Hygrothermal modelling of internal insulation to solid masonry walls
Hygrothermal Modelling of Internal Insulation
to Solid Masonry Walls

MSc thesis (30 ECTS)
Peter Otiv
S145166
Abstract

With the increasing need to act against global warming new ways of reducing carbon emissions are being sought out and governments are setting stricter targets to become more energy efficient. The construction industry is making advancements leading towards zero energy buildings but the existing building stock accounts for a high proportion of energy used. In these inefficient but architecturally significant buildings there is a large opportunity to make energy savings. Problems have arisen from trying to reduce heat loss in existing buildings where moisture levels increased in the building materials leading to structural damage and risks to health and comfort of users.

A new variety of internal insulation systems have been developed which are diffusion open and capillary active to facilitate moisture transport and drying. In this project the results of an experiment testing two insulation systems are used to validate hygrothermal simulations that artificially recreate the same circumstances. These validated models have then been tested in typical climates of Copenhagen, Esbjerg and Aalborg to examine how the insulated wall systems function in typical Danish climates. A damage evaluation was then made to determine whether the systems will function successfully.

The two walls were successfully validated with a maximum ±1°C and ±10% discrepancy in temperature and relative humidity respectively. Over the three locations when the Multipor insulation alone was applied to masonry, the system failed to keep relative humidity levels down and over-hygroscopic condensation occurs for long periods each year. When the hydrophobic treatment is applied to the façade the relative humidity stays much lower. Between the three locations Aalborg has the lowest relative humidity within the wall layers which coincides with lower average wind velocity although the same pattern was not seen in windier Esbjerg where the relative humidity was very similar to Copenhagen. The damage evaluation showed that frost damage is not a threat in any of the cases. Wood decay is a risk at the centre of the brick layer and between the brick and insulation layers occurring rapidly without the hydrophobic impregnation and more slowly with the treatment. Mould growth was found to occur in all cases between insulation and brick layers.

It was established that the Multipor system alone is not suitable to insulate a 1 ½ brick wall in typical Danish climates. Even with the hydrophobic treatment Multipor is not recommended because substantial mould and wood decay damage is still likely. The hydrophobic impregnation itself seems to be very beneficial in a Danish climate.
Acknowledgments

This project would not have been possible without the support of many people. I especially would like to express my gratitude to supervisors Søren Peter Bjarløv and Tommy Odgaard for their patience, motivation, advice and engagement through the learning process of this master thesis. Also for involving me in their research and providing the real experimental data used in this project. I would also like to thank Tessa Kvist Hansen for helping me with the plaster carbonisation.

Abbreviations

AAC– Autoclaved aerated concrete (insulation material)

CaSi – Calcium Silicate board (insulation material)

DMI – Danish Meteorological Institute

DRY – design reference year

DTU – Technical University of Denmark

PIR – polyisocyanurate (insulation material)

WDR – Wind driven rain

XPS – extruded polystyrene (insulation material)
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1 Introduction

With the new demands for energy saving such as the target to reduce greenhouse gas emissions in Denmark by 40% by 2020 (Government 2013) there are many new initiatives being made in all sectors to help achieve this target. Energy efficiency requirements for new buildings have already been set to strict low levels however the existing building stock is mostly very inefficient so renovation is also a key tool in meeting these requirements. Existing Buildings contribute 40% (The Danish Ministry of Climate Energy and Building 2012) of total energy consumption so there is great value in lowering their energy use. The energy efficiency of existing buildings can most easily be improved by reduction of heating demands from adding insulation materials with a low thermal conductivity to the envelope of the building.

It has been well established (Christensen 1984), (Kolaitis et al. 2013) that externally insulating a building is more effective and less problematic because a complete envelope can be made without thermal bridging and the usable internal space is not reduced. A problem arises in the many historical and architecturally important buildings where it is not acceptable for the façade to be covered. Here internal insulation is the only feasible solution however it is now a well-known problem (Straube & Schumacher 2007; Kolaitis et al. 2013; Vereecken & Roels 2015a) that lowering the temperature of the original wall often leads to high moisture levels within the wall.

Moisture can be problematic in several ways, whether it is located on the external or internal side of the wall or all the way through. On the outside frost damage can occur when water expands in freezing during cold weather, mould growth and wood rot are two modes of biological damage that usually occur in the interior. While frost damage is mostly a cosmetic issue, mould growth can be harmful to the health of the building’s inhabitants and wood rot in structural members can lead to total instability of the building.

There are several factors that cause moisture problems with internally insulated masonry buildings. Wind driven rain (WDR) plus high external and internal relative humidity contribute to moisture inside the materials of the wall. When a wall is insulated it becomes colder and unable to dry out because the heat energy is better contained within the building. The addition of a vapour barrier can keep moisture away from the inner wall layers however when WDR is present, frost damage can still occur in the outer surface of masonry. Additional difficulties occur when wooden beams are situated within the brick wall, as they commonly are in Danish buildings from the period between 1850 and 1930. It is hard to create a tight closure with the vapour barrier around these wooden beams allowing moisture to enter leading to mould growth and wood rot (Vereecken & Roels 2015b; Vereecken et al. 2015).

A new variety of internal insulation systems that don’t require a vapour barrier are now being produced by manufacturers that claim to be capillary active or hydrophilic to facilitate moisture transport. The process aims to redistribute condensed water formed between the insulation and brick layers, by drawing the moisture through the insulation to the internal surface where it can evaporate into the air as shown in Figure 1.1. While some research has been made showing positive (Scheffler & Grunewald 2003), (Pavlík & Černý 2009), (Simonson et al. 2005) and less encouraging results (Vereecken & Roels 2015b), (Vereecken & Roels 2011) more knowledge is still needed because there are so many different capillary active materials that can be combined and arranged in numerous ways.
Furthermore, while these materials have proven effective in central European climates they have not been extensively tested in Denmark before. An experimental study is now underway to analyse the hygrothermal effects of retrofitting interior insulation to typical Danish masonry walls such as those constructed in the period 1850 to 1930. Several different retro-fit insulation systems have been installed on identical masonry walls at The Technical University of Denmark’s (DTU) Lyngby campus. These are exposed to real outdoor weather conditions combined with controlled humid interior conditions. The insulation systems in the experiment have been selected because they are all potential alternatives to the traditional vapour barrier system and are either commonly used already or at the forefront of research.

The results of the experiment will give insight into whether the insulation systems are successful for the particular weather that occurs for the time they are tested in Lyngby. However this is a very specific criteria so this experiment alone does not prove the system will work in a typical climate of Denmark. In fact Denmark has six different characteristic climate zones (Danmarks Meteorologiske Institut 1991) so an additional investigation is required to help determine how the systems perform in these environments.

In this thesis a hygrothermal simulation will be made replicating two of the insulated walls from the experiment using the computer software Delphin. The model will be validated with experimental data recorded from the site at DTU, hereafter the exterior conditions will be changed to illustrate other locations namely Esbjerg and Aalborg that have quite different climates. This project will investigate the robustness of the insulation systems showing the risk of mould, wood rot and frost damage occurring which will provide an overview of whether the systems are sustainable in practice. By making tests in different locations with different climates a more reliable opinion can be formed on the effectiveness of the insulation system.
The first wall investigated is the Xella 80 kg/m³ Multipor system (Xella Danmark A/S 2016) which is a low density mineral board made from sand, lime, cement and water. The second wall to be simulated will be the same Multipor system but with a hydrophobic impregnation applied to the exterior surface of the brick which in theory reduces capillary uptake. More details about the materials will be presented later in the report but these systems have been chosen firstly to see whether a capillary active system will be effective enough to cope with a wet Danish climate. Secondly the hydrophobic treatment is tested to see if any improvements come from reducing the bricks capillary transport of rain and if this performs in synergy together with the Multipor insulation.

Below are the two main goals of this project and by achieving these the project intends to answer the question: *How does a masonry wall with a hydrophobic façade treatment and insulated with the capillary active material Multipor perform in terms of heat and moisture in a typical Danish climate?*

**Goals**

1. Create two hygrothermal models using Delphin of insulated masonry walls to the same specifications as in the experimental situations and validate with the experimental data.

2. Use this validated model to explore the effects when placed in different locations and so under different climatic conditions.

The report will be structured in the following way; Starting with a literature review in section 0 of the latest research in capillary active materials. This is followed by a review to find the most suitable methods of evaluating moisture damage in the walls in section 3. Section 4 contains a description of the method used including a description of the physical experiment that has provided the data for the simulation to be validated against. Then the results are presented in section 5. An evaluation of the risk of moisture damage due to the calculated conditions is made in section 5.6. Following this, a general discussion is made in section 6 to give a dialogue over all of the results found. Finally a conclusion is made in section 7 and extra material has been organised in an Appendix in section 8.
2 Literature Review

A literature review has been made to obtain the current status of development of capillary active insulation systems. This will begin with an outline of the arguments to be discussed in the review before the main discourse and finally a conclusion will be made of the literature review relating the findings of the literature to this project while also remarking on the use of computer simulations in the literature.

The first argument to be investigated is whether it has been shown that capillary active, diffusion open materials work in practice as they are theoretically intended and is this superior to traditional vapour tight constructions. To begin to discuss whether capillary active, vapour open insulation achieves its theoretical role this role should first be clarified, that is redistributing interstitial condensation between insulation and brick layers leading to a reduction in the overall moisture content in the construction. The next topic will compare the various materials to discuss which performs best in capillary action and vapour openness. Because of the broad range of systems under research, the review has been limited to similar materials to those chosen for the physical experiment here at DTU. This includes the following materials listed in Table 2.1. Finally a review of research into hydrophobic treatments will be made to give a better understanding of the theory behind their application.

Table 2.1. Capillary active materials chosen for literature review.

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IQ-Therm</td>
<td>PUR-foam is transformed into a capillary active material by adding holes filled with mortar.</td>
</tr>
<tr>
<td>AAC – Autoclaved aerated concrete</td>
<td>Air pockets worked in during the manufacturing process to reduce the density, and U-value whilst having hydrophilic properties. The Multipor tested in this project is a variance of AAC with lime added.</td>
</tr>
<tr>
<td>CaSi – Calcium Silicate board</td>
<td>Made from a reaction between calcium oxide and silica with a capillary active structure.</td>
</tr>
<tr>
<td>XPS – extruded polystyrene</td>
<td>Two commonly used moisture tight systems used as a reference to compare capillary open systems against.</td>
</tr>
<tr>
<td>PIR – polyisocyanurate</td>
<td>Two commonly used moisture tight systems used as a reference to compare capillary open systems against.</td>
</tr>
</tbody>
</table>

The first discussion question of whether capillary active materials really work in practice can be difficult to answer because this action is happening within the materials so it is not easy to see what is going on. This problem has been addressed in an experiment where (Vereecken & Roels 2011) developed an insightful technique adapting X-ray radiography equipment to give a more visual experimental comparison between capillary active materials and normal insulation techniques. The results show that some of the capillary active materials especially calcium silicate do work in distributing the moisture throughout the layer but it is inconclusive whether this reduces the entire moisture content or avoids interstitial condensation. The glue mortar used between brick and insulation layers clouded the results because it was much more hydrophilic than the insulation materials so water collected here rather than being distributed into the insulation. In this experiment more focus is given to the new measurement technique rather than the meaning of the results so further research with more realistic weather conditions would provide more valuable results.

By simulating a single leaf brick wall insulated with both capillary active CaSi and vapour tight XPS, it was established by (Vereecken & Roels 2015b) that capillary active insulation works successfully by removing moisture from the masonry interface in cases of wind-driven rain. In most simple internal insulating cases traditional vapour tight methods work best but here it was found that a vapour barrier is not suitable when the construction includes
wooden beams sitting inside the brick walls. However it was stressed that the success of capillary active insulation is highly dependent on the situation namely the amount of wind driven rain (WDR) and wall thickness.

In a project by (Vereecken et al. 2015) a hygrothermal simulation tool (Delphin) is used to analyse two vapour tight and two capillary active internal insulation systems. In this paper many simulations are carried out where parameters are altered in a probabilistic approach based on Monte Carlo analysis to find which insulation systems are appropriate for various conditions. The vapour tight systems are found to be the most thermally efficient particularly when WDR occurs on the wall whereas the moisture content and so thermal conductivity increases in the capillary active insulation. On the other hand this capillary active insulation was much more effective at avoiding frost damage because there were fewer periods with critical moisture content than in the moisture tight systems. It is also found that a moisture tight insulation system results in longer periods of high relative humidity (over 95%) in the brick so there is a higher risk of wood decay when wooden beams are present in the wall.

(Klöšeiko et al. 2015) conducted nine months of experiments after renovating a brick wall with four different types of internal insulation and recreated the results with a hygrothermal computer simulation. Three of the insulation materials were diffusion open, capillary active and the remaining one vapour tight and diffusion resistant. All insulation materials were found to sufficiently improve the thermal efficiency of the wall however the vapour tight polyisocyanurate (PIR) board experienced high humidity loads over the critical 80% threshold of mould risk. A notable finding was that it is important to carry out the renovation during a dry period where the wall has a lower moisture content.

So to conclude the first discussion about whether capillary active materials do work in practice as they are supposed to according to the theory, the findings of the various literature do confirm that moisture redistribution occurs. It was further found that capillary materials avoided problems with frost damage and over-hygroscopic moisture that occurred in the moisture tight materials. Many of the studies that compared multiple capillary active, diffusion open materials found that some worked better than others. The performance of the materials listed in Table 2.1 as found by the various literature sources will now be discussed.

One of the largest experimental tests of capillary active, vapour diffusive materials was the one performed by (Klöšeiko et al. 2015) where IQ-Therm, AAC and CaSi were compared against the moisture tight PIR board. The IQ-Therm board which consists of polyurethane with capillary active channels functioned unsuccessfully. The AAC and insulations acted more effectively in terms of moisture redistribution with the AAC having a lower thermal transmittance.

In the many simulations performed by (Vereecken et al. 2015) only one of the two capillary active systems - the Calcium Silicate seemed to function as intended in redistributing interstitial condensation between the brick wall and insulation, the other system of mineral wool with a “smart” vapour retarder was less effective

(Vereecken & Roels 2015a) makes some interesting comparisons of all the materials although the sources of data come from various places. From a comparison of capillary absorption, (Vereecken & Roels 2015a) it was found that Multipor performs very badly and it is questioned whether it is even fair to be called a capillary active material. CaSi on the other hand performs very well in capillary absorption, however it fairs less favourably when the thermal conductivity properties are compared. The Multipor does slightly better in thermal conductivity and the vapour tight polyurethane comes out best. Dry vapour diffusion resistance factor is the final comparison which tells how well the material will facilitate inward drying, allowing vapour to leave the brick/insulation interface which keeps the relative humidity levels down. Wood fire board and Multipor both perform slightly better than the CaSi here and the PUR containing materials (IQ, Therm and Xtra) perform poorly. Another conclusion from the
analysis is the glue mortar used to bond layers and increase thermal performance can often decrease the vapour open characteristics of the systems.

To conclude the comparisons of various capillary active materials made in the literature it can be said that calcium silicate performed well in capillary action in all cases where as IQ Therm and Multipor were much less effective. This difference was most explicitly shown by (Vereecken & Roels 2015a) when comparing values from experimental tests of the water uptake coefficient ($A_w$) which has been reproduced below in Figure 2.1 Water uptake coefficients for various insulation materials. This is a measure of capillary action.

![Figure 2.1 Water uptake coefficients for various insulation materials. This is a measure of capillary action.](image)

The second wall investigated in this report includes a hydrophobic façade treatment so a short literature review has been made on the subject to gain an understanding of the theoretical process and find state of the art research to be able to make a comparison with results found in this project. The intention of hydrophilic treatments applied to porous materials is to stop water uptake which has a number of benefits;

- It reduces the internal moisture content so reduces the risk of damage by frost
- low moisture content prevents reduction of thermal insulating properties
- when rain water passes quickly over the surface it becomes self-cleaning
Experimental research made to test the theory has produced results both in agreement and disagreement, (MacMullen et al. 2011) found a cream treatment applied to building façades was very effective and reduced household heating energy consumption significantly. However (Møller 2003) carried out tests on pre-treated roof tiles finding the treated tiles actually had a higher water uptake than identical untreated tiles. Slightly different hydrophobising substances were used but in both experiments the treated surfaces displayed water droplets forming – a sign that the contact angle was sufficiently increased to over 90° as in Figure 2.2. However in the tile experiment this lead to a higher moisture content and did not correspond to the theory of increased surface water run-off with a contact angle over 90°. The façade cream experiment was only made on a small scale and short time period of 24 hours so does not take into consideration the durability of such a treatment and effects of soiling whereas as the tile experiment spanned a longer period and showed signs that the treatment became less effective when soiling occurred.

Going on the presumption that the hydrophobic theory works, (Finken et al. 2016) carries out hygrothermal simulations showing the difference that effective hydrophobic impregnation can make. A similar arrangement is modelled as in this thesis, where the impregnation applied on the outer surface of a bare brick wall is partnered with capillary active insulation. By shielding the inner wall from WDR the impregnation highly reduces the relative humidity within the system, changing it from a high mould risk construction to fully moisture safe. The limitations of the study are that the 1D simulations cannot model the effect of cracks in the façade. It is also uncertain how effective the impregnation really is at stopping water intrusion and how long a time this effect lasts although a practical study is underway which could clarify this. These limitations will also be relevant to this project since cracks in the brick and the durability of the impregnation will not be modelled.

2.1 Conclusion of Literature Review

From the presented literature it has been found that capillary active insulation does work as the theory describes and can be favourable over vapour tight systems in certain circumstances. Furthermore it was found that Calcium silicate has much better capillary active properties than Multipor/AAC or IQ-Therm. The findings suggest that results of this project may show Multipor to act poorly in redistributing interstitial moisture if occurring in the walls. It is still worthwhile investigating this system to see how it performs in a Danish climate and particularly when the hydrophobic treatment is added which might reduce the moisture load put on the Multipor. The review of literature relevant to hydrophobic treatments were not able to conclude whether the theory is completely true however if it is, a very significant effect could be seen.

An extra topic relevant to this project is the complementary use of hygrothermal simulation software alongside physical experiments and how it can benefit a research project. Two of the sources ((Vereecken et al. 2015; Klöšeiko et al. 2015)) used hygrothermal simulation software to very different effects, firstly (Vereecken et al.
2015) used the powerful calculation power to make many simulations exploring the consequence of various parameter changes. Secondly (Klöšeiko et al. 2015) used simulation software in a very similar method to this project, using experimental data to validate calculated data prior to investigating other locations although this last process was not included in the paper. Few projects from literature sources use experimental data to validate hygrothermal simulations so this makes an extra point of interest to this project.
3 Damage Evaluation Literature Review

The damage evaluation is necessary to give a clearer assessment of whether the temperature and relative humidity conditions calculated in the wall are acceptable or not. The three main problems that occur from high moisture levels are mould growth, wood decay and frost damage. An evaluation for each of these three main modes of damage will be made from the results of the simulations, now a literature review will be made to investigate the best methods for calculating modes of damage to the wall. Another aim of the review is to clarify why each mode of damage occurs, how this effects the building and sum up how the models are calculated. This will be split into three sections starting with mould growth, then wood decay and frost damage with a final conclusion where the favoured methods will be decided.

3.1 Mould Growth

The results of the simulations in this thesis will be evaluated for conditions promoting mould growth because it is one of the first visual signs of biological activity due to excess moisture in building materials so it can be used as a warning before structural damage occurs. While mould itself doesn’t damage the building it is undesirable to the users for reasons of decreasing interior aesthetics, comfort and most importantly damaging to health. Some forms of mould can irritate symptoms of asthma or bronchial disorders and generally impair well-being (Ebbehøj et al. 2002) so it should not be accepted at any level inside a building. On the outside of a building mould or algae is unlikely to be harmful to users however it can be unsightly and even damaging to the materials. These species of mould or algae have very different criteria for propagation and so will not be addressed in the damage evaluation in this report.

A literature study has been carried out to obtain the most suitable method of modelling mould growth that is also appropriate to the materials used in this project. A detailed critical review of mould growth models has already been carried out by (Vereecken & Roels 2012) and shows that there are three main approaches (listed below) if choosing more advanced methods. Time of wetness method has also been included, because although very basic it is easy to implement and so worth considering. (Vereeeken & Roels 2012) carried out thorough tests of these models to compare the results of each method and found they give quite different results, this paper will be referred to throughout the review.

- VTT model (Hukka & Viitanen 1999) including an extended version (Viitanen & Ojanen 2007)
- Isopleths (Sedlbauer 2002; Smith & Hill 1982; Moon & Augenbroe 2005; Clarke et al. 1999)
- Biohygrothermal model (Sedlbauer & Kunzel 2000)
- Time of wetness (Adan Gerardus 1994)

3.1.1 VTT Model

Starting with the original VTT mould growth rate (Hukka & Viitanen 1999), developed at the VTT technical research centre of Finland gives a mathematical model that quantifies mould growth on the surface of wood influenced by temperature, relative humidity and time within and outside critical conditions. It will now be explained how the original model calculates an estimate for mould growth with comments on the strengths and weaknesses of the method followed by a description of the changes made in the newer revised version.
Equation 3.1 for mould growth in favourable conditions combines 3 more basic equations that model each stage of growth from initiation of the spores, steady growing phase and up to maximum limits of coverage.

\[
\frac{dM}{dt} = \frac{1}{7 \exp(-0.68 \ln T - 13.9 \ln RH + 0.14W - 0.33SQ + 66.02)^{k_1k_2}} 
\]

Mould index

\[ \begin{align*}
M & \quad \text{Mould index} \\
T & \quad \text{Temperature (°C)} \\
SQ & \quad \text{Surface quality (SQ=0 for sawn surface, SQ=1 for kiln dried quality)} \\
t & \quad \text{Time (h)} \\
k_1, k_2 & \quad \text{Coefficient for growth rate} \\
W & \quad \text{Timber species (0 = pine and 1 = spruce)} \\
RH & \quad \text{Relative humidity (％)}
\end{align*} \]

This equation was fitted to experimental data carried out on wood samples with fluctuating conditions of temperature and relative humidity. There are some limitations of the model due to the experimental data it is based on, specifically the short time period of the experiments (between 6 and 24 weeks) and the temperatures covered did not go below 5 °C. Equation 3.2 for the reduction of mould during dry periods was also developed although only using experimental data with time periods up to 14 days so this is less accurate for longer periods of time.

\[
\frac{dM}{dt} = \begin{cases} 
-0.032 & \text{when } t - t_1 \leq 6h \\
0 & \text{when } 6h \leq t - t_1 \leq 24h \\
-0.016 & \text{when } t - t_1 > 24h 
\end{cases} 
\]

The output quantity from calculation gives a number from 1 to 6 indicating the extent of mould growth expected, this scale is shown in more detail in Table 3.1 as developed by (Hukka & Viitanen 1999).

<table>
<thead>
<tr>
<th>0</th>
<th>No growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Some microscopic growth detected</td>
</tr>
<tr>
<td>2</td>
<td>Moderate microscopic growth detected (over 10% coverage)</td>
</tr>
<tr>
<td>3</td>
<td>Some growth detected visually</td>
</tr>
<tr>
<td>4</td>
<td>Coverage more than 10%</td>
</tr>
<tr>
<td>5</td>
<td>Coverage more than 50%</td>
</tr>
<tr>
<td>6</td>
<td>100 % coverage</td>
</tr>
</tbody>
</table>

Table 3.1: Mould growth index based on VTT model
3.1.1.1 Extension of VTT model

The original model was limited to pine and spruce sapwood but now has been extended with further experimental data (Ojanen et al. 2011) to include several more substrate types. The new models are also based on experimental results of a slightly longer period of time (up to 1 year). Additionally a wider variety of methods were used ranging from laboratory samples to full constructions in outdoor climates with temperatures ranging between – 5°C and 27 °C. Although the model becomes more complicated with the added materials, they have been classified into 4 levels due to their susceptibility to mould growth. These sensitivity classes have been related to scaling factors (see Table 3.2) based on the original pine sapwood model which is used as the benchmark high sensitivity material. The new scaling factors are applied in the equations for \( k_1 \) and \( k_2 \) (shown below as equations 3.3, 3.4 and 3.5) from Hukka’s original model.

**Table 3.2 New Sensitivity Classes**

<table>
<thead>
<tr>
<th>Sensitivity Class</th>
<th>( K_1 ) M&lt;1</th>
<th>( M_{z1} )</th>
<th>( K_2(\text{M}_{\text{max}}) )</th>
<th>RH_{min} %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Sensitive, VS</td>
<td>1</td>
<td>2</td>
<td>1 7 2</td>
<td>80</td>
</tr>
<tr>
<td>Sensitive, S</td>
<td>0.578</td>
<td>0.386</td>
<td>0.3 6 1</td>
<td>80</td>
</tr>
<tr>
<td>Medium Resistant, MR</td>
<td>0.072</td>
<td>0.097</td>
<td>0.5 1.5</td>
<td>85</td>
</tr>
<tr>
<td>Resistant, R</td>
<td>0.033</td>
<td>0.014</td>
<td>0 3 1</td>
<td>85</td>
</tr>
</tbody>
</table>

In equation 3.3 the factor \( k_1 \) signifies the growth rate under favourable conditions and in the original model was set to 1 when the mould index, \( M \) was less than 1, so this had no influence. In the revised model \( k_1 \) varies even when \( M \) is below 1 due to the various material sensitivity classes. In the below equations \( t_M \) refers to the time to reach the indicated mould index value e.g. \( t_{M=3} \) is the time period for the mould growth index to reach 3).

\[
k_1 = \frac{t_{M=\text{pine}}}{t_{M=1}} \quad \text{when} \quad M < 1 \tag{3.3}
\]

\[
k_1 = \frac{t_{M=\text{pine}} - t_{M=\text{pine}}}{t_{M=3} - t_{M=1}} \quad \text{when} \quad M \geq 1 \tag{3.4}
\]

While the equation 3.5 to give \( k_2 \) is unchanged in the revised version equation 3.6 for maximum mould index, \( M_{\text{max}} \) is reformed which has a significant influence on \( k_2 \). The equation now has the additional factors A, B and C specified in Table 3.2 which add further influence from the sensitivity classes.

\[
k_2 = \max\left[1 - \exp\left(2.3 \times (M - M_{\text{max}})\right), 0\right] \tag{3.5}
\]

\[
M_{\text{max}} = A + B \frac{RH_{\text{crit}} - RH}{RH_{\text{crit}} - 100} - C \left(\frac{RH_{\text{crit}} - RH}{RH_{\text{crit}} - 100}\right)^2 \tag{3.6}
\]
The original decline rate for mould growth when conditions are unfavourable (equation 3.2) has also been updated and an extra coefficient added to model different decline rates of the various sensitivity classes as shown in equation 3.7.

\[
\frac{dM}{dt} = \begin{cases} 
-0.00133 & \text{when } t - t_1 \leq 6h \\
0 & \text{when } 6h \leq t - t_1 \leq 24h \\
-0.000667 & \text{when } t - t_1 > 24h 
\end{cases}
\]

This extended VTT model is much more accurate but still limited in many ways for instance there are many missing materials especially paint and plaster that are commonly used on wall surfaces. Potential contaminations on a material surface is not considered either. The model is still based experiments of short durations and the fact that the new materials are modelled against pine sapwood is noted by (Vereecken & Roels 2012) as constraining them to the same growth curves.

In the experiment whose data this project uses, some estimations would need to be made to decide which substrate sensitivity class should be chosen for the materials used. Neither Multipor nor any form of plaster were directly represented in the classes described in the VTT model because the materials were not tested in the VTT experiments.

3.1.2 Isopleth Models

Isopleth curves can be used to model mould growth by plotting contour lines at the point where favourable conditions begin to occur on axes of relative humidity and temperature. Some of the earliest isopleth models developed in the past started with demonstrating the growth of different mould species on agar (an ideal substrate) during constant increments of relative humidity and temperature (Ayerst 1969). Numerous further investigations into mould growth have led to improved models of various species and conditions. The key parameters that the research has explored are;

- new varieties of species, using experimental and in mathematical modelling (Smith & Hill 1982), (Clarke et al. 1999),
- time of exposure in favourable mould growing conditions [Hens],
- growth on various building materials rather than ideal substrates (Sedlbauer 2002),
- germination time before growth begins (Sedlbauer 2002), (Moon & Augenbroe 2005).

Each successive piece of research has either produced a new model or improved an existing one, for example Clarke et al. (1999) produced the ESP-r model which is a set of curves for different mould growths depending on their preference to moisture. This is quite a simplistic device since it does not account for time of exposure, different substrates or fluctuating humidity.

Sedlbauer (2002) created a broader ranging model that has categories firstly of mould species with classes based on health risk to occupants and secondly on substrate sensitivity. In their review of this isopleth model (Vereecken & Roels 2012) points out that a constant relative humidity is used in the experiments which does not account for any dryer periods where growth would be delayed or reduced.

To solve this inaccuracy, Moon & Augenbroe (2005) added a germination curve for mould spores to account for fluctuating circumstances of temperature and relative humidity, so mould growth is delayed until favourable conditions resume. While this can be useful, it is quite a complicated procedure to switch between the spore germination graph and mould growth isopleth.
3.1.3 Biohygrothermal Model
As a continuation of Sedlbauer’s isopleth charts he has developed a biohygrothermal model which calculates the moisture balance in the spores of the fungus. This means that consideration is made to the germination period before mould growth is activated as well as periods of drying out. By doing this the whole approach becomes much more valuable because fluctuations between favourable and unfavourable conditions of mould growth can now be modelled. This model has also been integrated into the WUFI hygrothermal modelling software making it much more accessible.

(Vereecken & Roels 2012) calls attention to one problem with the biohygrothermal model and also Sedlbauer’s isopleth where mould growth is modelled in mm/day which is well representative in early stages of growth but is less indicative in later stages when many mould patches of different sizes and thicknesses are growing in different parts of a substrate. Inaccuracies are also found in the simplification of mould and bacteria species into one model spore, which does not agree with previous research found in isopleth models that show large variations between species.

3.1.4 Time of Wetness
TOW (Adan Gerardus 1994) is another popular method because it is very simple and fast to use but limited in the detail of results it gives because only factors of time and moisture are considered and neglects temperature, mould species and substrate. In the experiment that the method is based on only a single species of mould has been tested on one material at indoor temperatures so when comparing to different circumstances this method becomes very inaccurate. There is also no distinction between different levels of moisture so either conditions are seen to be optimal for mould growth or not possible and doesn’t consider various growth rates. These limitations are the reason TOW will not be used to analyse the results of this thesis.

3.1.5 Mould models Conclusion
A critical review has been made of predictive mould growth models and it was found that the VTT model is most favourable as provides a quite reliable estimate of mould growth based on realistic experimental data using different building materials whilst taking into consideration fluctuating temperature and humidity. The decay model during periods of unfavourable growing conditions is most accurate because it also includes cold periods. There still needs to be further research carried out however, to broaden the range of substrates applicable to this model. The VTT model is also very accessible now that it has been integrated into the same Delphin software which is being used for the hygrothermal modelling.

Sedlbauer’s biohygrothermal model was not chosen because of its less useful output of mm/day growth as units which becomes uninformative at higher levels of mould growth. The isopleth charts are individually easy to use and give an insight into the temperature and humidity conditions causing mould to grow. To gain any accurate results however, a combination of 2 or 3 different time periods are required which then becomes more troublesome. TOW provides a truly simplistic and easy to follow method but is too inaccurate to provide any useful results for this investigation where quite similar humidity and temperature conditions will be compared.

3.2 Fungal Wood decay
Fungal rot is a variety of fungi that can occur in wooden materials causing irreversible decay to the cell structure unlike mould that does not cause damage to its host material. While still highly dependent on conditions of moisture and temperature the tolerances are quite different to mould growth so cannot be modelled together.

There exist several approaches to modelling fungal decay and a review has been made before by (Brischke & Thelandersson 2014) which weighs up the strengths and weaknesses of each approach. While some methods
looked to map wood decay risk by climatic locations or service life there were only four that give a decay rate model based on laboratory data, and could be used for hygrothermal simulations. Out of these the model by (Viitanen et al. 2010) is shown to be most reliable as it is supported by the greatest volume of research from different sources and including field studies.

Again developed at the VTT technical research centre of Finland, (Viitanen et al. 2010) created an empirical model based on weather observations each lasting six hours in various locations across Europe. The model consists of 2 linked processes the first being an activation scale which has a minimum of 0 and a maximum of 1. This value rises steadily if the temperature is greater than 0 °C and relative humidity is above 95% but outside these conditions it falls at a rate of 0.5 per year. If 1 is reached the next process of mass loss is activated as seen in Figure 3.1, this is a calculation of the decay of the wood which is irreversible. The mass loss rate increases with relative humidity and temperature.

![Figure 3.1. Example of the VTT wood decay model (Viitanen et al. 2010) with activation and decay lines over four years based on real meteorological data](image)

3.3 Frost Damage
When porous and brittle materials such as brick experience a very high water content and sub-zero temperatures the water which fills the capillaries then changes state, expanding and putting pressure on the cell structure of the material. The degree of damage depends on the pore size and structure so it is highly variable in different materials.

(Fagerlund 1999) has carried out extensive work into frost damage mostly in concrete to find that materials can be defined as having a critical degree of saturation and if this point is exceeded the material will be mechanically damaged once exposed to frost. It is also found that the rate of freezing and the number of freeze thaw cycles has little effect on the critical degree of saturation although these factors can increase the size of the damage. In some experiments with masonry (Fagerlund 1972) it is found that 0.917 can be used as a basic fraction of critical saturation where frost damage could occur however it is best determined experimentally for every case.
A simple exposure index has been created by (Lisø et al. 2007) for freeze thaw cycles using climate data to define the number of occurrences where 4 days of rainfall precedes freezing temperatures. While easy to use this only takes into account climate and has nothing to do with the circumstance or properties of the building material itself, such as porosity, water uptake, tensile strength or orientation. All these important factors are neglected so this method can only be used to tell if being in a certain location exposes the entity to the risk of frost damage.

(Sedlbauer & Kunzel 2000) show that hygrothermal analysis software can be used to estimate frost damage by calculating the number of freeze thaw cycles when each occurrence is correlated with water content. It is found by (Sedlbauer & Kunzel 2000) that it is important to use the temperature at precise points within the material rather than simply outdoor temperature when counting freeze-thaw cycles. Correspondingly (Mensinga 2009) suggests comparing the material’s critical degree of saturation found experimentally with hygrothermal models of the whole building envelope to see if this water content level occurs during times of frost.

The hygrothermal modelling software Delphin uses a system based on research by (Sontag 2013) which simulates the ice crystallisation process. Two useful outputs are provided; ice volume per pore volume ratio and the number of freeze thaw cycles. The creators of Delphin have suggested in a German standards guide (WTA 2014) that 30% ice volume per pore volume ratio is a point where there a risk of causing damage. The freeze-thaw cycles are very accurately measured because it is taken into account that the freezing point of a capillary porous material is dependent on the water content not just temperature. The exothermic reaction is even accounted for in the materials freezing point with this model. There are still some points not accounted for in Delphin’s ice model, most notably the volume expansion when transitioning from water to ice.

3.4 Damage Evaluation Conclusion
A review has been made of literature on the 3 critical modes of damage that could occur in the wall to be tested in this project and three chosen models are shown below;

<table>
<thead>
<tr>
<th>Mould Growth</th>
<th>The revised VTT model (Ojanen et al. 2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood decay</td>
<td>VTT Wood decay model (Viitanen et al. 2010)</td>
</tr>
<tr>
<td>Frost damage</td>
<td>Delphin Ice volume/Pore volume ratio (Sontag 2013)</td>
</tr>
</tbody>
</table>

While there were many methods of predicting mould growth in materials, wood decay and frost damage has had less research and this can be appreciated in the varying complexities of the prediction methods reviewed. The three chosen methods are not only found to be the most accurate approaches they are also some of the best adapted to use with Delphin’s post processing software which will convey faster evaluation of the numerous simulations.
4 Method

In this section the methods used to obtain the results in this project will be described and reasoned. Firstly the experimental set-up will be described - although from a separate project it is important to be explained in order to see why the hygrothermal simulation methods were used. Following this a small study varying material properties in hygrothermal simulations is made to justify the material sampling carried out at the start of this thesis. After this the simulation process will be described starting with creation of input data files, then construction of the models in Delphin and lastly an explanation of parameter settings applied in the boundary conditions of the model.

4.1 The Container Experiments

To understand how the experimental results have been obtained that are used to validate the computer models developed in this report, it is necessary to describe this physical experimental set-up though it is not part of this project. The experiment underway at DTU consists of two containers with 24 brick walls with various internal insulation systems applied to them. Each brick wall has the identical brick and mortar arrangement which is designed to best replicate a typical wall from a Danish building built between 1850 to 1930 commonly found all over the country. Even though the bricks and mortar are newly manufactured they have been selected based on similarities to the clinker bricks and lime mortar traditionally used at the time. Each of these original walls has then been insulated in a unique way either using different materials or placed in different arrangements.

Each wall is 2 metres tall, 0.95 metres wide and 1½ bricks (348mm) thick sitting in holes cut into the container wall at 0.4 metre spacing. Uninsulated masonry walls have additionally been included as a point of reference. The edges of the walls are surrounded with a vapour tight membrane and the remaining areas of the container are insulated with a 300 millimetres thick layer of mineral wool. Sensors measuring temperature and relative humidity have been placed in the wall at 4 locations (there are more sensors but in locations not relevant to this project) as shown in Figure 4.1. More information specifying how the sensors have been calibrated and data treatment is included in appendix 8.5. The walls are oriented to face South West to induce high solar radiation levels (8 other
The indoor environment is designed to replicate normal comfortable conditions but with a slightly higher relative humidity maintained around 60% using a mechanical humidifier. The temperature is kept at 20°C with an electric radiator although some variations in both these parameters have occurred and can be noticed in the experimental Results in chapter 5.

Eventually all of these walls will be replicated with hygrothermal computer models but in this project only two of the walls have been selected, these models will first be validated by experimental data and then simulated in new conditions. Furthermore to investigate moisture problems associated with thermal bridging the experiment includes wooden beam and lath elements with an interior wall joined to the main wall. However these elements create a much more complex 3-dimensional problem which will not be simulated in this thesis.

The first wall selected for computer modelling (wall 2) is insulated with the original Xella system of 100mm Multipor and the other (wall 3) has the hydrophobic treatment added as can be seen in Figure 4.2. Wall 2 has been chosen for analysis because it is a widely used capillary active diffusion open system. Wall 3 has been selected because the hydrophobic treatment is an interesting tool that has potential to produce good results in a Danish climate that has a high amount of WDR.
4.2 Investigation into Material Properties

During this project material samples have been collected from the experiment to be tested and create new input materials for the models created in Delphin. To demonstrate why this was necessary, a small investigation has been made illustrating the importance of setting the material properties correctly when carrying out hygrothermal simulations. Firstly two different versions of the same brick will be compared, followed by a test to show whether modelling mortar between the bricks is necessary. The subject of sensitive material properties has been explored before on a broad scale by (Zhao et al. 2011) who made a stochastic study to show how the uncertainty of ALL input data could influence the results of a simulation. They found this theory to be true and that the influence of input data often fluctuates during the simulation depending on the time of year. Many different properties and parameters were investigated and they found the orientation of the wall to have the largest influence.

Figure 4.3: The two walls modelled in Delphin. The only variation is the version brick used from a) 2002 and b) 2004

In this study the Xella wall 2 system has been modelled as shown in Figure 4.2 the consists of a 1 ½ brick wall insulated by a 100mm Multipor layer and without hydrophobic impregnation. Two versions of the model were created which varied only in that two different materials used for the brick as displayed in Figure 4.3. The brick “Lime stone sand Xella Ytong” from Delphin’s material database (Figure 4.4) has two different dates, presumably from different batches. These two versions of the same brick were interchanged in the model

As can be seen in the table most of the critical properties are very similar between the 2 versions except for \( \mu \), the water vapour diffusion resistance factor which is 12 higher in the 2002 version. The thermal properties of each brick is very similar so the temperature results in the brick and Multipor layers are identical but a difference is seen in the moisture levels displayed here in Figure 4.5 as moisture mass density which conveniently totals all forms of moisture - ice, liquid and vapour. The brick moisture mass is quite altered which leads to differences in the multipor layer as the liquid and vapour is transferred further into the wall, shown in Figure 4.5. This change of moisture content in the brick makes a big difference to the risk of mould found in the multipor, which becomes 8 times greater with the 2002 version of the brick (Figure 4.6).
Figure 4.5. Moisture mass density in the brick layer (top) and Multipor layer (bottom) when two different material properties of the same brick are modelled.

Figure 4.6. Averaged Mould index in Multipor Layer
This investigation shows how seemingly small variations in a materials properties can be highly influential on the results of hygrothermal simulations, highlighting the importance of carrying out material testing to obtain accurate material input data when simulations are representing real situations. Another point to note is how the same material can have varied properties depending on the batch or year of production. This could be caused by a number of factors from different sources of raw materials to changes in manufacturing techniques.

4.2.1 Mortar vs Brick
Next a comparison of brick and mortar is made to investigate whether using a homogenous brick layer is allowable or not. In Figure 4.7 the original wall system (Ytong brick 2002 insulated with Multipor) is compared to the same setup except with the brick replaced by “historical lime plaster”.

![Figure 4.7. Comparing the moisture mass density when the brick layer is replaced with more plaster in the brick layer (top) and insulation layer (bottom).](image)

A much higher moisture mass density occurs in the brick compared to the all plaster wall and leads to a higher peak moisture content in the insulation layer. This shows that the brick is more liable to accumulate water and therefore it is the critical element of a masonry wall. This supports the argument of (Zhao et al. 2011) that 1D modelling of a homogenous brick layer is acceptable in real climate conditions although it could be said that it is better practice to include both materials because they are very different.
4.3 Creating the Model for Simulation

The process of creating the models in Delphin will now be described first outlining the main steps followed by a more detailed explanation of each of these stages. This includes creating the input files and parameter settings then the validation process where the simulation is adjusted until the calculated results match the experimental results. The chosen output formats are also described that are relevant to the results presented in section 5. The method for post processing of the damage evaluation is described before the results are presented in section 5.6.

The process of hygrothermal simulation has 3 main stages; gathering and assigning input data, then the calculation and finally processing of output data this is visualised in Figure 4.8. The first stage tends to be the most time consuming as it involves creating input files in a format Delphin can read from the raw, observed climate data and experimental data. This entails filtering data to the periods and time steps required, interpolation of missing values then converting into the time format used by Delphin. Even identifying the necessary data can be challenging due to the vast quantity recorded by the DTU weather station.

Once the input files are compiled the first action in Delphin is to define the construction such as the dimensions, layer thicknesses and materials. Next the climate conditions are assigned to the relevant boundary conditions and further related parameters are set, for example when a short wave radiation boundary condition is assigned to a material’s surface the absorption co-efficient of this surface must be defined.

Specifying the output data required is also an important part of the model preparation so that accurate results are produced that can be compared with the experimental results and further used in post processing calculations such as mould growth or frost damage assessments.

![Flow Chart](image-url)
When the model is complete the simulation is run and the results are reviewed, for the validation an iterative process now begins as the results are compared to the experimental data and differences show where changes to the input are required and the simulation is run again. Once the correct results are obtained the post processor is used to make graphical displays and calculate damage estimations such as mould assessments.

4.3.1 Climate Data
The climate files are made of a preliminary 2 year simulation period followed by the locally measured experimental data. The preliminary simulation is run so a stabilisation state can be reached in the wall’s materials, a Danish Design Reference Year (DRY) dataset was used. This was created by the Danish Meteorological Institute (DMI) by selecting the 12 most typical months from the years between 2001 and 2010 for each type of weather (Grunnet Wang et al. 2013). The reason for this is to create a typical climate year that does not contain any extreme weather suitable for use in building design. Denmark has been divided into 5 or 6 characteristic climate zones depending on the parameter (e.g. wind speed, diffuse irradiance etc.) so the climate data was taken from the appropriate zones for Lyngby in the validation of the experimental data and then changed for the further investigations into Esbjerg, and Aalborg (Copenhagen falls into the same climate zones as Lyngby). Data from the climate station at DTU (Andersen et al. 2014) has been used during the experimental period, here measurements are averaged from continuous readings which are recorded every minute.

<table>
<thead>
<tr>
<th>Preliminary period (2 years and 4 months)</th>
<th>Experimental period (12 months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPH DRY</td>
<td>Experiment</td>
</tr>
<tr>
<td>DTU DRY</td>
<td>DTU weather station</td>
</tr>
<tr>
<td>Auto-generated</td>
<td>DTU DRY data</td>
</tr>
<tr>
<td>Ext temp &amp; RH</td>
<td></td>
</tr>
<tr>
<td>Int temp &amp; RH</td>
<td></td>
</tr>
<tr>
<td>Wind velocity and direction</td>
<td></td>
</tr>
<tr>
<td>Direct &amp; Diffuse radiation</td>
<td></td>
</tr>
<tr>
<td>Long Wave Radiation</td>
<td></td>
</tr>
<tr>
<td>Vertical rain</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1 Summary of sources of data for boundary conditions

The long wave radiation is used from the DTU DRY data calculated from the DTU weather station however there was no live data for long wave radiation available during the experimental period so this 1-year file is repeated for the entire simulation. Long wave radiation has been shown to be quite influential on moisture levels within building components (Kehrer & Schmidt 2008) so it was important to include this parameter in the simulation.

4.3.2 Short Wave Solar Radiation
The DTU weather station has pyranometers measuring diffuse and direct, global and total radiation (Andersen et al. 2014). As explained in Figure 4.9 the direct radiation arrives unobstructed to the point of interest. Diffuse radiation is the radiation that is refracted along its path towards Earth so it does not have one single direction. The direct radiation is measured on a horizontal panel and Delphin performs a calculation to convert this to the component that is at normal incidence to the vertical wall. This calculation is based on the walls orientation (SW), slope angle (90°) and latitude (55.7°).
Some problems were found when modelling the solar radiation during the validation process. When matching the simulation to experimental results, the temperature at sensor P1 on the bricks surface is most sensitive to solar radiation. It was found that the simulated direct and diffuse radiation did not produce temperatures matching the experiment. The direct solar irradiance gives occasional high radiation values during the winter period presumably from days of no cloud cover. These daily peaks were much higher in the simulated P1 temperature than the experiment as seen in Figure 4.11 (top). The results were much improved as seen in Figure 4.11 (bottom) by using total irradiance data modelled as direct radiation. It is difficult to explain why this provided better results since it is not the correct method. It is possible that surrounding objects are obstructing direct sunlight on the wall when the sun is low in the winter. The most accurate way to solve this discrepancy would be to install a radiation sensor beside the wall at the same angle so that the radiation could be modelled as an imposed flux in Delphin.

![Figure 4.9 Showing the various types of solar radiation (Esri 2015)](image)

![Figure 4.10 Explaining various short wave radiation values measured from DTU climate station](image)

- **Total irradiance**
  - Direct: Varies due to zenith angle
  - Diffuse: Assumed equal from all directions
  - Ground Reflected Direct & Diffuse: directed from ground (0 incidence on horizontal surfaces)

- **Global irradiance**
4.3.3 Treatment of Recorded data

There have been some problems arising because of gaps in the recorded data from both the experimental data and the weather station at DTU. The experimental data which includes interior and exterior values of relative humidity and temperature is missing due to malfunctions in the sensors and the largest period without input data was from July to July. Different methods of interpolating the data were investigated including:

- Creating a high order polynomial trend line to make an average of the known data and replicate this in the missing areas. This was the most accurate way to copy the average values but it would neglect the daily fluctuations which are particularly significant in the external temperature and relative humidity.
- Another option is to copy directly the previous weeks data so that it is repeated a second time. This most realistically keeps the daily fluctuations however becomes a problem over longer periods of time because it loses the influence of the seasonal change of average conditions.
- Filling the missing periods with DRY data or data from another nearby weather station could be more realistic over longer periods because it would replicate the seasonal average change as well as including daily fluctuations. The only obvious downside is that the DRY data is from a completely different location.
It was decided that the second option was most suitable in this case because the missing data is only spanning over a short period of time so the seasonal average change is not significant.

### Table 4.2 Showing the difference between the raw and repaired experimental data.

<table>
<thead>
<tr>
<th>Original data:</th>
<th>Repaired data:</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Original Data Graph" /></td>
<td><img src="image2" alt="Repaired Data Graph" /></td>
</tr>
</tbody>
</table>

For the internal and external temperature and relative humidity sensors there were some short periods of missing data (less than 1 month) here the gaps were filled by duplicating the data from just before gap. For example if there was a gap of 4 hours from 1pm until 5 pm the previous 4 hours from 9am until 1pm will be copied into this space. The climate data from DTU’s weather was provided for every minute and this became too cumbersome when interpolating missing data so it was first filtered to readings every 15 minutes.

### 4.4 Construction of the Model

Once the input files are assembled building of the model in Delphin can begin, first the wall is drawn with accurate dimensions and orientation. Next the various materials are set to the layers drawn in the wall with the parameters specified and the model is discretized to divide it into a number of elements where the hygrothermal calculations will be made. The climate files are assigned to the relevant surface as boundary conditions and before the simulation is run the outputs are defined to extract the required results. An explanation will be made in this section of why the model was constructed as it was.

#### 4.4.1 1D or 2D Modelling

Due to the number of simulations made of different iterations it was necessary to save calculation time by using 1D models throughout the validation and investigation processes. This means that the mortar joints are neglected because the wall is assumed to be one homogenous layer of brick. It was concluded in a study (Vereecken & Roels 2013) that the impact of these joints is negligible when real climatic data is used during an investigation using hygrothermal computer simulations. In the study it was found that during a simulated imbibition test the results were very different between a homogenous brick layer and a masonry wall with mortar joints. On the contrary when these same elements were tested with real climatic data the moisture flux was very similar each time, so unless an extremely high volume of water uptake is occurring the effects of mortar joints can be safely neglected.

#### 4.4.2 Discretization Convergence test

A convergence test has been made to assess the accuracy of the discretization of the chosen finite element mesh. This process checks the number of elements that the model has been divided into is not so few that the results are inaccurate or too many so that the model is overcomplicated and therefore inefficient. Three models were created identical in every way apart from the level of detail of discretization, using the automatic discretization tool in Delphin a coarse, medium and very fine mesh was set as shown in Figure 4.12.
From the investigation it was found the coarser mesh also gives accurate results, however the size of the elements becomes so big that it is not possible to locate some of the outputs precisely at the same location as the sensors in placed in the experiment. This means that the temperature varies slightly because an average value across the whole element is calculated so it is important to choose an element size that allows for accurate positioning of outputs when they are required within the material layers.

A two year stabilisation period was run prior to the main output and an element located at the outermost edge of the brick adjacent to the interface with the plaster was chosen because the element sizes are smaller and more accurate at the layer interfaces. Figure 4.13 shows that some very small variation in the relative humidity occurred (approx. 0.1%) between the coarser and the medium sized mesh, with a similar difference between the medium and finer grid.

![Figure 4.12. The coarsest discretised grid model (left) includes 49 elements, medium 83 elements, and finer model (right) has 189 elements.](image)

### 4.4.3 Material Properties

Although samples of all the materials used in the experiment were sent to TUD for detailed testing the results of this test were unfortunately not ready by the time of writing this report, however some of the materials (including the brick) had already been tested at DTU (Dysted & Sandholdt 2015) and material files created for Delphin, so
these were used instead. The material database of Delphin also already contained up to date values for the Xella Multipor insulation and glue mortar from tests carried out at TUD. The historical lime plaster from the Delphin database was chosen as a representative for the plaster used in the experiment which has similar properties when compared to tests again made at DTU (Dysted & Sandholdt 2015).

4.4.4 Initial Conditions
Setting an accurate initial moisture content of the material layers is very important to achieve accurate results in the simulation. This is especially important in a brick sorption curve that can have a very different water content due to small variations of relative humidity. Three approaches have been identified. Firstly, the guidelines from ASHRAE (TenWolde 2008) suggest 80% as a standard practice or 90% for higher moisture contents due to new constructions containing extra moisture or a high frequency of driving rain. At the beginning of the experiment and several later dates a water content measurement was taken using a Troxler gauge offering another source for setting the moisture content level. A final method avoids setting the initial moisture content by simulating several years using DRY weather data allowing the material layers to reach a steady state before applying the observed experimental weather data. In the end it was decided that while using the values from the Troxler gauge would give the closest match to the experiment, it would only serve to add the stabilisation period to the simulation. In this project the results are only interesting once the wall has reached a stable state, therefore a preliminary simulation period in average climate conditions will achieve this fastest.

A two year initial simulation period was chosen to allow the materials to reach a quasi-steady state after which the experimental input data is run to simulate real conditions of the experiment. This period was found to be sufficient after making a 10 year simulation where it could be seen that a periodic equilibrium was achieved after 2 years. This method is recommended in the SUSREF guidelines (Peuhkuri et al. 2011) and the calculation time has been greatly reduced by doing this.

![Figure 4.14 Graph showing stabilising of yearly relative humidity levels](image)

4.4.5 Outputs
To make it possible to validate the model it was necessary to create outputs of temperature and relative humidity that match the locations of the sensors in the real experiment as shown in Figure 4.1 Cross section of insulated wall. This then allows a direct comparison of these two properties to be made between the simulation results and the experimental data.
The vapour mass per square metre was also calculated from these values using equations 4.1 & 4.2 and compared to the output from the Delphin simulation. This was useful so that a comparison of moisture levels in the wall could be made other than relative humidity which becomes less accurate when there is a minor discrepancy in temperature.

\[
\text{vapour pressure, } p_{\text{vap}} = \frac{p_{\text{v, sat}} \times RH}{100} \tag{4.1}
\]

\[
\text{Mass}_{\text{vap}} = \frac{V_{\text{air}} \times p_{\text{vap}}}{R_{\text{vap}} \times \text{T}} \tag{4.2}
\]

where:
- \(Mass_{\text{vap}}\) - vapour mass
- \(p_{\text{v, sat}}\) - saturated vapour pressure
- \(R_{\text{vap}}\) - Gas constant vapour
- \(V_{\text{air}}\) - volume of air
- \(p_{\text{vap}}\) - vapour pressure
- \(RH\) - relative humidity
- \(T\) - temperature
4.5 Validation by Altering Boundary Conditions

When using Delphin, boundary conditions must be assigned to the model to define how climate conditions act on the wall. This requires specific physical parameters most of which have not been measured in the experiment so the most suitable value is unknown. The first preliminary simulation was made using all input data with a “best guess” of all unknown parameters (see Table 4.3). These values either came from recommendations by the developers of Delphin at the Technical University of Dresden (TUD) or other experienced users at DTU.

Table 4.3. List of boundary conditions assigned in Delphin and related parameters.

<table>
<thead>
<tr>
<th>Boundary Condition</th>
<th>Coefficients</th>
<th>Initial</th>
<th>Adjusted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>Rain exposure coefficient (accounts for sheltering)</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>Short Wave Solar Radiation</td>
<td>Reflection coefficient of the surrounding ground (albedo)</td>
<td>0.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Long Wave Solar Radiation</td>
<td>Absorption coefficient of the building surface</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Heat Conduction</td>
<td>Emission coefficient of the building surface</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Vapour Diffusion</td>
<td>Exchange coefficient for heat flow:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>external</td>
<td>25 W/m²K</td>
<td>25 W/m²K</td>
</tr>
<tr>
<td></td>
<td>internal</td>
<td>8 W/m²K</td>
<td>4 W/m²K</td>
</tr>
<tr>
<td></td>
<td>Exchange coefficient for vapour diffusion</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>external</td>
<td>2e-7 s/m</td>
<td>2e-7 s/m</td>
</tr>
<tr>
<td></td>
<td>internal</td>
<td>3e-8 s/m</td>
<td>3e-8 s/m</td>
</tr>
</tbody>
</table>

When analysing these preliminary results it was found that there were a few areas where the simulation did not give values similar to the experiment. Since the climate data is accurately measured, it is not a point that should be adjusted. Instead the unknown variables that were originally guessed have been used to adjust the results so they fit better to the experimental data. Each investigated parameter was adjusted sequentially and results were plotted together against experimental data to see which produced the closest fit. This type of sensitivity analysis has been made to find the most suitable values for the below unknown parameters which will now be presented:

- Wind driven rain catch ratio
- thermal exchange coefficient at the internal surface
- Absorption coefficient of short wave solar irradiance
- Vapour exchange coefficient at the internal surface

4.5.1 Wind Driven Rain

Wind driven rain (WDR) has been calculated in Delphin by inputting the relevant recorded climate data; wind speed, wind direction and quantity of rain passing through the horizontal plane. It has been shown by (Anker Nielsen et al. 2012) that WDR is the most critical parameter along with the interrelated wall orientation in terms of average moisture level within a wall. However there is some speculation over the catch ratio i.e. the proportion of rain hitting the masonry wall and passing into the brick rather than rebounding off. While work is underway to obtain measurements of the catch ratio in the experimental project there is no data available at the time of writing this thesis so an estimate will have to be arrived at from simulations and research. Several studies have been made to investigate this property but it is complicated to model and difficult to define a single value because it varies depending on many circumstances, such as:

- wall orientation
- size of wall
- section of wall being investigated
The orientation of the wall was set to South West standing vertically as in the experiment, then a sensitivity analysis was made for the catch ratio comparing simulated relative humidity with the experimental values. As expected, the relative humidity at the outermost sensor, P1 is most sensitive to alterations of the catch ratio as shown in Figure 4.16.

![Figure 4.16 Relative humidity at sensor P1 with varied WDR catch ratios](image)

All points had to be considered when adjusting these parameters, even the innermost sensor- P4 was effected by changing the catch ratio and this is shown in Figure 4.17.

![Figure 4.17 Relative humidity at sensor P4 with varied WDR catch ratios](image)
4.5.2 Solar Radiation Surface Absorption Coefficient

Another discrepancy in the simulation was shown for the temperature at sensor P1 which is located in the brick layer 55mm from the outer surface. While the experimental and simulated average temperature seems to fit well with the seasonal changes there were much higher daily fluctuations in the simulated output. Here the output result is highly influenced by the boundary conditions applied to the outer surface with the two most affective being external temperature and solar radiation. Since the climate files are not possible to adjust the most obvious parameter to alter is the absorption coefficient of the building surface. A sensitivity analysis was made for the most likely values of solar absorption from 0.1 to 0.7 and results found that 0.6 provided the best fit in temperature at sensor P1. This can be seen in Figure 4.18 below where a comparison between the experimental data is made against the simulation results where the solar absorption coefficient is set to 0.6 and 0.7.

![Figure 4.18 Graph comparing solar radiation absorption coefficients](image)

4.5.3 Thermal exchange coefficient at the internal surface

Another inconsistency was found with the temperature at sensor P4 close to the inside surface of the wall, the thermal exchange coefficient is one influential factor that can be altered here. Originally this was set to 8 W/m²K as suggested by the Delphin creators for low air velocity which is typical for an indoor environment, 25 W/m²K is recommended for an outdoor environment because there is often a much higher air velocity. In this experimental set up inside the shipping container an even lower air velocity could be likely because there is no ventilation at all. The thermal exchange coefficient was adjusted in the sensitivity analysis which showed indeed that a lower value of 4 W/m²K was most suitable (Figure 4.19).
4.6 Modelling the Hydrophobic Impregnation

Once wall 2 was satisfactorily validated the same process was followed with wall 3 which consists of identical components with the addition of a siloxane based cream (Remmers Funcosil FC) applied to the outer surface of the brick to make a hydrophobic effect on the wall.

To recreate this hydrophobic behaviour 2 approaches were investigated:

1. In the outer 5-10mm of brick the water uptake coefficient ($A_w$) of the material was reduced, another sensitivity analysis was made based on the experimental measurements of relative humidity and temperature to find the most suitable value for $A_w$.
2. A contact layer was added which makes a fine layer that inhibits the water conduction and vapour diffusion.

As can be realised from Figure 4.20 the 1st method was initially not successful, here the outer 9mm of the brick has had its $A_w$ reduced 100 times. At first the relative humidity at P1 appears to match quite well to the experimental results however problems occur from November where in the simulated wall takes in much more moisture. To overcome this problem different variations were investigated by adjusting:

- the thickness of the hydrophobic layer,
- the location of the hydrophobic layer was moved back from the surface,
- different values of $A_w$ of the hydrophobic layer were investigated.

Eventually it was found that the water uptake coefficient was still too high and the results were only matched once this value was reduced to a 1000th of the original value. This shows that the hydrophobic impregnation is working very well to diminish capillary transport in the brick.
Figure 4.20 Relative Humidity at Sensor P1. Showing that decreasing the bricks water uptake \((A_w/100)\) was not enough to match the real experiment

The 2\textsuperscript{nd} method of imitating the hydrophobic treatment also provided accurate results, the process involved setting a contact layer in the brick behind the first element, 1mm in from the surface. If the contact layer was only assigned at the outer surface it was completely ineffective, this could be because the other boundary layers such as rain are assigned to this same point so the rain bypasses the barrier. It was also important to set the contact layer preventing water conduction (kept set to Delphin’s default value of \(5 \times 10^{15} \text{ m/s}\)) only, allowing vapour diffusion to still occur which is surprising since it has been found (Carmeliet 2001) that hydrophobic layers do inhibit vapour diffusion. Although this solution was found to be successful problems did occur during the calculation in Delphin when ice modelling was enabled. Additionally it was advised by personnel from the Technical University of Dresden that this method is less realistic than the 1\textsuperscript{st} method mentioned so this contact layer approach was not taken further.

4.7 Simulations in New Locations
The main change in the method after the validation process is the way the climate files are input into the programme, now simply repeating the same yearly data three times with the final year considered sufficiently stabilised to use for the results. The DRY dataset has been provided by the DMI (Grunnet Wang et al. 2013) however it did not include hourly measurements of rain so the DTU measurements have been used for all locations. This can be seen in Figure 4.21 to be an overestimation when comparing average yearly rainfall for the included locations with the DTU DRY year total but at least this is on the safe side. It has also been shown that wind speed and direction is of more importance in the impact of WDR. The output locations within the wall have been kept to the same as in the experiment so that they are easily comparable and also because they are the more crucial points when considering risk of material damage.
4.8 Method of Damage Evaluation

The evaluation includes assessing the following criteria as concluded from the literature review in section 3.

- mould growth index using the VTT model (Ojanen et al. 2011),
- wood decomposition also with VTT model (Viitanen et al. 2010),
- frost damage using the ice/pore volume Delphin output.

The following properties were set for the wall sensitivity to mould growth:

<table>
<thead>
<tr>
<th>Material:</th>
<th>Medium Resistant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface:</td>
<td>Sensitive</td>
</tr>
<tr>
<td>Decline:</td>
<td>Almost none</td>
</tr>
</tbody>
</table>

The mould growth sensitivity of Multipor was not included in the classification tests of (Ojanen et al. 2011) but a medium resistance level seemed suitable because while Multipor is unlikely to be as sensitive as wood, it is feasibly comparable to mineral wool and concrete which are in this category. To find a worst case scenario a sensitive surface with almost no decline during dry periods was chosen.

To help enable a comparison, the output locations of relative humidity and temperature are kept the same as the sensor locations in the experiment, also because these are the most critical points for the various modes of damage to occur. The only variation to this is rather than using the location of sensor P1 which is placed 48mm into the brick layer, the outer surface of the brick has been used for frost damage analysis where the most damage is likely to occur. Frost damage was assessed in 2 ways; ice/pore volume ratio in the outer 9mm of brick and frost thaw cycles in the outer most element. The ice/pore volume ratio was also checked from 9mm to 18mm depth but already temperatures were high enough that no ice occurred here. Wood degradation analysis is made at the location of sensors P2 and P3 of depths 177mm and 353mm respectively from the external surface. These are at locations where wooden elements such as beams or window frames are likely to be placed within a building. Sensor P4 at the insulations inner surface and also P3 at the brick and insulation interface are points where mould growth is a problem and is evaluated.
4.9 Potential sources of error

Here a summary is made of the different areas where error can occur in the calculations with comments on the size of the impact they could have on results.

- Material properties

As described in section 4.4.3 only some of the materials have been tested for properties such as water uptake and vapour diffusion where as other were taken from the Delphin material database. In section 4.2.1 it was shown that discrepancies in these properties can make significant differences in the walls moisture distribution.

- Calibration of sensors

The sensors used in the experiment have been calibrated to improve their accuracy as described in appendix 8.5, however it's possible some errors are made in the process. This would affect the results of the experiment which the simulation has been validated against. The fact that the simulation agreed closely with the experimental results before adjustments were made suggests that there are no significant errors in either part.

- Unknown parameters

Some of the parameters mentioned in section 4.5 that were adjusted to produce results that fit the experimental data could be more accurately specified if measurements were taken to confirm the values. The influence these factors have on the hygrothermal properties of the wall are also observed in the previous section. The WDR catch ratio will have the largest effect on moisture levels in the wall whereas thermal exchange coefficient was less critical.

- Global radiation

The discrepancy in global and direct radiation has been explained in section 4.5 and should only make a small difference to the temperatures of the wall which will furthermore influence moisture levels.

- Lyngby rain file

As mentioned in section 4.7 the Lyngby DRY rain input file has been used in all three locations these specific files were not available. This will affect moisture levels in the wall but it was shown that wind is the dominant aspect of wind driven rain.

- One Dimensional modelling

In this project hygrothermal calculations will only be made in one dimension, horizontally through the wall so this will not account for aspects that require 2D or 3D modelling such as mortar joints or wooden beam and lath elements. While it has been suggested in section 4.2 that mortar joints do not have a big impact on the movement of moisture, modelling wooden elements would give a more realistic insight into mould growth and wood decay risks. To do this accurately a 3D simulation would be required and not currently possible with available hygrothermal simulating software.
5 Results

This section will firstly show the results of the refined model that evolved from many simulations attempting to replicate experimental results in the validation process of the two walls. Discussion of the results will follow in each section so that the process is described and analysed in the same order as the project actually transpired. Wall 2 with the original Multipor insulation system will be presented first, followed by wall 3 that has the added hydrophobic façade treatment. Then the outcome of setting these two models with the boundary conditions for Copenhagen and Esbjerg will be presented to investigate how the insulation systems perform in the two typical Danish climates. The order of results and discussion is as follows;

1. Wall 2 validation of model
2. Wall 3 validation of model
3. Part discussion of validations
4. Simulation in Copenhagen comparing walls 2 and 3
5. Esbjerg & Aalborg climate walls 2 and 3 compared with Copenhagen
6. Part discussion of simulations in new locations
7. Results of damage evaluation
8. Part discussion of damage evaluation

A visual aid has been provided in every chart to help the reader find which of the 4 sensor locations is being presented, an example of this is shown below.

![Figure 5.1 Demonstrating the sensor P4 position on the inside surface of the insulation](image)

5.1 Validation: Simulated and Experimental Results of Wall 2

Wall 2 with the original Multipor insulation system and without any hydrophobic impregnation will now be presented. First the temperature will be displayed followed by the relative humidity, such was the working order during validation because temperature greatly influences the relative humidity. The outer and inner surfaces in the wall are presented in Figure 4.4 (the remaining two points in between are presented along with the vapour mass density results in the appendix 8.1). At the time of writing this report the experiment has been underway for one year (since 1st May 2015) so the simulation has been run for the same period plus the preliminary two year stabilisation period which is not shown. One period of the experiment lacks data in all outputs due to sensor failure during July 2015 and a second period is lacking only in sensor P1 during March 2016.
During the summer period the temperature fluctuates at sensor P1 by as much as 15 °C mostly due to solar radiation. At sensor P2 the daily fluctuations are greater in the experimental results than the simulation. The largest disagreement is found between the simulated and experimental results at sensor P4 (Figure 5.2 b)), the simulation estimates a temperature approximately 1 °C warmer although the same fluctuating pattern is closely imitated throughout.

Next the relative humidity is shown starting from the outside of the wall (Figure 5.3) where the external boundary conditions are at their highest level of influence. When the winter period is reached the exterior levels of relative humidity become so high that over-hygroscopic condensation occurs (over 95%) at P1. The simulation agrees with the experiment during this winter period but during summer the relative humidity is slightly lower. This is a point where the wind driven rain had a large influence on results as shown in the method section 4.5.1 where the catch ratio was adjusted to increase the effect so was turned up to 0.7. Above this and the relative humidity became unrealistically high at the other points in the wall.
The middle of the brick layer is displayed in Figure 5.4 where after 2 months the experiment has reached stabilised levels and over-hygroscopic condensation occurs all year round as confirmed in the simulation.
At sensor P3 in the interface between brick and insulation layers the relative humidity rises for the first six months gradually reaching a state of quasi-equilibrium whereas the simulation is already at this state because it has been simulating for a preliminary two years with DRY data.

Finally the relative humidity in the inner surface of the wall is displayed in Figure 5.6, low humidity levels are recorded during the first month after installation because the humidifier was being configured to produce the correct internal environment. As shown in Figure 5.2 the slightly higher temperature seen in the simulation is also reflected in the relative humidity which is slightly lower than the experimental results.
5.2 Validation: Simulated and Experimental results of Wall 3

In this section the results of the wall 3 simulation are plotted beside the experimental results to show whether the hydrophobic treatment has been adequately imitated. The temperatures are not shown here but can be found in the appendix 8.2 because there is very little change from wall 2 since the hydrophobic layer does not significantly alter the thermal properties of the wall. The relative humidity levels are changed however and have been presented here from the outside of the brick through to the inner surface of the insulation. The vapour mass density output which gives similar insight as the relative humidity levels, has been added to appendix 8.2.

Starting with the external side of the wall again, even though the simulation temperatures matched the experiment very closely at sensor P1 there is some disagreement in the relative humidity as presented in Figure 5.7. During the first two months the experiment has higher values than the simulation although following this they match quite closely. Possibly this initial discrepancy is where a stabilisation is occurring in the moisture content of the materials. It is in the winter period where the impact of the hydrophobic layer is really seen by keeping the relative humidity below 90% instead of fully saturated as occurring in wall 2. As shown in section 4.6 this was modelled in the simulation by creating a thin brick layer with a water uptake value 1000th smaller than the original brick so it is clear that the hydrophobic treatment is very effective here.

![Figure 5.7. Simulation vs Experimental results: Relative Humidity at sensor P1 of wall 3](image-url)
In the middle of the wall a longer time to reach the steady transitional state is shown in Figure 5.8 and Figure 5.9 which are points at the middle of the brick layer and between the brick and insulation layers respectively. The experimental data also finds a slightly higher relative humidity than the simulated results, here adjustments of the boundary conditions had less effect but more accurate material properties may have improved the simulations agreement. The rise in relative humidity is delayed compared to the outer surface of the wall (Figure 5.7) and still high enough to initiate mould growth although this lasts for a shorter period than wall 2.
As with wall 2 the relative humidity at wall 3’s inner surface (Figure 5.10) was slightly higher in the experimental results than the simulation but the same tendencies can be seen throughout. Again the relative humidity low in the beginning before the humidifier was functioning properly.

### 5.3 Part Discussion: Validation of wall 2 and 3

A discussion is made here about the precision of the simulation compared to the experimental results to determine whether the model is sufficiently validated. Since the physical experiment was not part of this project, speculation of the experimental results is not within the scope of this report.

The temperature profile in both walls has been accurately matched by the results of the simulation, the biggest variation was found at sensor P4 where values were approx. 1°C higher although the same tendencies were followed. While this discrepancy is small it is still surprising considering this point is so close to the interior where the measured temperature has been used for the interior boundary condition in the Delphin simulation. There is little room for alterations at this point since the only boundary conditions here are the internal relative humidity and temperature so the only adjustable parameters are the exchange coefficients of heat conduction and vapour diffusion.

The simulated relative humidity does not appear to match the experimental results as closely as the temperature, this could be because with relative humidity there is a dependency on both temperature and water vapour pressure. This relationship between relative humidity and temperature can be seen in equation 5.1.

\[
\varphi = \frac{p_v}{p_{\text{sat}}} = \frac{p_v}{288.68 \left(1.098 + \frac{\theta}{100}\right)^{0.02}}
\]

\( \varphi \): Relative Humidity \hspace{1cm} p_v: Vapour Pressure \hspace{1cm} p_{\text{sat}}: Saturated Vapour Pressure \hspace{1cm} \theta: Temperature

Although these small differences occur, the relative humidity is still adequately matched with the variation seldom reaching more than ± 10% so it can be argued that the model is suitably validated to continue with the simulation in new locations. Furthermore the vapour mass density presented in appendix 8.1 for wall 2 and appendix 8.2 for wall 3 makes good agreement between experimental and simulated results.
5.4 Results: Simulations in New Locations

Now that the model has been validated to show that it produces realistic results it can be tested in other locations rather than the specific conditions of the experiment. This section will report how the two walls and insulation systems behave in typical conditions for Copenhagen, Esbjerg and Aalborg using DRY climate data. First to be presented is a comparison of how the two systems perform in normal Copenhagen climate conditions. Secondly results are shown of the system in Esbjerg and Aalborg, three of the most varied climate conditions in Denmark have been included so an overall analysis of the system performance in Danish climates can be estimated. This section will display the relative humidity output through the wall and temperature behind the insulation layer (the remaining results can be found in the appendix 8.3) by a discussion that leads into the next section where a damage evaluation has been made.

5.4.1 Copenhagen Wall 2 versus Wall 3

The results will start with Copenhagen, comparing the normal Xella insulated wall (wall 2) with wall 3 with the hydrophobic treatment, following this all three locations Copenhagen, Esbjerg and Aalborg will be analysed together. The temperature results have been presented in appendix 8.3 which again show little difference between wall 2 and 3.

The outer point of the brick layer is shown first in Figure 5.11, here the relative humidity in wall 2 reaches levels above 95% where over-hygroscopic condensation will occur for long periods of the winter. With the hydrophobic treatment applied in wall 3 a large reduction in relative humidity is seen.

![Figure 5.11. Relative humidity at sensor P1 near the outside of the brick layer. Comparing wall 2 without hydrophobic treatment and wall 3 with the treatment.](image)

Looking further into the two walls in Figure 5.12 and Figure 5.13 it is seen that the very high humidity levels in the untreated wall 2 continue until the inner side of the brick layer while the treated wall 3 avoids over hygroscopic humidity levels altogether. The hydrophobic layer is not completely stopping moisture either, as vapour or liquid, entering the wall because the relative humidity level is clearly rising until the beginning of summer and even exceeds 90% (Figure 5.13) so a risk of mould growth is present. During the summer wall 3 is able to dry out significantly more than wall 2 with relative humidity levels dropping below 65% in the middle of the masonry as seen in Figure 5.12.
At the inner surface of the wall the higher temperature promotes drying out and so prevents very high relative humidity although the advantages of the hydrophobic treatment in wall 3 can still be seen in Figure 5.14.
It is also interesting to note the difference in thermal performance of the insulation with and without the hydrophobic layer, Figure 5.15 shows the temperature between the insulation layer and brick is slightly higher in wall 2 during the winter. This demonstrates that the insulation is less efficient when moisture content is very high, and while the temperature difference is very small would result in a reasonable amount of energy loss over the surface of a large room.

The difference between the two walls can be seen more clearly in a winter temperature profile of the whole width of the wall which is shown in Figure 5.16 during February. With the added hydrophobic impregnation in wall 3 the Multipor layer has a steeper temperature gradient showing that its thermal resistance is slightly higher although the brick shows a shallower temperature gradient suggesting that its thermal resistance is lowered.
5.4.2 Comparing Copenhagen, Aalborg and Esbjerg

Now the results from Aalborg and Esbjerg will be compared to Copenhagen to see how the two wall systems perform in different Danish climates. Due to the volume of results the less insightful aspects are shown in the appendix 8.4, this includes all temperature results and relative humidity at sensor P1 on the outer surface of the brick.

As previously shown in Figure 5.12, without the hydrophobic treatment the relative humidity at middle of the brick layer stayed over 99% all year-round with the Copenhagen climate. With these levels over-hygroscopic moisture is certainly occurring and similar results were found in the other two climates although Aalborg showed slightly lower levels (Figure 5.17).
In Figure 5.18 the hydrophobic treatment can be seen to be less effective at keeping the relative humidity low in the middle of the brick layer when placed in Esbjerg and Aalborg than it is in Copenhagen. It can be explained that the Esbjerg climate leads to a higher humidity in the bricks because higher wind speeds leading to more wind driven rain but the Aalborg result does not agree with this theory because here the wind speed is lower.

Next, looking at the untreated wall where the brick meets with the insulation layer in Figure 5.19 the Aalborg relative humidity level stays much lower whereas the other two locations are both very high, agreeing with the theory of wind driven rain. However all three stay over 90% so it is reasonable to say there is risk of mould damage in all of the locations.

The same lowered humidity can be seen between the layers when the hydrophobic treatment is applied in Figure 5.20 although this difference is less notable in the Aalborg climate. Furthermore, the treatment seems to have more effect in the Copenhagen climate than the other two locations by a margin of approximately 5%.
On the inner surface of the untreated wall there is quite a variance in relative humidity between the locations shown in Figure 5.21, most surprisingly over the winter Aalborg is at a much lower level while Copenhagen and Esbjerg reach their peak levels.

In Figure 5.22 when the hydrophobic layer is applied there is hardly any difference between the three locations which all have lower relative humidity over the winter. It is interesting to see there is little difference between the results of wall 2 and wall 3 in Aalborg.
Figure 5.22 Comparing the relative humidity between Copenhagen, Esbjerg and Aalborg at sensor P4 on the inside surface of wall 3 - which is the same with the added hydrophobic treatment.

The results are summarised in Table 5.1 to give an overview of the 3 locations. It is quite noticeable that Copenhagen is the higher risk location without hydrophobic impregnation (wall 2) but Esbjerg is more hazardous in wall 3, with the treatment.

Table 5.1. Giving a summary of the results of the simulations in DRY climates of Copenhagen, Esbjerg and Aalborg. The table lists the maximum, average and minimum relative humidity values over a year in wall 2 (without hydrophobic treatment) and wall 3 (with hydrophobic treatment).

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Copenhagen</th>
<th>Esbjerg</th>
<th>Aalborg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wall 2</td>
<td>Wall 3</td>
<td>Wall 2</td>
</tr>
<tr>
<td><strong>Brick</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>RH Max</td>
<td>100</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>RH Avg</td>
<td>98</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>RH Min</td>
<td>76</td>
<td>42</td>
</tr>
<tr>
<td>P2</td>
<td>RH Max</td>
<td>100</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>RH Avg</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>RH Min</td>
<td>99</td>
<td>62</td>
</tr>
<tr>
<td><strong>Plaster</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>RH Max</td>
<td>100</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>RH Avg</td>
<td>98</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>RH Min</td>
<td>96</td>
<td>66</td>
</tr>
<tr>
<td><strong>Multipor</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P4</td>
<td>RH Max</td>
<td>82</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>RH Avg</td>
<td>72</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>RH Min</td>
<td>62</td>
<td>45</td>
</tr>
</tbody>
</table>

Mould mild (>80%)  Mould rapid (>90%)  Wood decay (>95%)
5.5 Part Discussion Simulation in new locations

The discussion of the simulations in the three locations of Copenhagen, Esbjerg and Aalborg will be presented first comparing the general difference between the Xella insulating system in wall 2 with the same system plus hydrophobic treatment in wall 3. Then the difference between the three locations will be discussed focusing first on Copenhagen, followed by Esbjerg and finally Aalborg.

First looking at the Xella insulation system without the hydrophobic impregnation high relative humidity levels are seen in the brick and between the brick and insulation layers and over-hygroscopic moisture is formed during long periods of the year. In terms of the effectiveness of the Xella system as capillary active, diffusion open insulation it has been shown in other research that Multipor is not so good at redistributing moisture (Vereecken & Roels 2014), in this investigation some reallocation of moisture can be seen although it is not enough to avoid over-hygroscopic condensation. While the high interior relative humidity does not cause a problem, the driving rain and relative humidity on the exterior is clearly the source of the moisture found within the wall because the results are very different when the outer impregnation is applied in wall 3.

It could be perceived from the results of the DRY climate conditions presented in the previous chapter that the hydrophobic treatment is very effective in reducing the moisture content of the wall and slightly more successful in Copenhagen. The hydrophobic treatment greatly reduces the relative humidity levels from the outer surface of the brick layer up to the interior surface of the insulation. The temperature profile displayed in Figure 5.16 highlighted the different heat conductivity of the Multipor when dry and wet, there is quite a change and this again proves that the amount of moisture found in the untreated Xella wall (wall 2) is undesirable even if mould or wood degradation were not an issue. Some quite different results were found between the three locations - wall 3 with the hydrophobic treatment seems to work noticeably better in the Copenhagen climate. This can’t be explained by wind driven rain since the same rain file has been used in all locations and the wind velocity is higher in Esbjerg but lower in Aalborg.

In the Esbjerg climate the middle sections of the wall have a higher relative humidity when compared to Copenhagen, this can be explained by a higher wind pressure acting on the wall as shown in Figure 5.23. Furthermore it is interesting to see that the external surface of the wall has a lower relative humidity, maybe due to a local convective drying effect from the wind at this location.
The results in the Aalborg climate showed that at a slightly lower wind speed the hydrophobic treatment almost becomes unnecessary, wall 2 and wall 3 gave quite similar results at the interface between the insulation and brick layers but within the brick layer a notable difference was still found. This means that if it is certain that mould is the only damage issue then the untreated wall 2 may be adequate however if frost damage or wood degradation are issues at the brick layer then hydrophobic treatment is still beneficial.
5.6 Results of Damage Evaluation

An analysis has been made of the potential damage that could occur due to these presented hygrothermal conditions, comparing three locations in Denmark; Copenhagen, Esbjerg and Aalborg. Frost damage in the outer surface of brick will be presented first followed by wood decay in the middle of the wall and finally mould on the surfaces of the insulation layer.

5.6.1 Damage Evaluation - Frost

An ice/pore volume ratio of 30% has been given as the point where there is a risk of frost damage by the WTA (WTA 2014) and while this level is not breached it comes close in Copenhagen. The ice volume/pore volume ratios shown in Figure 5.24 compare the values for wall 2 and wall 3 in each location, most are well below the critical point where the volume of ice exceeds 30% of the space in the pores so from this perspective no frost damage should occur. This is confirmed by Figure 5.25 which gives the moisture content of the brick layer in wall 2 Copenhagen climate and is plotted against the temperature at the outside surface of the brick.

![Figure 5.24. Comparing Ice / Pore volume ratio (in %) for walls 2 and 3 (without and with hydrophobic treatment) at a depth 0 to 9mm in the brick during one winter period simulated with a) Copenhagen, b) Esbjerg and c) Aalborg DRY climates.](image)

Even though frost damage doesn’t seem to occur it is still interesting to compare the quantity of ice produced and the difference between locations also with/without hydrophobic treatment. Copenhagen has a larger production of ice over the winter period yet Aalborg has the coldest climate with the DRY yearly average of 7.5°C compared to 8.6°C and 8.2°C in Copenhagen and Esbjerg respectively (Grunnet Wang et al. 2013). Esbjerg has the smallest production of ice which could be explained by the high wind levels causing the face of the brick to dry out quickly. The hydrophobic impregnation seems to have not reduced the ice production in Esbjerg but in the other two locations a difference is noticeable.
5.6.2 Damage Evaluation - Wood Decay

Next the extent of wood decay is plotted as a percentage of its original mass that degrades over three years. The values at P2 and P3 are plotted together in Figure 5.26 and a separate chart is made for each wall because the scale of decay is very different with and without the hydrophobic treatment, furthermore each location has been displayed separately.

Starting with wall 2 without the hydrophobic treatment, very high levels are found in the middle of the brick layer at sensor P2 100% degradation occurs after approx. 2.5 years in all 3 locations. In between the brick and insulation layers at P3 there is a slower gain in wood decay especially in Aalborg shown in Figure 5.26 e), this is also not a constant incline therefore the activation level is intermittently below 1.

A large difference is seen when the hydrophobic treatment is applied, P3 between the layers registers little to no decay in all locations and P2 within the brick stays below 4% within the 3 year period. Even though this is a huge improvement compared to wall 2, a degradation level of 1% to 2% per year is not acceptable or sustainable for a wall construction. While Esbjerg and Aalborg have similar levels of decay of around 4%, Copenhagen has nearly half this amount which coincides with the relative humidity difference at these locations in wall 3 presented in section 5.4 previously.
In all the presented wood decay analyses the activation level was pre-set to 1 which means there is no delay for decay to occur if suitable conditions are met. This is done as a worst case scenario and also because the same situation repeats each year with consistently high levels of moisture so the activation period is simply delaying the inevitable. This analysis was also tested with the pre-set level at 0 and here sensor 2, where conditions are most favourable for wood degradation, had approximately 530 days activation time before mould growth began in all locations. Furthermore the full three year simulation period has been displayed although the amount of decay occurring particularly in the first year is not a true representation, because here the materials have yet reached the hygrothermal quasi-steady state.

5.6.3 Damage Evaluation - Mould
Figure 5.27 shows the mould index levels during a 3 year simulation of DRY climate with a chart for each location and both walls plotted together. Results of both sensors P3 and P4 are plotted together although the moisture levels are low enough that no mould is predicted at P4 on the inside wall surface except for a very small quantity.
at Esbjerg wall 2. In general it can be understood that adding the hydrophobic layer lowers the mould index at sensor P3 which is at the interface between the insulation and brick layers.

Figure 5.27. Mould index values during 3 year simulation of DRY climate data at a) Copenhagen, b) Esbjerg and c) Aalborg. The only mould growth registered at sensor P4, on the inner surface of the wall is shown in b) Esbjerg – wall 2.

While the results are not wildly different between the three locations, Copenhagen has the highest mould index in wall 2 but also the lowest in wall 3 when the hydrophobic treatment is present.

Table 5.2 Damage Evaluation Summary

<table>
<thead>
<tr>
<th></th>
<th>Max Ice / pore volume</th>
<th>Mould index at P3 (after 3 years)</th>
<th>Wood decay yearly (between brick &amp; insulation)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Wall 2</td>
<td>Wall 3</td>
</tr>
<tr>
<td>Copenhagen</td>
<td>22.5%</td>
<td>3.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Esbjerg</td>
<td>8%</td>
<td>3.4</td>
<td>1.9</td>
</tr>
<tr>
<td>Aalborg</td>
<td>16%</td>
<td>3.1</td>
<td>2</td>
</tr>
</tbody>
</table>
In Figure 5.28 a comparison is made between the VTT mould index values and Sedlbauer’s isopleth charts only for Copenhagen to see if any differences occur. Between the brick and insulation layers the isopleth chart in Figure 5.28 a) shows germination will occur in 1 or 2 days and the growth rate shown Figure 5.29 is around 3mm per day. On the inside surface of the wall shown in Figure 5.28 b) the conditions for spore germination are not met although it gets very close.

Figure 5.28. Showing substrate II mould growth isopleths for the Copenhagen climate in wall 2 without the hydrophobic treatment at a) sensor P3 and b) sensor P4.

Figure 5.29. Growth rate for Copenhagen climate in wall 2 without the hydrophobic treatment at sensor P3.
5.7 Part Discussion of Damage Evaluation

From the results of the ice/pore volume ratio it appears that frost damage is not a high risk in any of the locations for either wall although the highest ratio reached 22.5% in the normal Xella system in a Copenhagen climate. This is somewhat surprising given the high relative humidity found particularly in wall 2 Copenhagen and Esbjerg but can be explained because although over-hygroscopic water is found in the wall there is not enough liquid to significantly saturate the brick, at least not during cold periods. This result was concurred when looking at the water content of the brick layer, even though this reaches high levels over 30% in a few instances it does not happen when the outside temperature is close to 0°C. It should be remembered however that this simulation is limited to input data of typical Danish climates so in colder, wet winters much more ice could be produced. Since frost damage is irreversible and can occur in a short period of time simulating in extreme conditions is more informing than average environments that are more appropriate for mould growth and wood decay.

When comparing the results of the ice/pore volume ratio between the two walls the hydrophobic layer does appear to reduce these levels by as much as 30% which coincides with the large reductions in relative humidity seen in section 5.4. Amongst the locations, Esbjerg produced the lowest ice/pore volume ratio which could be due to the higher wind velocity accelerating convective drying at the surface of the walls.

The results of the wood degradation analysis in section 5.6.2 confirmed the risks of the high humidity levels seen earlier especially in wall 2 without the hydrophobic treatment a steady decay occurs throughout the three year period and 100% is reached in most cases. The hydrophobic treatment does make a huge difference limiting the period of decay to a few months each spring although a rapid deterioration occurs of 2% each time which would eventually cause problems in the structure.

In the presented results the risk of Wood decay reaches alarming levels in wall 2 and although much lower in wall 3 with the hydrophobic layer these are still unacceptable. There are some arguments however that show these findings could be less extreme than first thought. Firstly with wood degradation there is a relatively long activation period which was not included in these results but add approx. 530 days before wood decay begins in wall 2 and even longer in wall 3. Mould problems will occur earlier than this so it could be argued mould is more critical than wood decay. However, there is a counter argument to this because the manufactures of Multipor claim that mould will not occur behind the insulation due to its high PH level so if this is true wood decay becomes the critical problem by default.

Another point is that the type of building construction should be considered particularly how the wooden elements are included in the wall. If the element in question is a beam (e.g. element 1) or something that continues into the interior then drying will also occur by capillary action distributing water within the element. However if the element is only in the colder section of the wall such as a wooden lath supporting the beam, then the moisture has nowhere to go and wood decay will indeed occur.

Figure 5.30. Showing two types of wooden elements that could suffer from moisture problems in the wall construction.
In the end this conjecture cannot be concluded with the analysis carried out so far and there is an opportunity for a three dimensional simulation to be made in the future that would study the insulated wall with beam and lath elements included.

The mould index levels on the inner surface of the walls are almost all zero but the isopleth charts show that spore germination conditions are only narrowly avoided. There is a significant level of mould growth found at the interface between the brick and insulation layers but it is questionable whether mould in this location is an issue. As mentioned previously, there is the argument of the insulation manufacturer that mould growth is not possible on their Multipor product, due to its high PH. This is yet to be tested however, and investigation ought to be made into whether PH level neutralises over time or with the application of paint. Assuming that mould growth is still an issue all three locations accumulated a mould index of three within the three year simulation period which corresponds to “some growth detected visually” according to Table 3.1 on of the VTT model presented on page 10 of this report. The isopleth chart showed a mould growth rate varying between 1mm and 4mm per day which is difficult to compare to the VTT mould index but at least agrees that visual mould growth will be detected.

It is also interesting to note that even though the mould index values are very similar for all three locations they agree with the relative humidity levels presented in section 5.4 that exhibited similar variations. At the same sensor P3 between the brick and insulation layers, Aalborg showed up to 6% lower relative humidity levels than the other two locations and this is reflected in the mould index which is approx. 0.3 lower.

Overall, wood decay seems the most critical and severe mode of damage but mould growth could also be serious if it is found to be possible despite the opinion of the insulation manufacturers. Frost damage does not appear to be an issue for the Xella insulated wall in typical Danish climates although a slightly more severe winter could be a problem especially in Copenhagen.

6 General Discussion

All of the Results have now been presented and discussed individually so now an overall discussion will be made to bring together all of the findings from the different parts of this project. To begin with, the experimental results from wall 2 with the Xella insulation system have been recreated in a hygrothermal model. Next Wall 3 was modelled in section 5.2, which has the same Xella system but with a hydrophobic impregnation added to the façade. The simulation has been validated with reasonable accuracy but as discussed in section 5.3 there were some minor differences in the relative humidity values which were accentuated because of the dependency on temperature. A better perspective of moisture within the wall materials is given by the vapour mass density results.

Once validated the two models have been simulated in section 5.4 in three locations in Denmark; Copenhagen, Esbjerg, and Aalborg to investigate how the insulated wall, with and without hydrophobic impregnation copes in typical Danish climates. In Copenhagen and Esbjerg the wall without impregnation experiences levels of relative humidity high enough to form over-hygroscopic condensation all year round within the brick layer and between the brick and insulation layers. The higher wind velocities in Esbjerg appear to increase this problem and conversely in Aalborg, relative humidity levels are much lower throughout the wall due to the milder wind conditions. In all locations the hydrophobic treatment is found to very successfully reduce the relative humidity levels, more so in Copenhagen and Esbjerg since in Aalborg the non-impregnated wall already had much less moisture. This success further indicates that wind driven rain is the main cause of the high moisture levels found in the untreated wall.
To make a more practical assessment of the consequences of these calculated temperature and relative humidity levels a damage evaluation has been made in section 5.6 for both walls in the three locations. Starting with frost damage on the outer surface of the brick an analysis was made using ice-pore volume ratios and moisture contents. Next looking into points where wooden elements can commonly be found in the middle of the brick wall and between brick and insulation layers a wood degradation analysis was made based on the VTT model (Hukka & Viitanen 1999) explained in section 0. Finally the mould growth index was calculated at both sides of the insulation layer using another VTT method (Ojanen et al. 2011).

The ice/pore volume ratio results in section 5.6.1 showed that both walls are not at any risk of frost damage in any of the three locations and this was confirmed when looking at the total moisture content in the brick layer which remained below 30% during colder periods. Esbjerg showed the lowest ice levels which could be due to the wind velocity drying out the surface of the brick more.

A wood degradation analysis was also made for the central points of the wall and rapid decay rates were found all year round when the hydrophobic treatment is not present. Wall 3 with the impregnation had much less frequent periods of decay but they still occurred each year and would cause problems if wooden elements are present in the wall. Some argument was considered on whether these risks are critical in the wall and it was concluded that it depends on how the wooden elements are located in the wall but a 3D simulation would be required to address these concerns.

The mould growth study revealed that while nothing is expected on the inside surface of the wall, there is a risk between the insulation and brick layers of mould growing beyond the microscopic level within three years. Further conjecture on whether mould can actually grow on the surface of the insulation was discussed but since this is not yet conclusive it must be taken as a serious risk.

In summary of the damage evaluation it can be said that while frost damage is not a risk to either wall in any of the three locations, wood decay and mould definitely is. Whilst wood decay could have the most severe consequences to structural integrity, mould growth is likely to occur earlier.
7 Conclusion

This project has sought to use the results of a physical experiment into capillary active, diffusion open internal insulation to create validated hygrothermal models replicating the same systems. These models were then simulated in climates from three different locations in Denmark to ascertain how successfully they function here. This was evaluated based on whether mould growth, wood decay or frost damage are a possible risk. The main aim of this project has been to give an overview of how these two wall and insulation systems perform in typical climates in Denmark.

The findings of the project are presented in detail in chapters 5 and 5.65.6 but the main points will be synthesised here and then the implications will be discussed to reach an opinion as to whether the insulations systems work successfully in typical Danish climates. First of all the two walls were validated quite successfully with a maximum ±1°C and ±10% discrepancy in temperature and relative humidity respectively. In general over the three locations when the Multipor insulation alone was applied to masonry as in wall 2, the system failed to keep relative humidity levels down and over-hygroscopic condensation occurred for long periods of each simulated year. When the hydrophobic treatment is applied to the façade as in wall 3 a large difference is seen in the results with relative humidity being kept much lower and far from risk of over-hygroscopic condensation. Between the three locations Aalborg has the lowest average wind velocity which clearly lead to lower levels of relative humidity within the wall layers. Although Esbjerg has a slightly higher average wind velocity which clearly lead to lower levels of relative humidity within the wall layers. Although Esbjerg has a slightly higher average wind velocity than Copenhagen it did not increase relative humidity levels in the same way.

The damage evaluation showed that frost damage is not a threat in any of the cases although the wall without hydrophobic treatment came close to recommended limits of ice/pore volume ratio in the Copenhagen climate. Wood decay gave the most alarming results showing that at the centre of the brick layer and between the brick and insulation layer approx. 40% degradation would occur each year when the hydrophobic impregnation is not applied. The decay was much reduced although not stopped when the hydrophobic layer was added with 1% to 2% occurring each year. Mould growth was not a problem on the interior surface of the insulation however it will occur behind where the insulation meets the brick where a mould growth index of 3 occurs.

So from the results in can be determined that when only the Multipor is applied to the masonry wall high moisture levels are incurred which are likely to lead to decay in wooden elements and mould growth between the insulation and brick layers. It has been shown before in other studies (Vereecken & Roels 2015a) that Multipor functions poorly to redistribute moisture. The results of this project implies that Multipor alone is not recommended in the typical Danish climate as a capillary active insulation solution to the 1 ½ brick walls that are representative of buildings from the period 1850 to 1930 here in Denmark. While the hydrophobic impregnation greatly improves the moisture levels in the wall a risk of mould and wood decay still occurs so the complete wall system is still not advisable although the façade treatment has been shown to benefit other insulation systems before (Finken 2014). By investigating the three different locations in Denmark it is apparent that variations in the climate can lead to significant differences in the wall’s moisture levels so much so that the hydrophobic treatment may not be necessary particularly in Aalborg if wooden elements are not included in the wall.

The findings in this project does not mean that capillary active insulation should not be used in renovation of Danish buildings on the contrary it shows that the material investigated should not be applied as a capillary active insulation. Further work researching the other options is needed and already underway at DTU as a broader experimental project testing many other insulation systems.
It has been shown before that post insulating masonry walls can lead to moisture problems and in this project the same has been established so a more effective capillary active material is required. Promising results were found with the hydrophobic façade impregnation which successfully deals with the high wind driven rain loads found in Danish climates.

7.1 Recommendations for Further Work

- **Experiments to establish unknown parameters.** To improve validation results further studies could be made using the existing experiment such as a more thorough material characterisation and wind driven rain catch ratio at the specific location.

- **Create 2 and 3 dimensional models.** This would allow the wooden beam and lath elements to be modelled and give a greater insight into the risk of wood decay.

- **Simulate further climate locations.** There are three more climate zones in Denmark that could be simulated and the insulation systems are already being used all over Europe so studies elsewhere would be worthwhile.
8 Appendix

8.1 Validation: Simulated and Experimental Results of Wall 2

This section contains the remaining results for the validation of the unimpregnated wall 2. In Figure 8.1 and Figure 8.2 the simulated temperature values are compared to experimental output at sensor P2 and P3 in the middle of the brick and between brick and insulation layers respectively. Then the water vapour mass is compared at the 4 sensor locations shown from Figure 8.3 to Figure 8.6.

Figure 8.1 Validation of wall 2 - Temperature at sensor P2

Figure 8.2 Validation of wall 2 - Temperature at sensor P3
Figure 8.3 Comparing experimental and simulated vapour mass at sensor P1 in wall 2

Figure 8.4 Comparing experimental and simulated vapour mass at sensor P2 in wall 2
Figure 8.5 Comparing experimental and simulated vapour mass at sensor P3 in wall 2

Figure 8.6 Comparing experimental and simulated vapour mass at sensor P4 in wall 2
8.2 Validation: Simulated and Experimental Results of Wall 3

Here the remaining results are included from the validation of wall 3 that includes the hygrothermal impregnation. From Figure 8.7 to Figure 8.10 the temperatures in wall 3 with the hydrophobic impregnation are shown at all 4 sensors. Then from Figure 8.11 to Figure 8.14 the vapour mass density is are presented in each sensor location.

![Temperature at Sensor P1](image1)

**Figure 8.7 Validation of wall 3 - Temperature at sensor P1**

![Temperature at Sensor P2](image2)

**Figure 8.8 Validation of wall 3 - Temperature at sensor P2**

![Temperature at Sensor P3](image3)

**Figure 8.9 Validation of wall 3 - Temperature at sensor P3**

![Temperature at Sensor P4](image4)

**Figure 8.10 Validation of wall 3 - Temperature at sensor P4**
Figure 8.11 Comparing experimental and simulated vapour mass at sensor P1 in wall 3

Figure 8.12 Comparing experimental and simulated vapour mass at sensor P2 in wall 3
Figure 8.13 Comparing experimental and simulated vapour mass at sensor P3 in wall 3

Figure 8.14 Comparing experimental and simulated vapour mass at sensor P4 in wall 3
8.3 Simulations in Copenhagen DRY climate

Here the remaining results of the simulations in Copenhagen are presented from Figure 8.15 to Figure 8.18 the temperatures are compared between wall 2 and wall 3 for all 4 sensor locations.
8.4 Comparing Copenhagen, Aalborg and Esbjerg

In this section the remaining results of the simulations relating Copenhagen, Aalborg and Esbjerg are displayed starting with the relative humidity at sensor P1 in the front of the brick layer. Secondly the temperatures are compared for wall 2 and finally wall 3 with hydrophobic impregnation is displayed.

![Figure 8.19 Wall 2 Relative humidity at sensor P1 in Aalborg, Copenhagen and Esbjerg.](image1)

![Figure 8.20 Wall 3 Relative humidity at sensor P1 in Aalborg, Copenhagen and Esbjerg.](image2)
Remaining temperature results in Copenhagen, Aalborg and Esbjerg wall 2:

Figure 8.21 Temperature at sensor P1 Wall 2 in Aalborg, Copenhagen and Esbjerg.

Figure 8.22 Temperature at sensor P2 Wall 2 in Aalborg, Copenhagen and Esbjerg.

Figure 8.23 Temperature at sensor P3 Wall 2 in Aalborg, Copenhagen and Esbjerg.

Figure 8.24 Temperature at sensor P4 Wall 2 in Aalborg, Copenhagen and Esbjerg.
Remaining temperature results in Copenhagen, Aalborg and Esbjerg wall 3:

Figure 8.25 Temperature at sensor P1 Wall 3 in Aalborg, Copenhagen and Esbjerg.

Figure 8.26 Temperature at sensor P2 Wall 3 in Aalborg, Copenhagen and Esbjerg.

Figure 8.27 Temperature at sensor P3 Wall 3 in Aalborg, Copenhagen and Esbjerg.

Figure 8.28 Temperature at sensor P4 Wall 3 in Aalborg, Copenhagen and Esbjerg.
8.5 Description of Measurement System by Tommy Odgaard
APPENDIX 8.5 (WRITTEN BY TOMMY ODGAARD)

DESCRIPTION OF MEASUREMENT SYSTEM: CONTAINER PROJECTS WITH FOCUS ON SOLID MASONRY AND INTERIOR INSULATION

INTERNAL NOTE

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1 Container setup

The general container setup consist of 2 containers.

First one is supported by the foundation "Grundejernes Investeringsfond". Address: 120 C3. This container contain 16 walls, 8 facing SW, 8 facing NE.

Second container is supported by the foundation "Realdania", in collaboration with the company Xella. Address: 120 D4. This container contain 8 walls, all facing SW.

Both containers have a digital monitoring system and an analogue system which is connected to a computer which constantly logs the data. Additionally driven rain sensors with individual data loggers are installed in the same directions as the walls.
2 Digital system

The digital system has been set up by DTU technician Lars Kokholm Andersen (LKA). The system consist of sensors mounted in a wall, with wires assembled in patch panel(s) above each wall. 1 ethernet cable from each wall go to the middle of the container, where is it connected to individual Arduinos. The Arduinos have been programmed to read out the data from each sensor. The 8 Arduinos are connected to an USB hub, which is further connected to a computer. The computer then logs the data through LabView, and plots each measurement as a line in 3 different .txt files under the same timestamp. The 3 .txt files contain: Address, Humidity, Temperature. Each reading from sensor are isolated in the columns – note that addresses might change and the address of the sensors are only defined in the address .txt file!

The computers can be accessed through remote desktop, but can also be accessed physically in the container.

Lars Kokholm Andersen and Tommy Odgaard have the username & password.

2.1 Container 120 C3 "GI container"

The digital sensors are logged by 2 computers, isolating the directions SW / NE.

Up until 2016.04.16, both directions were monitored by BYG-F0130, isolating the directions with relays. This system were not stable enough and have been changed.

The system is built as described earlier in section 2. Up until 2016.04.16, 1 Arduino where used for all sensors in the container, with a relay/programming changing between the SW/NE direction. This system where not stable enough, and have been changed.

Computer 1: BYG-F0130.win.dtu.dk
Monitoring walls in NE direction, with address 1001 – 1128. This computer further log the analogue resistance measurements.

Computer 2: BYG-F0216.win.dtu.dk
Monitoring walls in SW direction, with address 1 – 128.

Data are moved to and stored in the following directory:

\byg-cserver1.win.dtu.dk\Research\26390_- _Anvendelighed_og_robusthed_af_indvendig_isolering

2.2 Container 120 D4 "Xella container"

The digital sensors are logged by 1 computer.

The system is built as described earlier in section 2. Up until 2016.04.16, 1 Arduino where used for all sensors in the container. This system where not stable enough, and have been changed.
Computer: BYG-F0131.win.dtu.dk
Monitoring walls in SW direction, with address 1 – 128.

Data are moved to and stored in the following directory:

\byg-cserver1.win.dtu.dk\Research\26400_-_Xella_indvendig_isolering

2.3 Defect sensors

The setup of the system cause that if a sensor is defect, then this will influence the entire circle. This manifests itself in two different ways:

› Sensor short wires, influencing the entire circle so no data is obtained.

› Sensor sends wrong signal, which may influence all other sensors in circle (+/- some percent RH or °C Temperature from other sensors). This error is troublesome to find, and require individual control measurements in each circle with handheld instrument, which is then compared to last monitored value on computer.

The defect will influence the entire circle, up until the first Arduino. This defect is the reason why the system were split up from 1 Arduino pr. container to 1 Arduino pr. wall.

The error is fixed by removing the sensor from the circle, thereby allowing the remaining sensors to work fully.

2.3.1 Identification of defective sensor

The following procedure can be used to identify a defective sensor:

› Login on computer with faulty circle

› In "LabView", change the frequency of digital measurements to short (~20 sek).

› Remove sensors from faulty circle until remaining circle is back online.

For easier identification of defect sensor, the blue handheld instrument for measuring individual sensors may be used. Sensors which doesn’t give an output on this is defective.

Note: Experience say that faulty sensors will not start fully working again. The ones we have tried have worked later for a short period, and then died again.

2.3.2 Replacement of sensors
2.4 Initial data sort by script

The data from the container are loaded, sorted and treated in a matlab script, which loads in the newest data from the previously mentioned server locations. The script have been developed by Tommy Odgaard during his industrial PhD at DTU, and he might be of assistance for further information on the code.

The script is set up to do an initial data analysis of the raw data from the digital measurements, before calibration data is applied.

The initial data sort is performed in the order of the following subsections.

2.4.1 Remove fluctuating values

In Matlab function: "funcRemoveFluctuating.m".

The function isolates all values for 1 sensor into a vector. This vector is then treated with the built-in matlab function "medfilt1" with a 10th order one dimensional median filter to remove spikes in the data.

This approach is looped for all columns to treat the full dataset.

2.4.2 Clean data for extremes

In Matlab function: "funcCleanData.m".

This function searches the dataset to remove extreme values and replace then with NaN. An example of an extreme value to be filtered occurs due to a failing sensor. Around the time of failure, the system has a tendency to write temperatures at +120 and -40 degrees Celsius. As these values are extreme and will not occur in Denmark, they are filtered away.

The following values are filtered:

- Relative Humidity: 5 < RH[%] < 100
- Temperature: -35 < T[°C] < 50

2.5 Calibration

Performed in the start of the project, only for relative humidity.

44%, 75%, 93%, 97%, 93%, 75%, 44%. Measured against precise equipment, calibrated against Rotronic calibration salt solutions.

Steady points plotted for all 7 points.

Linear line fitted to measurements for each sensor.
2.5.1 Application of calibration data

In Matlab function: "funcIncludeCalibHum.m". Calibration is applied after the initial data sort described in 2.4.

Linear equation applied to individual sensors, changing value from monitored to real value.

If RH > 99.98 in the raw there, then this value is reapplied.

If RH > 99.98 after application of calibration data, this is adjusted to 99.99.

If RH < 0 after application of calibration data, adjusted to 0.
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