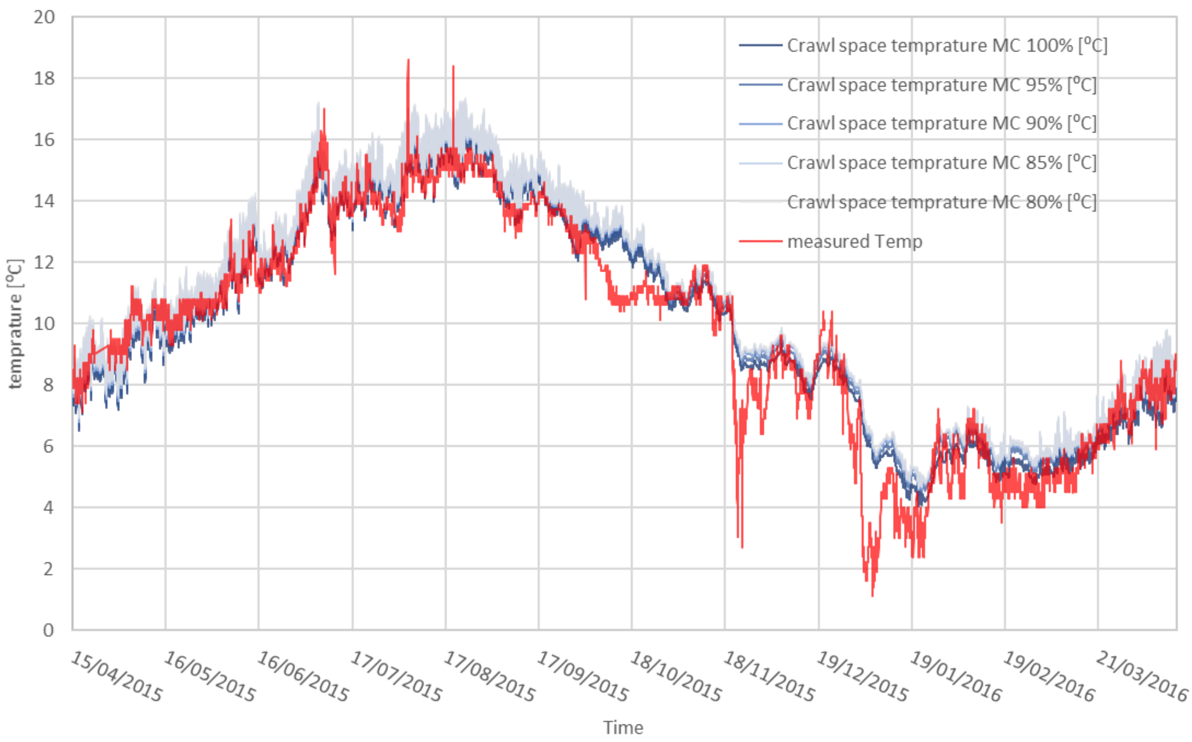

Figure 8: Crawl space temperature [°C] Simulation with scheduled ventilation and varying soil moisture content

Figure 9 shows the variants in which an AFN is used instead of scheduled ventilation. The benefit of using an AFN is that it is also applicable to a variant study. Different insulation strategies affect the crawl space temperature and therefore also influence the pressure difference. This affects the ventilation rate. For calculating the ventilation, the input parameters of the model are the size and type of the openings in combination with meteorological data like wind speed, wind direction, and atmospheric pressure. Whereas, with scheduled ventilation, an estimation should be made about the ventilation or measurements should be conducted. In the case of conducting ventilation measurements to calculate temperature and RH, it would be faster to just measure the temperature and RH itself.

In Figure 9, the crawl space temperature is shown under different simulation variants. In red the real-world measurements are shown for comparison. For the variants, the soil moisture content was set at 100% or 95% relative humidity. Additionally, the variant with 100% RH was run with a coefficient of discharge of 0.5 instead of 0.6 in the two other cases. Earlier in Figure 6, the ventilation rates are shown as well as the effect of a lower coefficient of discharge on the ventilation rates.

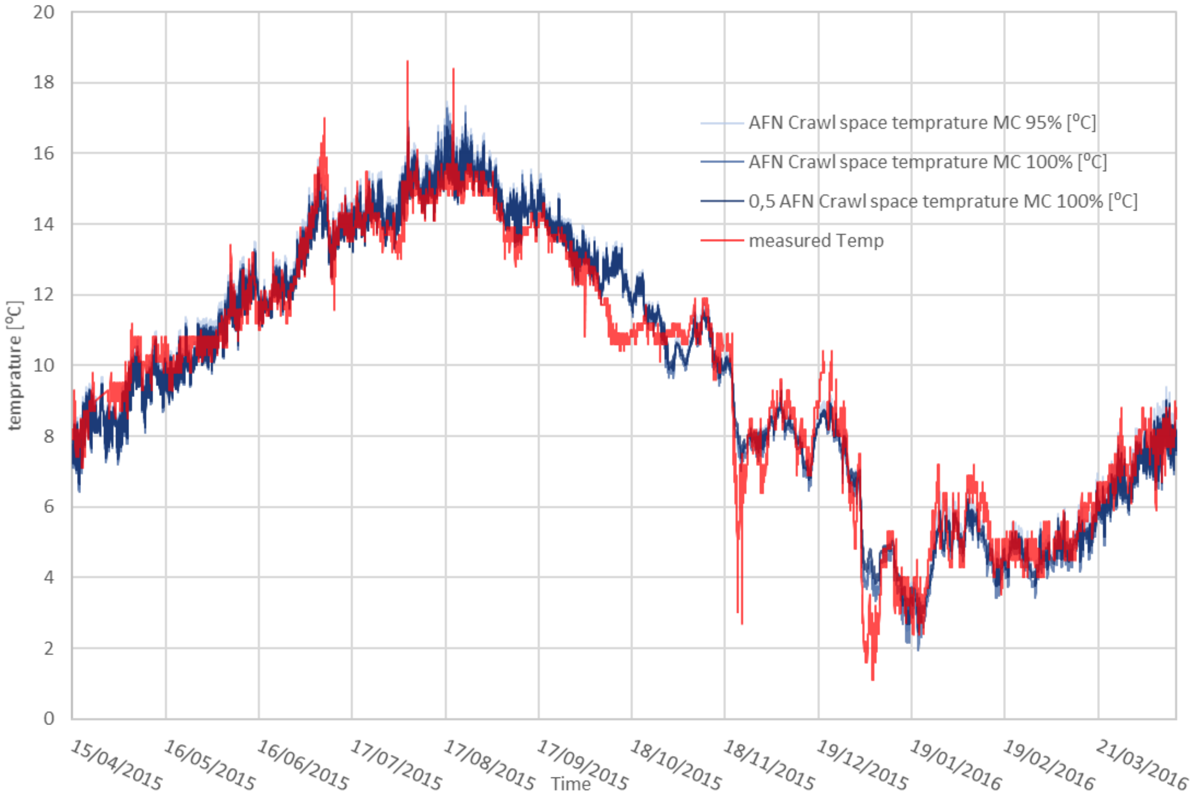

Figure 9: Crawl space temperature [°C] simulation results, AFN with varied soil moisture content

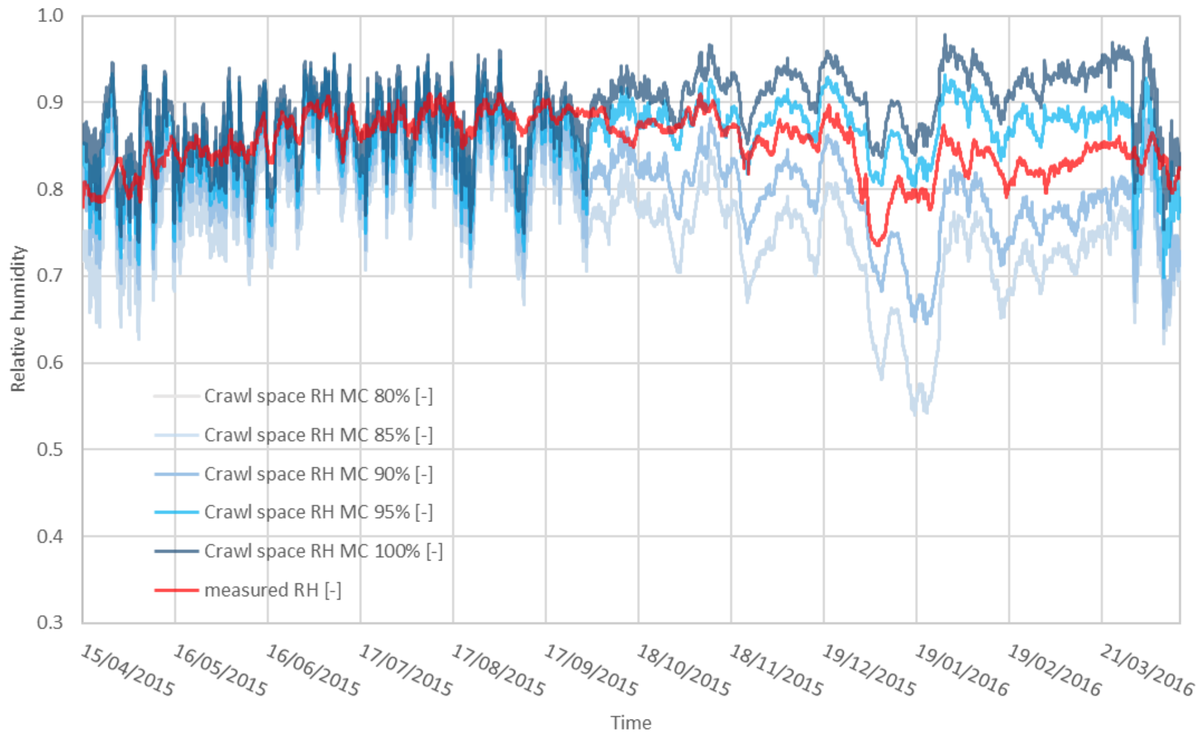

Figure 10: Crawl space RH [-] simulation results with scheduled ventilation under varying soil moisture content

In Figure 10 the relative humidity in the crawl space is plotted. These results can be compared to the real-world measurements, which are plotted in red. It appears that the simulated relative humidity follows the same path as the measurements during the winter period, however, the simulated values are usually either somewhat too high or too low. In the summer the simulated data looks uncertain. The amplitudes seem too high and irregular. However, this can be explained by the high ventilation rate. Due to large air change rates, the outside condition influences the crawl space more, causing larger temperature changes. Figure 11 shows the simulated relative humidity for the AFN simulations. These also seem to have high amplitudes. This is probably also due to the sporadic higher ventilation from time to time. While the scheduled ventilation variants have a very similar shape as the measurements in the winter, this is not always the case for the AFN variants.

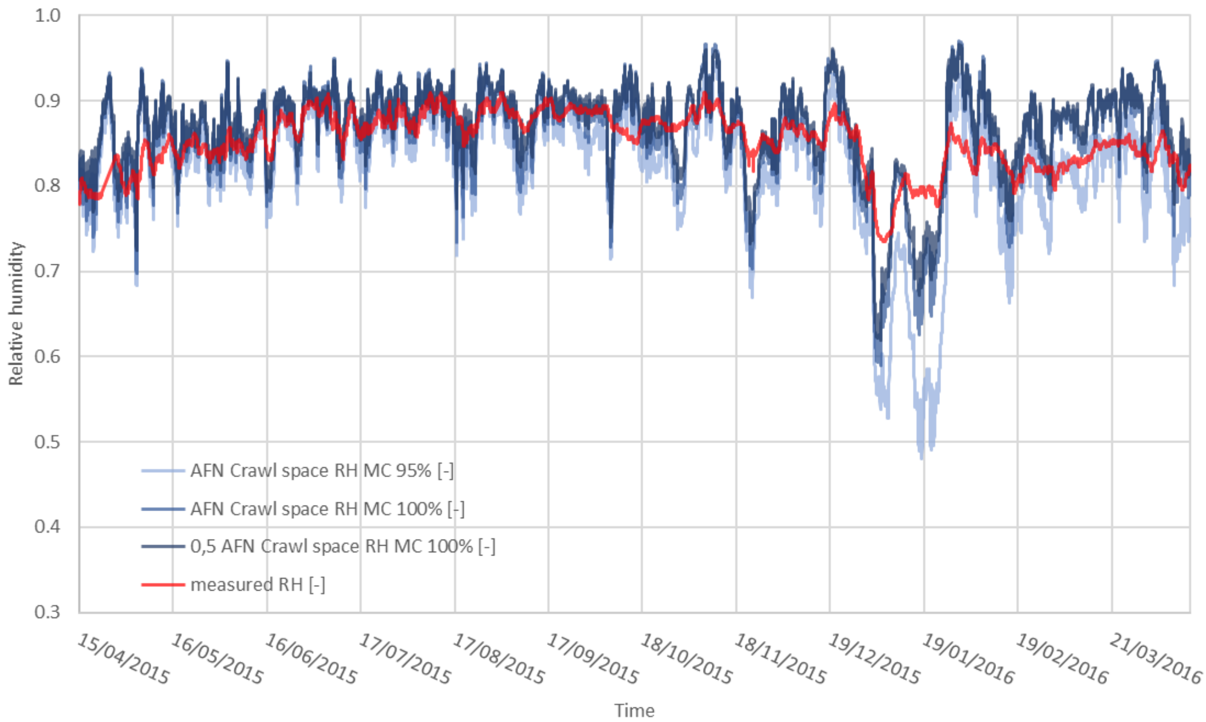

Figure 11: Crawl space RH [-] simulation results with AFN with varied soil moisture content

In Figure 12 and Figure 13 the absolute humidity is shown for the variants. This depicts the moisture simulations without having temperature-dependent values, unlike relative humidity. In the case of the measurements as well as the simulations, the absolute humidity was calculated using the RH and the temperature. The figures show a good comparison of the real-world measurements with the simulated absolute humidity.

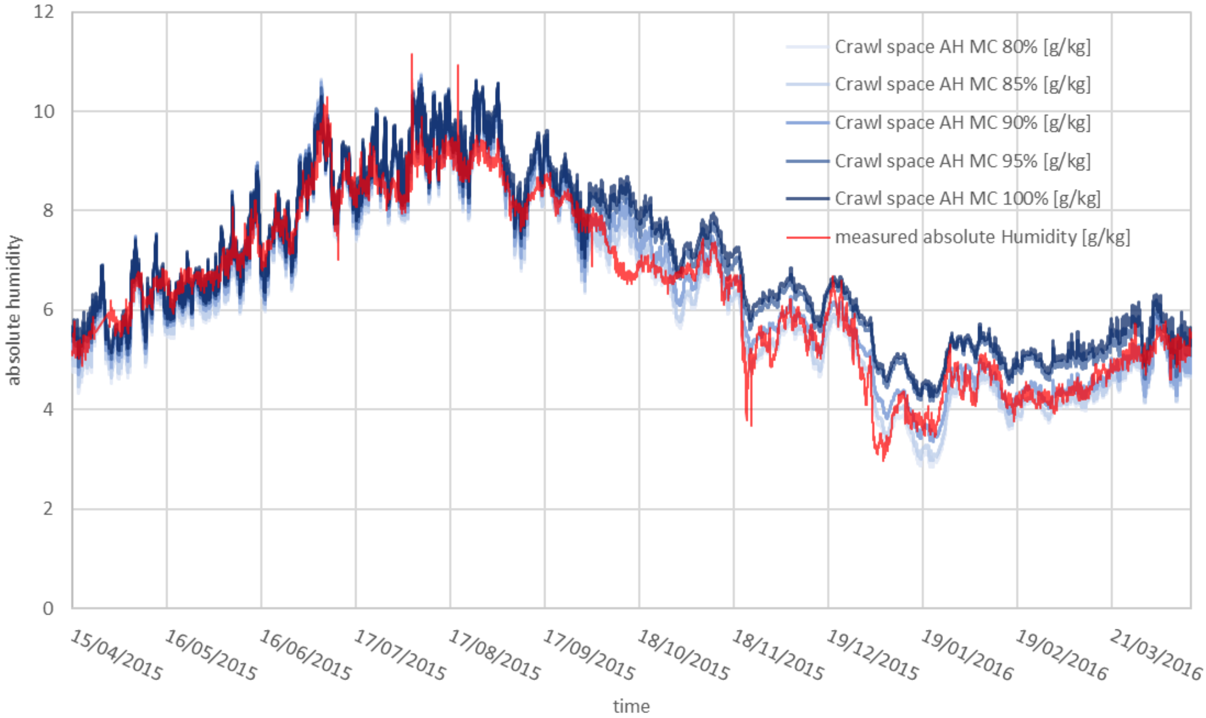

Figure 12: absolute humidity [g/kg] simulation results using scheduled ventilation with varying soil moisture content

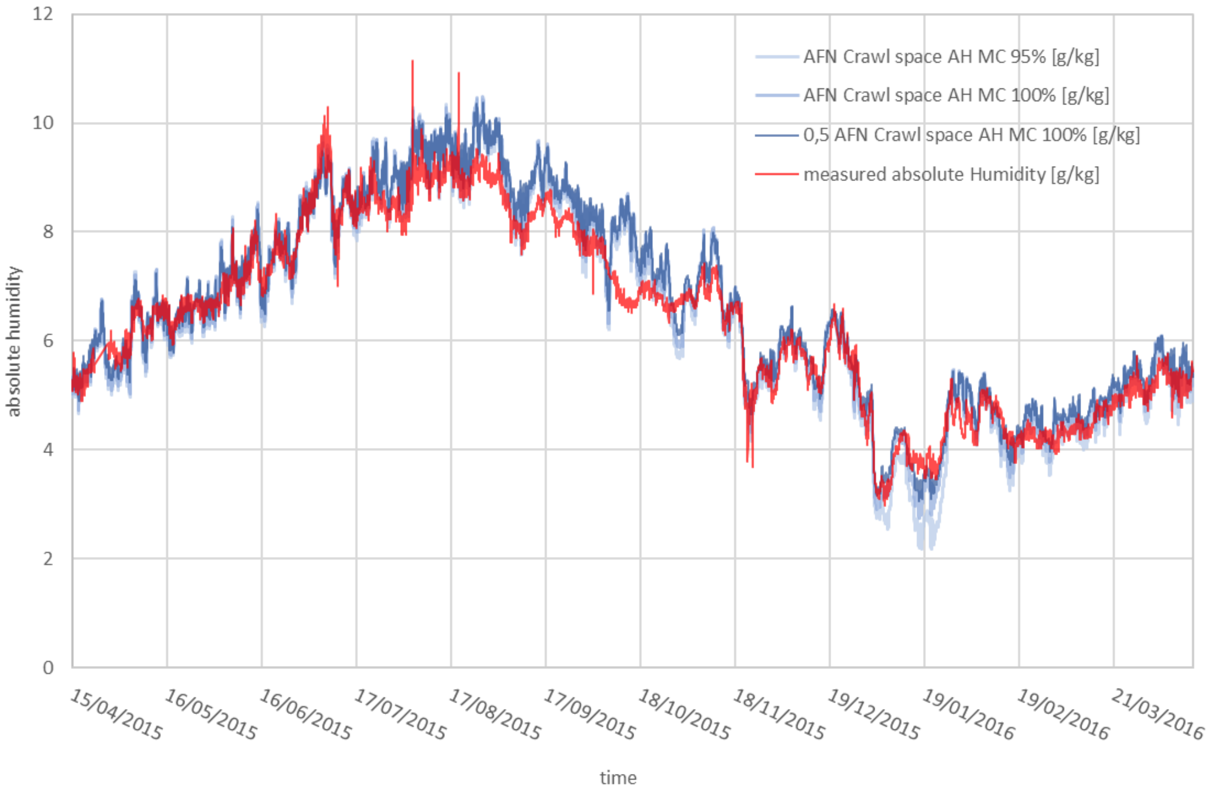

Figure 13: absolute humidity [g/kg] simulation results using AFN with varied soil moisture content

3.4. Validation

To validate the simulation, it is useful to show the simulation plotted over time together with the measured data and the outside weather conditions. The plotted data in Figures 14, 15, and 16 are the simulation results for the temperature, RH, and absolute humidity respectively. The displayed variants are the 95% soil MC scheduled ventilation model and the 100% soil MC 0.5 coefficient of discharge AFN model. These two variants seemed to fit the measured data best.

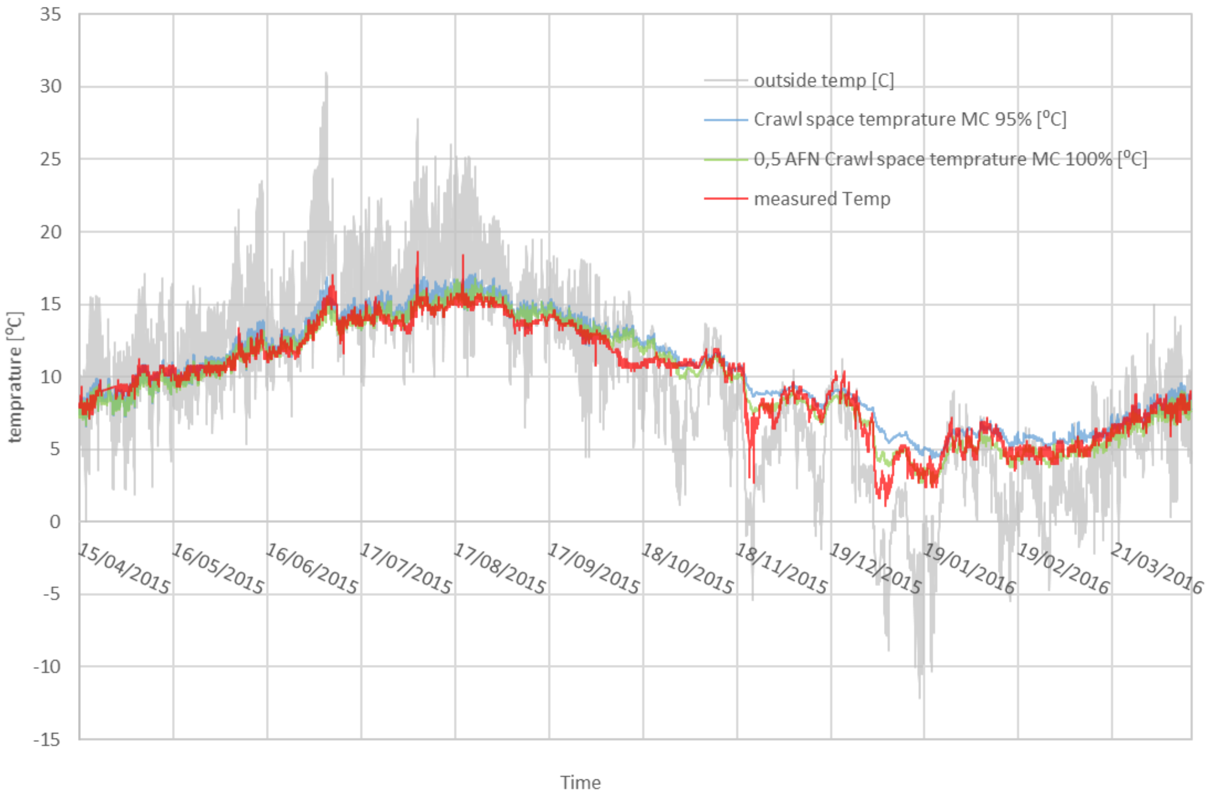

Figure 14: crawl space temperature measured and simulated together with the outside temperature

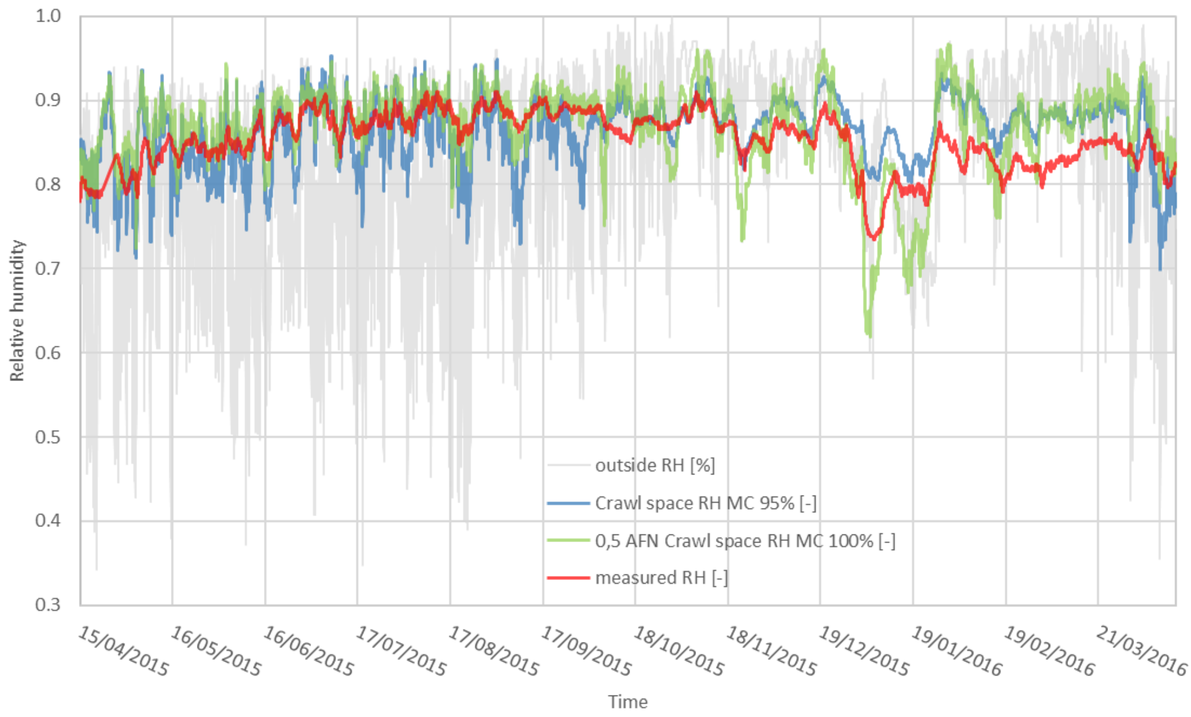

Figure 15: RH of the crawl space measured and simulated together with the outside RH

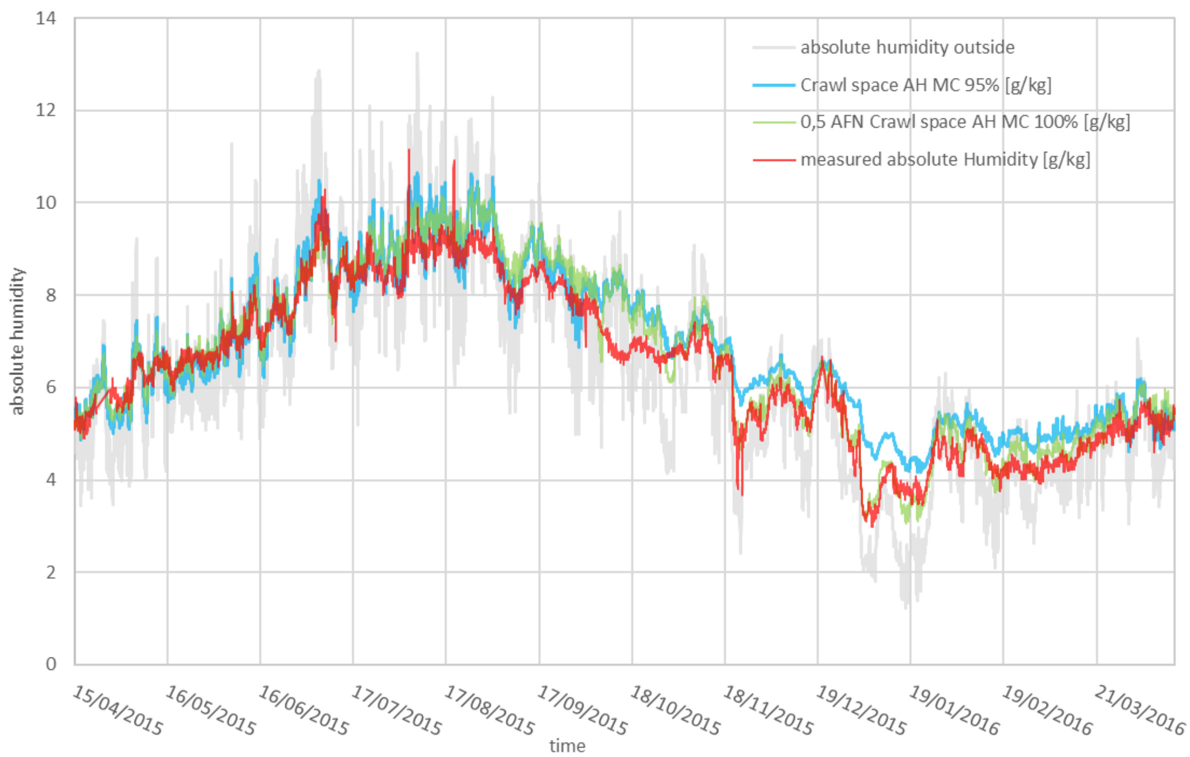

Figure 16: crawl space absolute humidity [g/kg] measured and simulated together with the outside absolute humidity

For the validation of models, the mean bias error (MBE) and the coefficient of variation of the root mean square error (CV RSME) are used. The MBE and the CV RSME are the most used methods of validation in building energy simulations (Coakley et al, 2014). Even though these methods of validation have been used on hygrothermal models before, these are not commonly used for hygrothermal simulations at this moment.

A model based on hourly data can be considered calibrated if the MBE is within 10% and the CV RSME is within 30% (Havinga, 2019). The Equations used to calculate the MBE and the CV RSME are depicted in Equations 5 and 6 below.

$$MBE(\%) = \frac{\sum_{i=1}^{N_p}(m_i - S_i)}{\sum_{i=1}^{N_p}(m_i)} \quad (5)$$

$$CV\ RSME(\%) = \frac{\sqrt{(\sum_{i=1}^{N_p}(m_i - s_i)^2/N_p)}}{m_{avg}} \quad (6)$$

m_i= measured data point

S_i= simulated data point

N_p= number of data points

M_{avg}= average of the measured data points

In Table 5 the results of the MBE and the CV RSME are depicted for the temperature, RH, and absolute humidity. A coloured layout is used to indicate which values are desirable. In this case, the values for the CV RSME should be as close to 0% as possible. A value of 0% is highlighted in green, while values of 15% or -15% are highlighted in red. For the MBE the same layout is used but with red indicating values of 5% or -5%. These criteria are stricter than the previously mentioned 30% and 10%.

It can be observed that 7 out of 8 variants of the model using different ventilation methods and ground moisture contents can be considered calibrated because they are within 30% and within 10% for the CV RSME and MBE respectively. The "0.5 AFN crawl space MC 100%" model shows the lowest CV RSME and was therefore selected to be the model to use for the variant study. It was expected that the model using a pressure-dependent AFN would provide the lowest CV RSME since the AFN would replicate real-world conditions better than a scheduled air change rate could. Additionally, using the highest moisture content probably also replicated the real-world conditions best since the building is located close to a lake.

Table 5: MBE and CV RSME for the different simulations.

	Temprature crawl space		RH crawl space		absolute humidity crawl spac	
	MBE	CV RSME	MBE	CV RSME	MBE	CV RSME
Crawl space scheduled ventilation MC 80% [C]	-9.03%	12.35%	10.62%	12.06%	4.57%	8.13%
Crawl space scheduled ventilation MC 85% [C]	-8.76%	12.16%	9.34%	10.74%	3.50%	7.48%
Crawl space scheduled ventilation MC 90% [C]	-8.02%	11.66%	5.65%	7.11%	0.46%	6.37%
Crawl space scheduled ventilation MC 95% [C]	-6.37%	10.56%	-1.08%	4.81%	-4.54%	8.15%
Crawl space scheduled ventilation MC 100% [C]	-4.01%	9.33%	-4.55%	7.15%	-6.28%	9.22%
0.6 AFN Crawl space MC 95% [C]	-1.86%	7.35%	3.46%	7.54%	1.44%	6.82%
0.6 AFN Crawl space MC 100% [C]	0.38%	7.40%	-0.75%	5.18%	-0.91%	6.04%
0.5 AFN Crawl space MC 100% [C]	-0.23%	7.28%	-1.75%	4.67%	-2.05%	5.71%

Chapter 4: Variant study

Having a validated model, we can now take a closer look at different insulation strategies, to see which insulation strategies lower the risk of encountering hygrothermal problems. What those hygrothermal problems can be is already touched upon in the introduction and will be further explained in Section 4.1.2.; Section 4.2. will show the results of the simulations for the selected performance indicators based on the risks explained in Section 4.1.2.

4.1. Methodology

Section 4.1.1. will cover which insulation strategies will be considered. For the variant study, we use the same geometry of the building and the same materialization. The only exception is in the materialization and placement of the insulation layer(s) for the different ground floor variants. In order to make the results of the variant study more locally relevant it was opted to use a Dutch climate file for the variant study and use Dutch input variables to calculate the undisturbed ground temperatures. 4.1.2. gives an overview of which hygrothermal problems can be encountered. Finally, Section 4.1.3. lists the performance indicators that will be used to determine which construction has the least chance of hygrothermal risks.

4.1.1. Insulation strategies

In the variant study, two types of insulation strategies were selected: insulation of the bottom of the crawl space and insulation of the ground floor. The reason behind choosing both these insulation strategies is that these two strategies are fundamentally different. Whereas the difference in placement of insulation material underneath or on top of the ground floor comes with its own differences (mainly condensation issues in the construction itself, for which the HAMT model is not suited) the placement of insulation material will not affect the crawl space conditions significantly (Matilainen & Kurnitski, 2003).

In addition to the two strategies (bottom insulation or ground floor insulation) the moisture content of the soil was set to either high (370 kg/m^3) or low values (9,2 kg/m^3). The presence of a moisture membrane (or soil cover) at the bottom of the crawl space was considered. Finally, the ventilation was set to only infiltration (through cracks) or ventilation through the ducts in addition to the infiltration through cracks. This would add up to 2^4 (16) different variants due to two choices in four different strategies.

Besides these sixteen variants, there are three additional variant numbers. Variant 1 is not a simulation variant but represents the weather conditions outside. The variant study was done using a different climate file. Variant 2 is the building from the case study placed in these new weather conditions. Variant 3 is the reference variant in which the ground floor of the building is stripped of its insulation to represent an uninsulated building. Therefore, the airtightness from the ground floor was decreased to an air mass flow coefficient of 0.3300288 kg/sPa. Table 6 gives an overview of the nineteen variants mentioned.

All variants are simulated for a duration of two years. This way the initial conditions have less impact on the simulation results. Only the second year of the simulations is used in the results section.

Table 6: Variants of different insulation strategies

number	insulation stratagy	high or low moisture contend soil	ventilation	membrame
1	outside conditions	-	-	-
2	Reference variant from validation study	high	Yes	-
3	Reference variant from validation study uninsulated floor	high	Yes	-
4	Bottom insulation of crawl space with EPS pearls	high	Yes	yes
5	Bottom insulation of crawl space with EPS pearls	high	Yes	no
6	Bottom insulation of crawl space with EPS pearls	high	only infiltration	yes
7	Bottom insulation of crawl space with EPS pearls	high	only infiltration	no
8	Bottom insulation of crawl space with EPS pearls	low	Yes	yes
9	Bottom insulation of crawl space with EPS pearls	low	Yes	no
10	Bottom insulation of crawl space with EPS pearls	low	only infiltration	yes
11	Bottom insulation of crawl space with EPS pearls	low	only infiltration	no
12	insulation underneath ground floor with spray foam	high	Yes	yes
13	insulation underneath ground floor with spray foam	high	Yes	no
14	insulation underneath ground floor with spray foam	high	only infiltration	yes
15	insulation underneath ground floor with spray foam	high	only infiltration	no
16	insulation underneath ground floor with spray foam	low	Yes	yes
17	insulation underneath ground floor with spray foam	low	Yes	no
18	insulation underneath ground floor with spray foam	low	only infiltration	yes
19	insulation underneath ground floor with spray foam	low	only infiltration	no

* the variant study was done using a different climate file. Therefore the simulation was first run using a new climate file before alterations were made to the floor in the validated model.

The construction of the ground floor was simulated in 1D. Therefore, some simplifications to the geometry were necessary since a wooden ground floor supported by wooden beams requires a 2D simulation. In Figure 17 the two variants of the ground floor are depicted as well as their geometrical simplification.

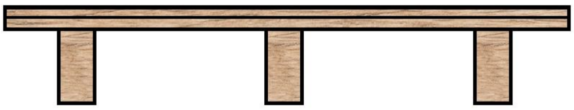

Figure 17a: Cross-section of the ground floor for the uninsulated floor and the variants with insulation on the bottom of the crawl space

Figure 17b: Simplified cross-section of the ground floor

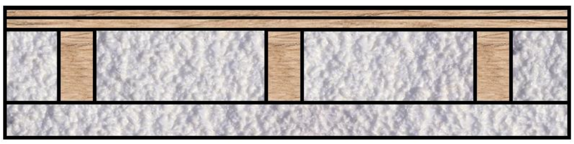

Figure 17c: Cross-section of the ground floor with insulation (variants 12 till 19)

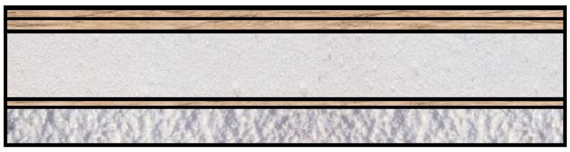

Figure 17d: Simplified cross-section of the ground floor with insulation.

The simplification of the uninsulated floor is done by simply leaving the wooden beams out of it, due to the free circulation of air in between the beams and due to the beams only covering a relatively small percentage of the surface of the floor. Therefore, the added thermal resistance of the beams to the construction is negligible. Thus, the beams can be considered to be exposed to the crawl space environment in these cases, especially the lower part of the beams.

In the case of the simplification of the variants with insulation material, the beams still only cover a small part of the floor's surface. However, due to the large difference in insulation (k-value) it will influence the simulations. Therefore, the layer consisting of wooden beams and insulation materials was modelled as insulation material, with a higher k-value. Underneath it, a layer of wood was simulated so the moisture content at the lowest parts of the wooden beams could be estimated. However, due to the simplifications of 2D to 1D that are necessary for EnergyPlus to simulate heat and moisture transfer EnergyPlus might not be the right tool for the determination of moisture content inside of constructions. The simulation results about moisture content yielding from EnergyPlus may be inaccurate.

4.1.2. Assessment of hygrothermal risks

Hygrothermal problems often occur at building joints after a renovation in which insulation material was added. For example, the connection between roof and wall, floor and wall, or floor beams and walls. This is often caused by thermal bridges creating a cold area where vapour condensation might occur, or condensation due to airflow through the construction resulting from a small gap in the construction near a building joint. Condensation is one of the causes of water accumulation in constructions. There are multiple ways accumulation of water in the building envelope can be caused. For example, leakages or wrong installation of rainwater drainage pipes can also cause moisture accumulation.

Condensation has a higher chance of occurring if the environment has a high RH. If the RH is high condensation occurs on surfaces with lower temperatures. For example, a crawl space is relatively cold in the summer, when the crawl space is ventilated with warm humid air condensation might occur.

Accumulation of moisture in constructions can lead to various negative effects. The best-known effects are corrosion, decay of materials, and mould growth. In brickwork salt efflioresce and frost damage can occur due to build-up moisture in the materials. This study will focus on wood decay and mould growth. These hygrothermal risks are selected due to the occurrence in a crawl space situation. A crawl space often contains wooden floor beams. Therefore, wood decay and mould growth are serious risks. There are models available to determine mould growth and wood decay based on RH and temperature. The RH and temperature can be simulated using whole building simulation.

To simulate the other hygrothermal risks, 2D HAMT models or sometimes even 3D HAMT models are required. These models like all others require input about the environment that borders the construction. For a residential area, this is often a temperature of around 20 ^{o}C and an RH of 50% depending on the season. Most often 2D and 3D HAMT calculations are only made with laboratory conditions.

When looking at the ground floor there is little scientific literature available about crawl space conditions. This study uses a whole building simulation to determine crawl space conditions. While the HAMT model in EnergyPlus is only 1D, the results from our case study showed it to be capable of simulating the crawl space environment well

The crawl space conditions can be used to determine certain hygrothermal risks. For example, knowledge of the temperature and humidity in the crawl space at any time can be used to determine the risks of mould growth on exposed wooden beams in a crawl space. Temperature, time, and humidity are the three main indicators for mould growth. Mould requires time to grow in favourable mould growth conditions. To assess mould growth there are Sedlbauer's isopleths (Sedlbauer, 2001) and the VTT mould growth model (A. Hukka, H. A. Viitanen, 1999) additionally there is the Wufi-Bio model (Sedlbauer & Krus 2003).

In all the mentioned methods mould growth is coupled to materials or material classes. Figure 18 depicts the critical RH for mould growth on wooden materials used in the VTT. Because of the research from Hukka A. and Viitanen H. A. (1999) 80% RH is often considered to be the critical point. Figure 19 gives the Sedlbauer Isopleths.

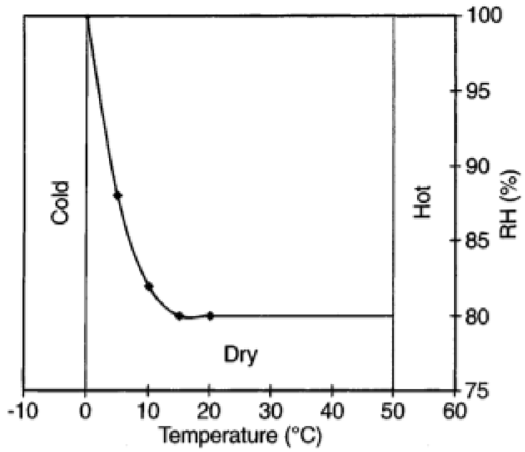

Figure 18: VTT mould growth model critical RH (A. Hukka, H. A. Viitanen, 1999)

For the risk assessment of mould growth, WUFI-Bio will be used. This is because it uses Sedlbauer's ideas with the possibility of a translation function to Mould indexes. Therefore, it seemed most suited to use while evaluating the risk of mould growth.

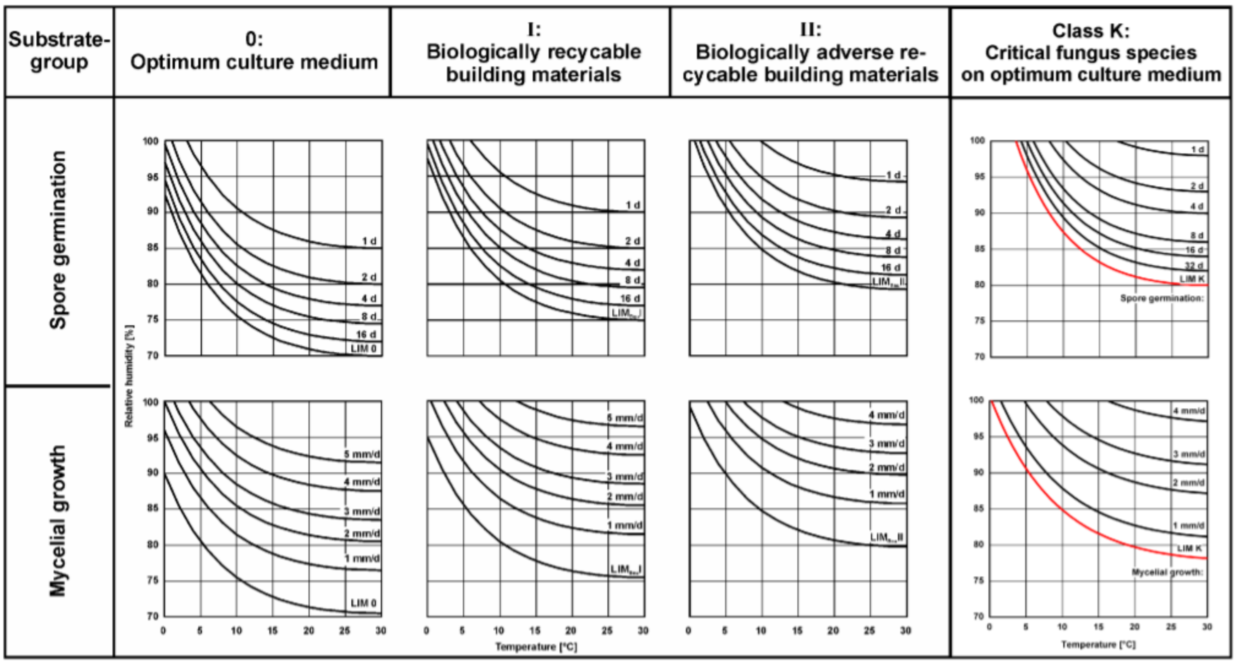

Figure 19: the Sedlbauer's isopleths for mould growth boundary conditions (Sedlbauer, 2001)

Besides mould growth, wood decay is another problem that can occur due to hygrothermal problems in constructions. In the case of wood decay, prediction models using RH and temperature over time as input have been developed. For example, the "VTT wood decay model" (H. Viitanen et al., 2010) and a numerical simulation model by Saito (Saito et al., 2012). A comparison between these models was made (Kvist Hansen et al., 2020). In this comparison, it was concluded that both models overestimated the mass loss (ML) due to wood decay. It was concluded that it is better to look at the moisture content, which should be lower than 0,25 kg/kg for wood. However, these models could still be used to compare different variants (Kvist Hansen et al., 2020).

Despite the recent questioning of the VTT model for wood decay, the VTT model will be applied to the variants to quantify risky conditions for wood rot and compare the variants with each other. The VTT model (H. Viitanen et al., 2010) requires RH and temperature as input. The VTT model will first calculate a "Δa" to indicate the occurrence of wood decay. Then if it is present (a=1), it calculates the mass loss in %. See Equations 7, 8, 9, 10, 11, and 12 for the description of the model.

$$a(t) = \int_0^t da = \sum_0^t (\Delta a) \tag{7}$$

$$\Delta a = \frac{\Delta t}{t_{crit}(RH,T)} \text{ , if T} > 0\ ^0\text{C and RH } > 95\% \tag{8}$$

$$\Delta a = \frac{\Delta t}{17520}, \text{if the conditions from Equation 8 are not met} \tag{9}$$

$$t_{crit}(RH,T) = \left(\frac{2.3T+0.035RH-0.024T*RH}{-42.9+0.14T+0.45RH}\right) * 30 * 24\ [h] \tag{10}$$

$$ML(t') = \int_{t\ at\ a=1}^{t'} \frac{ML(RH,T)}{dt}\ dt = \sum_{t\ at\ a=1}^{t'} \left(\frac{ML(RH,T)}{dt} *\ \Delta t\right) [\%] \tag{11}$$

$$\frac{ML(RH,T)}{dt} = -5.96 * 10^{-2} + 1.96 * 10^{-4}\ T + 6.25 * 10^{-4}\ RH\ [\%/h] \tag{12}$$

ML = mass loss [%]

a = occurrence of wood decay (value between 1 and 0) [dimensionless]

t = time [h]

t_{crit} = calculated critical time before decay (mass loss process) initiates

RH = relative humidity [%]

T = temperature [^{0}C]

Please note that the model uses RH and temperatures of the crawl space itself as an input and not RH and temperatures inside of the construction. Inside the insulated construction variants, temperatures are higher and therefore the RH is lower.

Additionally, the wood decay model is based on the decay of untreated pinewood. Therefore, the results of the VTT wood decay model would represent what would happen when a sample of pinewood would be placed in the middle of the crawl space. This may provide insight into what might happen when a wooden floor beam is directly exposed to the crawl space conditions. This can occur for example when insulation materials are not installed carefully leaving air gaps exposing wooden floor beams.

In summary, the hygrothermal risks associated with crawls spaces with wooden floors are mould growth and wood decay. For both these risks, models have been developed to evaluate the risks of occurrence. These models can also be used to quantify the effects of mould growth and wood decay. Another way to assess the occurrence of wood decay is the moisture content of the wood.

4.1.3. Performance Indicators

The two most important performance indicators are the temperature and relative humidity of the crawl space. With these two indicators, absolute humidity, wood decay, and mould growth can be calculated. The data will be presented with climate charts among others. This might give some more insights into the relationship between the RH and temperature.

The data resulting from the mould growth models is included as a performance indicator. The same goes for the mass loss due to wood decay. The moisture content of the wooden beams is also included in the results section. However, the moisture content in the wooden beams might not be accurate due to the simplifications from 2D to 1D.

The models for mould growth and wood decay all have RH and temperature as their input. Therefore, the RH itself may be a reasonable performance indicator. In order to give a good insight into the RH, the 24 hours, 7 days, and 30 days maximum moving averages were calculated. Besides the average RH, the average RH in the heating season was calculated as well. Also, the number of weeks the RH was on average above 80% was calculated.

Furthermore, the energy savings for the different insulation strategies are included in the performance indicators since they are the main driving force behind the insulation of existing buildings. The same goes for the cooling energy demand.

4.2. Results

Here the results of the different variants discussed in 3.1 are presented. A comparison will be made using the performance indicators discussed earlier, these are shown in Table 7.

Table 7: Performance indicators for the different variants

	3. Crawl space, no insulation, ventilated, high MC	4. Crawl space, bottom ins, vent, GC, high MC	5. Crawl space, bottom ins, vent, no GC, High MC	6. Crawl space, bottom ins, inf only, GC, high MC	7. Crawl space, bottom ins, inf only, no GC, high MC	8. Crawl space, bottom ins, vent, GC, low MC	9. Crawl space, bottom ins, vent, no GC, low MC	10. Crawl space, bottom ins, inf only, GC, low MC	11. Crawl space, bottom ins, inf only, no GC, low MC	12. Crawl space, floor ins, vent, GC, high MC	13. Crawl space, floor ins, vent, no GC, high MC	14. Crawl space, floor ins, inf only, GC, high MC	15. Crawl space, floor ins, inf only, no GC, high MC	16. Crawl space, floor ins, vent, GC, low MC	17. Crawl space, floor ins, vent, no GC, low MC	18. Crawl space, floor ins, inf only, GC, low MC	19. Crawl space, floor ins, inf only, no GC, low MC
insulation stratagy	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
average temperature [°C]	11.97	14.31	14.17	14.59	14.46	14.38	14.22	14.67	14.51	11.09	10.17	11.21	10.28	11.46	10.53	11.59	10.64
average ventilation [ach]	1.024	1.089	1.086	0.765	0.766	1.091	1.087	0.767	0.766	0.967	0.929	0.734	0.728	0.983	0.943	0.737	0.730
average RH [-]	0.8486	0.6302	0.6378	0.6225	0.6304	0.6277	0.6350	0.6195	0.6274	0.7707	0.8936	0.7715	0.9053	0.7534	0.8121	0.7529	0.8207
average absolute humidity [g/kg]	7.48	6.54	6.56	6.56	6.58	6.54	6.55	6.56	6.57	6.48	6.98	6.52	7.11	6.49	6.52	6.53	6.61
average surface temperature floor [°C]	19.04	19.34	19.33	19.38	19.42	19.40	19.34	19.49	19.40	19.89	19.80	19.87	19.75	19.87	19.82	19.90	19.83
cooling energy demand [kWh]	-2285	-2562	-2556	-2565	-2723	-2718	-2587	-2837	-2585	-2875	-2718	-2862	-2668	-2837	-2752	-2875	-2803
heating energy demand [kWh]	7807	7502	7495	7213	7232	7355	7492	6949	7233	6314	6616	6290	6427	6486	6573	6038	6322
heating seison average RH [-]	0.8288	0.6289	0.6353	0.6248	0.6321	0.6267	0.6329	0.6222	0.6295	0.7288	0.8753	0.7306	0.8928	0.7142	0.7899	0.7143	0.8041
RH max 30 day moving average [-]	0.9080	0.7338	0.7428	0.7469	0.7513	0.7292	0.7392	0.7464	0.7505	0.8840	0.9428	0.8846	0.9440	0.8616	0.8754	0.8611	0.8758
RH max 7 day moving average [-]	0.9386	0.7942	0.8022	0.7916	0.7942	0.7905	0.7993	0.7913	0.7938	0.9380	0.9595	0.9371	0.9648	0.9310	0.9085	0.9298	0.9089
RH max 24h moving average [-]	0.9620	0.8465	0.8532	0.8443	0.8470	0.8426	0.8508	0.8439	0.8465	0.9599	0.9821	0.9596	0.9850	0.9572	0.9374	0.9567	0.9371
# weekly averages above 80% rh [weeks]	44	0	1	0	0	0	0	0	0	23	51	22	52	19	32	19	35
mould index class 1 [-]	5.29	0	0	0	0	0	0	0	0	3.47	6.00	3.50	6.00	2.77	3.11	2.74	3.30
mould growth class 1 [mm]	490	0	0	0	0	0	0	0	0	279	705	281	772	222	247	219	264
mould index class 2 [-]	3.20	0	0	0	0	0	0	0	0	0.98	4.86	0.96	5.30	0.39	0.46	0.36	0.52
mould growth class 2 [mm]	254	0	0	0	0	0	0	0	0	128	435	127	490	90	97	87	101

Table 7 shows that variants 13 and 15 have the least favourable hygrothermal conditions, with weekly average RH above 80% in 51 and 52 weeks respectively. Variants 4-11 show the most favourable hygrothermal conditions, this is due to a higher crawl space temperature. Although variants 4-11 show better hygrothermal conditions it is variants 12-19 that show the least energy usage. Thus, it seems as if there is a trade-off between these two insulation strategies.

Table 8 Shows The energy balance of the different variants. Variants 4-11 show little improvements in the energy savings department. When the heating energy savings are added up to the increased cooling energy demand the net result is that there are hardly any energy savings (between 0.3% and 3.1%). Energy savings are more notably present in variants 12-19 these energy savings are between 7.5% and 11.7%. please note that these numbers are largely dependent on the project itself. In projects with other geometry, heating/cooling installations, and materialization these numbers might differ. That being said, It seems that insulation at the bottom of the crawl space results in fewer energy savings.

Table 8: Energy savings of the different variants

	3. Crawl space, no insulation, ventilated, high MC	4. Crawl space, bottom ins, vent, GC, high MC	5. Crawl space, bottom ins, vent, no GC, High MC	6. Crawl space, bottom ins, inf only, GC, high MC	7. Crawl space, bottom ins, inf only, no GC, high MC	8. Crawl space, bottom ins, vent, GC, low MC	9. Crawl space, bottom ins, vent, no GC, low MC	10. Crawl space, bottom ins, inf only, GC, low MC	11. Crawl space, bottom ins, inf only, no GC, low MC	12. Crawl space, floor ins, vent, GC, high MC	13. Crawl space, floor ins, vent, no GC, high MC	14. Crawl space, floor ins, inf only, GC, high MC	15. Crawl space, floor ins, inf only, no GC, high MC	16. Crawl space, floor ins, vent, GC, low MC	17. Crawl space, floor ins, vent, no GC, low MC	18. Crawl space, floor ins, inf only, GC, low MC	19. Crawl space, floor ins, inf only, no GC, low MC
insulation stratagy	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
cooling energy demand [kWh]	-2285	-2562	-2556	-2565	-2723	-2718	-2587	-2837	-2585	-2875	-2718	-2862	-2668	-2837	-2752	-2875	-2803
heating energy demand [kWh]	7806.93	7501.94	7495.4	7213.38	7231.98	7354.75	7491.68	6948.51	7232.55	6314.03	6615.86	6290.11	6427.08	6485.92	6572.61	6038.28	6322.27
Total energy demand	10091.5	10063.9	10051	9777.9	9955.14	10072.4	10078.7	9785.73	9817.94	9188.88	9333.54	9151.71	9095.14	9322.91	9324.14	8913.04	9125.61
energy usage as percentage of the reference	100	99.7271	99.5985	96.8926	98.6489	99.8105	99.8734	96.9702	97.2894	91.0558	92.4893	90.6875	90.1269	92.3839	92.3962	88.3224	90.4288
percentage energy savings	0	-0.2729	-0.4015	-3.1074	-1.3511	-0.1895	-0.1266	-3.0298	-2.7106	-8.9442	-7.5107	-9.3125	-9.8731	-7.6161	-7.6038	-11.678	-9.5712

Table 7 shows a lot of information however they are all yearly averages and yearly data. This causes the table to show less difference between the variants for some performance indicators. In order to provide more detailed information, Table 9 provides seasonal averages for the temperature, RH, and absolute moisture content.

Table 9: Seasonal averages for the temperature, RH, and absolute humidity of the variants

	3. Crawl space, no insulation, ventilated, high MC	4. Crawl space, bottom ins, vent, GC, high MC	5. Crawl space, bottom ins, vent, no GC, High MC	6. Crawl space, bottom ins, inf only, GC, high MC	7. Crawl space, bottom ins, inf only, no GC, high MC	8. Crawl space, bottom ins, vent, GC, low MC	9. Crawl space, bottom ins, vent, no GC, low MC	10. Crawl space, bottom ins, inf only, GC, low MC	11. Crawl space, bottom ins, inf only, no GC, low MC	12. Crawl space, floor ins, vent, GC, high MC	13. Crawl space, floor ins, vent, no GC, high MC	14. Crawl space, floor ins, inf only, GC, high MC	15. Crawl space, floor ins, inf only, no GC, high MC	16. Crawl space, floor ins, vent, GC, low MC	17. Crawl space, floor ins, vent, no GC, low MC	18. Crawl space, floor ins, inf only, GC, low MC	19. Crawl space, floor ins, inf only, no GC, low MC
insulation stratagy	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Temperature average [°C]																	
Winter - 20 march	8.37	9.97	9.94	10.33	10.30	10.00	9.97	10.37	10.33	6.92	6.57	7.08	6.74	7.11	6.81	7.27	6.97
Spring: 20 march - 21 June	11.82	15.58	15.46	15.88	15.76	15.64	15.51	15.95	15.86	10.60	9.67	10.69	9.75	10.98	10.08	11.09	10.16
Summer 21 June - 23 September	15.75	18.63	18.39	18.78	18.57	18.72	18.43	18.89	18.59	15.41	14.00	15.46	14.03	15.86	14.40	15.92	14.43
Autumn 23 september - 20 december	11.77	12.80	12.64	13.10	12.95	12.88	12.70	13.20	12.99	11.27	10.27	11.44	10.44	11.74	10.69	11.93	10.84
RH average [-]																	
Winter - 20 march	0.84	0.64	0.65	0.64	0.65	0.64	0.64	0.64	0.65	0.76	0.88	0.77	0.90	0.75	0.81	0.76	0.83
Spring: 20 march - 21 June	0.83	0.57	0.58	0.56	0.56	0.57	0.57	0.55	0.56	0.78	0.89	0.78	0.90	0.77	0.81	0.77	0.81
Summer 21 June - 23 September	0.89	0.67	0.68	0.66	0.67	0.67	0.68	0.66	0.67	0.83	0.93	0.83	0.93	0.81	0.85	0.80	0.85
Autumn 23 september - 20 december	0.83	0.64	0.65	0.63	0.64	0.64	0.64	0.63	0.64	0.70	0.87	0.70	0.89	0.68	0.77	0.68	0.79
Absolute humidity [g/kg]																	
Winter - 20 march	5.67	4.84	4.87	4.96	5.00	4.84	4.87	4.96	5.00	4.68	5.29	4.77	5.44	4.69	4.96	4.77	5.10
Spring: 20 march - 21 June	7.18	6.29	6.33	6.27	6.31	6.29	6.31	6.27	6.30	6.24	6.62	6.28	6.73	6.27	6.17	6.30	6.24
Summer 21 June - 23 September	9.81	8.95	8.94	8.89	8.89	8.96	8.93	8.90	8.86	8.94	9.12	8.95	9.17	8.96	8.62	8.97	8.65
Autumn 23 september - 20 december	7.16	5.97	5.98	6.01	6.02	5.97	5.97	6.01	6.01	5.93	6.81	5.98	7.01	5.93	6.23	5.97	6.39

In Table 9 it can be observed that the variants with a vapour tight ground cover seem to have a lower absolute humidity relative to the variants without a ground cover. In the winter the variants with a ground cover seem to have the highest absolute humidity. This could be explained by observations made that ground moisture evaporation occurs more during the winter (Matilainen & Kurnitski, 2003).

This can also explain why the yearly averages of the absolute moisture content seem so similar among the different variants. The yearly outside absolute moisture content seems to be the dominating influence on the absolute moisture content in the crawl space. The second most influential factor seems to be the evaporation from the ground. The presence of vapour tight ground covers can be clearly noticed in variants 12 and 14 compared to 13 and 15. These variants have a high ground moisture content and vary in the presence of a vapour tight ground cover. Variants 16 and 18 compared to 17 and 19 show similar results. However, these variants (variants 16-19) have a lower ground moisture content. This can explain the smaller difference between the presence and absence of a vapour tight ground cover in these variants (variants 16-19).

When we look at the RH it seems that the variants without a vapour tight ground cover (variants 5,7,9,11,13,15,17,19) always have a higher RH than their counterparts with a vapour tight ground cover (variants 4,6,8,10,12,14,16,18). It can be observed that the variants with insulation materials on the bottom of the crawl space (variants 4-11) show little difference in RH. This can possibly be explained by the presence of insulation material at the bottom of the crawl space acting as a vapour resistance.

Figures 20, 21, and 22 show the temperature, RH, and absolute humidity respectively, belonging to variants 3, 6, and 14. Variant 3 represents an uninsulated reference situation. Variant 6 is a variant with Insulation material on the bottom of the crawl space, a vapour tight ground cover, high soil moisture content, and only infiltration through cracks. Variant 14 is a variant with Insulation material attached to the ground floor, a vapour tight ground cover, high soil moisture content, and only infiltration through cracks. These three variants are selected because these represent the two different insulation strategies and the uninsulated variant. Furthermore, these variants are the most promising ones from both strategies. Note that we are not including 8-11 and 16-19 because of the lower moisture content in the soil. Therefore, they are less suited for risk assessment.

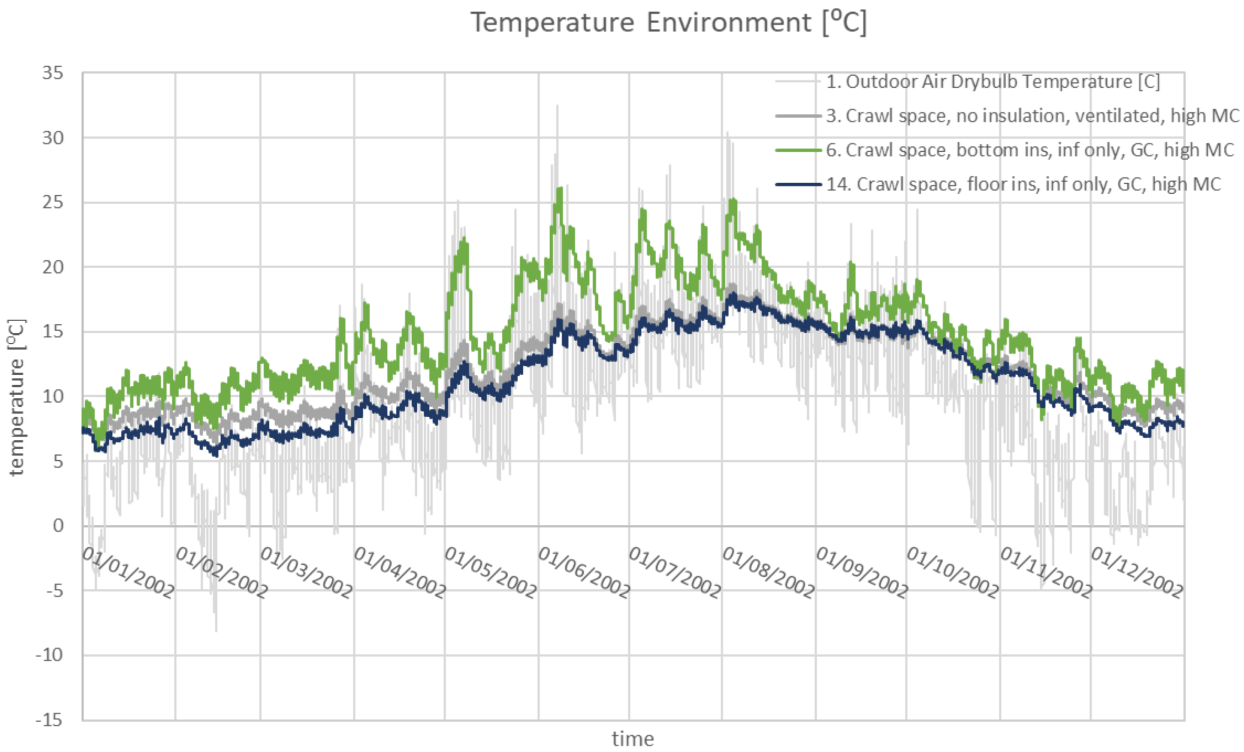

Figure 20: Temperature [^{o}C] of variants 3, 6, and 14 over one year (the 2nd year)

In Figure 20 it can be observed that variant 6 has higher crawl space temperatures, while variant 14 has the lowest temperature year-round. Table 7 shows that this is due to the location of the insulation material. Variants 4-11 have higher crawl space temperatures than the other variants. Variants 12-19 seem to have the lowest temperature.

The most notable observation that can be made from Figure 21 is that the relative humidity seems lowest in variant 6. This once again can be confirmed by Table 7 to be caused by the location of the insulation material.

Figure 22 shows the absolute humidity of the crawl space. Variant 3 seems to have the highest absolute humidity. This is probably due to variant 3 being the only variant in the figure without a vapour tight ground cover.

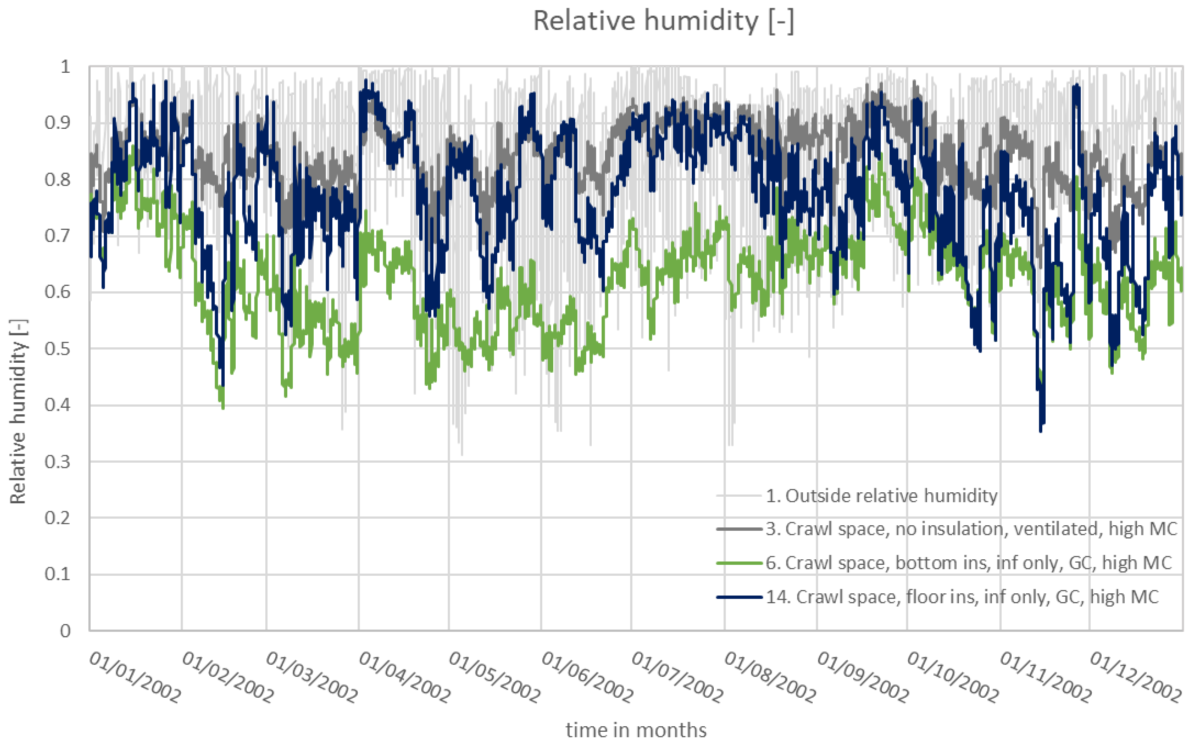

Figure 21: Relative humidity [-] of variants 3, 6, and 14 over one year (the 2nd year)

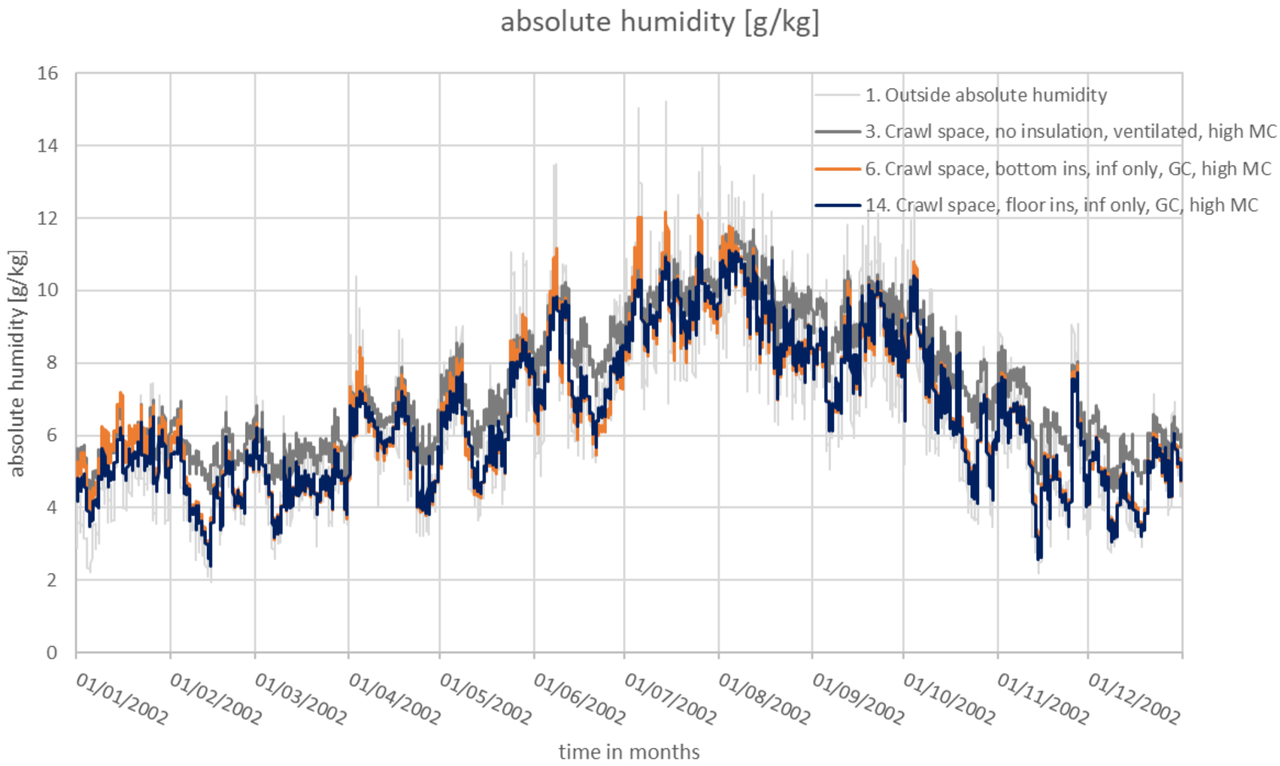

Figure 22: Absolute humidity [g/kg] of variants 3, 6, and 14 over one year (the 2nd year)

Figures 23, 24, and 25 show the climate charts for variants 3, 6, and 14 respectively. Using the climate charts, it can be observed that conditions with the highest RH seem to occur during the summer. When warm humid air is used to ventilate a reliably cold crawl space this might result in high RH. This is also frequently supported by literature (Iwamae et al. 2003; Kurnitski, 2000). This is one of the reasons variants 6 and 14 were selected instead of 4 and 12. The main difference between these is the ventilation. Variants 6 and 14 have less ach. This can also be seen in Table 7.

The climate charts in Figures 23 and 25 show that during summer the exceedance of this fungal growth curve is largest. In Figure 23 all the weekly averages exceed the mould growth curve whereas in Figure 25 most of the summer weekly averages exceed the mould growth curve.

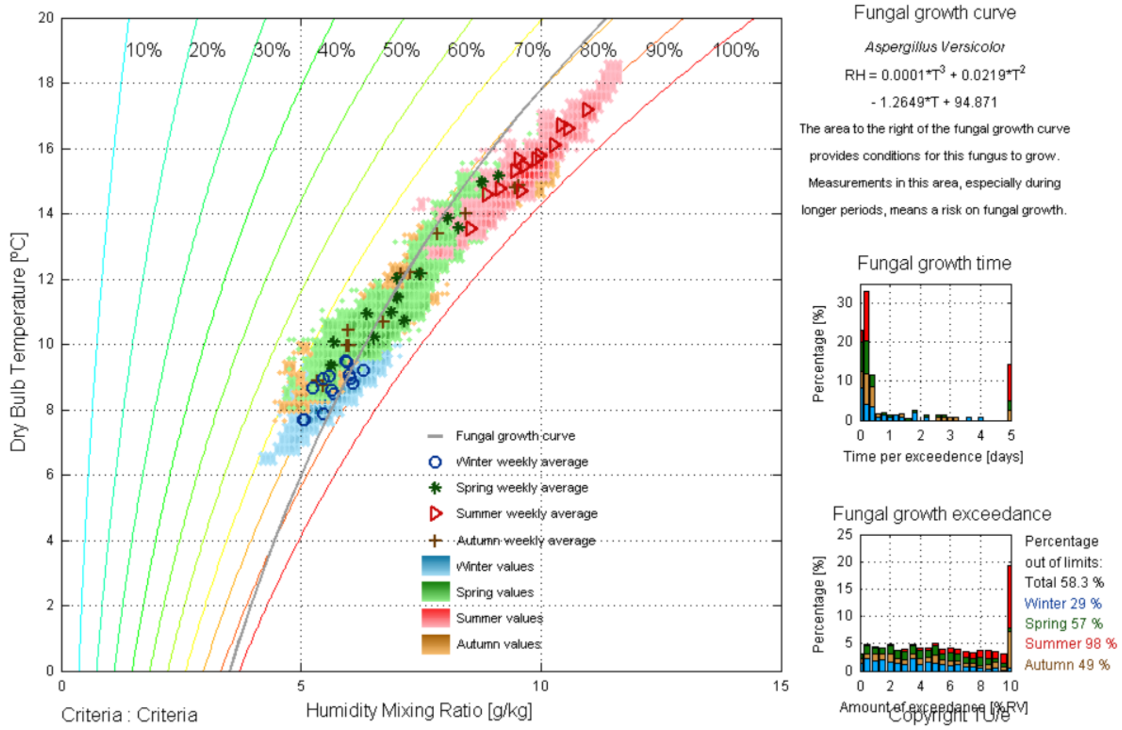

Figure 23: climate chart of variant 3, the uninsulated but ventilated variant

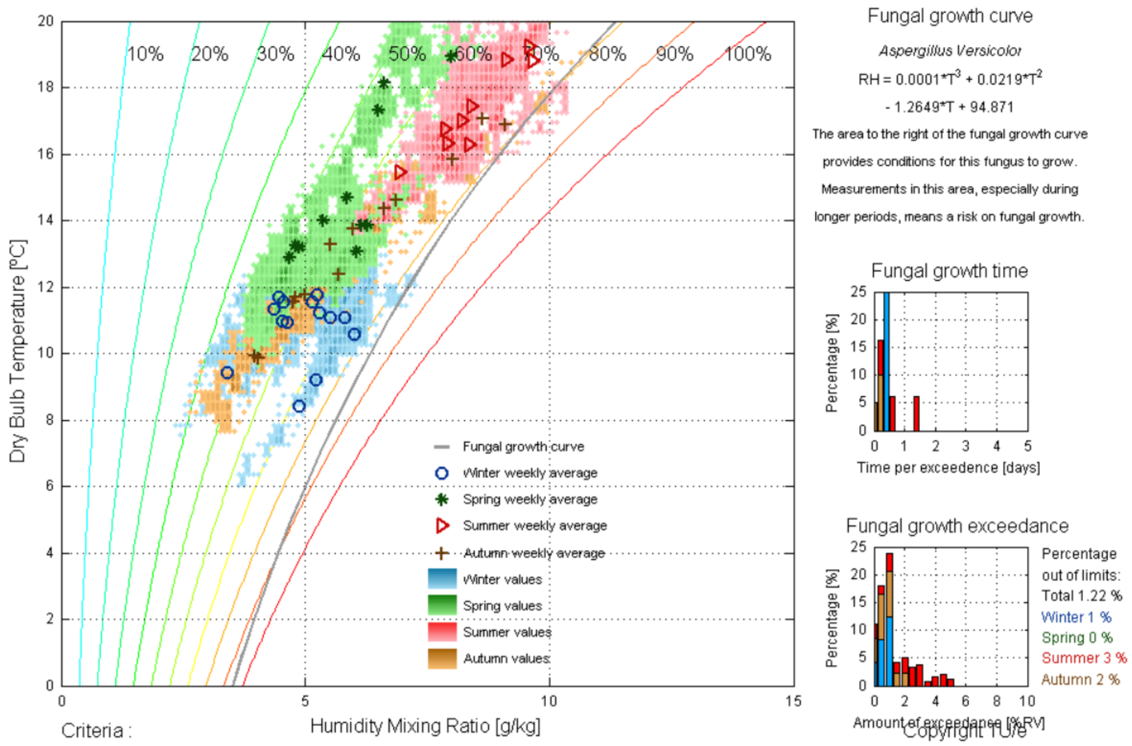

Figure 24: climate chart of variant 6, the bottom insulation, infiltration only, vapour tight ground cover variant

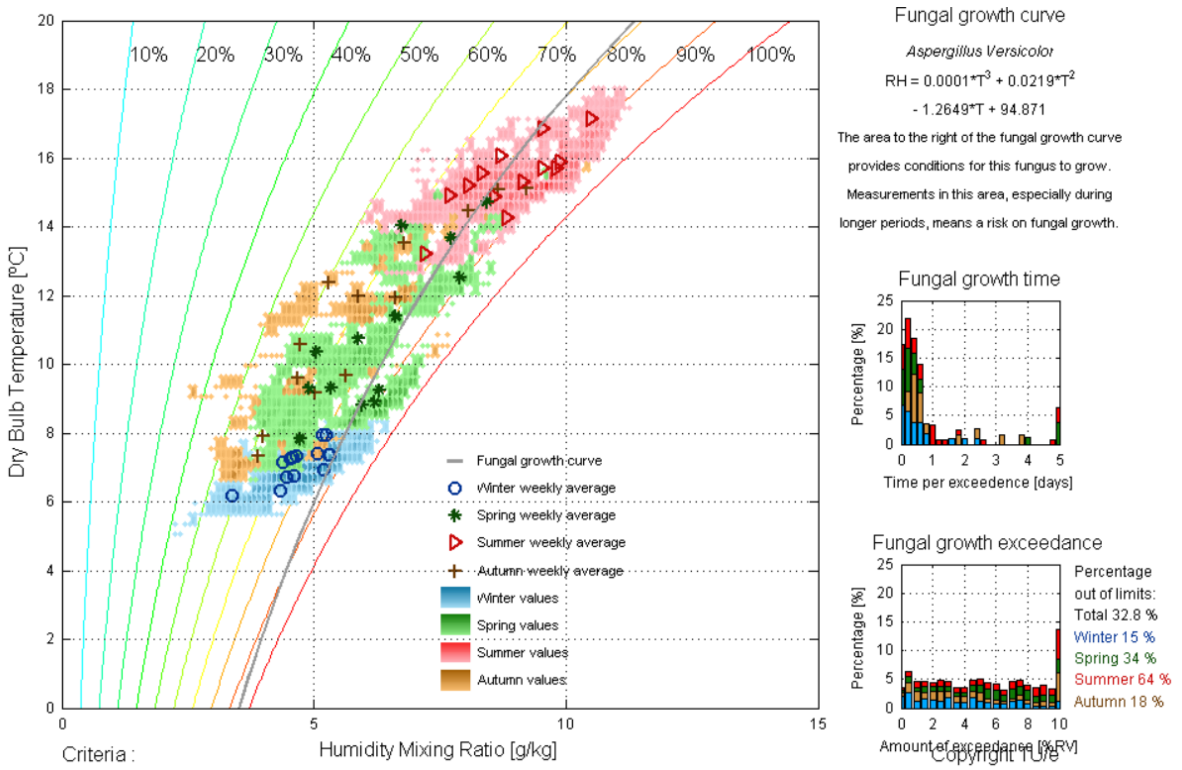

Figure 25: climate chart of variant 14, the floor insulation, infiltration only, vapour tight ground cover variant

Due to colder temperatures, mould growth is less likely to occur since at lower temperatures a higher RH is required. Therefore, we take a closer look at a typical week during the summer.

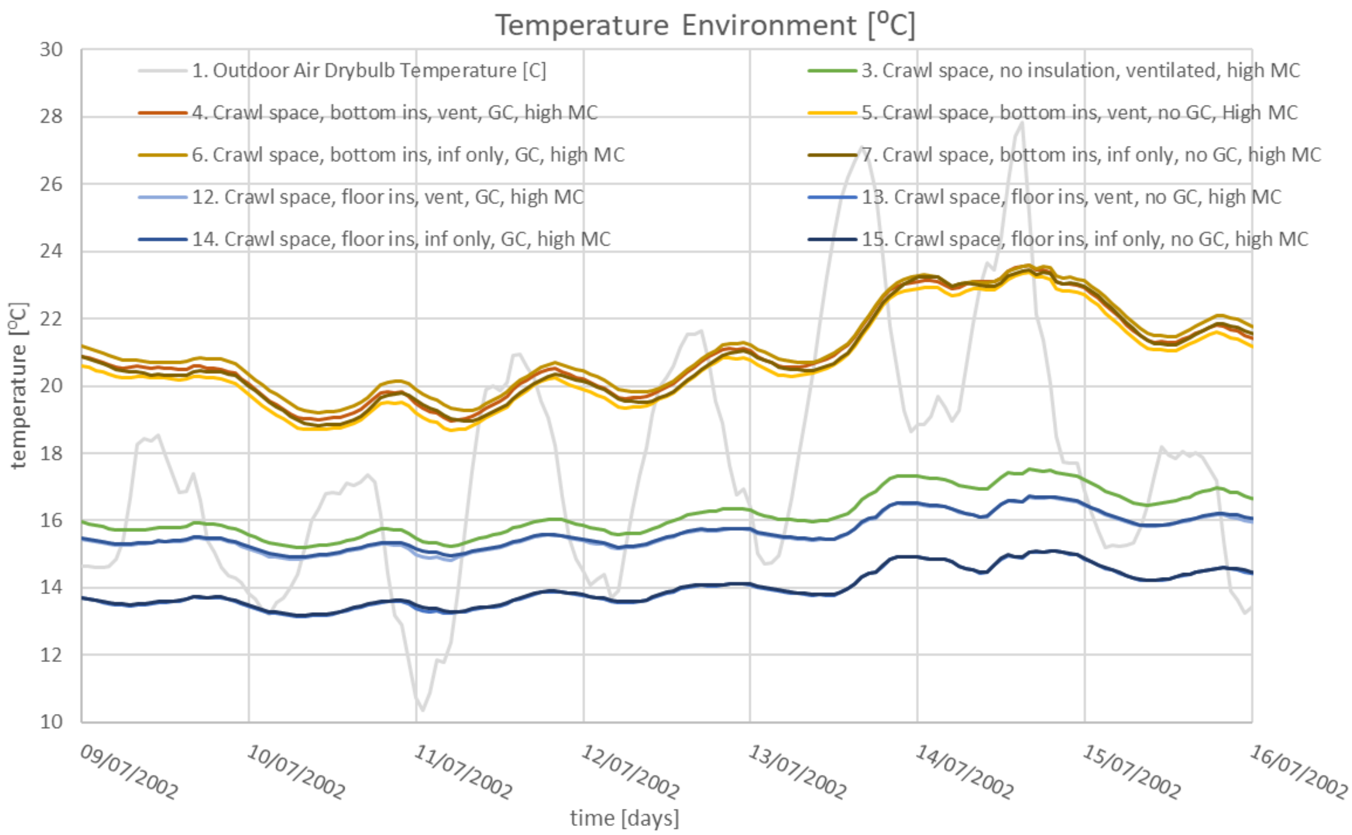

Figure 26: a typical summer week crawl space temperature [^{0}C] for variants 3-7 and 12-15 with the outdoor conditions

Figure 26 presents the temperature in the crawl space during week 28 (9th July – 16th July). Figures 26, 27, and 28 only show the variants with higher moisture content in the soil, because these variants have a higher chance of introducing hygrothermal risks. The crawl space with bottom insulation shows a higher temperature year-round (see Table 7). This also is the case in this summer week. Figure 27 gives the RH in the crawl space for the corresponding week. It can be observed that the variants without insulation and the variants with floor insulation have higher RH than the variants with bottom insulation. In all the cases it can be observed that the variant with the vapour tight ground cover has a lower RH than the corresponding variant without. This seems to have a higher impact on the variants with floor insulation. Figure 28 shows the absolute humidity during the same week. With Figure 28 can be concluded that the large difference in RH between variants 4-7 and 12-15 is primarily due to the large temperature difference since the absolute humidity is relatively close for all the variants.

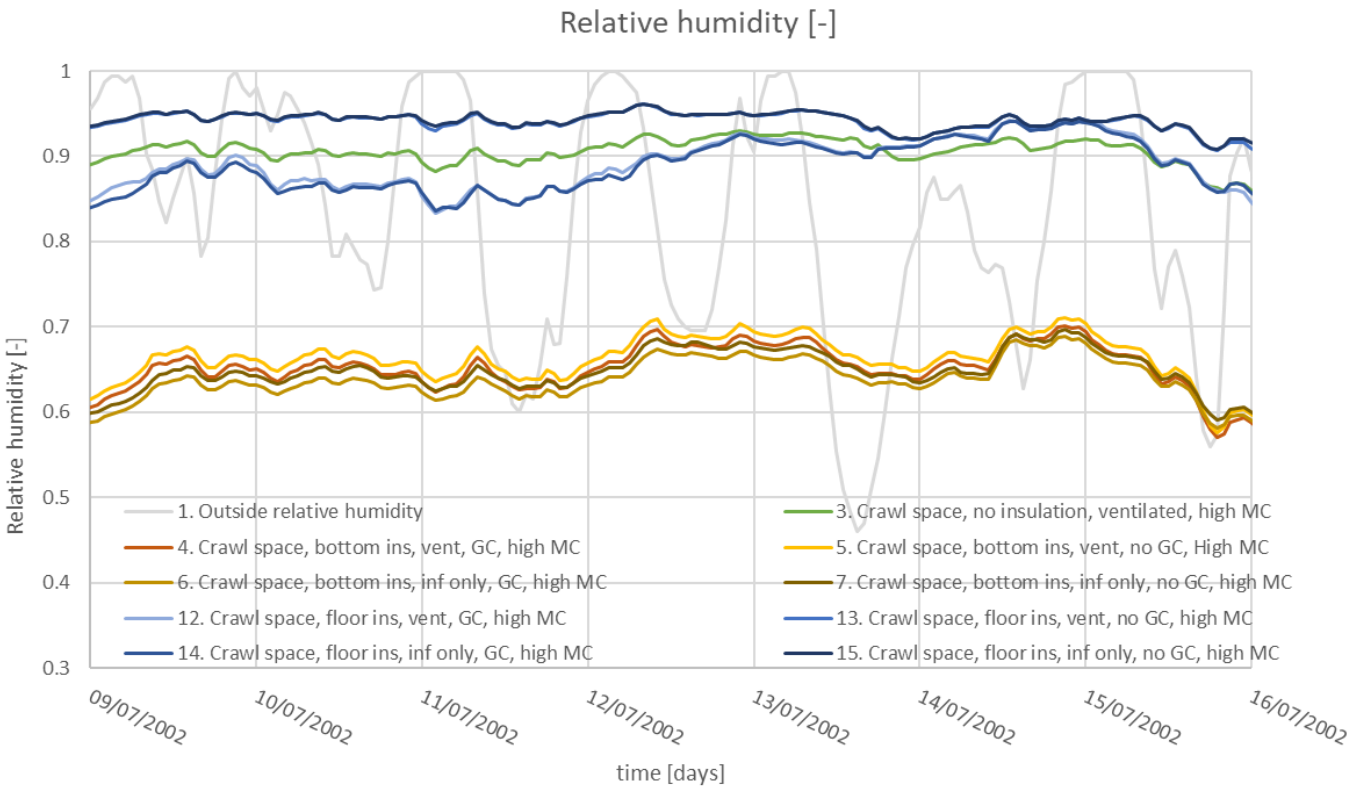

Figure 27: a typical summer week crawl space RH [-] for variants 3-7 and 12-15 with the outdoor conditions

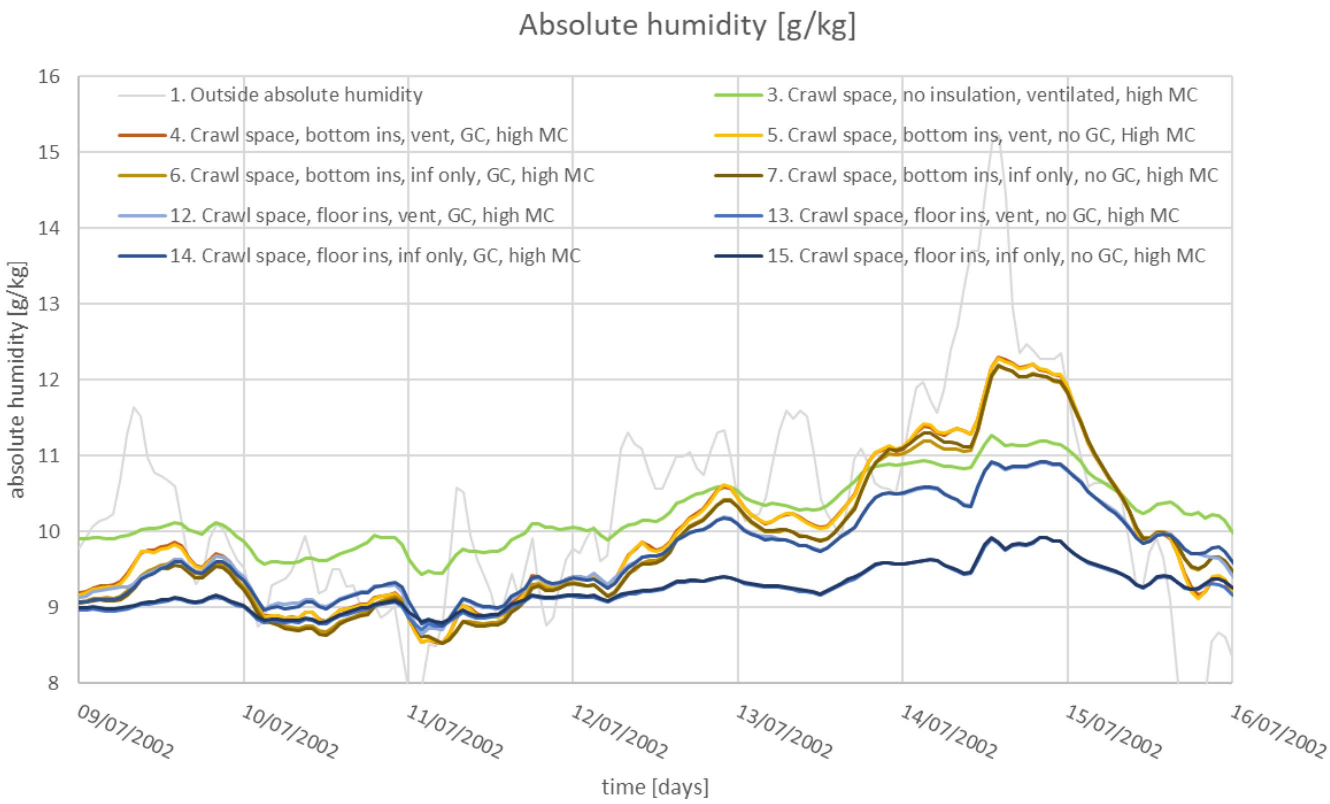

Figure 28: a typical summer week crawl space absolute humidity [g/kg] for variants 3-7 and 12-15 with the outdoor conditions

Table 7 showed most of the performance indicators mentioned. However, Table 7 does not mention wood rot. Table 7 showed that variants 13 and 15 have the most humid crawl space. Additionally, variants 13 and 15 are the only variants that frequently pass the 95% RH threshold. To further explore this, in Figure 29 we depict the VVT wood rot model applied to the crawl space conditions.

The VTT model, earlier described by Formulas 7-12, was applied using the crawls space temperature and relative humidity from the second year of the simulation. These yearly conditions for the temperature and RH were used for multiple consecutive years. According to the VTT model, exposure to these crawl space conditions would result in wood decay in the third year of exposure (see Figure 29).

However, in variants 13 and 15 the wood is not directly exposed (see Figure 17) to the crawl space conditions. Therefore figure 29 resembles what would happen if we placed a small sample of untreated pinewood in the middle of the crawl space while not touching the ground.

Using temperatures and RH that are found in the construction at the location of the beams would not result in wood rot, because of the higher temperatures due to the insulation material. However, if there would be a large crack or breach in the insulating material so that the wooden floor beams would be exposed to the crawl space conditions Figure 29 may give accurate predictions about the mass loss due to wood decay.

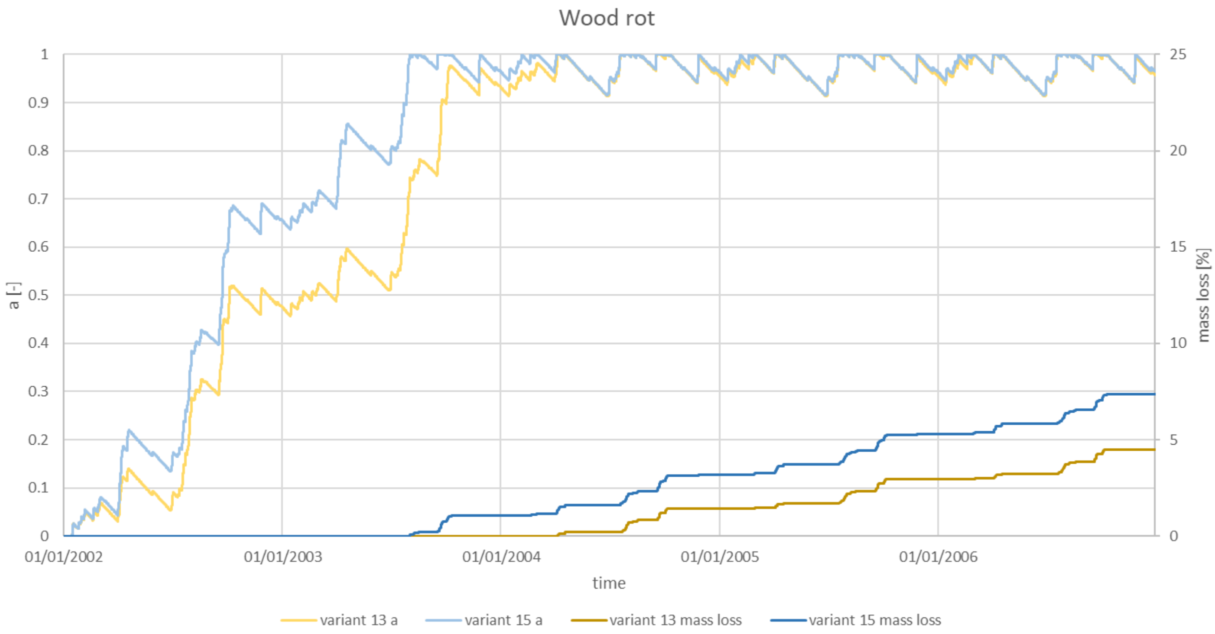

Figure 29: the VTT wood rot model applied to variants 13 and 15

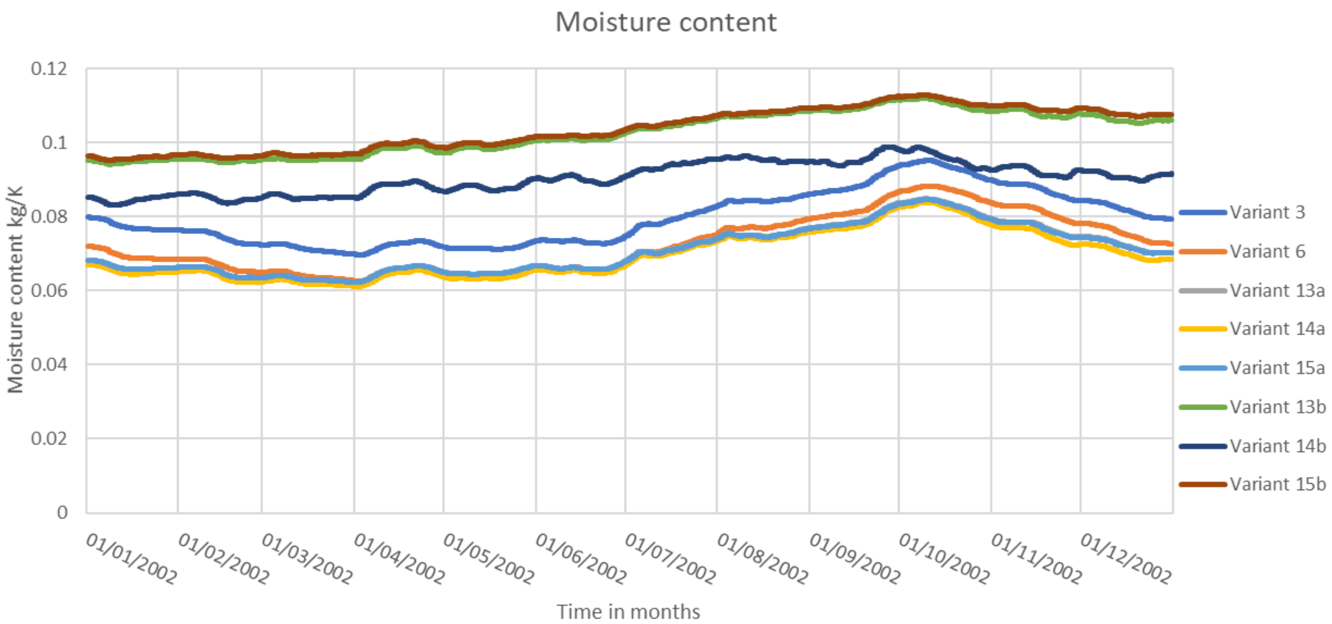

Figure 30: Moisture content in the wooden floor for the discussed variants. The variants with an “a” and “b” behind them have data for the bottom of the beam and the top of the beam respectively

Most wood-decaying fungi have optimum conditions at a wood moisture content of 20- 30 % (wt). (Singh, 1999). Figure 30 shows the moisture content in the beams. It can be noted that the moisture content in the beams stays below 12% (wt). Therefore, wood rot is not likely to occur in these constructions.

However, the moisture content might not be accurately simulated due to simplifications that were made to the construction (see Figure 17). These simplifications were made because EnergyPlus is only capable of performing 1D simulations, while the floor construction would otherwise require 2D simulations.

Chapter 5: Discussion and Conclusion

5.1. Discussion

In the validation study, the model was fitted to the real-world measured data by varying among other things the ventilation, ground temperature, and soil moisture content. This resulted in a CV RSME of less than 10% for the temperature, RH, and absolute humidity. However, since there was only one case study to which the model was attuned, it might be that certain temperature or moisture flows are overestimated and others are underestimated. This might lead to more inaccurate results in other cases. Perhaps this might even lead to more inaccurate results in cases with different variants of insulation materials.

Furthermore, EnergyPlus's HAMT module cannot cope with air leakage, precipitation-related moisture problems, or condensation problems from high relative humidity (Simon Pallin, 2017). Knowing that there are some naturally occurring phenomena EnergyPlus is not able to simulate confirms that this risk is present. However, it must be noted that the effects of adding insulation to the bottom of the crawl space seem to follow patterns observed in literature. Therefore, further validation with more cases is necessary to get a better understanding of exactly how capable EnergyPlus is in performing hygrothermal whole building simulations.

In this study, the assumption was made that the risk of the model being only attuned to one specific case does not drastically affect the validity of the model when testing different insulation strategies. This assumption should be investigated further, this can be done by performing further validation work on different cases. This can prove if whole building simulation is suited to make these kinds of predictions for the temperature and RH in the crawl space. That being said, it is also important to keep in mind that a 7.28% CV RSME and an MBE of -2.05% is considered highly accurate and indicates the enormous potential of whole building simulation combined with HAMT.

Adittionally, in the case study the ventilation of the crawl space was simulated (see Figure 6). When looking at the results of the simulated ventilation it seems as though 0.35 ach for the summer and 1.4 ach for the winter, instead of 0.35 ach for the winter and 1.4 ach for the summer, might have been a better fit according to the AFN pressure dependant simulations.

The main notable result from the variant study is that the bottom insulation shows lower RH in the crawl space. This is probably due to higher temperatures in the crawl space, whereas in the variants with ground floor insulation the crawl space becomes colder. This is probably due to it gaining less heat from the residential area above it. Which, in turn, is the result of better insulating properties.

The variants with ground floor insulation show a larger decrease in energy demand for heating the building compared to the variants with insulation on the bottom of the crawl space. However, they also show a larger cooling demand than the variants with bottom insulation. When subtracting the increased cooling energy demands from the reduced heating demand. The energy savings of insulation on the bottom of the crawl space is only 3% and when applying insulation materials to the ground floor energy savings can get up to 11%. Additionally, the variants with bottom insulation seem highly influenced by the ventilation capacity of the crawl space.

Cases with a vapour tight ground cover always showed a lower relative humidity than cases without a ground cover. An interesting phenomenon seemed to occur when adding the number of air changes in the comparison. It was notable that in variants 12 up to 19, the cases with a vapour tight ground cover had a slightly higher RH when there was more ventilation compared to when only infiltration through cracks was simulated. Whereas in the cases without a vapour tight ground cover, a slightly higher RH was observed in the cases with less ach. This could be due to the main source of moisture in the crawl space with a ground cover. This main source is probably hot summer air cooling down. Unlike the cases without ground cover, in these cases, it is probably evaporation from the ground.

5.2. Conclusion

From the variant simulations, we can conclude that the chance to introduce hygrothermal risks into a crawl space when insulating is lowest when using bottom insulation. Additionally, vapour tight ground covers can be used to reduce the relative humidity in crawl spaces. This effect is more notable in the variants with insulation underneath the ground floor compared to variants with insulation on the bottom of the crawl space.

Furthermore, it was observed that the variants with insulation underneath the ground floor performed better in terms of energy savings. However, the variants with insulation underneath the ground floor also negatively influenced the crawl space climate making the space damper. Whereas the insulation material on the bottom of the crawl space improved the crawl space climate. However, the energy savings of these variants were low. There appears to be a trade-off between insulation value and hygrothermal risks.

Despite the hygrothermal risks of the damp crawl space climate caused by insulation underneath the ground floor, the beams never obtain dangerously high moisture contents. However, surfaces in this crawl space might be affected by mould growth. Furthermore, if cracks and gaps do occur in the insulation layer protecting the wooden beams, hygrothermal problems might still be introduced.

A 2D or 3D simulation with different software might give further insight. The simulation results of the whole building simulation give a climate for the crawl space which can be used as an input for more detailed 2D or 3D HAMT calculations in programs like Delphin and Comsol. For example, details of wooden beams to wall connections in a crawl space can be calculated as well as cracks in insulation layers.

These findings can be helpful in the decision-making process of which insulation method should be used in renovation projects. Additionally, it can quantify the risks that come with certain variants. Whereas the validity of the quantification for mould growth and wood rot models are up for debate (Kvist Hansen et al., 2020) they can still be used to compare the hygrothermal risks of different insulation strategies.

5.3. Future work

Future works following this research might include further validation. There might be settings that suit the case study even better. So further validation and fitting of this model can be done. However, it would be the most interesting when different cases and weather conditions are used. This study only has one case study for the model to adjust to. Perhaps the model is not as accurate when applied to other buildings than the building from our case study. Therefore, more validation work with different case studies is recommended for future works.

Furthermore, a combination of whole building simulation and 2D or 3D detailed simulations might lead to interesting and accurate results for wooden beam wall connections in crawlspaces. The hygrothermal risks often occur at corners and construction joints. To accurately predict moisture content in the materials or RH at the surface of the materials 2D or 3D simulations are required. For these simulations however the crawl space environment is a required input. This can be extracted from a 1D HAMT whole building simulation model.

Additionally, there is not much information available in the WUFI database on innovative insulation material properties. Perhaps the model could even obtain a better validation if certain material properties are finetuned. For example, there is quite a large range of material properties for concrete. Concrete can have densities between 2000 kg/m3 or 2600 kg/m3 according to EN 206. This difference in density might influence the vapour resistance or the moisture storage functions. Concrete is not the only material that can have differences in material properties. There are for example hundreds of wood types.

Finally, because EnergyPlus is open-source software it might be interesting to see what would improve if certain modules are updated or added to the HAMT module from EnergyPlus. This might lead to more accurate results. The main limiting factor for EnergyPlus would then be that it is a 1D simulation tool.

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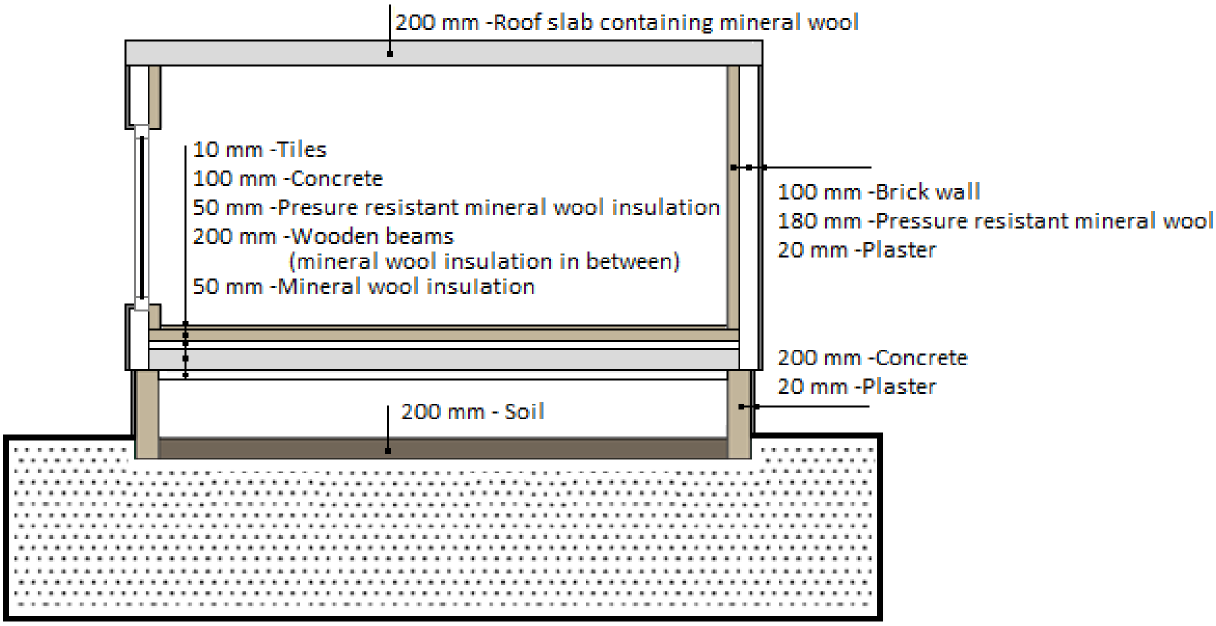
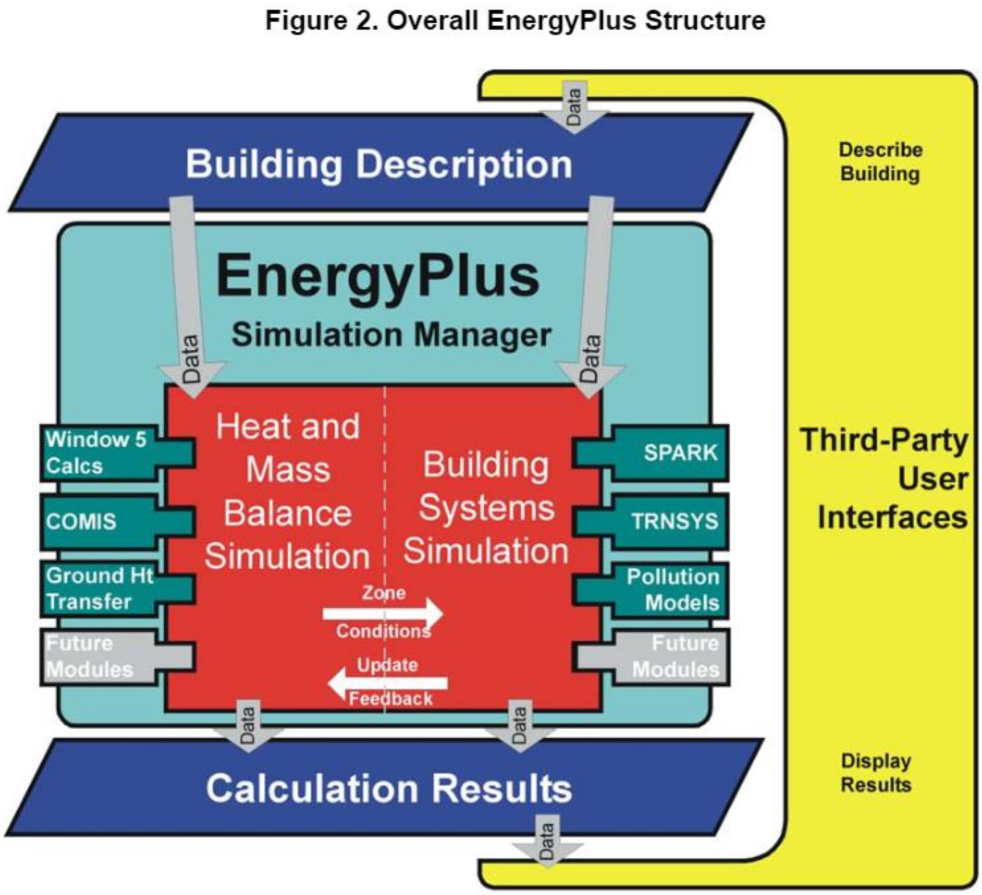
Appendixes

A1: Materialization of the modelled geometry



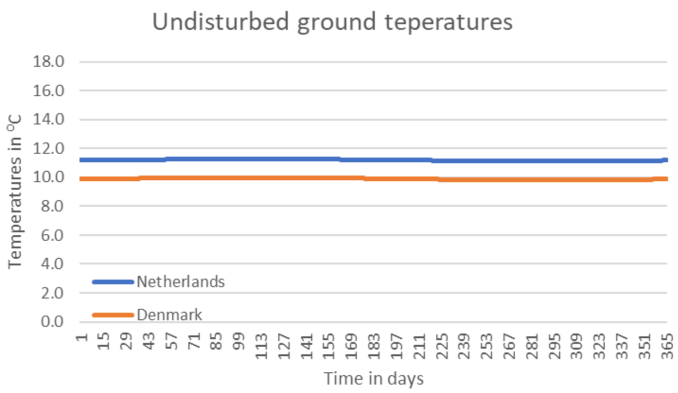
A2: Overall EnergyPlus structure (Crawley et al., 2004)



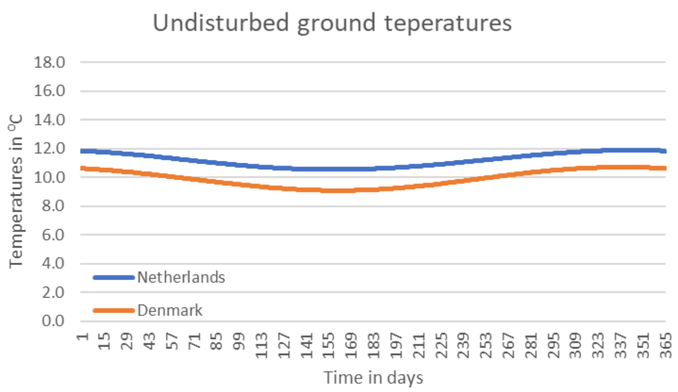
A3: Xing ground temperatures (Xing, 2010)

Region	Country	Station	Latitude	Longitude	$T_{s,avg}$	$T_{s,amplitude,1}$	$T_{s,amplitude,2}$	PL_1	PL_2
4	MKD	KRIVA-PALANKA	42.20	22.33	11.6	8.7	0.0	24	10
4	MKD	OHRID	41.12	20.80	12.1	8.8	-0.4	30	24
4	MKD	SKOPJE-AP	41.97	21.65	12.9	10.0	1.1	22	-2
4	MLT	LUQA	35.85	14.48	19.3	6.3	-0.6	43	35
4	MNE	PLEVLJA	43.35	19.35	9.5	9.2	0.8	26	27
4	MNE	PODGORICA-GOLUBOVCI	42.37	19.25	15.4	9.0	0.1	25	5
4	MNE	TIVAT	42.40	18.73	15.6	7.9	-0.7	27	26
4	NLD	AMSTERDAM-AP-SCHIPH	52.30	4.77	11.2	6.4	0.4	29	-3
4	NLD	DE-BILT	52.10	5.18	11.1	6.3	0.2	27	-4
4	NLD	DE-KOOY	52.92	4.78	11.2	6.1	0.4	32	-34
4	NLD	DEELEN	52.07	5.88	10.6	6.9	-0.2	26	12
4	NLD	EINDHOVEN	51.45	5.42	11.4	6.3	-0.1	23	1
4	NLD	GILZE-RIJEN	51.57	4.93	11.3	6.3	-0.1	28	9
4	NLD	GRONINGEN-AP-EELDE	53.13	6.58	10.5	6.4	-0.6	27	34
4	NLD	HOEK-VAN-HOLLAND	51.98	4.10	11.7	5.8	0.4	33	-25
4	NLD	LEEUWARDEN	53.22	5.77	10.7	6.1	0.1	30	12
4	NLD	MAASTRICHT-AP-ZUID	50.92	5.78	11.7	6.4	-0.2	21	7
4	NLD	ROTTERDAM-AP-ZESTIE	51.95	4.45	11.4	6.4	-0.2	29	1
4	NLD	SOESTERBERG	52.13	5.28	11.0	6.5	-0.2	26	17
4	NLD	TWENTHE	52.27	6.90	11.0	6.3	-0.1	26	-5
4	NLD	VALKENBURG	52.18	4.42	11.4	6.1	-0.1	31	19
4	NLD	VLISSINGEN	51.45	3.60	12.0	6.3	0.1	31	9
4	NLD	VOLKEL	51.65	5.70	11.2	6.3	-0.1	21	10
4	NLD	WOENSDRECHT	51.45	4.33	11.2	6.3	0.0	26	8
4	DNK	AALBORG	57.10	9.85	9.3	6.8	-0.6	31	14
4	DNK	BILLUND	55.73	9.17	9.2	6.9	-0.6	29	21
4	DNK	CHRISTIANSO(LGT-H)	55.32	15.18	9.6	7.3	-0.9	42	34
4	DNK	ESBJERG	55.53	8.57	10.1	6.4	-0.2	31	0
4	DNK	FORNAES(CAPE)	56.45	10.97	9.6	6.9	-0.4	37	21
4	DNK	HAMMER-ODDE	55.30	14.78	9.7	7.3	-1.0	37	33
4	DNK	HOLBAEK	55.73	11.60	9.8	7.5	-0.2	30	10
4	DNK	HVIDE-SANDE	56.00	8.13	10.8	7.1	-0.7	37	43
4	DNK	KARUP	56.30	9.12	9.5	6.9	-0.6	29	10
4	DNK	KEGNAES	54.85	9.98	10.2	7.0	-0.2	34	6
4	DNK	KOEBENHAVN-KASTRUP	55.62	12.65	9.8	7.1	-0.4	31	4
4	DNK	ODENSE-BELDRINGE	55.48	10.33	10.0	7.0	-0.7	28	25
4	DNK	ROENNE	55.07	14.75	10.3	7.3	-1.0	34	31
4	DNK	ROSKILDE-TUNE	55.58	12.13	9.4	7.3	-0.7	31	27
4	DNK	SKAGEN	57.73	10.63	9.9	6.5	-1.2	35	34
4	DNK	SKRYDSTRUP	55.23	9.27	9.4	6.7	-0.6	30	5

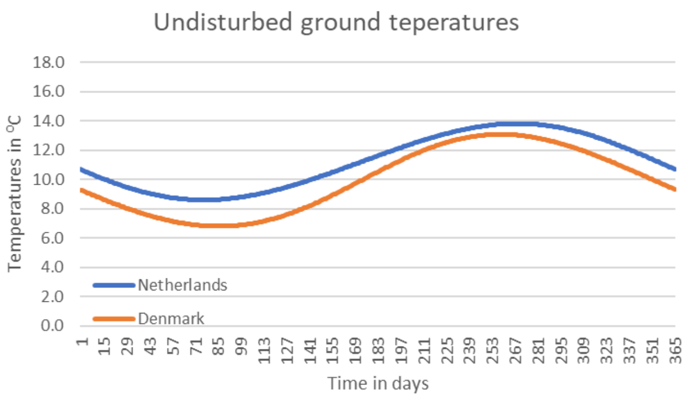
A4: Comparison of the undisturbed ground temperatures in Denmark and the Netherlands at different depths calculated with the “Undisturbed Ground Temperature Model” developed by Xing



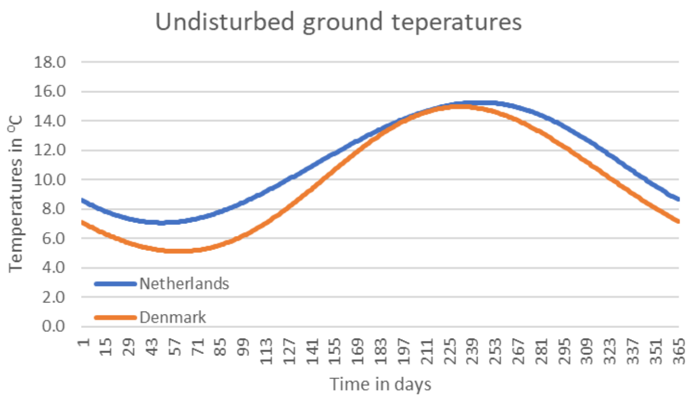
Undisturbed Ground Temperature 10m depth



Undisturbed Ground Temperature 5m depth



Undisturbed Ground Temperature 2m depth



Undisturbed Ground Temperature 1m depth

A5: table of physics comparison between WUFI, HAMT and EMPD (Simon Pallin, 2017).

Natural phenomenon:	**WUFI Pro**	**HAM-T**	**EMPD**
Moisture storage capacity	x	x	x
- with temperature dependency			
- with relative humidity dependency	x	x	x
Water (liquid) transportation	x	x	
- capillary pressure driven	x	x	
- gravity driven			
Water (vapor) transportation	x	x	
- with relative humidity dependency	x	x	
Air leakage (Infiltration/Exfiltration) through materials	x		
- with temperature dependency			
- wind and ventilation driven			
Surface water absorption (capillary suction)	x		
Combined diffusion and capillary suction	x		
Precipitation	x		
Stagnant water on surface			
Exchange of moisture between model and interior conditions		x	x
Moisture effusivity, contact resistance between materials			
Intermediate condensation	x		
Thermal conductivity	x	x	x
- with temperature dependency	x		
- with relative humidity dependency	x	x	
Heat storage capacity	x	x	x
- with relative humidity dependency		x	
Radiation exchange at boundary surfaces	x (exterior)	x	
Intermediate radiation exchange inside air cavitities			
Exchange of heat between model and interior conditions		x	x
Thermal effusivity, contact resistance between materials			