



CHALMERS
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Implementation of aerogel-based plaster in Sweden

A hygrothermal parametric study on wall constructions in the Swedish building stock

Master's thesis in the master's programme Structural Engineering and Building Technology

ERIK HAUGBAK
AMAR TALIC

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF BUILDING TECHNOLOGY

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MASTER'S THESIS ACEX30

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Department of Architecture and Civil Engineering

Division of Building Technology

Building Physics Modelling

Chalmers University of Technology

SE-412 96 Göteborg

Sweden

Telephone: + 46 (0)31-772 1000

Cover:

Case study building in the area Forsåker in Mölndal, Sweden. Photo taken by author.

Department of Architecture and Civil Engineering

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ABSTRACT

As global warming continues, new solutions and technologies are constantly being sought to reduce human impact on the climate. This happens in many sectors, including the construction sector which also accounts for significant emissions. A new type of material has therefore been developed in Europe during the last decade, in this study referred to as aerogel-based plaster. It is a plaster containing aerogel granules which has a low thermal conductivity and is developed for buildings in need of renovation. As this plaster has an insulating ability, it can decrease the energy consumption of the building while the character defining elements can be preserved. The material has been studied in central European climate, while this study aims to explore the suitability of using the material in Sweden. Common building constructions in Sweden have been investigated through in-depth hygrothermal and energy simulations. Parametric studies have also been performed where factors such as damage in the water repellent layer, thickness of aerogel-based plaster, climate condition, and drying rate have been investigated. In addition, an analysis has also been made of the energy performance of the material and how it behaves in Swedish climate. The results suggest that the material can be used in the Swedish climate on many different wall constructions without the construction being damaged in terms of moisture. However, one crucial parameter is that the material is protected from rain as it can absorb a lot of water. This can be done by a suitable type of finish, such as water repellent paint. The energy simulations formed the basis for a simplified economic evaluation for the reference building, which showed that aerogel-based plaster is suitable when a thinner insulating layer shall be considered. When a thicker layer can be applied, other materials may be more beneficial since the cost of aerogel-based plaster largely depends on its thickness.

Key words: insulation, aerogel, aerogel-based plaster, plaster, renovation, external insulation, listed buildings, moisture transport

Implementering av aerogel-baserad puts i Sverige

En hygrottermisk parameterstudie på väggkonstruktioner i det svenska byggbeståndet

Examensarbete inom mastersprogrammet Konstruktionsteknik och Byggnadsteknologi

ERIK HAUGBAK

AMAR TALIC

Institutionen för arkitektur och samhällsbyggnadsteknik

Avdelningen för byggnadsteknologi

Byggnadsfysikalisk modellering

Chalmers tekniska högskola

SAMMANFATTNING

I och med att den globala uppvärmningen fortgår försöker man ständigt hitta nya lösningar och tekniker för att minska människans påverkan på klimatet. Detta sker inom många sektorer, inklusive byggsektorn, som också står för betydande utsläpp. En ny typ av material har därför utvecklats i Europa under det senaste decenniet, som går under namnet aerogel-baserad puts. Det är en puts som innehåller aerogelgranulat som har låg värmeledningsförmåga och är väl lämpat för byggnader i behov av renovering. Då putsen har en isolerande förmåga kan den sänka byggnadens energiförbrukning medan den karaktärsbärande elementen i byggnaden kan bevaras. Materialet har studerats i centraleuropeiskt klimat, medan denna studie syftar till att undersöka lämpligheten i att använda materialet i Sverige. Vanliga byggnadskonstruktioner i Sverige har undersökts genom fördjupade hygrottermiska- och energisimuleringar. Parameterstudier har också utförts där faktorer som skador på det vattenavvisande lagret, tjocklek på putsen, väderförhållanden och torkhastigheter har undersökts. Dessutom har en analys gjorts av materialets energiprestanda och hur det beter sig i det svenska klimatet. Resultaten tyder på att materialet kan användas i det svenska klimatet på många olika väggkonstruktioner utan att konstruktionen skadas fuktmässigt. En viktig parameter är att materialet är skyddat mot regn eftersom det kan absorbera mycket vatten. Detta kan göras med en lämplig typ av ytbehandling, till exempel vattenavvisande färg. Energisimuleringarna låg till grund för en mindre ekonomisk utvärdering av referensbyggnaden, som visade att aerogel-baserad puts är lämpligt när ett tunnare isolerande skikt ska beaktas. När ett tjockare skikt kan appliceras kan andra material vara mer fördelaktiga eftersom kostnaden för aerogel-baserad puts till stor del beror på dess tjocklek.

Nyckelord: isolering, aerogel, aerogel-baserad puts, puts, renovering, tilläggsisolering, kulturbevarande byggnader, fukttransport

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Preface

This project is carried out at Chalmers University of Technology in Gothenburg at the Department of Architecture and Civil Engineering during the spring semester of 2021. The project originates from an ongoing research field at Chalmers regarding the same topic. PhD student Ali Naman Karim is the project's supervisor, and the examiner is Associate Professor Pär Johansson. All work has been conducted on Chalmers campus.

Many thanks to doctoral student Karim and Associate Professor Johansson who provided great support and knowledge around the subject and contributed with guidance, ideas and consultation that was necessary to be able to carry out the work. Acknowledgements also goes to doctoral student Kaj Petterson and Stadsbyggnadskontoret in Gothenburg for information and consultations. Finally, many appreciations to our opponents Felicia Spaak and Malin Eriksson who contributed with inspiration and ideas to the project.

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Erik Haugbak, Amar Talic

1 Introduction

Global warming is becoming an increasing problem facing humanity and in line with this, humans must become better at reducing greenhouse gas emissions and trying to find and apply new technologies that can help in the green transition. One of these technologies is an aerogel-based plaster (AP) with very good insulating capability that have big potential to reduce energy consumption in the Swedish building stock as shown in a study by Karim et al., (2020b). The energy saving aspects of the material are well investigated by previous studies, however, more research is needed on its hygrothermal performance in Scandinavian climate, recognized as wet and cold. Also, its behaviour regarding moisture and energy in combination with common constructions in the Swedish building stock requires more research. This thesis partially investigates the possibility to adapt Aerogel-based plasters into the Swedish building market. Also, whether the AP can be used in combination with common building constructions which are listed or in a state of needed renovation. This is because it is an area where it has been predicted that AP has great potential to be used since listed buildings often have high energy demand and character defining elements that needs to be preserved after a renovation.

A literature study is conducted to present the definition of a listed building with character defining elements, how moisture is transported in building materials and to clarify the properties of AP and its main component aerogel. The information is needed not only to get knowledge about the topic but also to be able to perform the hygrothermal simulations. Parameters that have been investigated are temperature, relative humidity, and water content for the different construction and at different points in the included materials. The simulations have been extended with parametric studies to validate the obtained results. The thesis also contains energy simulations and an economic assessment comparing AP with other insulation materials based on the energy savings.

1.1 Background

The long-term goal is that Sweden will have no net emissions of greenhouse gases into the atmosphere by 2045 and thereafter achieve negative emissions (Regeringen, 2017). In order to achieve the ambitious goal, it is necessary to find pathways for all energy-consuming sectors. One area that accounts for large emissions is the construction industry, which in Europe accounts for 40% of the energy consumption (European Commission, 2020). The Swedish Energy Agency states that 21.2% of the total energy consumption in Sweden proceeds from heating and hot water in residential and commercial buildings (Swedish Energy Agency, 2020). When the buildings are constructed, operated, and maintained appropriately it is possible to gain remarkable energy savings. One approach is to focus on the thermal insulation system and materials by renovating old buildings.

The initiative by the European Commission, “Renovation wave“ (2020) aims to renovate 35 million energy-inefficient buildings by 2030 as a step to reduce 55% of the emissions. The retrofitting of existing buildings is crucial to reach the energy goals. 85-95% of the buildings are expected to still be standing by 2030 but also from an environmental aspect of extending the life span of a building.

In the Västra Götaland county in Sweden, there are 5957 buildings that are protected by the planning and building act in according to a report from 2013 from the county administrative board in Västra Götaland (Länsstyrelsen Västra Götalands län, 2013). The buildings are protected against alterations that might affect the cultural heritage value. This includes adding additional external insulation that can have a negative effect on the appearance of the building. AP could therefore be a suitable option for these buildings of which already have a plaster façade.

Aerogel-based plasters have great possibilities to be a part of the green transition for both Sweden and Europe. However, there are uncertainties that must be investigated properly before the industry is ready to use the material on a large scale. The long-term performance and the hygrothermal performance of the material in respect to Swedish climate conditions needs to be investigated in depth.

1.2 Aim

The aim of this project is to investigate and evaluate the required conditions for applying AP on façades to provide a moisture safe construction in buildings that have a cultural heritage value and where alterations may be limited.

The study is also investigating the moisture performance of different common types of wall constructions in Sweden so that the conclusion will be whether a common wall construction in Sweden is suitable for an application of AP.

The aim is also to analyse the optimum thickness for AP considering the energy- and moisture performance of a listed building and how it relates to the economic aspects.

1.3 Limitations

AP can be linked to a lot with the environmental aspects where the material is expected to have great potential. However, no emphasis will be placed on a holistic analysis, such as the impact from production, reusing and recycling possibilities. No life-cycle assessment will be implemented either.

There are also economic aspects to consider in the project, which can be determining whether the intended users find the material beneficial compared to the savings in energy usage. The economic evaluations in this thesis will not cover deeper economic evaluations, instead investigations will be made to analyse the potential savings regarding energy savings. Only rough estimations will be performed to cover the installation costs and give an estimation to the economic benefits. The energy simulations of the case study building are only based on the wall transmittance. Complete energy analysis of the building is therefore not conducted in this thesis.

Chemical and physical properties and behaviour of the aerogel are essential parts of how the material behaves regarding heat conduction which is important for this study. However, analyses on a molecular level of the aerogel will not be done in this thesis because the focus will lie on the final plaster product which will be applied on the buildings.

Today there are many different brands and products of aerogel-based plaster on the market, but it is still a relatively new product and hence the data is in many cases deficient and limited. Contact has also been made with companies to obtain more data

about their products without response. Due to this, only two different products from two different producers are examined and the simulations are made upon one of these products. However, there are more products on the market, but to limit the work and to obtain as correct conclusions as possible, this approach is used.

1.4 Method

In the project, many different sub-steps are carried out in parallel, and which are also based on each other. Figure 1.1 shows a schematic picture of the course of action and which parts that are based on each other.

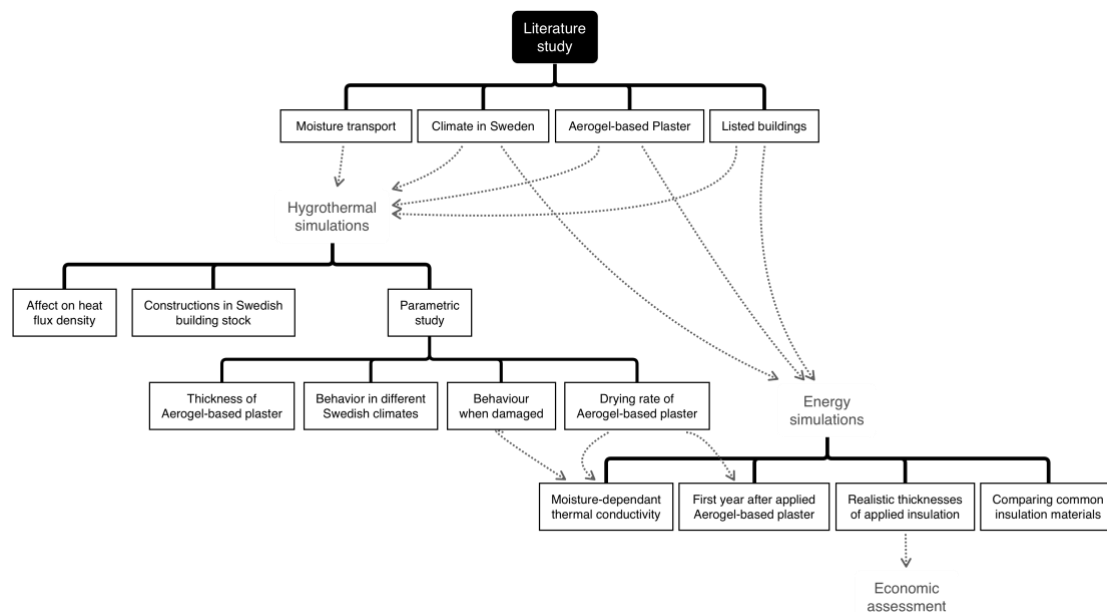


Figure 1.1 Course of action of the project and its various sub-parts. Main parts are the literature study, hygrothermal simulations and energy simulations.

1.4.1 Literature study and interviews

To gather knowledge and information about previous research in the subject, a literature study is conducted where English-language and Swedish-language scientific articles, books, websites, regulations, and standards are used as information sources. Science direct, Google and Chalmers library are used as search engines to find references where keywords such as aerogel-based plaster, super-insulating plaster, renovation etc. are used to find relevant information. Data is also retrieved from company websites where product-specific properties are available to get a better understanding of the material and to gain required data. The literature study results in four parts: moisture transport, climate in Sweden, aerogel-based plaster, and listed buildings.

One interview is conducted with a building permit administrator and antiquarian at the city planning office of Göteborgs stad. The interview is conducted through emailed questions and the subject has asked to be anonymous.

1.4.2 Hygrothermal and energy simulations

Information from the literature study is gathered into the main part of the study and presented with the chosen input data in Chapters 7 and 8. The hygrothermal simulations are performed in the computer software WUFI® 2D where six different wall constructions that are common in the Swedish building stock including a case study building are simulated with and without AP to get an understanding of how the wall constructions behave from a hygrothermal point of view. Both in their current situation and after the AP has been retrofitted. Heat flux density is examined in addition to see the heat transport in the wall constructions selected. To validate the results, a parametric study is also conducted where four different parameters are examined. These are: Thickness of aerogel-based plaster, behaviour in different outdoor climate conditions, various levels of damage in the water repellent layer and drying rate of the aerogel-based plaster.

The second sub-study in the project is the energy simulations which are also based on the literature study except the part concerning moisture transport. The computer software used is Simulink® and the energy simulations branch out in four parts: moisture dependent thermal conductivity, first year after applied aerogel-based plaster, realistic thickness of applied insulation and comparing common insulating materials. Information from the hygrothermal simulations is also gathered to be able to perform two parts of the energy simulations. Finally, an economic assessment has been made according to the net present value (NPV) method to compare AP with two conventional insulation materials based on the realistic thickness of applied insulation.

2 Material overview of Aerogel-based plasters

During the recent decade, a new insulation product has been developed and is starting to show up on the market. The product is an aerogel-based plaster (AP) which is a conventional plaster with added aerogel granules (FIXIT AG, n.d.-b). Aerogel is a material with special properties and research is ongoing as it is considered to have big potential in several areas, including thermal insulation. When mixing the aerogel granules with plaster, very low thermal conductivity is reached, similar to conventional insulating materials like mineral wool, (FIXIT AG, 2015c). This can be compared to plasters on the market today that have a typical thermal conductivity of 0.5 (Karim et al., 2020a).

Aerogel-based plaster has been developed in the central countries of Europe and this is also where most of the found studies on the subject have been done. Most of the full-scale examples can be found in Switzerland where the material was first introduced (Stahl et al., 2014). Figure 2.1 shows a building in Zurich that has been retrofitted with AP.



Figure 2.1 Building in Zurich, Switzerland, covered externally by an aerogel-based plaster system. Picture taken by Ali Naman Karim (2019).

2.1 The characteristic component of Aerogel-based plasters: Aerogel

According to Sachithanadam et al. (2016), aerogel is a special group of materials first discovered in the 1930s by the American scientist Samuel Stephens Kistler. The materials appear as half transparent solid white cloud as shown in Figure 2.2. Aerogels have key characteristics as a solid material with very low density, high thermal insulation capacity and highly porous. Aerogel is a collective name for products that have the mentioned properties and are available in different forms such as powder, fixed forms, granulates etc. There are also many different manufacturing techniques and different material compounds that aerogel can be manufactured from but the main three steps for manufacturing is according to Dowson et al., (2012): gel preparation, ageing and drying.



Figure 2.2. Silica aerogel granules (Karim et al., 2020a).

The first step is gel preparation and is made by reacting a silicon precursor with water in a solvent containing an alcohol at ambient temperature and pressure to form silica nanoparticles (Dowson et al., 2012). By then soaking the gel in a solvent, for example methanol, an aging process takes place and is done to strengthen the structure. It is then during the drying process that the material gets its final shape, and this is usually done in supercritical conditions, about 240°C and 100 bar which makes the alcohol in the gel to a supercritical liquid. This condition means that the phase between liquid and gas disappears, and hence there is no surface tension on the gel matrix. This allows the structure to maintain intact without large shrinkage, which would otherwise be the case. The drying process is expensive due to the special conditions required, hence, other methods have been in development. One such is low-temperature supercritical drying, which means that the solvent in the gel preparation is replaced by liquid carbon dioxide which has a colder critical point, 40°C at 100 bars. Another process is called subcritical where the drying takes place at both ambient temperature and pressure. This causes the surface to partially collapse, but with treatment it can regain its shape up to 85%. The

disadvantage is that the material has a higher density but at the same time it also becomes mechanically stronger, which can have other advantages.

After the three steps, the result is a very complex structure. The connections are the size of a few nanometres and the material has very little solid component and makes it consist of 80-99.8% air (Dowson et al., 2012). The thermal conductivity thermal conductivity (λ -value), is approximately in the range of 0.017-0.024 W/mK for a silica aerogel in normal conditions (Sachithanadam et al., 2016). The first aerogel invented was made from silica but due to technological and engineering progress they can today be made of various types of materials such as aluminium, carbon and cellulose. However, the most common and used aerogel today is still silica with air as the gaseous component since it is the most researched and investigated one. The interest of aerogel among researcher and private sector is growing rapidly since its special properties which assumed can contribute to a better environment. The most practical use of aerogels today is thermal insulation, and this has gained popularity in Europe the recent decade. The material's ability to be recycled, reused and its fire protection capability will also be important properties for a commercialization of the aerogel in society. This, together with its other already good properties, makes it an easier and thinner alternative to today's conventional insulation materials. The main drawbacks are the production cost and the fluctuations in the global economy. According to the Allied Market Research (2020) the global aerogel market is valued to \$701.0 million in 2019 and is estimated to reach \$1,395.5 million by 2027.

2.2 Aerogel-based plaster as a product

The aerogel-based plaster was patented in the early 2010s by Thomas Stahl, Samuel Brunner and Mark Zimmermann as an insulating rendering with high performance thermal insulation (Stahl et al., 2014). Stahl et al. states that the background to the origin of the material invention stems from renovation restrictions of historical buildings and the work in reducing their energy consumption. The material can be an asset in reducing necessary thickness and at the same time achieve the desired thermal performance (Stahl et al., 2014).

Several countries in Europe have used and are using this material as a tool to retrofit older buildings as pilot projects. An article by Ghazi Wakili et al. (2018) describes a retrofit project of a 30 m tall multi-family building in Berlin where they applied AP as part of the study. The country who has a larger amount of examples of buildings retrofitted with AP is Switzerland where the producer and developer FIXIT AG is located (FIXIT AG, n.d.-a). Today there are a few other producers of different APs and one of them is the German company Interbran Baustoff GmbH and their brand XERAL.

2.2.1 Production and application of Aerogel-based plaster

The AP is a combination of water, aerogel, mixture of minerals and binders together with additives. Both FIXIT AG and Interbran Baustoff GmbH produces their products as a dry-components-only mixture called FIXIT 222 and XERAL SP 028 respectively, with binders, aggregates, and additives according to Table 2.1. Water is added to the dry mixture to produce the fresh mortar.

Table 2.1 Composition ingredients of the AP-products FIXIT 222 and XERAL SP 028.

	FIXIT 222 (FIXIT AG, n.d.-b)	XERAL SP 028 (Interbran Baustoff GmbH, 2020)
Binding agents	Hydraulic lime NH5 Hydrated lime White cement	Calcium hydroxide Cement
Aggregates	Aerogel granulates Light mineral aggregate	Silica granules Perlite
Additives	Water retaining agent Air entraining agent Hydrophobic agent	No information.

According to the processing guidelines from the producer, FIXIT AG, of FIXIT 222 the application surface must be clean, dry, and mechanically stable but it also needs to be pre-treated with a base mortar so that the surface becomes a better substrate for the AP, see preparatory layer in Figure 2.3. If the surface is unstable or assumed to be critical even though an adhesive has been applied then it is recommended to mount a plaster base grid (Wenjet) before applying the AP (FIXIT AG, 2019). The application should take place with a plastering machine to get as good result as possible and if several layers shall be applied then a rough surface is needed for the next layer to attach as good as possible. To avoid shrinking problems related to the drying process, the drying phase must have a duration of at least one week. Under perfect conditions, AP dries at a rate of 3 mm per day (FIXIT AG, 2019). To achieve a strong surface of the AP a stabilizer is applied in wet form before a reinforcement layer in form of a mortar to create a robust surface. The last layers applied is an undercoat (a sort of primer) and above that final renders and paint coatings as shown in Figure 2.3. Different products are recommended depending on the surface but a common product is FIXIT 203 which is a render with hydraulic lime (FIXIT AG, 2019).

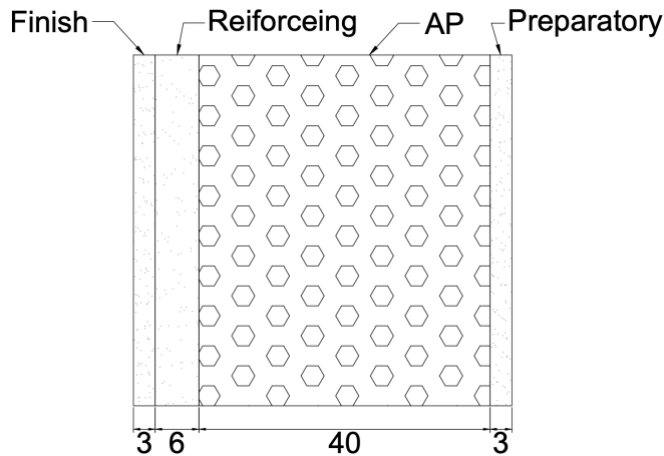


Figure 2.3 Dimensions in [mm] and layer order of the layers in the AP-system. With the finish layer facing the outdoor climate. The thickness of the AP varies.

The technical product data sheet (2020) for the XERAL product mentions that an adhesive and bonding mortar should be applied for better bonding and that a sealant primer must be applied if the surface is of absorbent character. It can be assumed that the surface needs to be clean and dry for the application of both primer, preparatory mortar, and plaster.

2.2.2 Properties of Aerogel-based plaster

The developers of the AP, Stahl et al., (2012), performed measurements to determine the hygrothermal properties of AP. The results are shown in Table 2.2. Further measurements have been performed on the material and with different approaches. Nosrati and Berardi (2018) measured different properties of aerogel-enhanced plaster with different compositions by varying the proportion of aerogel, plaster, and water. The results in Table 2.2. from Nosrati and Berardi (2018) corresponds well to the results presented by Stahl et al. (2012). They also showed that increasing the percentage aerogel reduced the thermal conductivity but also reduced the mechanical strength.

Table 2.2 Density, thermal conductivity, and water vapour permeability coefficient of AP from different sources.

Source	Type	ρ [kg/m ³]	λ [mW/mK]	μ [-]
(Stahl et al., 2012)	Laboratory	200	25±2	4
(Nosrati & Berardi, 2018) 70-90% Aerogel	Laboratory	200	27	N/A
(Nosrati & Berardi, 2018) 70% Aerogel	Laboratory	230	32	N/A
(FIXIT AG, 2015c)	Product	220	28	4-5
(Interbran Baustoff GmbH, 2020)	Product	200	26	5

A modelling of the AP and its various layers requires data to be implemented in the WUFI® 2D software. In many cases, the data is incomplete, and information needed is missing. Therefore, information has been retrieved from various sources to get it as complete and accurate as possible. The table below shows how the different layers are structured in WUFI® 2D and the properties of the layers. The modelling done here is based on FIXIT's application model as most information about its products can be found but worth remembering is that different manufacturers recommend different application layers and processes for their AP. The properties in Table 2.3 has been set when creating the new AP material. WUFI® 2D also takes the water absorption coefficient of the material into account and a value of this parameter is presented in the laboratory study by Ibrahim et al. (2014) of AP and set to $0.184 \text{ kg/m}^2\text{s}^{0.5}$.

Table 2.3 Properties of the different materials used in combination with AP inserted in WUFI® 2D.

Materials	Preparatory	AP	AP reinforcement	AP finish
Thickness (mm)	3 ¹	40	6 ¹	3 ¹
λ (10 °C) (W/mK)	0.83 ²	0.028 ⁴	0.33 ⁶	0.47 ⁷
ρ [kg/m ³]	1600 ²	220 ⁴	1250 ⁶	1250 ⁶
Porosity [m ³ / m ³]	0.53 ³	0.98 ⁵	0.53 ³	0.53 ³
C_p [J/kgK]	850 ³	990 ⁵	850 ³	850 ³
μ [-]	17 ¹	4.0 ¹	7 ¹	7 ¹
w(100% RH) [kg/m ³]	253 ³	526 ⁴	253 ³	253 ³
A_{cap} [kg/m ² s ^{0.5}]	0.122 ³	0.184 ⁵	0.122 ³	0.122 ³

1: Based on values used in Stahl et al., (2017).

2: Data from DOP (2015a) and TDS (2020) of product “Fixit 211” from manufacturer FIXIT AG.

3: Assumed value based on plaster material in WUFI® 2D material catalogue.

4: Data from DOP (2015b) and TDS (2020b) of product “Fixit 222” from manufacturer FIXIT AG.

5: Values from laboratory study by Ibrahim et al., (2014).

6: Data from DOP (2017) and TDS (2020c) of product “Fixit 223” from manufacturer FIXIT AG.

7: Data from DOP (2015a) and TDS (2020a) of product “Fixit 203” from manufacturer FIXIT AG.

Important input data when describing a new material as AP is the moisture storage function (moisture sorption isotherm, w_ϕ), moisture-dependant thermal conductivity (λ_ϕ) and temperature-dependant thermal conductivity (λ_T). Table 2.4 shows the mentioned relations which are dependent on the relative humidity. Table 2.5 presents the temperature-thermal conductivity relation at a constant relative humidity of 50%. The moisture sorption isotherm and the moisture-dependant thermal conductivity vary between different sources. Two of the sources are stated in Table 2.4 below.

Table 2.4 *RH-dependant thermal conductivity λ_ϕ and water content w_ϕ of aerogel-based plaster in two different studies.*

RH	0%	30%	50%	70%	80%	95%	100%
Values based on a laboratory-based study by Nosrati & Berardi (2018)							
Thermal conductivity (mW/mK)	26.1	27.2	27.2	27.7	N/A	35.8	N/A
Water content (%)	0.0	1.1	2.8	3.7	N/A	11.0	N/A
Water content (kg/m ³) (calc.)	0.0	2.2	6.16	8.14	N/A	24.2	N/A
Values based on a full-scale study in Sissach/Switzerland by Stahl et al. (2017).							
Thermal conductivity (mW/mK)	27.0	N/A	27.4	N/A	28.6	N/A	364.0
Water content (kg/m ³)	0.0	N/A	3.54	N/A	8.51	N/A	526.0

Nosrati & Berardi (2018) does not present any values for a fully saturated sample and is therefore assumed to have the same value as for 95% RH. Due to the lack of values at 100% RH, values from Stahl et al. (2017) are used. The third row in the table contains converted values from the percentual moisture content based on the density of the material. Table 2.5 states the temperature-thermal conductivity relation based on the laboratory study by Nosrati & Berardi (2018), the other mentioned source does not treat this relation and thereby the values below are used in the models.

Table 2.5 Temperature dependent thermal conductivity, λ_T , for 80% aerogel-enhanced plaster at a constant RH of 50% (Nosrati & Berardi, 2018).

Temperature	Thermal conductivity
-10 °C	0.0265 W/mK
0 °C	0.0267 W/mK
10 °C	0.027 W/mK
20 °C	0.0269 W/mK
30 °C	0.0274 W/mK
40 °C	0.0275 W/mK
50 °C	0.0277 W/mK

2.2.3 Studies on the hygrothermal performance of Aerogel-based plaster

The hygrothermal performance of aerogel-based plaster has been investigated earlier and promising results are shown. Stahl et al. (2017) performed a case study on the historic mill of Sissach with both in-situ measurements and modelling of the hygrothermal properties. Temperature and humidity sensors were applied at the interface between wall and plaster on the western façade and logging data over 15 months. No moisture accumulation was detected beneath the insulating plaster. The computer modelling was performed with weather data corresponding to an average cold year in Zurich and the simulation time was 5 years. Three different cases were investigated, one of which was the original case consisting of a stone wall prior to retrofit. The second simulation represented a probable situation on site consisting of a stone wall with 80% relative humidity simulated with 50 mm AP. The third case should be considered as an extreme case and is similar to the second simulation but with an increased relative humidity to 99.9%. This would correspond to a case where retrofitting of AP took place immediately after a long rainy period. The result showed that even if the wall was completely wet, they will dry out because the high-performance plaster is vapour permeable and thereby does not induce any moisture accumulation over time. The extreme case dries out over a period of 1.5 years and all cases reach quasi steady state after 2 years, which means that their fluctuations can be considered constant.

Another French study was performed by Ibrahim et al. (2014) which investigated the hygrothermal performance of an aerogel-based plaster by simulations and in-situ measurements on an experimental set-up on a test-cell to validate the simulation results. Different scenarios were tested such as external insulation with the plaster, internal insulation, non and both internal and external insulation. The result showed that added interior thermal insulation can cause several moisture problems such as condensation

risk and inability to dry out over time. The added aerogel-based plaster on the exterior wall with no insulation and with internal conventional insulation, however, decreases the risk of moisture problems or even removed the risk completely. Also, it reduced the heat losses as expected.

2.2.4 Economic and environmental performance of Aerogel-based plaster

The economic aspect of aerogel-based plaster is an important factor depending on whether the product will be used in a greater extent. The product is today more expensive than commercial plaster and insulation products (Ibrahim et al., 2015). It goes without saying that this is because it contains aerogel, and the high price depends on the acquisition of raw material used when manufacture aerogel and the process itself (Garrido et al., 2019). The drying of aerogel today is expensive, and can be hazardous, making the process difficult for industrial scale. To reduce the costs of the manufacturing process, other potential drying processes can be used which include lower pressure and/or temperature. However, these processes also have disadvantages (Sachithanadam et al., 2016).

The economic parameter of aerogel-based plaster also varies within different producers and brands. The product FIXIT 222 costs approximately €30/m²/cm in 2019 (Fantucci et al., 2019). When taking into consideration cost related to the application process and other additional costs the price was approximately €60/m²/cm. Another producer, *Interbran Baustoff GmbH*, offer a bag of aerogel-based plaster to the price of €169,85 that contains 13kg plaster which equals a price of €23,49/m²/cm (Interbran Baustoff GmbH, 2021). The climate is also a decisive parameter that affect how profitable the investment of an aerogel-based plaster is. More energy is saved when the plaster is applied on places with a colder climate. According to study performed in France 2015, the optimum rendering thickness is in the rage of 1.7-4.4 cm and the payback period is between 1.4-2.7 years depending on the climate. The cities investigated was, Stockholm, Moscow, Montreal and the three French cities of Nice, Bordeaux and Strasbourg and for Stockholm the values was 3.26 cm and 2.1 year. (Ibrahim et al., 2015).

A study conducted in Portugal by Garrido et al. (2017) performed an economic life cycle assessment of different thermal insulation plasters and non-commercial plasters (laboratory produced). The case study involved many different thermal insulation plasters with varying compositions and properties and a comparison was made to a reference case with no insulation applied. The plasters were applied in a layer of 4 cm and thereafter the performance was measured, and the conclusion was that after a lifetime of 30 year none of the cases were economically profitable. Also, a life cycle assessment for the product FIXIT 222 was performed with results that showed its global warming potential. The impact of 1 kilogram of the product was estimated to be equal to 4.25±11% kilogram of CO₂-equivalents (Carbotech, 2019). The energy payback was also calculated based on an application of 5 cm plaster on a standard brick wall. The result showed a value of 2.9 years.

3 Moisture transportation and behaviour in buildings

Moisture content in building elements, material envelope or buildings as a whole depends on many things. Precipitation, moisture from the ground, moisture content in building materials, outdoor air, and indoor air with activities such as showering and cooking (Hagentoft, 2001). The moisture can be stored or transported in or out of materials since its porous structure and can change the thermal properties and even damage the building, hence it is of great importance to understand the fundamentals of moisture transport.

3.1 Transportation mechanisms of moisture transport

Moisture transport in and out of materials can take place at three different ways, diffusion, convection and capillary suction (Hagentoft, 2001).

3.1.1 Moisture transport due to diffusion

When water vapour is transported from a high concentration to a lower, it is called moisture diffusion according to (Hagentoft, 2001) and depends mainly on material properties. It is a decisive factor for the material in terms of its ability to dry out and depends to a large extent on its tightness. The moisture flow through diffusion can be described as steady-state diffusive flux g [$\text{kg}/(\text{m}^2/\text{s})$] and are defined by Hagentoft (2001) according to Equation 6.1.

$$g_d = \delta_v \frac{v_1 - v_2}{d} \left[\frac{\text{kg}}{\text{m}^2/\text{s}} \right] \quad (6.1)$$

Where δ_v [m^2/s] is the vapour permeability of the material and d [m] the width of the layer. The humidity by volume is denoted v_1 and v_2 [kg/m^3] on each side of the layer respectively.

3.1.2 Moisture transport due to convection

When water vapour molecules, water droplets or snow crystals is transported by flowing air, it is named moisture convection (Hagentoft, 2001). These pressure differences can fluctuate and be large in buildings, which means that extensive moisture problems can arise. When warm air indoors is transported to outside and cooled by the outdoor air, condensation can occur in worst case, major damage occurs as a result. The net moisture rate entering the structure due to moisture transfer convection is defined by Hagentoft (2001) according to Equation 6.2.

$$G = R_a (v_{in} - v_{out}) \left[\frac{\text{kg}}{\text{s}} \right] \quad (6.2)$$

Where R_a [m^3/s] is the air flow rate. The humidity by volume of the entering air is v_{in} [kg/m^3] and the existing v_{out} [kg/m^3].

3.1.3 Moisture transport due to capillary suction

The third form of moisture transport is called capillary suction and takes place in the liquid phase when water is transported due to difference in pore water pressure (Hagentoft, 2001). This can especially happen in driving rain when the water has direct contact with the surface or a wall and can then be absorbed into the structure. The moisture flow due to capillary suction is expressed by Hagentoft (2001) according to Equation 6.3.

$$g_s = \frac{A}{2\sqrt{t}} \left[\frac{kg}{m^2s} \right] \quad (6.3)$$

Where A [$kg/m^2s^{0.5}$] is a water sorption coefficient and t is the time [s].

3.2 Moisture damages in buildings

According to (RISE, n.d.-b) moisture damage can take different forms and thus affect different parts of a building. Some crucial building physical values can also change due to moisture damage.

Frost damage is one type and can occur because water changes phase from liquid to solid when the temperature drops below $0^\circ C$. During this transformation phase, the water expands up to 9% of its original volume and if the pores in the material are filled with water, it can then crack (RISE, n.d.-d).

When materials become damp, the conditions for organic growth can become favourable and mould can form (RISE, n.d.-c). Mould are originally fungi that are found in varying amounts naturally in the air, which means that they attach and are present on all surfaces. If these fungi gain a foothold, they spread with their spores and if the conditions are favourable, they grow into themselves and form so-called hyphae. Through nutrient uptake and oxygen, these also grow into networks called mycelium which can be referred as moisture damage. However, it depends on the situation since the problems correlate to the type of organism that has attached to the material. In the end, the result of mould can be discoloration, odour.

As there are different types of organisms, conditions for mould growth also change (RISE, n.d.-c). In general, the limit for mould growth is 75% in relative humidity for organic material such as wood and is accelerated at a higher moisture content. In inorganic materials, for example insulation materials, the limit for mould is significantly higher, about 90-95% in relative humidity and on dirty surfaces, 75% applies to all materials. Other crucial factors for mould are temperature and duration of the favourable conditions. The critical temperature and humidity limits for mould growth on wooden materials are described in Figure 3.1 below by Viitanen (2001). High relative humidity and temperature then indicate an increased risk of mould growth.

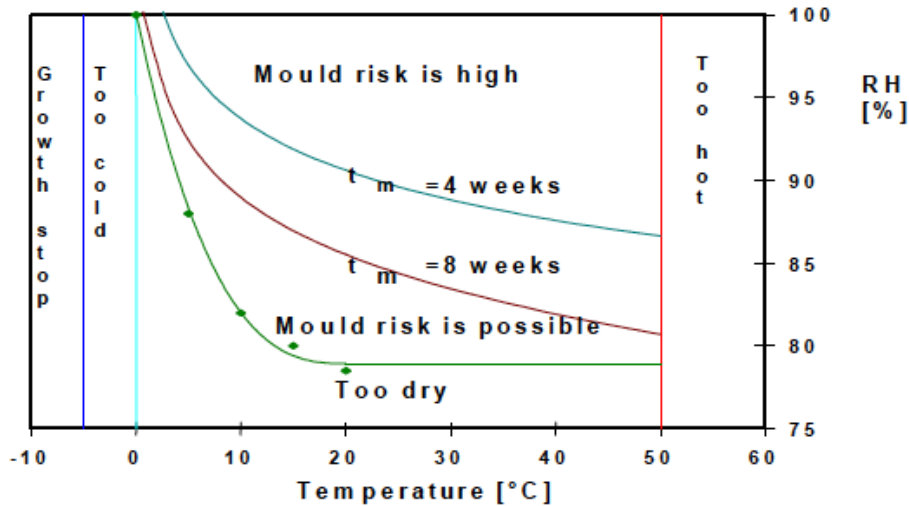


Figure 3.1 An overview on the critical relative humidity and temperature limits for the risk of mould growth on wooden materials, Viitanen (2001).

To determine the mould growth a method developed by Hukka & Viitanen (1999) can be used. The method can be implemented as a mathematical script in MATLAB® which needs input parameters such as temperature and relative humidity in each timestep. The script then calculates the mould growth index (MGI). The definition of can be seen in Table 3.1 below and has been suggested by Viitanen (2001). The index goes from 0-6 with no growth up to coverage of the whole surface.

Table 3.1 Definition of mould growth index by Hukka & Viitanen (1999).

Index	Growth rate	Description
0	No growth	Spores does not grow
1	A few – visible by microscope	Initial phase of hyphae
2	Some – visible by microscope	Hyphae cover more than 10% of the surface
3	A few – visible to eye	Growth of new spores
4	Some – visible to eye	Cover more than 10% of the surface
5	Much – visible to eye	Cover more than 50% of the surface
6	Very much and dense	Cover almost whole surface

3.3 Moisture assessment of wall structures

How a construction is affected by moisture and the type of damage that occurs depends on many different parameters such as thickness, material and climate. Below is a description of how different building materials and constructions are affected.

3.3.1 Moisture assessment of aerated concrete walls

Aerated concrete is a common construction material that from production contains a lot of moisture, which means that it must be able to dry out, which takes a long time, approximately a year (RISE, n.d.-a). This is especially important as the material has an insulating ability that is impaired by water content, which means that energy will go lost. It is also important to protect the material from rain and precipitation in connection with transport and assembly. If this does not happen, and no proper drying later, moisture problems can occur, but rarely in the form of moisture convection and subsequent condensation as the material is very airtight. The type of damage that occurs also depends on the type of material that is present in connection with the lightweight concrete. If, for example, a wooden material is applied to the inside in the form of a panel, the moisture can instead accumulate there, which can lead to mould growth.

3.3.2 Moisture assessment of solid concrete walls

Solid concrete is in many ways similar to lightweight concrete from a moisture point of view (RISE, n.d.-a). It is very airtight, which means that moisture diffusion, when the moisture is transported from areas with high content to lower, does not occur. This also affects the possibility of condensation to occur negatively, which gives positive effects from a moisture point of view. As in the previous case, it is also very important that the material has the ability to dry out from each side so that moisture does not accumulate and become confined during the construction process. A solid concrete wall today often has the addition of insulation, either externally or internally depending on the type of construction. With external insulation, the temperature gradient changes and the wall will become warmer which improves the performance. With internal insulation, the concrete wall will instead be cold at the same time as the moisture content is increased, which means that a vapour barrier is needed on the inside that counteracts moisture transport.

3.3.3 Moisture assessment of solid brick walls

A solid brick wall consists of a load-bearing structure in the middle and a façade, both in brick and sometimes plaster as a façade and is very different from a moisture point of view compared to a concrete wall (RISE, n.d.-a). It normally withstands rain because it has the ability to dry out quickly, but problems can still arise. Damage that occurs is frost damage due to driving rain, meltwater, leakage that makes the facade wet and does not have time to dry. When sub-zero temperatures than occur, the water freezes, which means that the material breaks, and cracks occur. In these cracks, water can then be capillary sucked, which gives rise to water penetrating even deeper into the structure. In some cases, an entire wall can be penetrated. The winter season in Sweden is especially critical as many freezing-thawing cycles occur. Other critical cases are when

a protective facade has a water-repellent surface treatment. If it is not intact, large amounts of moisture can accumulate locally.

Solid brick walls were common in the past, but nowadays they are unusual (RISE, n.d.-a). They are built as an insulated cavity wall with insulation in the form of mineral wool and a possible air gap between facade and insulation to protect from moisture. The wall usually does not have a vapour barrier and if it, in addition, does not have an internal plaster, there is nothing that makes it airtight, which means that moisture diffusion also occurs. With internal additional insulation which makes the wall colder, major problems can arise due to condensation and rain that hits the surface cannot dry out as well as before.

3.3.4 Moisture assessment of solid wood walls

Wood is an organic material that has the advantage that it itself has moisture-controlling properties, which means that moisture can be redistributed in and through the material (RISE, n.d.-a). However, this means that moisture diffusion can occur to a large extent, which can mean that the material cracks if it is placed in an environment that is drier than itself when the water penetrates through the material. Another important aspect is to protect the material from getting wet, such as rain during assembly. This should be done with regular controls. If the material is instead wet, there is a risk that it will be trapped, and mould growth will form. This can eventually lead to extensive rot if the problems continue.

The solid wooden wall usually has external insulation and some type of façade such as a wood panel or render (RISE, n.d.-a). When moisture diffusion occurs, it is important to have a vapour barrier in a warm position of the wall to avoid condensation on the inside. It is also important to protect this from being punctured as moisture easily accumulates around the holes. One solution is to instead place the vapour barrier outside the solid wooden wall. However, this requires sufficient insulation on the outside as the most important thing is to avoid condensation. Between the insulation and the façade, there is usually an air gap to prevent water that hits the façade from entering the structure. On the inside, there is also the possibility of insulation, for example, behind a gypsum board. In the case of additional insulation, as in previous cases shown, an internal application must be careful from a moisture point of view as it makes the wall colder and more exposed.

4 Swedish climate and climate data

Despite its latitude and position on the northern hemisphere, Sweden has a relatively warm climate during its winter months (SMHI, 2009). This is due to the westerly and south-westerly winds which are dominant, but the proximity to the North Atlantic also affects the temperature. The low-pressure zones cause the temperature to change from hot to cold or vice versa and also provide abundant precipitation all year round and are greatest in summer and autumn. The most precipitation follows the winds and ends up in the west and the least precipitation falls on smaller islands in and along the Baltic Sea and in narrow valleys in the mountain areas. During the winter, precipitation falls in the form of snow except on the coasts where rain is most common, exceptions occur. High pressures can also redirect low pressures north or south of the country, which can give rise to long periods of dry weather.

In summer, the average temperature is around 17°C in the southern part of the country, and the highest temperature observed in Sweden is 38°C (SMHI, 2009). The winter season provides colder weather with an average temperature in January of about 0°C in the southern part of the country and around -16 in the coldest areas in the north. In some cases, in these areas, the temperature can drop to -40°C and in extreme cases to -50°.

Based on the information above from SMHI and data available in the software WUFI® 2D, the following cities are shown with its weather characteristics to demonstrate the differences in Swedish climate as shown in Table 4.1 below.

Table 4.1 Weather characteristics of four Swedish cities collected from WUFI® 2D.

	Gothenburg	Stockholm	Lund	Kiruna
T _{max} [°C]	27.8	29.4	28.3	25.1
T _{min} [°C]	-12.2	-18.6	-10.1	-41.4
T _{mean} [°C]	8.8	6.8	9.2	-1.7
RH _{max} [%]	94	99	97	96
RH _{min} [%]	19	22	25	23
RH _{mean} [%]	74	79	81	77
Normal Rain Sum [mm/a]	1074	639	818	533
Main direction of Driving rain	South	Southeast	Southwest	North

5 Listed buildings with character defining elements

Listed buildings are protected buildings with character defining elements which provides a cultural heritage value to the community (Boverket, 2018). Listed buildings can be historical buildings, or architectural monuments which in many cases have a higher energy use and have higher heating demands compared to modern standards. Listed buildings can also be buildings in a specific area which has a heritage value. Building regulations are continuously getting stricter and modern buildings are built after present standards which makes them more energy efficient than existing buildings. One of the main reasons why older buildings have high heating demands is the poor building envelope, with inefficient windows, air leakages through exterior walls, and the lack of insulation in the walls.

5.1 Listed buildings and decisive actors in Sweden

Listed buildings in Sweden have different types of protections, most are protected through the Planning and Building Act (Länsstyrelsen Västra Götalands län, 2013). Some are protected as architectural monuments as state interests which are protected by state law and regulations. The Planning and Building Act (SFS 2010:900, Ch. 8 §13) states “A building that is particularly valuable from a historical, cultural-historical, environmental or artistic point of view must not be distorted.” (Translated from Swedish). It also regulates retrofitting and maintenance, that buildings must be maintained and taken care of to protect technical properties, but it also needs to be maintained so that the cultural heritage values are kept.

Before a property owner can perform reconstructions, the owner usually need a building permit and it is the city building committee who decides whether the reconstruction can be performed or not (Boverket, 2020). This by controlling if the changes correspond to the detailed development plans or comprehensive plans for that area. There are difficulties for property owners who, for example, plans to retrofit their building so that the building becomes energy efficient by applying additional insulation on the external surfaces that will affect the appearance of the building (Ståhl et al., 2011). In the interview with one of the building permit administrators and building antiquarians from the municipality of Gothenburg the aspects of culture values are important parts when applying for a building permit. If the building is a part of a detailed development plan which aims to preserve the heritage value of the area, then the façade reconstruction can be considered as a major change and that it will affect the cultural heritage appearance. He also explained that the city can order an antiquarian impact assessment from antiquarian consultants describing the measure and its impact on the building. There are no clear statistics of how many listed buildings there are in Sweden, and the decision making is somewhat of a case-to-case consideration. The statistics available are often dependent on physical inventories by different authorities like the Swedish National Heritage Board, county councils and county museums.

5.2 Plaster facades and masonry constructions in Sweden

This thesis is focused on AP and the buildings of which AP can be retrofitted. The national board of housing, building, and planning in Sweden (sv. Boverket) conducted a project called BETSI (2010) to investigate and report the buildings' energy use, technical status and indoor environment. The project states that multi-family houses in Sweden have a total wall surface area of 41 ± 21 million m^2 of plaster façade and 42 ± 28 million m^2 of brick façade. Karim et al., (2020) conducted a numerical energy study of a reference building retrofitted with AP in Sweden and concluded that if 10% of Sweden's multi-family houses with plaster façade had been retrofitted with AP, the annual potential energy saving would be 74 ± 48 GWh.

Björk et al., (2013) have in the book "*Så byggdes husen 1880-2000*" described the Swedish building stock, how it has evolved during the time period 1880-2000 and the common building techniques. According to the book it was common to build multi-family buildings with brick as the main structural component between the years of 1880 to 1930. In the ending of 1930s, the brick began to be replaced by light-weight concrete blocks which had a better thermal insulation property than ordinary brick. The façades were either left with a more decorative brick or a layer of plaster, but no insulation was included in the walls during these years either. Not until after the war years (1930s to mid 1900s) insulation became more common in the new buildings together with concrete, aerated concrete and light-weight concrete blocks (Björk et al., 2013).

5.3 Established additional insulation procedures in Sweden

Why a building is listed usually depends on its appearance, history and where it is located (Boverket, 2018). Therefore, it is of great importance in renovations that the appearance is preserved. Internal insulation often means additional insulation on the inside. Internal insulation methods are good since the outside appearance of the building is maintained, it also saves energy and is cheap and easy to implement. However, the internal living space is reduced and disruption of tenants during installation. Possible moisture problems may occur due to the changed temperature distribution in the construction (RISE, n.d.-b). The original wall usually gets colder and the risk of moist air leaking out in the construction can lead to condensation, opposite from external insulation.

External insulation methods are a more expensive solution since it needs scaffolding and a support structure. But on the other hand, no disturbances of tenants and an even better solution from an energy point of view since thermal bridges can be covered. Also, the living space remains the same.

According to Table 9:2a in the Swedish building regulations (BFS2011:6) the average U-value of the building should not exceed $0.4 \text{ W/m}^2\text{K}$ for multi-family buildings. The U-value should not exceed $0.6 \text{ W/m}^2\text{K}$ for commercial buildings, when bigger changes are performed (BFS 2011:6, 2011). The regulations also state that if the building does not achieve the maximum permitted primary energy demand, then the walls should not exceed a U-value of $0.18 \text{ W/m}^2\text{K}$. According to the building permit administrator and building antiquarian from the municipality of Gothenburg, these protected buildings are deprived from the requirements on U-values and maximum permitted energy usage.

The building permit administrator was also asked in the interview what the common procedure was for retrofitting external insulation on older buildings. Retrofitting additional insulation on existing buildings is usually performed by applying the extra insulation directly on the old façade. The exact procedure is often dependent on the building in question and can be determined by evaluating whether the windows can or should be replaced or moved out to compensate for the additional wall thickness. An important aspect to consider is the insulation thickness which can be regulated by either the appearance of the building or the need of insulation to reach certain heating demand goals. According to the interview with the building permit administrator the question whether the windows should be moved outwards has been a big issue and that additional insulation measures during the 70s and 80s it was not as common as it is today. He also explains that the moving of windows is due to the deepening of the window niche and that it affects the amount of daylight entering the room, but the retrofitting usually does not affect the daylight to the extent that it is considered reasonable to move the windows.

6 Case study building

In order to concretize the work and to get closer to a real scenario, a case study has been chosen. The appointed building was built in 1856 and has been used in a paper factory complex located in Mölndal, Sweden, a smaller city south of Gothenburg. The factory was liquidated in 2005 and has since then been in development (Papyrus, n.d.). The new owners Mölndala Fastighets AB, which is a municipal company owned by Mölndal Stad, have the task to develop the area according to the detailed development plans.

The building is a rectangular 3-storey building (and attic) placed in a northeast to southwest direction as shown in the Figure 6.1 below and is in the north point of the old factory area. According to the cultural history description and historical building inventory by Lindholm & Lange (2015) the appointed building, also named 213, was reconstructed from its original form in the year 1900. The authors believe that the top floor was added in the reconstruction process.



Figure 6.1 Satellite image of the case study building in Mölndal (Google Maps, n.d.).

The structural parts of the building consist of brick and the façade of a plaster coating on both the internal and external side. The brick wall thickness of the external walls is approximately 39-40 cm according to measures made on site, see Figure 6.2. This corresponds well with the building techniques at that time with 1 1/2 brick thickness (1 brick ~ 250 mm) and plaster on both sides of the brick (Björk et al., 2013). The windows are wood-framed 2-pane windows with different sizes and opening abilities.



Figure 6.2 The appointed building in February 2021, picture taken during a study visit.

The building has two stories and attic visible on the northwest façade, but the southeast façade has three stories exposed due to the lowered ground level towards the river. So, the building has three floors, one which is partially under ground level and two floors which are all above. The building is 9 m wide and 27.5 m long, the floor has a height of approximately 3 meters including the slabs, sketches of the building is seen in Figure 6.3 and Figure 6.4.



Figure 6.3 Sketches of the long facades. Top figure: Northwest façade, bottom figure: southeast façade [mm].



Figure 6.4 Sketches of the short sides. Left figure: Northeast facade, right figure: southwest façade [mm].

Table 6.1 states the number of different windows and doors in each wall and their total area, the walls are divided in their direction of latitude. To analyse the wall with different insulating materials the windows and doors must be extracted from the wall areas due to different U-values of each component. The doors have two different dimensions so there are two types of doors compared to the windows which have five different sizes, the dimensions are stated in Table 6.2.

Table 6.1 Number of doors and windows in respective wall in the studied case building.

	NW	NE	SW	SE
Door 1	3	0	0	0
Door 2	1	0	0	0
Window 1	16	2	2	20
Window 2	0	0	0	2
Window 3	0	0	2	0
Window 4	0	0	1	0
Window 5	0	1	0	0

Table 6.2 Dimensions of the doors and windows of the case study building.

	Height [m]	Width [m]	Area [m ²]
Door 1	2.5	1.4	3.5
Door 2	2.3	1.0	2.3
Window 1	2.0	1.2	2.4
Window 2	1.0	1.0	1.0
Window 3	1.2	1.2	1.44
Window 4	0.8 (∅ - m)	-	1.97
Window 5	1.7	1.2	2.04

The staircase is a protruding part of the building and to simplify the numerical model it is included in respective wall. So, the northwest wall of the staircase is included in the northwest main wall area, the same applies for the southeast wall. The windows and doors in each staircase wall are also included in respective main walls. The total wall areas including staircase walls, windows and doors is described in the second row in Table 6.3. Effective wall areas without windows and doors are stated in the last row of Table 6.3. The total effective wall area used in the numeric simulation is the sum of the areas in Table 6.3, which is 469.82 m².

Table 6.3 Wall areas with and without staircase, windows, and doors.

	NW	NE	SW	SE
Wall area + staircase + windows + doors	190.32 m ²	69.69 m ²	69.69 m ²	257.82 m ²
Effective wall area	139.12 m ²	62.85 m ²	60.04 m ²	207.82 m ²

Further, information regarding the U-values of different components is necessary to perform the energy simulations for the whole building and this refers to the windows, doors, the roof, and the foundation as well as the wall. In this thesis where the walls are the only variable in the different modelling cases and the other building parts will remain the same for all cases, they can be excluded from the models by only using the wall properties while performing energy calculations.

7 Models and method for hygrothermal and energy assessment

This chapter describes how the different models for moisture and energy analysis are built up and which conditions apply to each model. The models are divided into two parts, hygrothermal and energy.

7.1 Hygrothermal analysis of wall constructions in Swedish building stock

The hygrothermal performance of six different construction types are investigated and evaluated. The cases are based on common wall construction types in the Swedish building stock that have an interesting type of construction and that differs from each other. First the construction is simulated in its original form to see how it performs originally and later, simulated with an external layer of AP to see how it affects the hygrothermal performance of the construction. In all six main models the outermost layer is render and when applying AP this layer is first removed and later the AP-system is applied on the material underneath. The AP-system consists of 4 different layers, from interior: preparatory mortar, aerogel-based render, reinforcement, and finish layer.

The models are named with numbers starting from 1. The first main construction type, the reference case without AP is called M1 (model 1) and the same construction simulated with AP is called M2. The next main construction type simulated without AP is called M3 and the same construction simulated with AP is called M4 and so on. Hence, the six main wall constructions without AP are named with an odd number starting from 1 and the same construction with AP is then named with even numbers starting from 2. In Table 7.1 below, an overview of the construction types in its original form can be seen.

Table 7.1 An overview of the reference models which are based on wall constructions in Swedish building stock.

Model	Layer from inside	Thickness [mm]
Reference, M1	Plaster	20
	Brick	375
	Render	20
Sandwich, M3	Concrete	80
	EPS	140
	Concrete	60
	Render	20
Aerated concrete block, M5	Plaster	20
	Aerated concrete	250
	Render	20
Solid wood, M7	Plaster	20
	Wooden panel	25
	Solid wood	76.2
	Brick façade	30
	Render	20
Brick with internal wood wool board, M9	Plaster	20
	Wood wool board	50
	Brick	250
	Render	20
Concrete and aerated concrete, M11	Concrete	150
	Aerated concrete	150
	Render	20

To compare the models and to see the impact of the AP, points have been chosen where data has been extracted. Points that start with an A indicate that it is part of the AP-layers and points without a letter are in the main construction. Figure 7.1 below illustrates the AP-system which is applied to a model where A1 and A2 belong to the AP-layer and point 1 belongs to the main construction which AP is applied on.

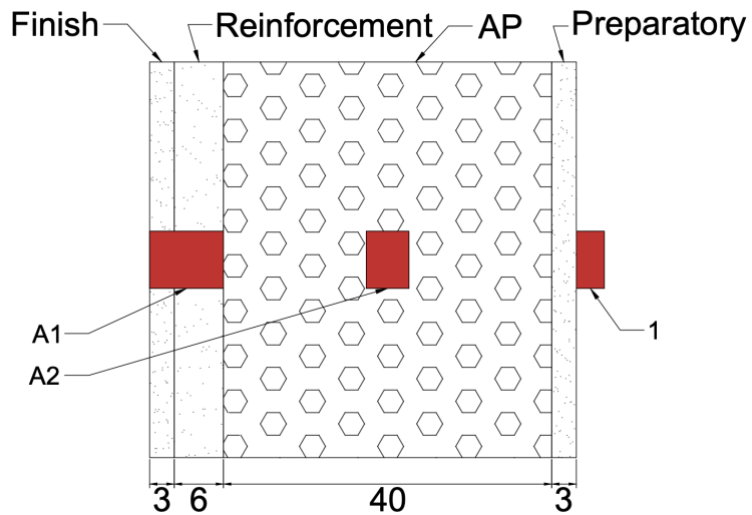


Figure 7.1. The studied points of the AP-system which is applied to a reference model. Layers from left (outside) to right (inside): finish, reinforcement, AP, and preparatory layer [mm].

The reference models have the same data points as the AP models with the exception that the outermost plaster is replaced with the AP-system seen above.

7.1.1 Reference case – M1

The reference case (M1) which is based on the case study building have a construction that can be seen in Table 7.1 above and consists of plaster on inside, brick and render on the outside. An overview of the investigated points for M1 can be seen in Figure 7.2 where water content, temperature and relative humidity have been analysed. Point 5 is directly affected by the outdoor conditions and point 4 correlates to the indoor climate, this combined with the thin thickness does not argue for multiple measuring points in these layers. The results become very similar. Point 1 and 3 are the outermost elements in the brick layer and will show the transition conditions in the layer. Point 2 acts like a control point that shows the conditions between the two outermost points and describes the extent of high moisture loads from the external side if they would occur.

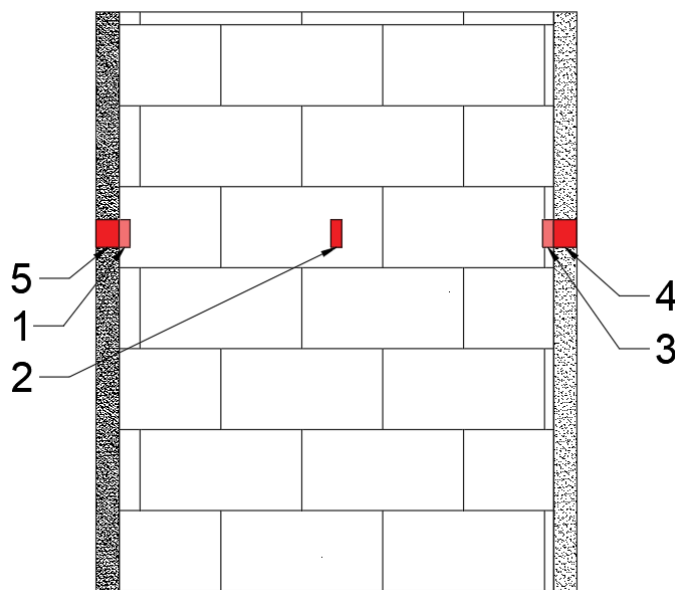


Figure 7.2 Investigated points for reference model M1. Layers from left (outside) to right (inside): Render, brick, plaster.

In the AP-model M2, which is based on the main construction of M1, the outermost plaster (point 5) has been removed and the AP-system have been applied according to Figure 7.1.

7.1.2 Sandwich – M3

Lamellhus (sv.) is a common construction in Sweden and was built a lot during the 1970s and a common construction is called *sandwich*. The load-bearing exterior wall consists of concrete, EPS, concrete, and render and the investigated points for M3 can be seen in Figure 7.3 below. Point 8 in the render is directly affected by the outdoor conditions and on the opposite side, point 7 correlates to the indoor climate. The thickness of the two concrete layers motivates two investigation points for each layer, point 1, 2, 6 and 7. The EPS is investigated on its inside, outside and in the midpoint of the material.

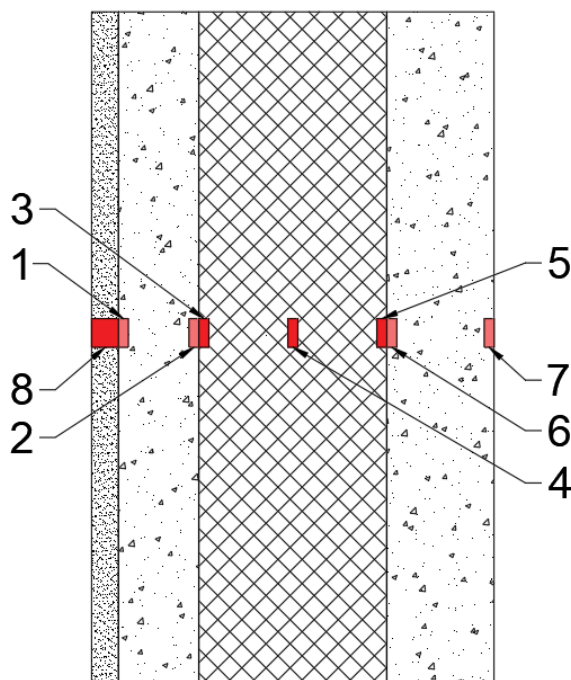


Figure 7.3 Investigated points for reference model M3. Layers from left (outside) to right (inside): Render, concrete, EPS, concrete.

7.1.3 Aerated concrete, reference model – M5

The “Point house” (Punkthus, sv.) was developed during the late ’30s. They can be of various size but often contains one staircase catered in the building and apartments formed around and they occur throughout Sweden around the semi-central parts of the cities. The typical wall construction is, as described by Björk et al. (2013), only 250 mm wide aerated concrete blocks covered with a plaster layer on both internal and external sides. The layers used in M5 can be seen in Table 7.1.

There are five analysed points which can be seen in Figure 7.4 below. The first and last point (5 and 4) are studied to investigate the possibility of freeze-thawing cycles and mould growth respectively. Point 1 and 4 are typical interface points which are interesting to compare after that the AP has been applied. Point 2 acts like a validation point since the aerated concrete block is very wide.

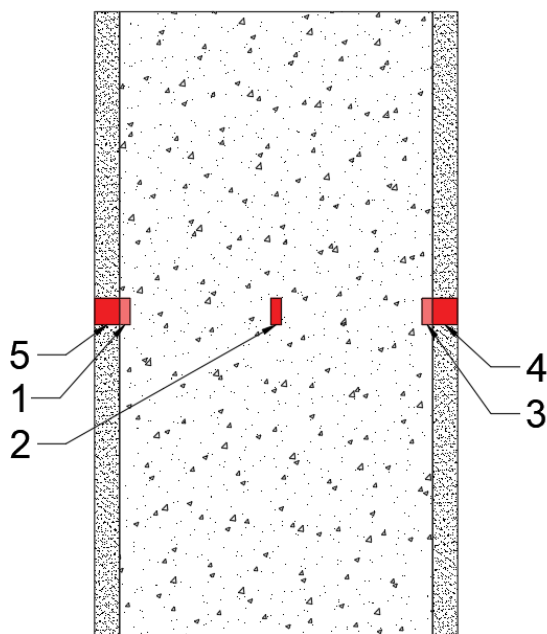


Figure 7.4 Investigated points for reference model M5. Layers from left (outside) to right (inside): Render, aerated concrete, plaster.

7.1.4 Solid wood - M7

Landshövdingehus (sv.) is considered since it represents a construction of solid wood and was built in the late 19th century and in the beginning of the 20th century. The first floor has a construction based on stone and the second and third in wooden material. An overview of the construction and the investigated points can be seen in Figure 7.5 below and the load bearing construction are made of solid wood with additional wooden panels towards the interior. The exterior is formed with a layer of bricks and render applied outside.

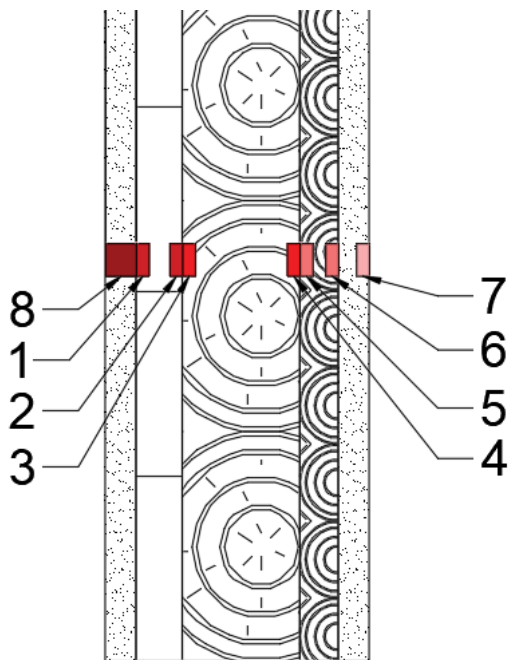


Figure 7.5 Investigated points for reference model M7. Layers from left (outside) to right (inside): Render, brick, solid wood, wooden panels, plaster.

7.1.5 Brick wall with wood wool board – M9

Lamellhus (sv.) from the 1940s are made from masonry brick with render on the exterior side of the wall and on the interior side a wood-wool board was applied as insulation. The wood-wool board was covered with a layer of plaster. The investigated points are illustrated in Figure 7.6 and the points are chosen with reference to the same arguments as previous models.

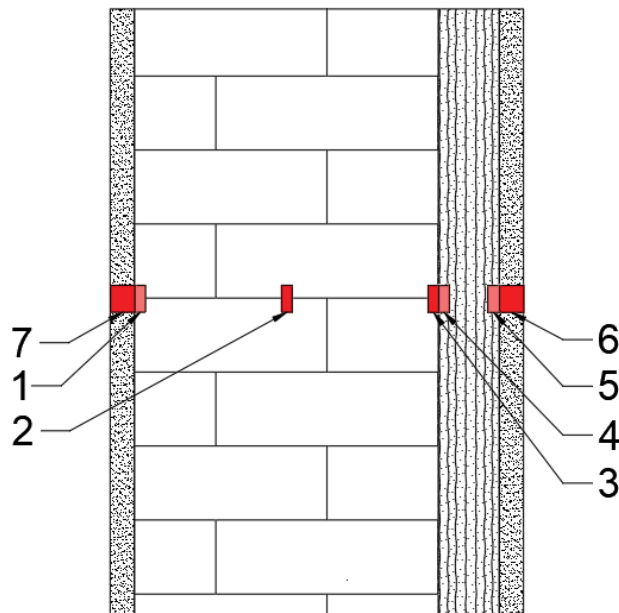


Figure 7.6 Investigated points for reference model M9. Layers from left (outside) to right (inside): Render, brick, wood-wool board, plaster.

7.1.6 Concrete and aerated concrete - M11

A panel house (Skivhus, sv.) is a type of high-rise building with an elongated body, usually built on a rectangular floor and normally equipped with lifts. Like the lamellhus (sv.), these are usually placed parallel to each other. This type of building became very common in Sweden during the 1960s and 70s with the industrialized construction of the million-program. The load-bearing wall is made of an outside layer of aerated concrete and ordinary concrete on its inside. The investigated points are illustrated in Figure 7.7 to check the whole construction.

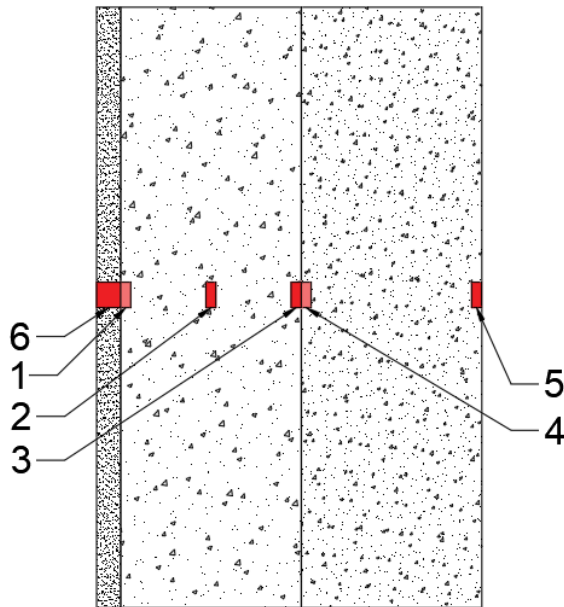


Figure 7.7 Investigated points for reference model M11. Layers from left (outside) to right (inside): Render, aerated concrete, concrete.

7.2 Simulation models for energy analysis

The energy analysis compares the common insulation materials, rock wool and EPS, with AP to study their respective energy saving potential compared to the economic aspects. The energy study is divided into four cases where different parameters are changed to analyse how the AP is affected and how it correlates to the thermal properties and how the energy demand changes. The following cases are studied:

- E1 - Material comparison with the same thickness of the insulating materials
- E2 - Realistic thickness of additional insulation layer
- E3 - Moisture-dependent thermal conductivity
- E4 - First year after application of AP

The cases are presented in Figure 7.8 below where the changed parameters are AP thickness and thermal conductivity. E1 is based on the three insulation materials, AP, rock wool and EPS which are set to be 30 mm thick and no other additional layers except the exciting construction and a finishing render. E2 includes the additional layers of the AP and the AP itself has a thickness of 40 mm to illustrate a realistic case which might have a limitation of an additional insulation thickness. E3 includes the moisture-dependant thermal conductivity variation into the simulation. E4 shows the first year after that the AP-layers have been applied including the drying time.

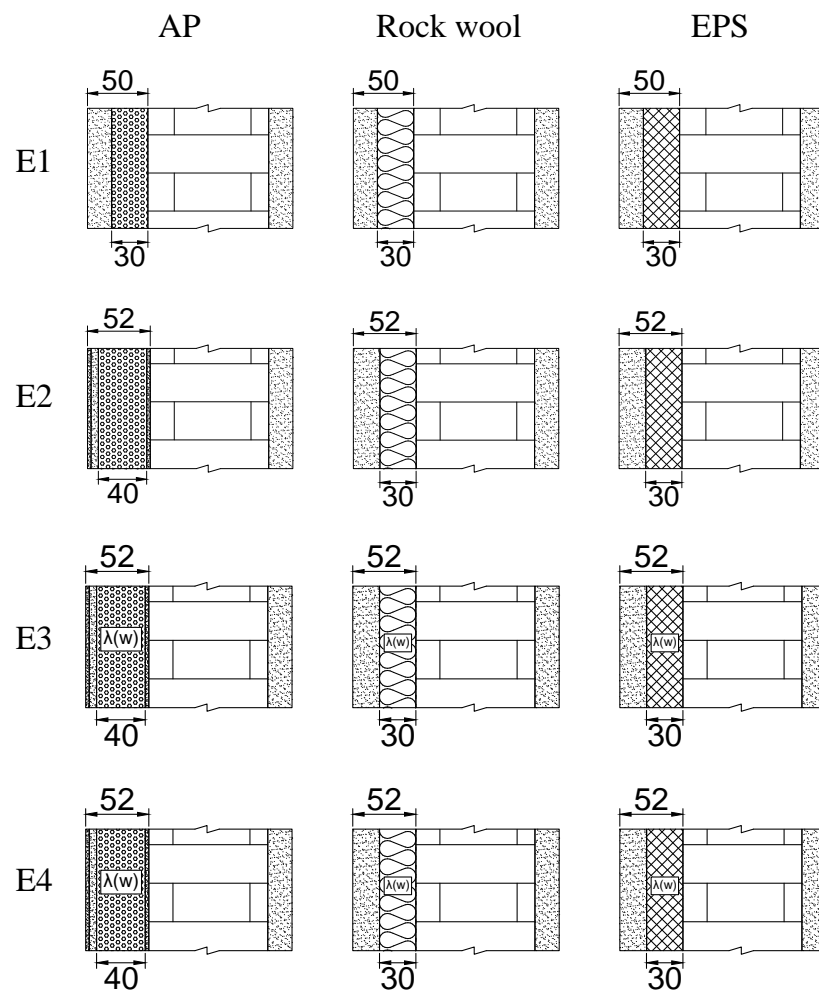


Figure 7.8 The four different cases for the energy simulation.

7.2.1 Material comparison – E1

This simulation will provide reference values for comparing the two other materials with the AP by heating demand, energy savings per heated floor area and percentual change compared to the reference building. Here, the walls have the same total thickness, and the insulation materials have the same thickness, see Table 7.2.

Table 7.2 Layers of the different walls in the E1-model.

E1	Material	d [mm]	λ [W/mK]
Reference wall	Render	20	0.8
	Brick	375	0.6
	Plaster	20	0.8
AP wall	Render	20	0.8
	AP	30	0.027
	Brick	375	0.6
	Plaster	20	0.8
Rock wool wall	Render	20	0.8
	Rock wool	30	0.032
	Brick	375	0.6
	Plaster	20	0.8
EPS wall	Render	20	0.8
	EPS	30	0.04
	Brick	375	0.6
	Plaster	20	0.8

7.2.2 Realistic thickness of additional insulation layer – E2

The model is constructed in a way which only allows a retrofitting of maximum 52 mm additional insulation to the existing wall. This can be related to a real case where the historical value of the building would be the limiting factor. Due to the additional materials in the AP-system (finish, reinforcement and preparatory) the minimum thickness is 12 mm. Adding 40 mm AP generates a total thickness of 52 mm. So, within these 52 mm exterior from the outer brick surface both insulation, plaster and other materials should be fitted. The AP-wall is now including the additional layers used with the application of AP, the other walls remain as in E1, see Table 7.3.

Table 7.3 Layers of the different walls in the E2-model.

E2	Material	d [mm]	λ [W/mK]
Reference wall	Render	22	0.8
	Brick	375	0.6
	Plaster	20	0.8
AP wall	AP-finish	3	0.47
	AP-reinforcement	6	0.33
	AP	40	0.027
	AP-preparatory	3	0.83
	Brick	375	0.6
	Plaster	20	0.8
Rock wool wall	Render	22	0.8
	Rock wool	30	0.032
	Brick	375	0.6
	Plaster	20	0.8
EPS wall	Render	22	0.8
	EPS	30	0.04
	Brick	375	0.6
	Plaster	20	0.8

7.2.3 Moisture-dependant thermal conductivity – E3

This simulation takes the moisture-dependant thermal conductivity into account and connects the water content from WUFI® 2D of the materials to achieve the results of a more realistic simulation. This is performed for a “dry” and a “leaking” case where the leaking case is a wall with a damaged water repellent layer (paint) which allows rainwater to penetrate the wall and provides moisture for capillary suction.

The boundary condition in WUFI® 2D for this is setting the adhering fraction of rain to 70%, meaning that 70% of the driving rain hitting the wall is accessible for capillary suction. The dry case has an intact hydrophobic layer, and no water is accessible for

capillary suction i.e., adhering fraction of rain is set to 0%. The wall layers are the same as in E2, see Table 7.3.

7.2.4 First year after application of AP – E4

The first year of AP includes the time from when the AP is applied to investigate how the drying rate affects the energy performance during the first year compared to the corresponding model E3-dry. The energy simulation is based on the water content in the insulation materials from WUFI® 2D and the thermal conductivity used is the moisture-based thermal conductivity.

In this model there is no damage or leakage, meaning no rainwater is accessible for capillary suction. The existing materials, brick, and render, are at a relative humidity of 80% and the AP-layers at 99% RH as initial conditions in WUFI® 2D. The wall layers are the same as in E2, see Table 7.3.

8 Prerequisites and conditions for numerical models

The parametric study is performed in two different simulation software. The hygrothermal simulations are run in the software WUFI® 2D and the energy simulations are run in MATLAB® and Simulink®. Following chapter describes the properties, boundary conditions and how the models are built in the software.

8.1 Hygrothermal properties of construction materials

The study will include performance simulations of different common wall constructions and will therefore require the hygrothermal properties of the analysed materials. The materials to be used in the study are stated in Table 8.1 below, including hygrothermal properties from the material catalogue in the simulation program WUFI® 2D. The materials are based on the wall types described in Chapter 7.1.

Table 8.1 *Thermal conductivity and water vapour permeability coefficient of different building materials from the material catalogue in WUFI® 2D.*

Material	Thermal conductivity [W/mK]	μ -value [-]
EPS	0.04	30
Rock wool (Roxul RockBoard)	0.032	1.1
Plaster (Cement lime plaster, stucco)	0.8	19
Concrete (C35/45)	1.6	248
Aerated concrete (500 kg/m ³)	0.12	8
Wood-wool board	0.08	9
Brick (Masonry solid)	0.6	10
Gypsum board	0.2	8.3
Solid wood (Spruce tangential)	0.14	83.3

8.2 WUFI® 2D – Hygrothermal simulations

The commercial computer software WUFI® 2D (v. 3.4) is used to check the hygrothermal performance of the reference building and the different models. After the user has defined the model, which can consist of several different layers, WUFI® 2D calculates the moisture and heat transport in the different building parts by performing non-stationary calculations. Various climate data are also available, which means that the user is not limited geographically (WUFI, 2021). Following transport equations are considered, Equation 8.1 and 8.2 below:

$$\frac{\partial H}{\partial T} \frac{\partial T}{\partial t} = \nabla(k\nabla T) + h_v \nabla(\delta_p \nabla(\varphi P_{sat})) \quad (8.1)$$

$$\frac{\partial w}{\partial \varphi} \frac{\partial \varphi}{\partial t} = \nabla(D_\varphi \nabla \varphi + \delta_p \nabla(\varphi P_{sat})) \quad (8.2)$$

where H , T , w and ϕ represent the enthalpy of moist building material, temperature, moisture content and relative humidity. k , h_v , δ_p , P_{sat} and D_ϕ represent the heat conductivity of moist material, evaporation enthalpy of water, water vapor permeability, saturation pressure and liquid conduction coefficient. For the numerical solution, WUFI® 2D applies the finite volume technique for the spatial discretization of the transport equations (Ibrahim et al., 2014).

8.2.1 Modelling conditions

To get the most accurate results possible, the settings must be carefully considered in the program. Since the modelling takes place in 2D, a cross section is created with a maximum height of 300 millimetres. Materials are then assigned to each wall component. Since AP is a new material, it cannot be found in the WUFI® 2D database, so a new material with correct properties must be created. This also applies to the three additional materials used when applying AP.

Each construction type in the hygrothermal analysis in WUFI® 2D is divided into two models, one reference case before the AP is applied and one after the AP has been applied. The reference model is run first so that the initial conditions for the retrofitted model can be extracted from each material layer in the reference model. The simulations start on the 10th of October and continues for five years. The values are extracted from the end of the simulation to simulate how the wall construction will behave after the AP has been applied. The initial conditions for the reference models are not of great importance due to that the parameters converge toward a steady yearly variation at the end of the simulations. If any of the models seem to not converge at the end of the simulation, then the initial conditions are adjusted to reach convergence. With this method it is possible to analyse the direct effect of retrofitting AP to the existing wall construction.

8.2.2 Boundary conditions

To simulate the model, boundary conditions must be determined in the model. A boundary condition can be adiabatic, exterior, or interior. Adiabatic is selected for the top and bottom of the cross-section view of the model since no mass transfer is added or removed from this side. Exterior is selected on the outside of the model and there are

several things to define, both related to the surface itself and the climate. Characteristics found in Table 8.2 below has been defined for the exterior surface.

Table 8.2 *Boundary conditions and input data for exterior surface.*

Characteristic	Unit	Value
S _d -value	[m]	-
Heat Transfer Coefficient	[W/m ² K]	Wind dependent
Short-Wave Radiation Absorptivity	[-]	0.4 (Limestone, bright)
Long-Wave Radiation Emissivity	[-]	0.9 (Limestone, bright)
Adhering Fraction of Rain	[-]	0
Climate	[Location]	Gothenburg; LTH Data
Azimuth	[deg]	0
Inclination	[deg]	90
Driving Rain Coefficient R1	[-]	0
Driving Rain Coefficient R2	[s/m]	0.07

The resistance to moisture diffusion in materials is described by the S_d value and is expressed in meters of air. A value of less than 1 meter means that the material is relatively open to moisture diffusion. Examples of such materials can be wallpapers or paint. A higher value of 1-10 meters indicates a more difficult permeability and can be wood panels, plastic wallpaper. Materials such as a vapor barrier instead have a very high S_d value of more than 50 m. For the simulations the S_d-value is defined as without coating i.e., 0 m.

The short- and long wave radiation is based on the surface layer and the most similar material available to the finishing layer of AP is bright limestone. It represents the fraction of total incident solar radiation that is absorbed by the component and the portion of solar radiation that is reflected by a material, respectively. The climate selected is Gothenburg and this location is applied to all simulations unless otherwise stated.

The adhering fraction of rain describes the part of the rainwater that will be able to be capillary absorbed on the façade. On horizontal surfaces, all rainwater contributes to the capillary suction and the coefficient is therefore 1. For a vertical wall a standardized value of 0.7 is used. The manufacturer advocates that when applying AP, a hydrophobic layer should be applied to the surface, i.e., some type of paint. To simulate this, the adhering fraction of rain has been set to 0. This means that no rain is available to be absorbed by capillary suction by the construction. For later simulations of damages this fraction will be altered to illustrate that the hydrophobic layer is defected.

The azimuth decides what direction the façade is facing and based on the weather analysis an azimuth of 0° , south in WUFI® 2D, has been set to consider the worst-case scenario even though the appointed building in the case study has a direction facing southwest. Weather data from SMHI shows that the average wind direction is 176° according to data measured from 1977 to 2020 in Gothenburg (SMHI, 2021). This corresponds to a south-southwestern direction. However, in this study the interesting parameter is the wind direction while there is any type of precipitation. Figure 8.1 illustrates the amount of precipitation and wind direction at a given day of the year with data from SMHI reaching from 1995 to 2020, measured in Gothenburg.

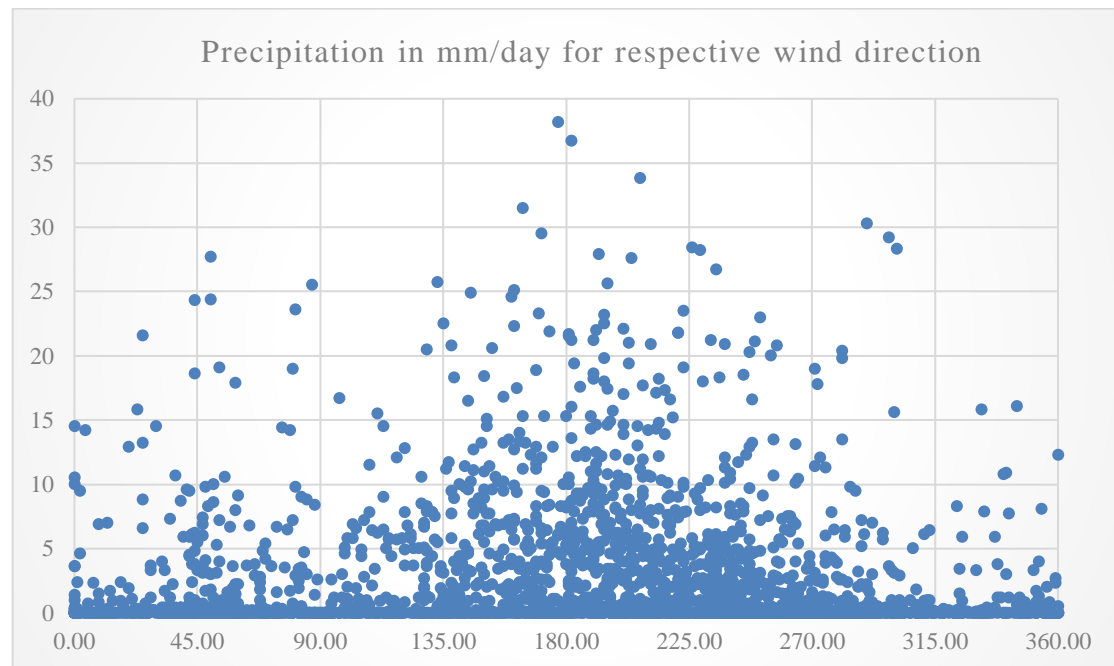


Figure 8.1 Precipitation in mm/day with wind direction in degrees occurring simultaneously in Gothenburg (SMHI, 2021).

Similarly, to Figure 8.1 the data from WUFI® 2D illustrates the driving rain (mm/a), which can be seen in Figure 8.2, also shows higher amount of precipitation from a southern direction.

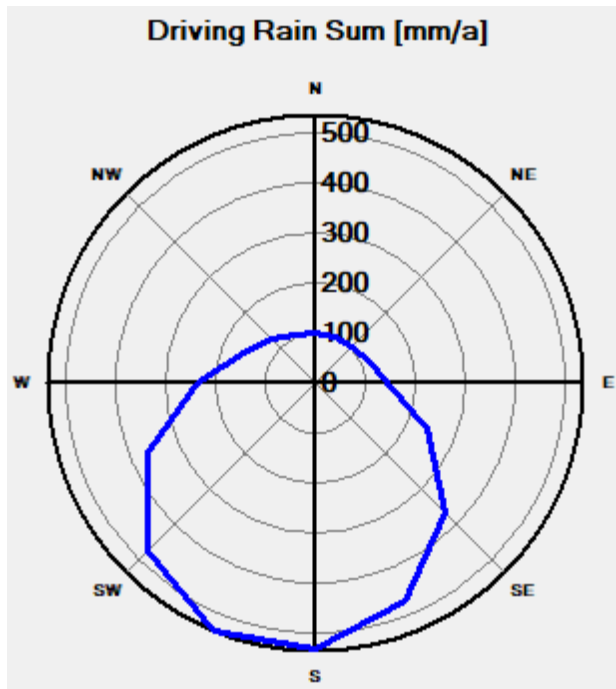


Figure 8.2 Driving rain in Gothenburg for the climate data in WUFI® 2D.

R1 and R2 in Table 8.2 estimates the driving rain load since the rain load on walls is determined by the driving rain rather than the normal rain. For vertical walls, as in this case, R1 is 0. R2 is about 0.2 s/m for free-standing locations without influence from surrounding buildings as this model represents. In the centre of a façade R2 has an approximated value of around 0.07.

WUFI® 2D has some default settings for defining the interior boundary conditions. The climate is selected as *EN 15026* which calculates an indoor climate based on the climate data file. Table 8.3 below states the interior surface boundary conditions in the model.

Table 8.3 Interior surface boundary conditions.

Characteristic	Unit	Value
Sd-value	[m]	(Treated as an indoor surface)
Heat transfer coefficient	[W/m ² K]	8

8.2.3 Moisture safe constructions

To analyse the results generated in the study of AP and to determine whether a model is considered as a moisture safe construction or not, a few conditions are determined as guidelines. The criteria are summarized in Table 8.4.

To determine whether a construction is moisture safe one indicator is the mould growth indexing (MGI) method which will be used and if the MGI is below 1-2 it will be considered acceptable. Further, if the overall moisture content is increasing over time with no indications of convergence it can be considered as an unsafe construction or that a troubleshooting must be performed. But an increasing moisture content in a

material can be an indication that the material is not able to dry out before the next load of moisture enters the material and can lead to serious moisture damages.

Another indicator are the freezing-thawing cycles which usually occur in the outermost layers where the temperature drops below 0°C. In the simulations, a value of -1 has been used to exclude cycles with a temperature of slightly below zero degrees within a small-time limit (i.e., just a few hours). Materials freezing is not a risk at itself but combined with moisture in the material it becomes a risk as described in Chapter 3. Hence, only freezing cycles that at the same time have a relative humidity of over 80% are considered. Many freezing-thawing cycles at high moisture contents is considered as an unsuitable condition.

Table 8.4 Moisture damage criterions for evaluation of the results.

	Mould growth	Freezing thawing	Water content
Risk for damage	>75% RH	Number of cycles when $T \leq -1^{\circ}\text{C}$ $\text{RH} \geq 80\%$	Increasing after applying AP

8.3 MATLAB®/Simulink®

The energy and heating demand of the appointed building will be performed using the software Simulink® which works together with MATLAB®. Simulink® allows you to run simulations on your system with several functions and input data. The software gives a good overview of the system with easy-to-use interface and can output graphs of desired parameters.

For this study the system in question is the case study building, and the input data consists of the building dimensions, U-values, and weather data (outdoor temperatures). The model is based on fundamental heat transfer physics and energy calculations which outputs the maximum heating demand of the year and the yearly energy demand for a year. The system can be built to simulate several parts related to energy use of a building by, for example, including solar radiation, ventilation, shading functions, internal heat gains and heat recovery. The energy simulations in this study are performed to evaluate and compare the energy performance of different insulation systems, including AP. Therefore, the energy simulations are at a limited level and considered sufficient for the purpose of the study.

The model which is used in this study only simulates the heat transfers related to the external walls, to be able to analyse the results with different insulation materials. The influence on the buildings heating demand and energy demand from roof, windows, doors, and foundation is assumed to be equal in all cases and is therefore neglected in the simulation. This means that the resulting heating demand and energy demand is only dependent on the external wall conductance. The input data used in the energy simulations are stated in Table 8.5.

Table 8.5 Input data used in energy simulations based on the case study building, known values, and assumed values.

Notation	Definition	Value
A_{wall}	External wall area ¹	469.8 m ²
A_{temp}	Heated floor area ¹	939.6 m ²
V_{room}	Volume of the building ¹	2473.5 m ³
ρc_{air}	Volumetric heat capacity of air ²	1200 J/m ³ K
$T_{\text{ext}} [^{\circ}\text{C}]$	Outdoor temperature	Climate data file (Gothenburg)
T_{heater}	Desired indoor temperature ³	20 °C
R_{se}	Thermal resistance of exterior surface ²	0.13 m ² K/W
R_{si}	Thermal resistance of interior surface ²	0.04 m ² K/W

1: Case study building

2: Introduction to Building Physics - Hagentoft (2001)

3: Assumed value

The variable in the model is the outdoor temperature which is extracted from the climate weather data file from WUFI® 2D consisting of hourly measured temperatures in Gothenburg. Further, the system depends on the external wall area, U-value, specific heat capacity of the air in the building and setpoint of the heater. The heater setpoint regulates at which indoor temperature the heater will be activated to remain the desired indoor temperature which outputs a heating power [W]. The system then evaluates if the indoor temperature is below the setpoint temperature and weather it should output a heating effect. So, if the indoor temperature is above the setpoint (20 °C) then the output is 0 W, and no heat is added to the building.

The thermal conductance of the walls and temperature difference between the outdoor and indoor temperature outputs a, generally negative, heating power (W) which is added to the heater output. So, if the added effect is negative, it will lower the indoor temperature and a positive effect does the opposite and the reduced or increased indoor temperature is returned in the system for a new time step. Equation 8.3 describes the heat balance applied in the energy simulation of the building.

$$Q_{trans} + Q_{heater} = 0 \quad (8.3)$$

The output from the wall transmittance is based on Equation 8.4 were the usually negative heating power lowers the indoor temperature in the system when the indoor air temperature is higher than the outdoor air temperature.

$$Q_{trans} = A_{wall} * U_{wall} * (T_{ext} - T_{air}) [W] \quad (8.4)$$

The heater in the system compensates for the heating demand generated from the wall transmittance to keep the indoor temperature above T_{heater} (20 °C). The heating power from the heater is used to measure the heating energy of the building. The final output in the system is the heating energy per square meter heated area, A_{temp} .

8.4 Economic assessment

Whether a new technology comes into use or not depends largely on its cost and therefore a simplified economic comparison has been made between AP and conventional insulation materials, EPS and rock wool. The method used is called net present value (NPV) and is based on determining the profitability of an investment regarding an interest rate (Fernando, 2021). Equation 8.5 describes how to calculate the NPV.

$$NPV = \sum \frac{C_{benefits}}{(1+r_i)^t} - \sum \frac{C_{costs}}{(1+r_i)^t} [SEK] \quad (8.5)$$

To be able to evaluate if different benefits and costs have different investment periods the equivalent annual cost factor (EAC-factor) is determined according to Equation 8.6, (Kenton, 2020). Then the EAC is determined by dividing the NPV by the EAC – factor.

$$EAC - factor = \frac{1}{r_i} \left[1 - \left(\frac{1}{1+r_i} \right)^T \right] [-] \quad (8.6)$$

Table 8.6 presents the values used for the calculations. The discount rate is set at 5 % and the energy growth rate that corresponds to the inflation, is set at 2 %. The area is heated floor area and is calculated based on the reference case with 4 floors. The values of energy savings are taken directly from the energy simulations in Simulink®, for detailed description, see Chapter 8.3.

Table 8.6 Data used in the calculations for the economic assessment.

Data	Value
Discount rate ¹	5 %
Energy growth rate ²	2 %
District heating price ³	0.9 SEK/kwh
Area (case study building)	939.6 m ²
Energy savings AP	Extracted from Simulink®
Energy savings rock wool	Extracted from Simulink®
Energy savings EPS	Extracted from Simulink®
Lifetime ¹	30 years

1: Assumed value based on economic assessment calculation examples from course modules at Chalmers University of Technology, course *Sustainable Building Renovation*, ACE166.

2: Based on benchmark value from Swedish National Bank, (Sveriges Riksbank, 2018).

3: Assumed value based on energy distribution company Göteborgs Energi, (Göteborg Energi, n.d.).

The major estimate in the economic assessment is the investment cost for AP since scarce information is available. Fantucci et al. (2019) states that the price for the FIXIT product is €30/m²/cm and €60/m²/cm in total including labour and other additional costs. This is then multiplied with the thickness of 4 cm and the wall area for the reference case (469,82 m²). The price is then converted into Swedish crowns by multiplying by 10 for simplicity. The investment cost for rock wool and EPS has instead been based on a price list from ÅF (2018) where prices for new buildings and various renovations are listed.

When using Equation 8.5 the NPV can be calculated for each investment and each savings in energy. In this case, the lifetime is equivalent for each renovation alternatives, 30 years and hence the EAC-factor, Equation 8.6, is equal for all. The EAC is then given by dividing the NPV with the EAC-factor. The total is then the addition of the EAC for investment and energy savings for each alternative.

9 Results

Chapter 9 shows the results of the hygrothermal simulations and the energy simulations with study of various parameters to check accuracy of the results. Also, an economic evaluation is performed to compare AP with conventional insulation materials.

9.1 Results from hygrothermal simulations in WUFI

In this sub-chapter the results from the WUFI® 2D simulations are presented for each model pair (reference wall and AP-model). The results are overall similar between the models and the main differences are depending on material properties and geometries (layer thicknesses).

The results presented in the chapters are based on the set criterions for a moisture safe construction described in Chapter 8.2.3, which are in short:

- A. Stable or decreasing water content over time.
- B. Low risk of frost damage due to freezing-thawing cycles.
- C. Low risk of mould growth in the construction or internal surfaces.

The water content criteria are based on the existing construction prior to the retrofit which means that the AP layers are excluded for this comparison. All the models are also summarized and compared followed by a parametric study of chosen parameters based on the results from the model simulations.

9.1.1 Reference case – Model 1 & 2

The reference model M1 did not show any indications of moisture problems in the simulations which can be expected due to the prevention of water entering the construction capillary. By retrofitting the AP, M2, the total water content in the construction was reduced. Figure 9.1 is a boxplot and illustrates the total water content in the brick and internal plaster layers in both M1 and M2. In the boxplot, five values are shown: the median, the mean, the lower and upper quartile the minimum and maximum value. The median is marked by a line in the middle of the box and the mean value is marked by an “x”. The lower and upper quartile are marked by the top and bottom of the box while the minimum and maximum values are marked by the “T”-shapes. The interquartile range (IQR, the box) holds the middle 50% of the obtained values. The figure is based on the values of the last two (out of five) years where both simulations have reached a constant yearly mean value. M2 indicates a clear decrease in water content but as the box indicates, the water content variation amplitude is larger in M2.

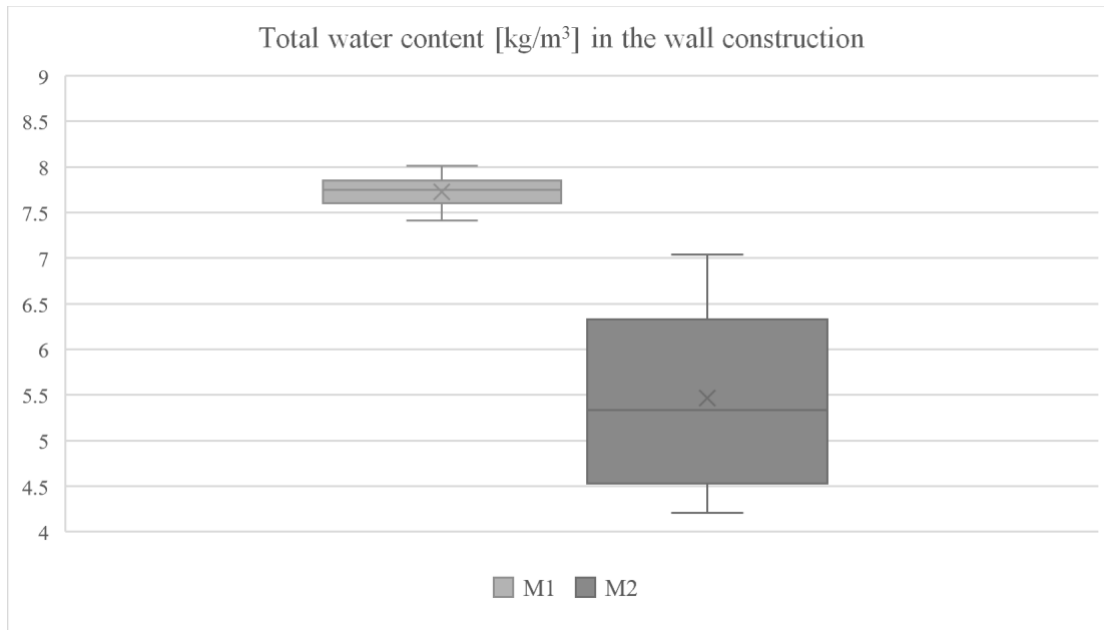


Figure 9.1 The total water content in the construction for M1 and M2. Where M1 is the reference model and M2 is the model with the AP-system.

The freezing-thawing investigation showed that no cycles occurred in point 1, with and without AP. There is an occurrence of sub-zero temperatures in the point in M1, but the relative humidity is below 80% which is why no cycles can be accounted. Moving outwards in the construction, to the outermost point in M1 which is point 5 and comparing the cycles with point A1 in M2 showed other results. Point 5 did not indicate any freezing-thawing cycles due to the lack of moisture at freezing temperatures while point A1 had 8 cycles. Both points are the outermost points in the models, so the differences are both moisture and temperature. Point 5 has a higher minimum temperature ($\sim -8^{\circ}\text{C}$) due to heat from the wall and inside which is limited in point A1 by the applied AP and the minimum temperature becomes lower ($\sim -12^{\circ}\text{C}$). Point A1 also shows a higher relative humidity than point 5 which exceeds 80% and contributes to the freezing-thawing cycle counting. The water content in point A1 is although lower than what the result show in point 5 so the higher relative humidity in point A1 is an effect of the difference in material properties between the two renders. **Error! Reference source not found.** below summarizes the results from the freezing-tawing cycle analysis.

Table 9.1 Number of freezing-thawing cycles in respective point of M1 and M2 for one winter season.

Studied point	Number of cycles
Point 1, M1	0
Point 1, M2	0
Point 5, M1	0
Point A1, M2	8

9.1.2 Sandwich construction – Model 3 & 4

Overall, in the constructions, the temperature, relative humidity, and the water content shows seasonal variations as expected for both M3 and M4. The temperature is low during the winter season, simultaneously as the relative humidity and water content is high. The difference in total water content is clearly visible in Figure 9.2 below. In M3, the average total water content is around 26.75 kg/m^3 and in M4 the average is around 24.75 kg/m^3 which shows the improvement of AP. The total water content of the two walls also remains stable over time which is a decisive factor for the moisture performance assessment.

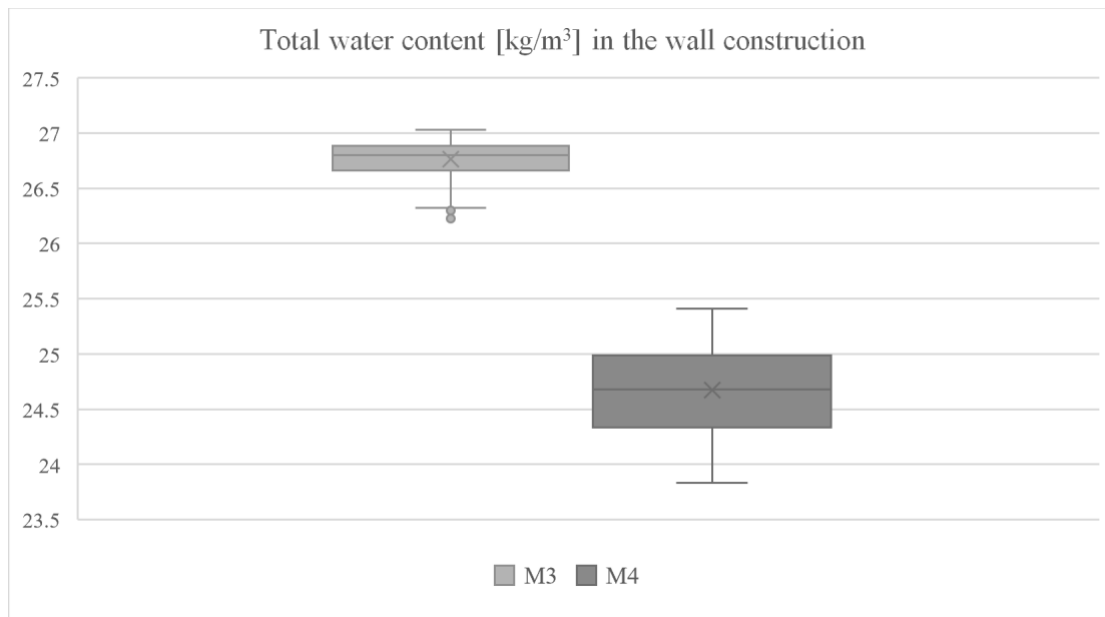


Figure 9.2 Total water content in the construction for M3 and M4.

Point 8 and A1 in M3 and M4 shows temperatures in the winter as low as around -10°C for M3 and -12°C for M4. The occurring sub-zero temperatures in M3 in the render creates freezing-thawing cycles which have been counted to 2, see Table 9.2. This is also the case for M4, where point A1 show even more freezing-thawing cycles, 11. Hence there is also a risk for the AP to deteriorate. The different materials in the construction also behave as expected individually. For example, the water content drops drastically from the outer concrete in M3 which has a water content of about 65 kg/m^3 to the middle of the EPS which holds no more than 0.6 kg/m^3 . This depends on material characteristics.

Table 9.2 Number of freezing-thawing cycles in respective point over one winter season.

Studied point	Number of cycles
Point 1, M3	0
Point 1, M4	0
Point 8, M3	2
Point A1, M4	11

9.1.3 Aerated concrete – Model 5 & 6

After the simulation of M5 no outline results were obtained. The materials behave as expected both individually and as an ensemble. The large aerated concrete layer in M5 has an insulating capability which is seen by the results. Point 1 shows temperatures similar to outdoor conditions with maximum of 40°C and a minimum of around -10°C and point 2 shows a decreased amplitude with a maximum of 28°C and a minimum of around 5°C. The water content in the aerated concrete also remains on a stable and low level, alternating around 5.4 kg/m³ in point 2. When applying AP on the wall it become both warmer and dryer as expected. Figure 9.3 shows the total water content and it is clearly visible that an application decreases the water content. However, the amplitude of the seasonal alternating water content has increased.

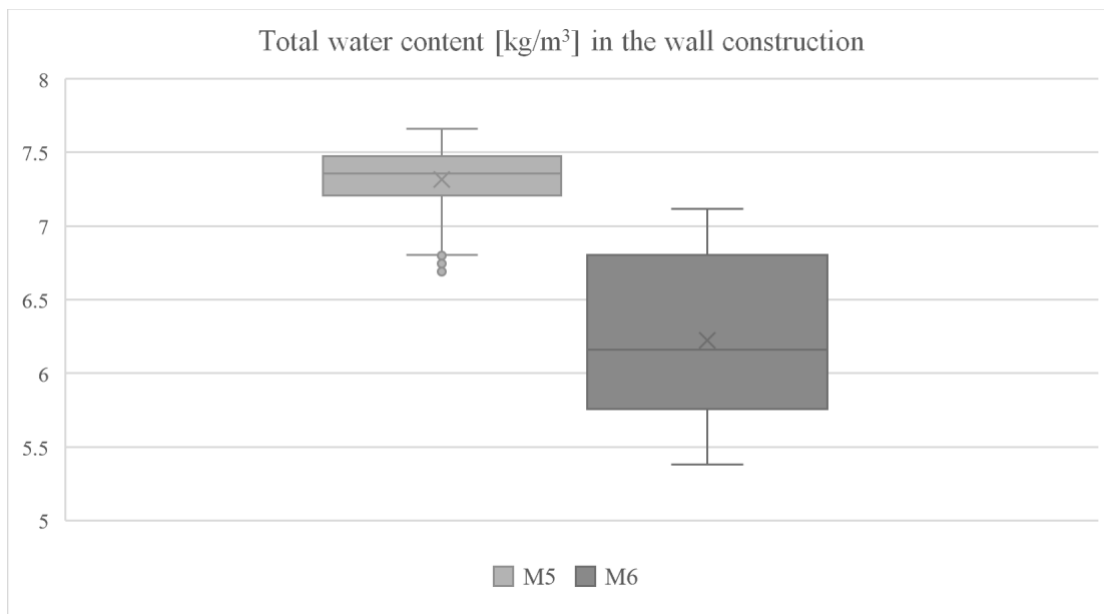


Figure 9.3 Total water content in the construction for M5 and M6.

The freezing-thawing cycle analysis showed one cycle per winter season in M5 in point 1 (aerated concrete) while the same point in M6 had no signs of freezing-thawing cycles. The analysis in the outermost points point 5 and A1 showed similar results as

previous models, namely an increase in cycles in M6. The number of freezing-thawing cycles are presented in Table 9.3 below.

Table 9.3 Number of freezing-thawing cycles in respective points in the construction over one winter season.

Studied point	Number of cycles
Point 1, M5	1
Point 1, M6	0
Point 5, M5	2
Point A1, M6	10

Since the water content remains on a stable level for all layers in M6, the freezing-thawing cycles are limited and that the relative humidity remains at a reasonable level, the construction is assessed to be moisture safe.

9.1.4 Solid Wood – Model 7 & 8

The wood-construction model had similar results as the previous models with a reduction in water content and relative humidity. Figure 9.4 illustrates the total water content in the construction in M7 and M8, and the reduction is clear.

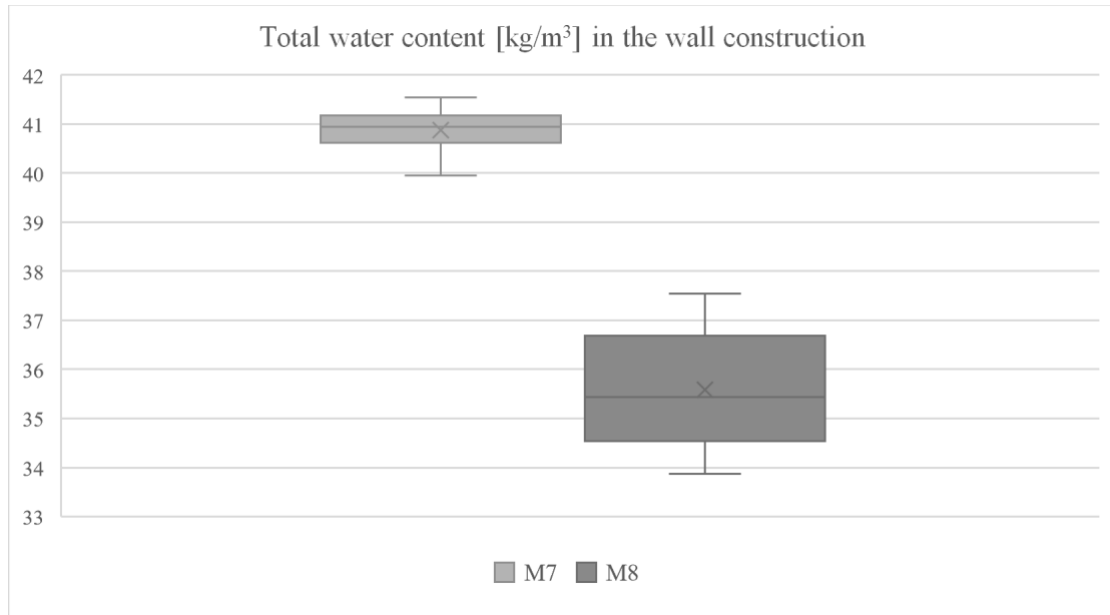


Figure 9.4 Total water content in the construction for M7 and M8.

The models did not show any freezing-thawing cycles in point 1 but as the previous models there were readings in the outermost points, point 8 and point A1. Point 8 had no freezing-thawing cycles while point A1 had 9 cycles during a winter season, see Table 9.4.

Table 9.4 Number of freezing-thawing cycles in respective point in the construction over one winter season.

Studied point	Number of cycles
Point 1, M7	0
Point 1, M8	0
Point 8, M7	1
Point A1, M8	9

9.1.5 Brick wall with wood wool board – Model 9 & 10

These models were one of the model pairs that showed the largest percentual difference in water content which can be seen in Figure 9.5. The AP lowered the water content in all points but mostly in the brick and wood wool board layers.

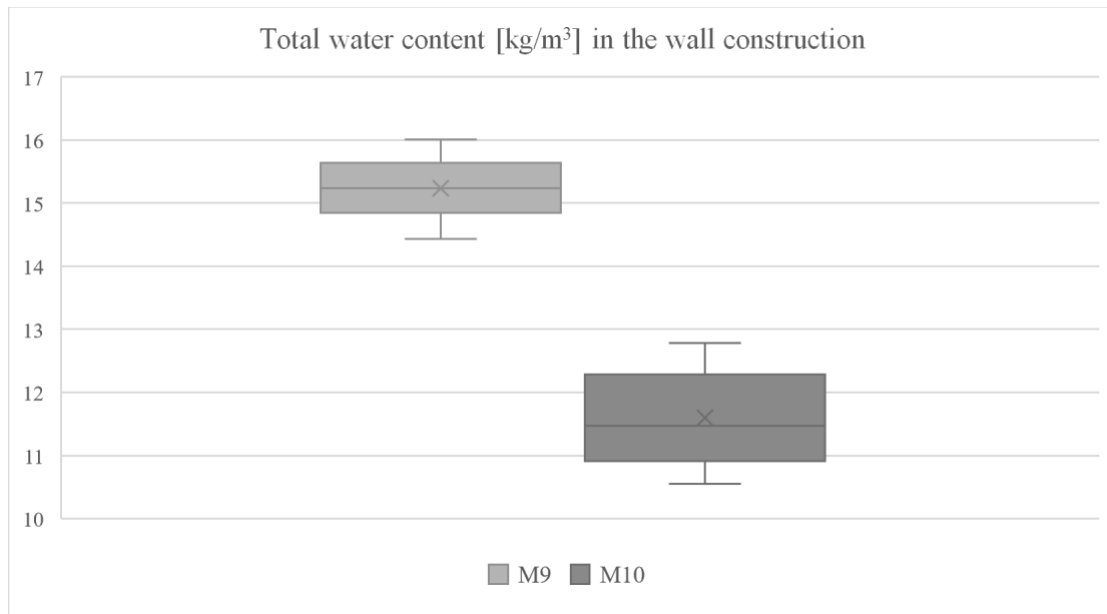


Figure 9.5 Total water content in the construction for M9 and M10.

The freezing-thawing analysis showed no cycles in point 1 regardless of model but point A1 in the AP had 11 cycles during a winter season, the number of cycles in the points are presented in Table 9.5 below.

Table 9.5 Number of freezing-thawing cycles in respective point in the construction over one winter season.

Studied point	Number of cycles
Point 1, M9	0
Point 1, M10	0
Point 7, M9	0
Point A1, M10	11

9.1.6 Concrete and aerated concrete – Model 11 & 12

In contrast to M1/M2 and M7/M8, this model pair had the lowest percentual difference in water content between the two models, which can be seen in Figure 9.6 below. The largest difference was in point 4 which is located centrally in the construction, although the larger reduction could be an effect of the initial conditions set for the concrete layer which is relatively wide. Regardless, the application of AP is affecting the construction positively regarding the moisture safety.

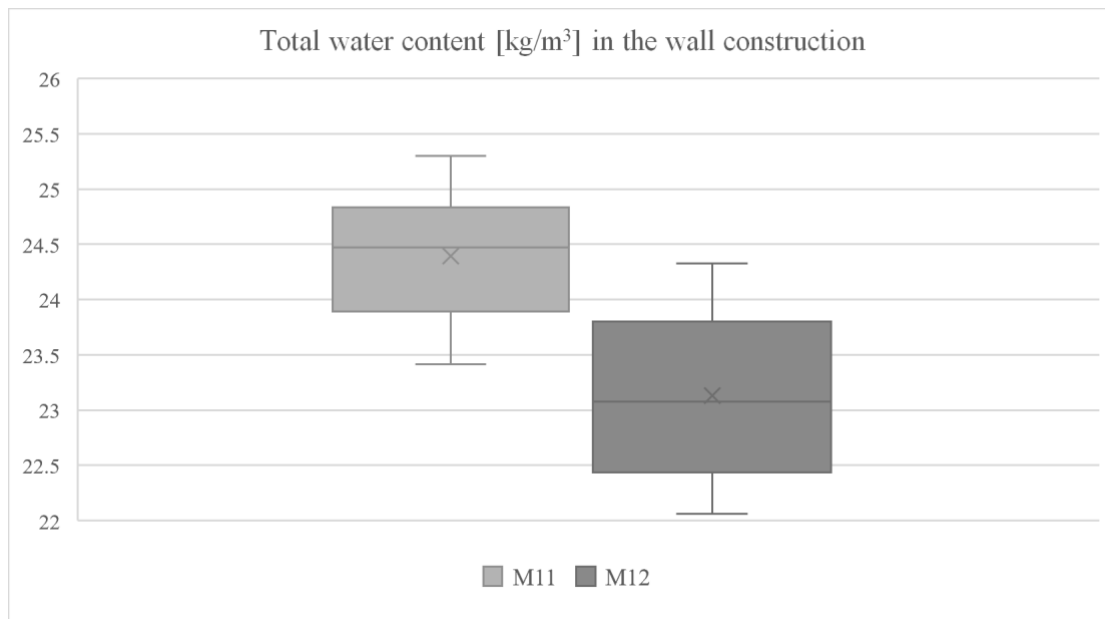


Figure 9.6 Total water content in the construction for M11 and M12.

The models show the same pattern for freezing-thawing cycles as in previous cases. M11 does not experience any cycles in point 1 and 6 closest to the exterior which means that both the render and the aerated concrete is safe for this aspect. However, as the outer part of the wall gets colder with AP, M12 experience 9 cycles in A1. With the above considered, the assessment is that the wall is safe from a moisture point of view.

9.1.7 Summation of all models

All models showed good results regarding water content variation and freezing-thawing cycles which indicates a moisture safe construction according to the pre-set terms. The third parameter is the MGI, mould growth index, which have been studied in the innermost plaster layer in each model. As Figure 9.7 illustrates, none of the models exceeds 80% RH in the internal plaster and will not show indications of mould growth in the MGI tool.

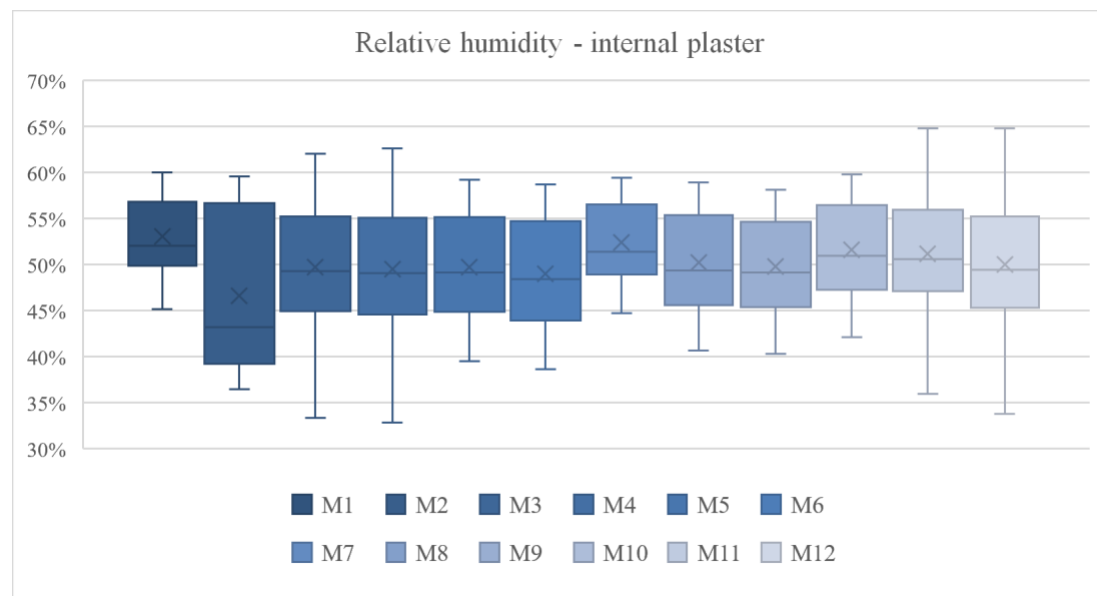


Figure 9.7 Relative humidity in the innermost point of each model.

Remaining points in the models are as well below 80% RH and can be considered moisture safe and free from mould growth. Although it is worth mentioning that the two points in the AP-layer, A1 and A2, have a higher relative humidity than the other parts of the construction. A1 is occasionally reaching a maximum relative humidity of 84%, although the MGI is not indicating any mould growth due to the insufficient moisture content, that the plaster is a non-organic material and that the temperatures are not beneficial for mould growth. There is a risk of organic growth or discoloration on the surface which is a matter of maintenance like any other façade and not a matter of moisture safety.

9.1.8 Change in the heat flux density

The heat flux density [W/m^2] is used to investigate whether heat is entering or exiting the construction and its magnitude. **Error! Reference source not found.** illustrates the heat flux density in M1 and M2 over two years with start in October. The heat flux density is measured in between the internal plaster and the load bearing brick layer. Negative values indicate heat transferring from right to left in WUFI® 2D, which is in this case from the inside to the outside. As the figure shows, the AP-model M2 reduces the maximum outgoing heat by approximately 66% during the winter season. There is also a reduction in maximum ingoing heat during summer season.

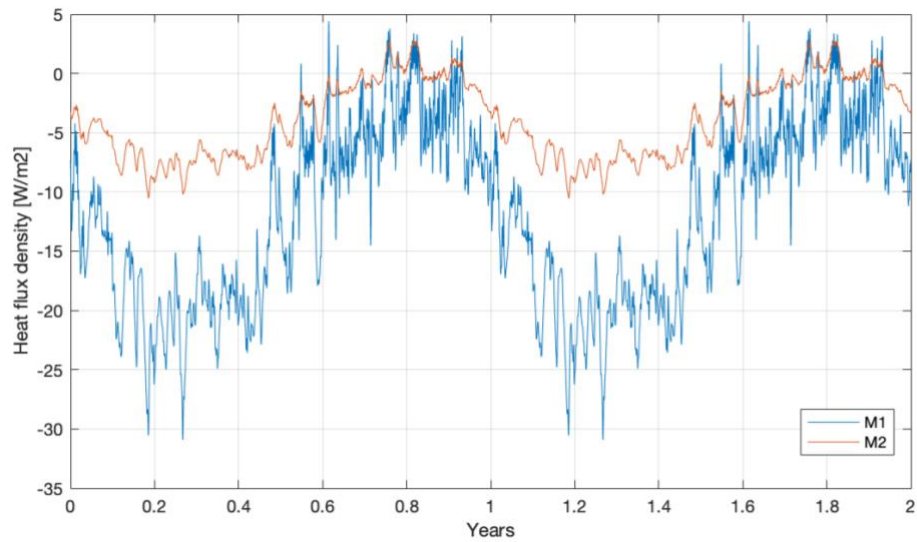


Figure 9.8 Heat flux density [W/m²] over two years, with start in October, for M1 and M2 between the internal plaster and the load bearing brick layer. Negative values indicate heat being transported from the inside to the outside.

9.2 Parametric study

There are many different parameters that affect the results achieved and to be able to draw correct conclusions, a parameter study is performed. This is because certain specific parameters that have been specified can change and thereby affect the result.

9.2.1 Drying rate of Aerogel-based plaster

Based on the moisture dependant thermal conductivity mentioned in Chapter 2.2.2, an analysis has been made. The analyse investigates the time it takes from the point that the AP has been applied to the point that the thermal conductivity reaches 0.027 W/mK which is when the AP is considered to be dry. This has a relation to the drying rate and is combined in the results below. The water content data in the insulation material is extracted from WUFI 2D® which is then translated with the moisture dependant thermal conductivity relation of the material. This generates the thermal conductivity of the material over the simulated period.

The analyse is made for five scenarios to cover a wider base of initial conditions, where all scenarios begin the simulation with 99% water saturation (RH) of the applied AP-layers, the scenarios are:

- A. 5% relative humidity in the brick and internal plaster at application
- B. 50% relative humidity in the brick and internal plaster at application
- C. 80% relative humidity in the brick and internal plaster at application
- D. 99% relative humidity in the brick and internal plaster at application
- E. 80% relative humidity in the brick and internal plaster at application and 10% of the driving rain available for capillary suction (damaged or defective hydrophobic coating)

Running the model with a saturation of 100% in any of the materials generated numerical errors which resulted in outline values, so the highest saturation values are set to 99%. It is important to remember that the difference between the scenarios is the change in initial conditions of the reference materials, namely the brick and internal plaster. The AP-layers are always kept at a 99% RH as an initial condition. Figure 9.9 below shows how the thermal conductivity of the AP changes over time after application for the five scenarios. The “dry” level (0.027 W/mK) is marked in the graph as well.

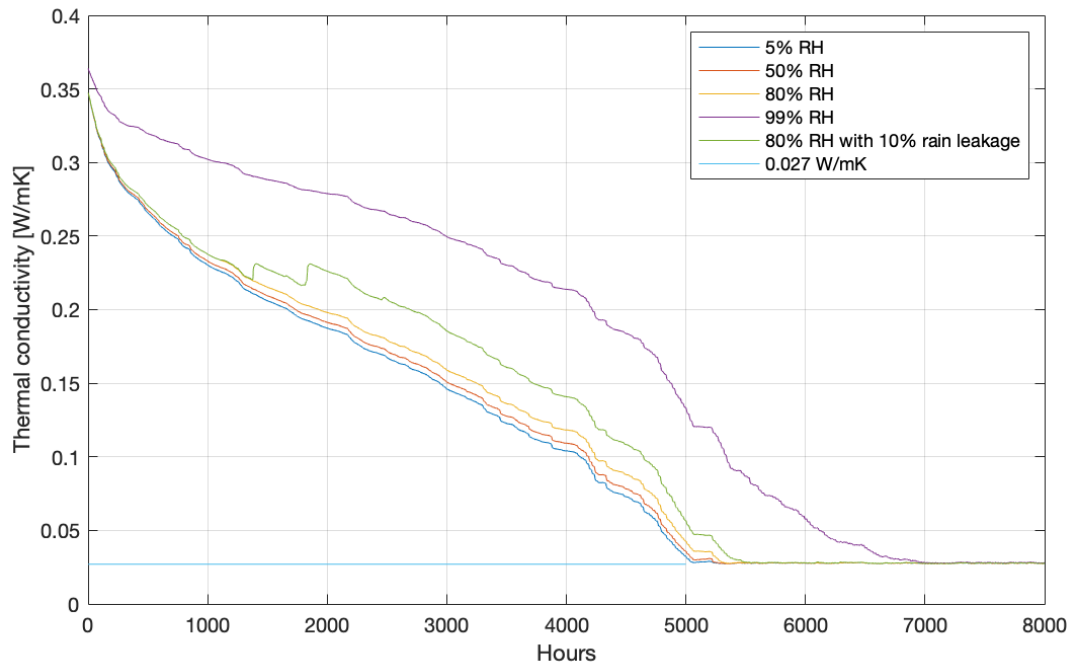


Figure 9.9 Thermal conductivity-based drying rate of the AP for different initial condition in the existing construction.

A saturated construction (D) clearly generates the longest drying rate. The exponential increase of thermal conductivity with increasing water content is severely affecting the results in this study, as the difference between C and D scenarios illustrates. The rain leakage scenario (E) extends the drying rate by a few days compared to C due to the wetting rain cycles which provides the construction with water for capillary suction.

The figure above translated into number of days until the AP reaches a thermal conductivity of 0.027 W/mK is presented in Table 9.6 below.

Table 9.6 Days until the AP is considered dry i.e., reaches a thermal conductivity of 0.027 W/mK.

Scenario	A	B	C	D	E
Days until “dry”	218	220	222	292	231

Consequently, the water content in the existing construction does not have a large impact of the drying rate unless the wall is almost completely saturated which is quite unrealistic. A different parameter which has a larger impact on the drying rate is the time of the year of which the AP is applied. For this study the existing construction is assumed to have a relative humidity of 80% and no leakages or damages are included. Each scenario starts at the first day of the month. Figure 9.10 illustrates the moisture dependant thermal conductivity and the time in hours from application in the first six months.

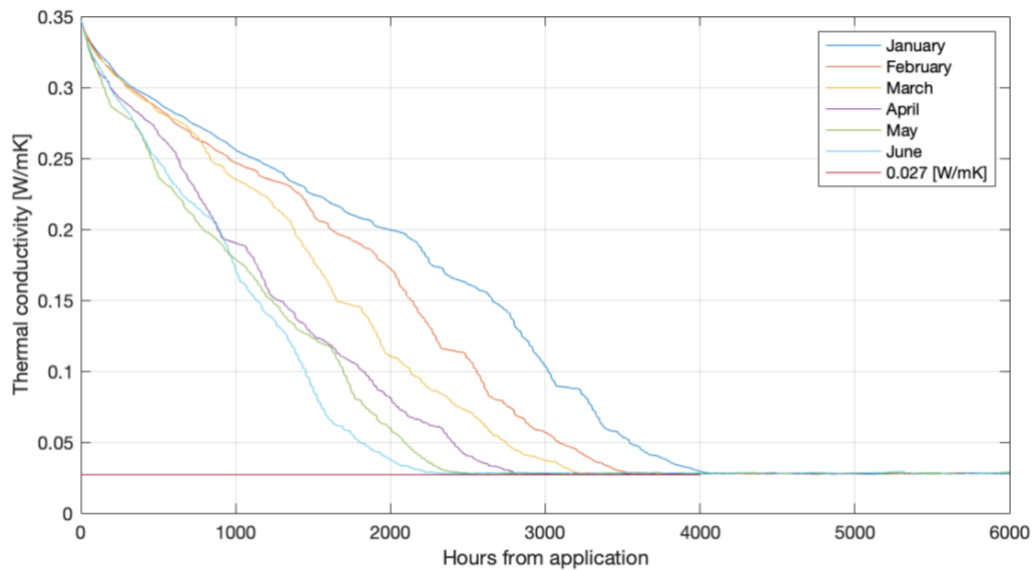


Figure 9.10 Thermal conductivity-based drying rate of the AP for January to June.

The figure shows clearly that application during the colder months have a longer drying rate. Figure 9.11 illustrates the last six months and as can be seen, the drying rate is not elongating towards the colder months as could be expected with regard to the results in Figure 9.10. Here, the longest drying rate is achieved by application in September and the two shortest are July followed by December.

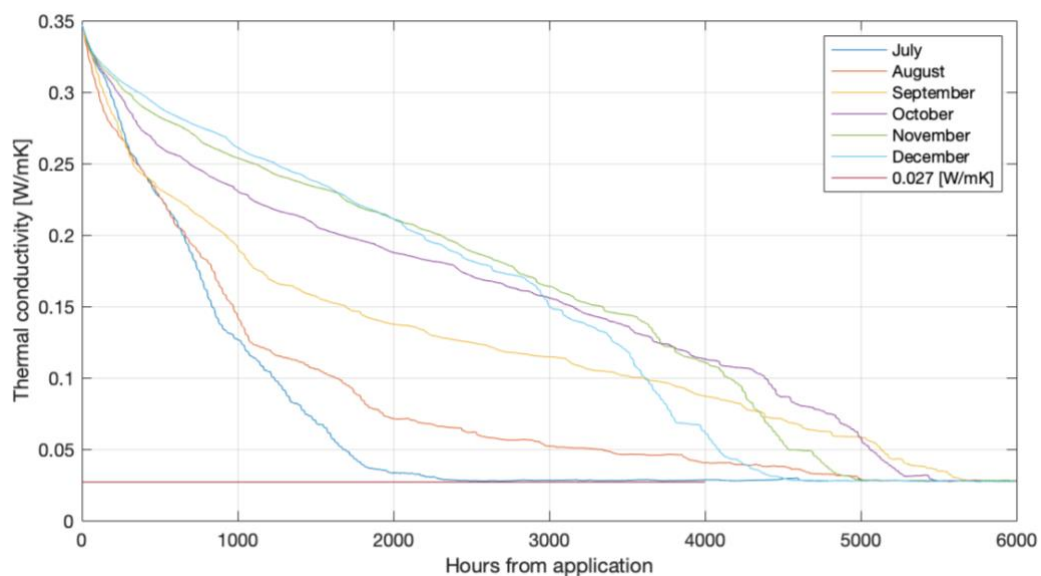


Figure 9.11 Thermal conductivity-based drying rate of the AP for July to December.

The drying rates in days for each month are presented in Table 9.7 below, where the longest drying rate is achieved when application of the AP is done in September. It is important to remember that the AP should not be applied if the outdoor air or substrate temperatures can sink below 5°C before it has dried according to the producer's guidelines (FIXIT AG, 2019). For Gothenburg this would imply that applying the AP between October and May, when there is a risk of temperatures below 5°C, should be

performed with precautions to ensure that the AP can dry according to the stated guidelines.

Table 9.7 Drying rate for different dates of application.

Month:	January	February	March	April	May	June
Days until “dry”	174*	158*	138*	119*	105*	97
Month:	July	August	September	October	November	December
Days until “dry”	104	214	238	229*	212*	196*

*risk for temperatures <5°C

9.2.2 Behaviour of construction with a damaged water repellent layer

The performance of the construction depends on how well it remains damage-free. Since this tends to happen over time in the form of cracks or mechanical stress, this is part of the parameter study. To protect the facade and the AP layer, the manufacturer strongly recommends a hydrophobic layer, and this has been simulated by setting the adhering fraction of rain to zero in the original simulations, which means that no rainwater is available for capillary suction. To investigate the effects of a damage, this factor is now gradually changed from 20 to 80% for M1 and M2 to study what happens when a damage occurs, and water can be absorbed by the facade. The results are shown in Figure 9.12. The total water content has been measured in the interior plaster and brick which remain after that the AP has been applied to avoid irregular volumes and water absorbing capacities.

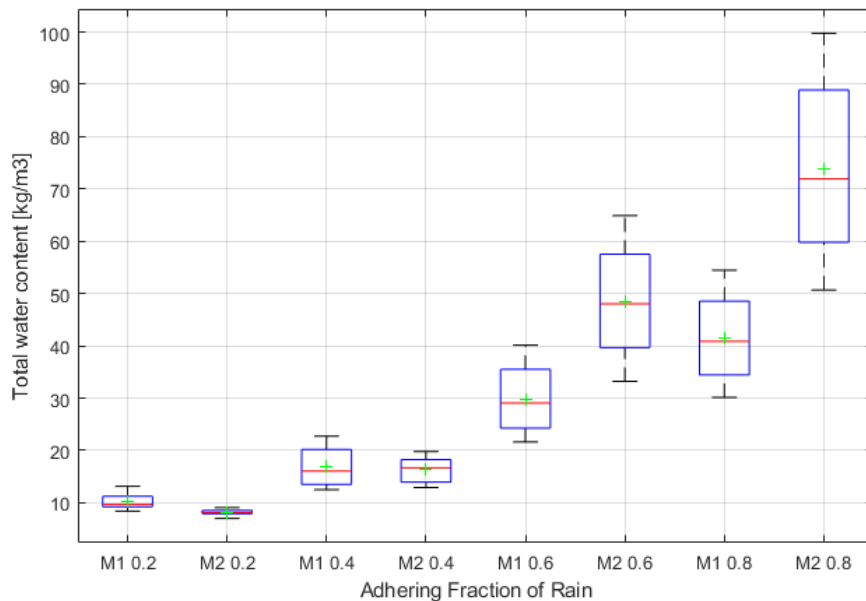


Figure 9.12 Total water content [kg/m^3] shown for M1 and M2, excluding the AP-system with different adhering fraction of rain to simulate a damage on the water repellent layer.

The results show that the water content is lower with a small damage simulated by an adhering fraction of rain of 20% and 40% for M2 with AP applied. When the damage becomes larger and the fraction is set to 60%, the opposite is shown with a larger total water content in M2 compared to M1 and an even larger difference with a fraction of 80%. A higher damage also contributes to greater amplitude in the water content of the structure. The results only show that for a small damage the total water content is less in the wall with AP compared to the reference wall.

The heat flux density is also affected by damage to the construction. Figure 9.13 shows that the heat flux density gradually increases with increasing factors that represent damage to the wall. Negative values in the figure occur due to heat being transported from the inside to the outside, which is defined as negative in WUFI® 2D.

For a value of 20% adhering rain, the average heat flux density is around 12 W/m^2 and for a value of 80% the heat flux density is about 14.5 W/m^2 for M1. As mentioned in Chapter 9.1.8, the heat flux density is lowered with AP compared to the reference case, M1, due to its insulating capability. Also, M2 is affected more by the increasing rainwater accessibility than M1 since its magnitude is larger for an adhering fraction of rain of 80%.

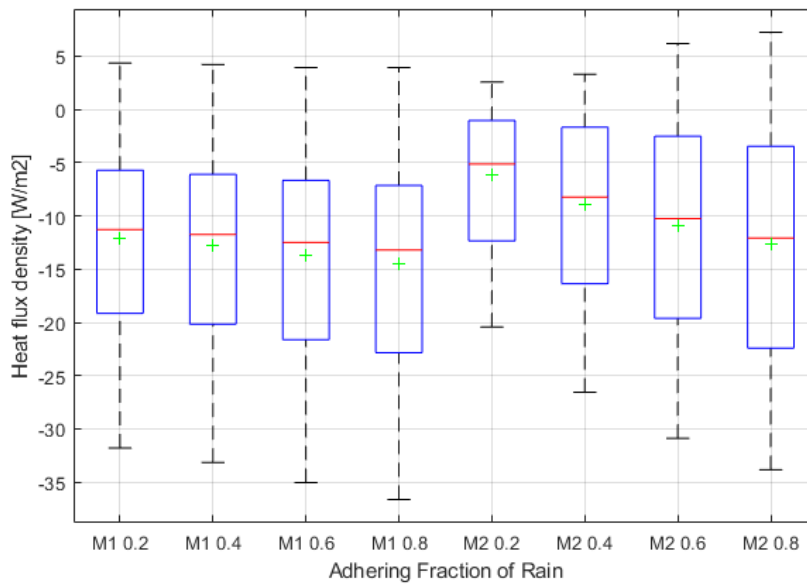


Figure 9.13. Heat flux density [W/m^2] shown for M1 and M2 between the internal plaster and the load bearing brick layer with different adhering fraction of rain. Negative values indicate heat being transported from the inside to the outside.

9.2.3 Thickness of Aerogel-based plaster

As the range of recommended thickness is relatively large, 30-150 mm according to the manufacturer FIXIT AG (2020c), it is of interest to investigate what can happen in the construction if the thickness is increased and how much it affects the moisture performance of the wall.

As the results from the different models in previous chapters has showed, the application of AP benefits the moisture safety of the construction and increasing the thickness is, as expected, improving the moisture safety further. The increase in thickness also reduces the heat loss and improves the energy efficiency. The thickness parameter study will therefore be simulated with an adhering fraction of rain of 70% so that the simulation corresponds to a possible damaged hydrophobic layer (water repellent paint). This parameter study investigates at which thickness of the AP that can provide a protection form penetrating rain to water content levels equal or less than the measured levels in the reference model M1. As previously mentioned, the retrofitting of AP without a hydrophobic layer or a damaged layer increases the water content in the construction. The AP thicknesses which are analysed are: 40, 50, 70, 90, 110, 130, 150 mm.

Figure 9.14 below illustrates the total water content in M1 and in M2 for different AP thicknesses and both wall models are simulated with an adhering fraction of rain of 70%. As expected, the AP-model has an increase in water content due to the rain penetrating the construction and the ability of AP to transport moisture capillary.

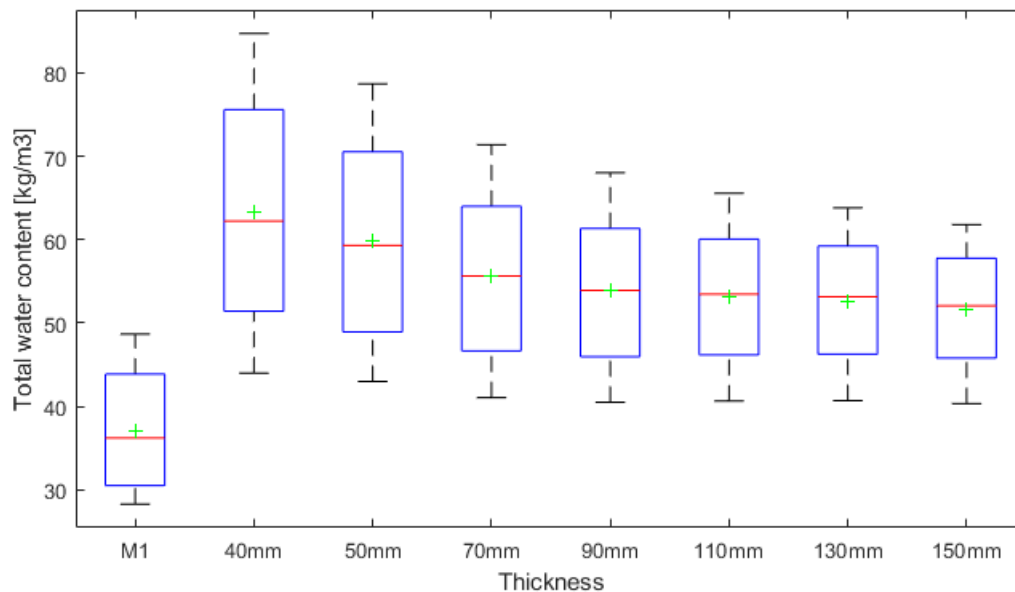


Figure 9.14 Total water content in the construction for different AP thicknesses, rain penetration included. “+” marks the mean and the red line marks the median.

By increasing the AP thickness the moisture inertia increases and the variations in water content decrease, as can be seen by the graph above. The mean value, marked with an “+” in the graph, and the median is decreasing with the thickness but does not reach the previous levels of M1. This reinforces the importance of the producer’s instructions that a hydrophobic layer is necessary and that damages to this layer or that the layer has been defectively applied can have serious consequences. The 90-millimetre model has

a mean water content of 53.94 kg/m³ while the 150-millimetre model stays at 51.56 kg/m³ which is a decrease of 2.38 kg/m³.

9.2.4 Behaviour in different Swedish climates

The hygrothermal properties of AP depend on the climate being considered and therefore this is an interesting parameter to investigate. Climatic data from Gothenburg were originally chosen to simulate the models, mainly because it is the place where the study is carried out but also because the Swedish west coast has an interesting climate with a lot of precipitation and humid air. Places selected for the parameter study are the cities of Lund, Stockholm, and Kiruna to account for the changing climate in Sweden depending on location which is described in Chapter 4.

M1 and M2 have been used for the climate parameter study and the results then show what happens to the reference case with and without an application of AP for the different cities. The result can be seen in Figure 9.15 below and a similar pattern is shown for all cities. An application clearly improves the reference wall by lowering the total water content. In addition, the inter quartile range (IQR) that contains 50 % of the obtained values grows bigger which means that the amplitude of the result has increased. The biggest improvement in result shows Kiruna followed by Stockholm, Gothenburg and Lund based on a mean value. After this parameter study, it can thus be concluded that the results obtained in chapter 9.1 do not only depend on the chosen location.

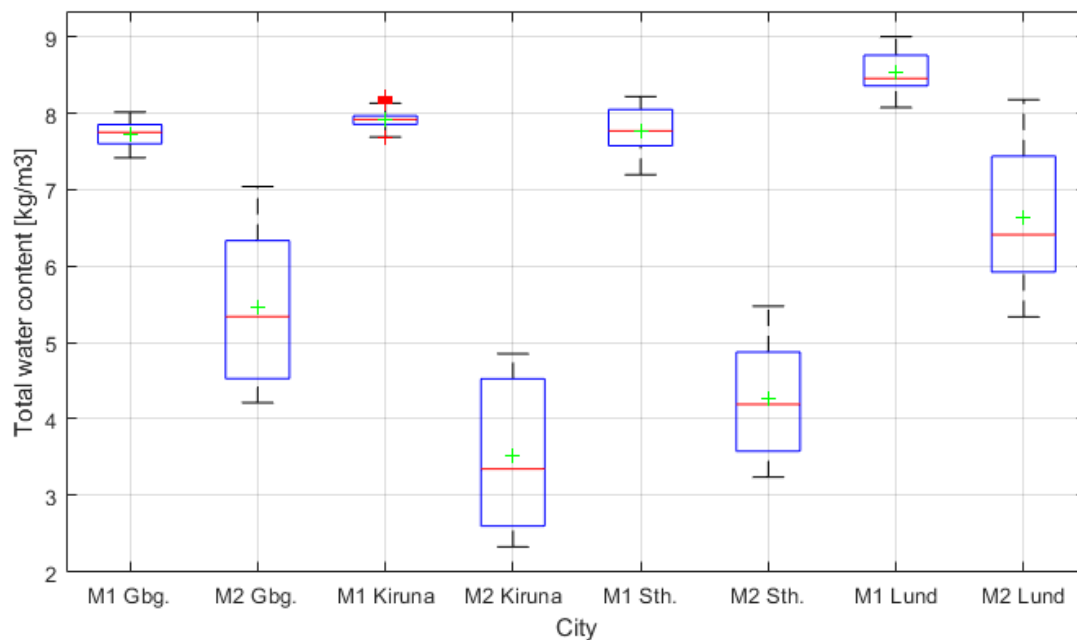


Figure 9.15 Total water content [kg/m³] for M1 and M2 in each city.

9.3 Results from energy simulations in Simulink

For the energy simulations four scenarios or models have been investigated to analyse how the AP can be compared with commonly used insulation materials in Sweden. The models are described in detail in Chapter 7.2.

9.3.1 Comparison between commonly used insulating materials – E1

This case has, as mentioned, the same amount of insulation as shown in Figure 9.16.

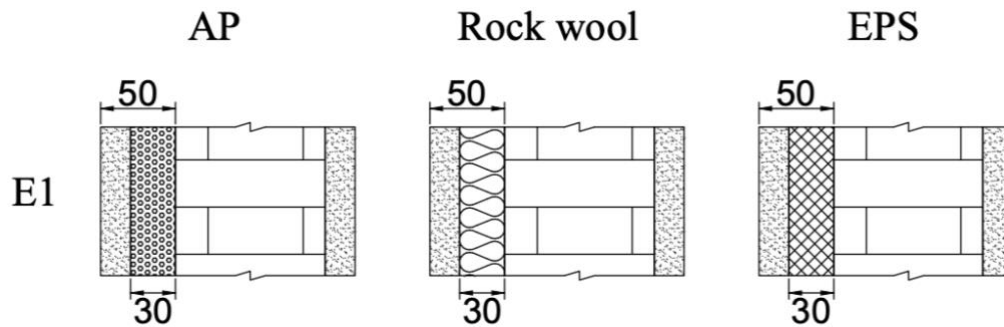


Figure 9.16 Added insulation layers for case E1.

The results from this case are presented in Table 9.8 and as can be seen, both the heating demand and energy savings are more beneficial with AP than the two others. This is predicted mainly due to the thermal conductivity of the materials.

Table 9.8 Heating demand and energy savings for the different insulation materials.

	U-value	Heating demand	Energy savings	Energy savings
Reference	1.18	17.43 kW	-	-
AP	0.51	7.64 kW	31.98 kWh/m ²	56.18%
Rock wool	0.56	8.38 kW	29.58 kWh/m ²	51.96%
EPS	0.63	9.35 kW	26.4 kWh/m ²	46.38%

9.3.2 Realistic thickness of additional insulation – E2

The total thickness of the added layer is in this case is 52 mm for all three cases. The rock wool and EPS are 30 mm thick and have a finishing render of 20 mm. The AP-wall is retrofitted with 40 mm AP as shown in Figure 9.17 and the other layers are the additional layers in the AP-system.

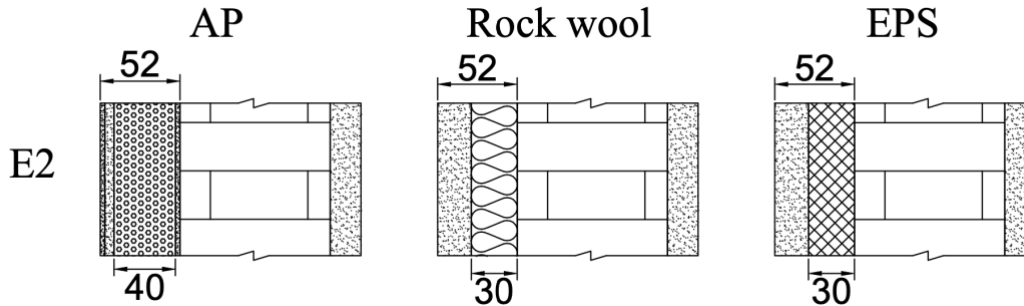


Figure 9.17 Added insulation layers for case E2.

The results which can be seen in Table 9.9, shows that there is a change in the AP-wall only, which is predictable because the changes are only done in the AP-wall. The AP-wall is certainly providing a better insulation due to the combination of a lower thermal conductivity and the ability to build a thicker insulating layer than the two other materials. These results are predictable based on the input data and the material properties which highlights the beneficial thermal conductivity and application method of the AP, compared to the two other materials.

Table 9.9 Heating demand and energy savings for the different insulation materials for realistic thicknesses.

	U-value	Heating demand	Energy savings	Energy savings
Reference	1.18	17.43 kW	-	-
AP	0.44	6.43 kW	35.95 kWh/m ²	63.15%
Rock wool	0.56	8.38 kW	29.58 kWh/m ²	51.96%
EPS	0.63	9.35 kW	26.4 kWh/m ²	46.38%

9.3.3 Effects of moisture dependant thermal conductivity – E3

The analysis is performed for two cases, the first case is a “dry” case where the walls have an intact hydrophobic layer (i.e., paint) and no rain is available for capillary suction into the construction. The second case is a “leaking” case where the hydrophobic layer is damaged, and rainwater can penetrate and be transported into the construction. Here, the adhering fraction of rain is set to be 0.7. Other than the difference in adhering fraction of rain, the two cases are the same as show in Figure 9.18.

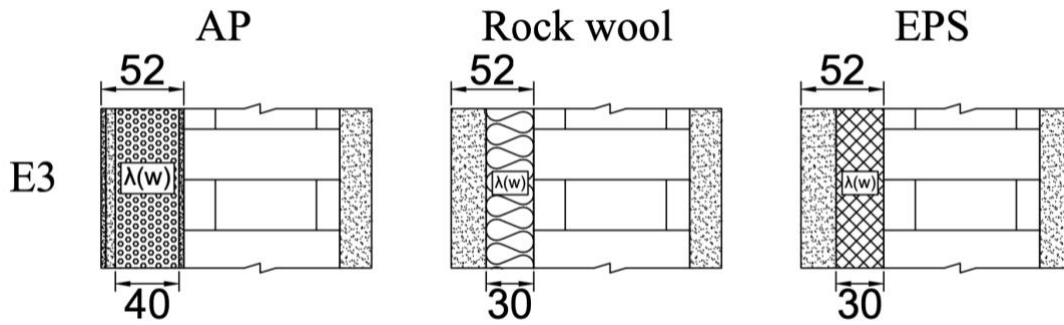


Figure 9.18 Added insulation layers for case E3 with moisture-dependant thermal conductivity.

Table 9.10 presents the results from the dry case and the differences, compared to Table 9.9, are small. The AP case is somewhat lower in energy savings due to more noticeable variations in thermal conductivity while the two other materials, of which the thermal conductivity is not as affected by the moisture variations, remains the same.

Table 9.10 Heating demand and energy savings with moisture-dependant thermal conductivity considered for a “dry” case with 0% adhering fraction of rain.

	U-value	Heating demand	Energy savings	Energy savings
Reference	1.18	17.43 kW	-	-
AP	Varying	6.49 kW	35.65 kWh/m ²	62.63%
Rock wool	Varying	8.38 kW	29.58 kWh/m ²	51.96%
EPS	Varying	9.35 kW	26.4 kWh/m ²	46.38%

For the leaking, or damaged, case the results have drastically changed. As presented in Table 9.11 the heating demand in the AP case is much higher than in Chapter 9.3.2 (E2), the same applies to the energy savings which are much lower. The two other materials remain the same in this case as well, which is not that unpredictable. When comparing the moisture-dependant thermal conductivity of the two materials and the AP, the rock wool and EPS are not that affected by the levels of water content the materials are experiencing in these simulations and remain their prescribed thermal conductivity of 0.032 W/mK and 0.04 W/mK, respectively.

Table 9.11 Heating demand and energy savings with moisture-dependant thermal conductivity considered for a “leaking” case with 70% adhering fraction of rain.

	U-value	Heating demand	Energy savings	Energy savings
Reference	1.18	17.43 kW	-	-
AP	Varying	15.29 kW	9.51 kWh/m ²	16.7%
Rock wool	Varying	8.38 kW	29.58 kWh/m ²	51.96%
EPS	Varying	9.35 kW	26.4 kWh/m ²	46.38%

So, in the dry case all three materials remain their prescribed thermal conductivity due to the low levels of water content while the damaged AP-wall had a large increased U-value. Figure 9.19 illustrates the moisture-dependant thermal conductivity variation of the AP for one year (starts in October) and the material is highly affected. During the winter months the thermal conductivity variates around 0.35 W/mK and as the graph shows, the thermal conductivity remains above 0.027 W/mK during the entire year.

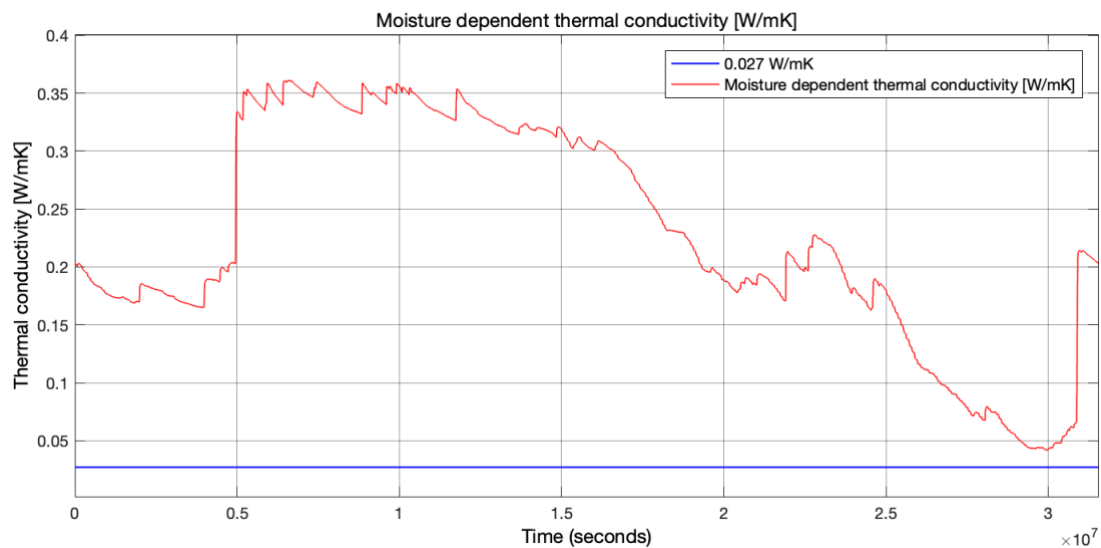


Figure 9.19 Thermal conductivity of the AP during one year with water accessible for capillary suction, start in October. Time in seconds.

The high thermal conductivity has a direct impact on the wall U-value and results in higher heating and energy demands. Figure 9.20 below illustrates the U-value of the AP based wall and how it variates during the year.

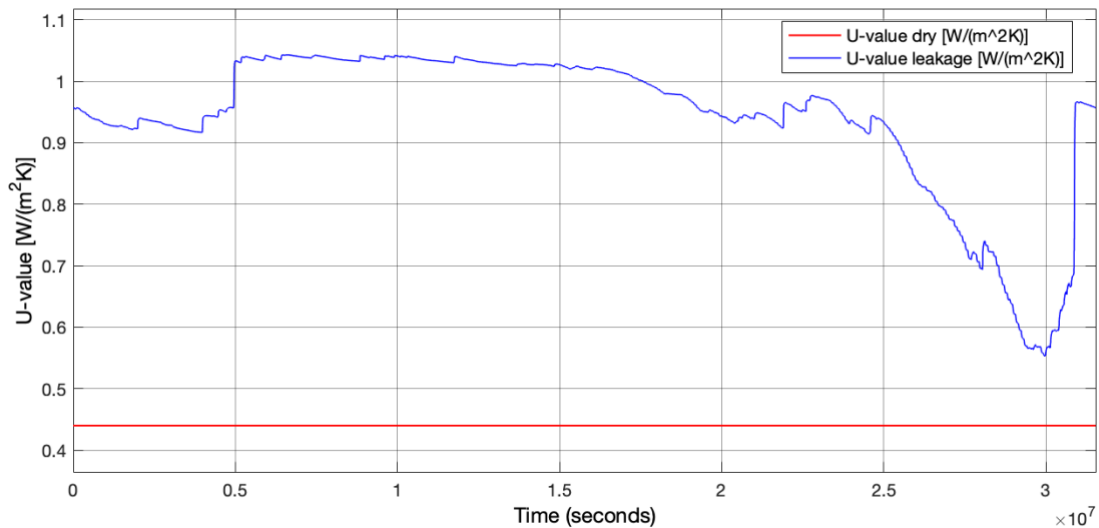


Figure 9.20 Varying U-value of the wall with AP, with water accessible for capillary suction and a dry case.

The U-value in the figure above is not ideal for a renovated wall with an additional insulation. As mentioned in Chapter 5.3, the Swedish building regulations state that the U-value of a wall should not exceed 0.4 and 0.6 for multi-family buildings and commercial buildings respectively.

9.3.4 The first year after applying Aerogel-based plaster – E4

This case has the walls build up as in case E3, but the difference is that this case begins the simulation directly after application. Figure 9.21 illustrates the walls in case E4.

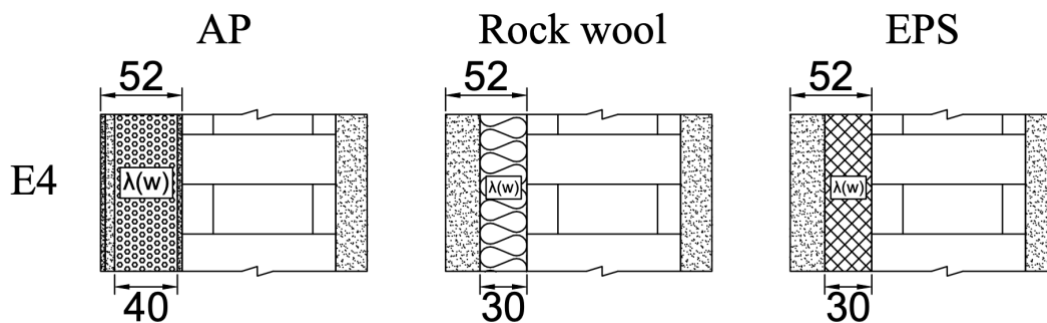


Figure 9.21 Added insulation layers for case E4 with moisture-dependant thermal conductivity.

The layers in the AP-system are set to have an initial relative humidity of 99% while the other walls are in their dry state i.e., 50% RH.

The energy savings during this year is around 30.27% (17.23 kWh/m²), which is lower than in the realistic case (63.15%) in Chapter 9.3.2. Figure 9.22 illustrates the thermal conductivity during the first year after that the AP has been applied and as it dries out it lowers its thermal conductivity as was seen in the drying rate study in Chapter 9.2.1. The U-value of the wall follows the thermal conductivity and drying rate, see Figure 9.23.

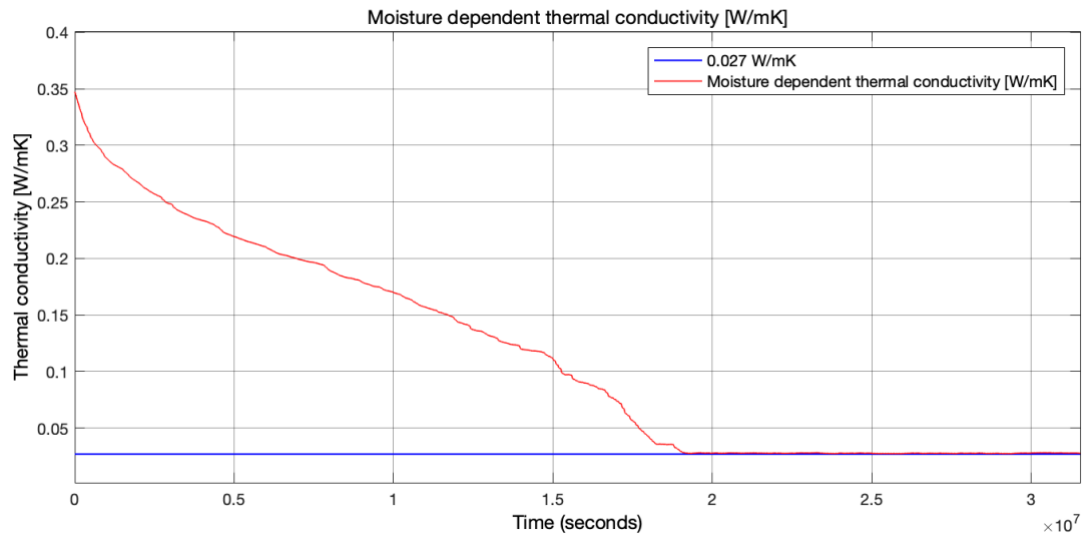


Figure 9.22 Thermal conductivity of the AP during the first year after application.

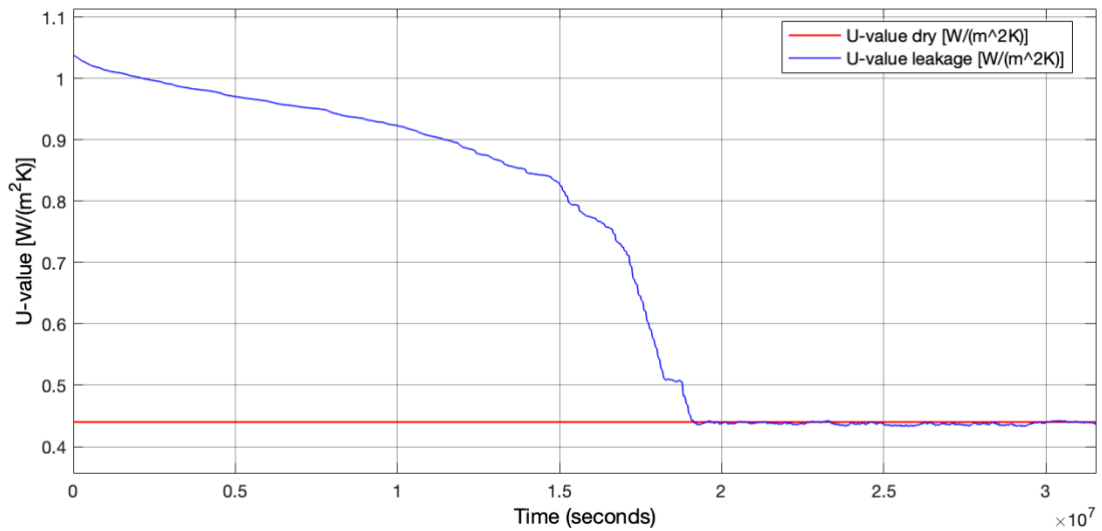


Figure 9.23 U-value of the AP-wall based wall during the first year after application.

The first year saves approximately 52% less energy than the dry case in model E3 which does not include the drying period of the AP.

9.4 Economic assessment

The calculated investment cost for the different renovation alternatives can be seen in Table 9.12 below and the data used can be found in Chapter 8.4.

Table 9.12 Investment cost for the renovation alternatives.

	AP	Rock wool	EPS
Investment cost [SEK]	1 127,568	892,658	892,658

The results in Table 9.13 show that the investment for AP is more expensive than both rock wool and EPS, but that the energy savings are greater for AP than the other alternatives, which are expected results. As mentioned in previous chapters, the energy savings are lower the first year due to the drying process of AP. However, this has marginal effects over 30 years and does not affect the result.

Table 9.13 Economic calculation of different renovation strategies, values in [SEK].

	Investment cost AP	Energy savings AP	Investment cost rock wool	Energy savings rock wool	Investment cost EPS	Energy savings EPS
NPV	-1,073,874	567,061	-850,150	470,510	-850,150	419,927
EAC-factor	15.37	15.37	15.37	15.37	15.37	15.37
EAC	-69,857	36,888	-55,303	30,607	-55,303	27,317
Tot	-32,969		-24,696		-27,987	

10 Discussion

The purpose of this study is to investigate hygrothermal properties of different wall constructions in Sweden when applying AP and to determine to what extent these can be considered moisture-safe or not. A reference case was used as a starting point for concretizing the work and the three criteria used to assess whether a construction can be considered moisture-safe or not are the following:

- A. Stable or decreasing water content in the construction.
- B. Low risk of frost damage due to freezing-thawing cycles.
- C. Low risk of mould growth in the construction or internal surfaces.

The results obtained are promising for a commercial usage in Sweden and all wall constructions show an improvement from a moisture point of view. Mainly because the total water content in the construction decreases after an application of AP and that no risk of mould growth was demonstrated. The risk of frost damage is at a slightly higher level with AP compared with a construction without, this is because the construction has become colder on the exterior side. Many parameters affect the results and to validate these, a parameter study was also carried out.

The hygrothermal analysis have showed similar results as previous studies done on the subject. There is a difference which has the climate as an underlaying factor but comparing the results with previous studies is difficult due to the lack of information on conditions and used material properties in previous studies.

Of the three moisture safety criteria's, the freezing-thawing criteria is complicated to define since different materials have different sensibilities to freezing. The studies showed that the freezing-thawing cycles were minimal, according to the stated definition of a cycle. The finish layer in the AP constructions indicated more cycles due to the reduced heat conducted through the wall and these cycles indicates that there is a possible risk of frost damage. The damaged areas can become a way for rainwater to penetrate the construction and as the damage analysis showed, the consequences can be severe. It is important to mention that the properties of the finishing layer material recommended by the producer is even less documented. So, the behaviour in this material regarding the matter of freezing-thawing e.g., frost damage, is too unsure to be able to draw any conclusions.

The drying rate study resulted in two parts, the first was the drying rate for different initial conditions of the existing materials and the second was the drying rate for different application months. The first study showed predicted results, that the more moisture there is in the construction, the longer the drying rate becomes. Although, one of the models included a damage simulation and 80% relative humidity in the construction which resulted in a shorter drying rate compared to the undamaged model with 99% relative humidity. The hypothesis for the damaged model was that the drying rate would have been longer, but the moisture content seems to be much higher in the 99% RH-case. Probably due to the steep moisture sorption isotherm of the AP between 80-100% RH so the effects of the damage are small in comparison.

The time of an application plays a major role in the drying and thus energy performance of the material. An application at a time in wet conditions can generate a more than twice as long drying time compared to an application during the summer. This means that it can take very long time for the material to reach the low thermal conductivity of 0.027 W/mK, which means that "the large energy savings" cannot be assumed to start immediately after an application. The analysis showed that the optimal month for

application was June of which the drying rate was shortest, 97 days. The longest drying rate was achieved when applying the AP in September, most likely due to the heavy wind driven rains, the high relative humidity and the low temperature.

The parameter study of different façade damage magnitudes has provided strong arguments for the application of a sealed hydrophobic layer on the exterior side to provide a barrier between the AP and the precipitation. The AP has showed good results regarding moisture safety but has a clear backside if in contact with accessible rainwater due to its ability to absorb water. With the heavy and often occurring wind driven rains in the Swedish climate, or more specific in the Gothenburg area, the AP constantly refills its water content, and the drying occurs through the capillary suction of the surrounding materials, including the internal layers. So, to remain a moisture safe construction it is important that the hydrophobic layer is intact. It is also important to mention that, according to the study, the smaller damages where 20-40% of the rain hitting the wall becomes accessible for capillary suction showed better results compared to how the reference wall corresponded to the same level of damage. The more serious consequences appear when the damage allows more than 40% of the rain to be accessible for capillary suction, which is unrealistic to not notice as a building caretaker.

The thickness analysis was intended to investigate how the moisture behaviour changed depending on the thickness. An increased thickness had no negative effect on the moisture safety, on the contrary it had a positive effect showed in decreasing water content. The study could have been extended to analyse the heat flux for different thicknesses. But due to the results from the moisture analysis and the fact that more insulation would lower the thermal conductivity of the wall it was assumed that the results would be beneficial for the AP and unnecessary to present. The study showed that after 90 mm the additional thickness was not considered as a sufficient moisture reduction to justify the additional 60 mm of AP but if the thickness is necessary for achieving certain energy targets there are no risks of compromising the moisture safety of the construction which is the important part in this specific study.

With a change in the location and thus the climate in the simulations, a certain difference in results was obtained. In each case, the water content of the structure was lowered while the amplitude increased. Kiruna had the best result with a decrease in average of around 60%, followed by Stockholm, Gothenburg and Lund. The differences in results may seem to be due to the difference in the annual precipitation for the different locations. The greatest precipitation is obtained in Gothenburg, followed by Lund, Kiruna and Stockholm. However, this does not correlate with the result, and it is rather due to a combination of many different parameters around the climate such as time for precipitation, humidity, solar radiation. The precipitation also has a greater risk of being in the form of snow that cannot be capillary absorbed by a construction.

Evaluating the energy performance of a wall or building with the AP can be considered as the most studied subject on the material based on the reports and journals studied at the beginning of this project. So, the energy performance of a building was not the major focus but how the energy performance is affected depending on different parameters connected to the specific climate and Swedish building norms.

The realistic thickness simulation was aimed to model the simulation so that it could be compared to a real case where you must choose between three different insulation materials, AP, rock wool and EPS. One of the benefits of the AP is that there is no need for additional constructions like studs and plaster boards, with the exception that the AP needs a reinforcement mesh at certain thicknesses. The other two materials can be

directly applied to the existing wall but need a thicker layer of render or a so-called render board applied between the insulation material and the external render to carry the render. These conditions allow the AP to be somewhat thicker than the rock wool and EPS, but the total thickness of the new layers remains the same. A thicker AP combined with the lower thermal conductivity improves the energy performance of the building more compared to the other two materials.

Using the stated thermal conductivity of 0.027 W/mK showed good results in the energy simulations which remained when the water content from the moisture simulation was connected to the thermal conductivity. Although, the results were drastically changed when a damage to the hydrophobic layer was simulated. As the damage simulation showed, the AP can absorb a lot of water which directly affects the thermal conductivity. With an adhering fraction of rain set to 0.7 the thermal conductivity of the AP varied between 0.05-0.35 W/mK. So, the AP is sensitive to higher levels of water content regarding the thermal conductivity compared to rock wool and EPS which did not get affected by the increased levels of water content. The moisture dependant thermal conductivity of the rock wool and EPS are taken from the material database in WUFI® 2D and haven't been further investigated or controlled against alternative sources. This may be a possible source of error, but the assumption is that alternative properties would not differ at the level that the results would be different.

The last analysis in the energy simulations were the comparison between the first year after that the AP had been applied and a year where the AP has dried out. The results were that during the first year the energy savings are 52% less than a later year. Compared to the reference case the energy usage during the first year are 30.3% lower meanwhile a later year with the AP is 62% lower, which is a significant difference. The other two materials, rock wool and EPS, don't have this disadvantage because they don't have a drying process and reach their full effect right after application.

The economic evaluation used the net present value method, which is a commonly used method for calculating the profitability of various investments. The conclusion that can be drawn with the assumed values of lifetime, interest rate, cost of district heating, inflation, etc. is that no alternative will pay back, and rock wool is the alternative that accounts for the least "loss" followed by EPS and AP. It does not matter that AP is better from an energy point of view. The economic evaluation is a challenge in several ways and many sources of error can occur. First of all, the cost is related to the AP itself is estimated by a source to be around €30/m²/cm for the material and double the cost of labour and assembly. However, it is important to keep in mind that prices can differ considerably between countries. An application of AP consists of a total of several different layers that must have time to dry out. The work is thus estimated to have some interruptions as not everything can be done at once, which reasonably entails a greater cost. Compare this with rock wool and EPS where the process is assumed to be shorter. Other sources of error in the calculation are the input data. The price of district heating and inflation can vary a lot. The lifespan of 30 years is also an estimate. The new material has only been developed for about a decade and from this it cannot be said with certainty that it has a lifespan of 30 years as it has been assumed in this example.

As the investment cost is strongly dependent on the thickness, a difference in results is also obtained if this parameter is changed. At a calculation of 40 mm, the AP alternative becomes more expensive than the conventional alternatives, but already at 30 mm, the result is the opposite. The calculation thus means that a thinner layer of AP is economically preferable, which means that it is well suited to listed buildings that can

be protected from changes in appearance and façade. If such regulations do not exist and plans have been made for a thicker external insulation, the result will be different. As the investment cost for AP in this calculation strongly depends on the thickness, the investment cost will increase a lot when applying a thicker layer. A thickness of about 8-9 cm will instead make rock wool and EPS the better investment choice. A note regarding the NPV-values is that negative results occur in all tested cases but do not have to be a major disadvantage, for example, a renovation may be necessary to be able to use the building at all due to maintenance reasons. Other aspects can be stricter energy regulations or to protect the cultural heritage value of an old building.

Further development of the economic evaluation is to ask for a real economic offer from a company regarding renovation costs for rock wool and EPS as this probably gives more accurate results compared to “ÅFs lilla prisbok” by ÅF (2018). Greatest focus should, however, be placed on the price estimate of AP as it is most relevant and interesting in the context.

One of the first sources of possible errors was the material properties. In order to analyse the AP and related additional materials in WUFI® 2D, a full insight on the properties is essential for tenable results. The producer FIXIT only provides the key values in the declaration of performance sheets and technical data sheets, which is not near the amount of information needed for these types of studies. The information has been complimented by different studies which focused on the hygrothermal properties e.g., the moisture sorption isotherm and moisture dependant thermal conductivity. The lack of information also complies for the existing materials used for the reference models, like the brick, ordinary plaster/render, and concrete. But the properties of these materials have not been of the greatest importance because the focus has been on comparing the results before and after that the AP had been applied so that the effects of the application of AP is validated.

A proposal for an extension of the analysis is to include rain in the study in the form of putting a value on the adhering fraction of rain that has been done in other simulations. This is to see if the same result had been obtained in the other cities compared to Gothenburg, which showed an increasing water content over time. It would have been especially interesting to see differences between Gothenburg and Stockholm and Kiruna as Lund has a similar climate to Gothenburg. In summary, it can be said that the chosen climate has a very large impact on the result, which is also reasonable, but this gives rise to further considerations. It would have been interesting to examine the climate data in detail to try to find and look more closely at the specific parameters that affect the result.

11 Conclusion

This study concludes that AP demonstrates a promising result from a moisture and energy point of view in a Swedish climate. The study gives results that are in line with previous research on the subject, which further strengthens it.

The conclusions from the study are that the AP is a perfect addition to the building materials in Sweden but that it has certain limitations, and the risks are more present than other insulating materials. Retrofitting a wall with AP on the exterior surface provides an exceptional thermal insulation but keeping it out of contact with liquid water is of high importance. What can be seen from the producer guidelines and that can be confirmed by the study is that a hydrophobic layer should be applied e.g., hydrophobic paint to reduce the water exposure.

Comparing the AP with commonly used materials in Sweden the study shows that the AP performed better in an energy and moisture performance point of view. Although, the consequences due to a damage or leakage are higher with AP. The studied models, which cover a large part of Sweden's historical or older building stock, work well with the AP. When it comes to the economic aspects, the AP is more suitable when walls only can be retrofitted with thinner layers of additional insulation i.e., older, and listed buildings. For thicker layers the benefits of the AP system do not meet the investment as other insulation systems may work better.

For further studies a more detailed economic analyse is recommended to produce a better basis for decision-making in the construction sector. The long-term performance is also an unknown factor which needs further research.

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DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF BUILDING TECHNOLOGY
CHALMERS UNIVERSITY OF TECHNOLOGY

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