Vapour-open, non-capillary active internally insulated historic solid brick masonry:

The influence of hygrothermal properties on the hygrothermal performance.

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Ninah Hubregtse
4595556

Msc Architecture, Urbanism & Building Sciences
Master track: Building Technology

Mentors
Dr.ir. Willem van der Spoel
Environmental & Climate Design

Dr.ir. Wido Quist
Heritage & Technology

External Collaborator
Ing. Kitty Huijbers
ABT bv

Delegate of the Board of Examiners
Ir. Leontien de Wit
Interiors Buildings Cities

Delft University of Technology
Faculty of Architecture & the Built Environment
Department of Building Technology

Julianalaan 134
2628 BL Delft
The Netherlands

ABT bv

www.abt.eu
Contact: info@abt.eu

Abstract

Energy consumption has become a significant global issue due to climatic and environmental challenges, a lack of energy resources, and rising energy prices. The building stock accounts for 40% of the total energy consumption. Therefore, efforts should be made to explore possibilities to reduce the energy consumption and related CO_2-emissions, not only by the construction of modern and energy-efficient buildings, but also through energy retrofitting existing buildings. Historic buildings often have thermal discomfort, cold draughts close to the exterior walls, and high energy consumption due to heat losses. Hence, the improvement of energy efficiency of historic buildings is important. Moreover, preserving architectural heritage can reduce our reliance on new materials for new buildings and reduce energy use in manufacturing processes. The potential for energy efficiency of historic buildings depends on an appropriate compromise between the need to conserve cultural heritage inherited in the building and energy efficiency measures.

Reducing energy consumption and raising thermal comfort is possible by adding thermal insulation to the building envelope. Most historic buildings have facades with cultural, historic and aesthetic value, therefore, internal insulation is proposed as a suitable measure. The application of internal insulation changes the hygrothermal behaviour of a facade significantly and might result in hygrothermal risks such as frost damage, interstitial condensation and mould growth. The change in hygrothermal behaviour depends on the type of internal insulation system. Nowadays, vapour-tight and vapour-open, capillary active, internal insulation systems are mostly used for historic buildings.There is no consensus about the third internal insulation system: a vapour-open, non-capillary active due to a lack of knowledge about the hygrothermal behaviour of this system from theoretical and practical perspectives.

The aim of this research is to gain insight into the most influential hygrothermal properties of vapour-open, non-capillary active, internally insulated historic solid brick masonry. Through literature review, background information is obtained on the hygrothermal behaviour of vapour-open, non-capillary active internal insulation of historic solid brick masonry by exploring the factors that influence this behaviour. Prerequisites for the risk-free hygrothermal performance of a vapour-open, non-capillary active, internally insulated historic solid brick masonry wall are defined based on the risk of mould growth due to interstitial condensation and taking moisture-sensitive wooden elements into account. This approach is sufficient for one-dimensional and two- or three-dimensional situations.

The influence of hygrothermal properties on the hygrothermal behaviour of vapour-open, non-capillary active, internally insulated solid brick masonry of historic residential buildings is studied by a parameter study, which is carried out through Heat, Air and Moisture simulation software WUFI 2D.4. To gain insight into the influence of the hygrothermal properties on the hygrothermal performance, the boundary condition of the outdoor environment is simplified by excluding solar radiation and wind-driven rain. In the parameter study, four hygrothermal properties were studied: the μd-value of the finishing layer, the μd-value of the insulation layer, the thermal performance of the insulation layer and the moisture storage capacity of solid brick masonry. Finally, a prediction method of the hygrothermal performance of a building component is explored, which can be a useful tool to quickly assess the hygrothermal performance of a building component, without conducting advanced Heat, Air and Moisture simulations which might not be available.

From the research, it can be concluded that for the studied hygrothermal properties and boundary conditions, the moisture storage capacity of historic solid brick masonry has the most influence on the hygrothermal behaviour of a vapour-open, non-capillary active internally insulated historic solid brick masonry facade. The outcome of this research shows that a high moisture storage capacity of solid brick masonry has a lower risk on mould growth due to interstitial condensation at the interface between the solid brick masonry and insulation layer. Furthermore, the explored prediction method shows quite adequate predictions for the single variation of the parameters.

Acknowledgement

During my studies at the TU Delft, I had the opportunity to learn, get inspired, and interact with people, which shaped my imagination about a sustainable future of the built environment and also my personal life. This exciting period ends with this graduation project, the master thesis *‘Vapour-open, non-capillary active internally insulated historic solid brick masonry: The influence of hygrothermal properties on the hygrothermal performance’*. After eight months of intensive work, this finishes my master Architecture, Urbanism & Building Sciences with the master track Building Technology.

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1 Introduction

Energy consumption has become a significant global issue due to climatic and environmental challenges, a lack of energy resources, and rising energy prices (Vereecken & Roels, 2014). Therefore, the reduction of energy consumption and related CO2-emission is crucial (Hansen, 2019). The existing building stock has significant potential to achieve this decrease (Vereecken & Roels, 2014). In Europe, the building stock accounts for 40% of the total energy consumption (Hansen, 2019). Historic buildings are often far less energy-efficient than new buildings, they account for a significant portion of the overall energy consumed by buildings (Janssen et al., 2019). Furthermore, historic buildings often have thermal discomfort, cold draughts close to the exterior walls, and high energy consumption due to heat losses (Jensen et al., 2020). Hence, the improvement of the energy efficiency of historic buildings is important.

Historic buildings preserve the character of humans and give humans a sense of identity. Therefore, it is essential to conserve historic buildings. Moreover, preserving architectural heritage can reduce our reliance on new materials for new buildings and reduce energy use in manufacturing processes. One of the most effective strategies to promote the sustainability of historic buildings is to continue keeping them in use. It is necessary to make conservation upgrades in order to extend the lifespan of historic buildings. The preservation of architectural heritage entails supporting effective measures for energy reduction to reduce climate change and keep historic buildings in use (Andreotti et al. 2020). Hence, the focus is to improve the energy efficiency of historic buildings to keep the historic buildings in use. It may seem conflicting to preserve historic, cultural and aesthetical values while also enhancing the energy efficiency of historic buildings. The potential for energy efficiency of historic buildings depends on an appropriate compromise between the need to conserve cultural heritage inherited in the building over the period of its several centuries of existence and energy efficiency measures (Blumberga et al., 2016).

The thermal performance of the building envelope, the HVAC system, and occupant behaviour all affect the energy efficiency of buildings. According to Vereecken & Roels (2016), the first and most significant retrofit step should be the thermal upgrading of the building envelope. Reducing energy consumption and raising thermal comfort is possible by adding thermal insulation to the building envelope (Klõseiko et al., 2015). Most facades of historic buildings have cultural, historic and aesthetic value. Therefore external insulation is often not possible and internal insulation is proposed as a suitable measure to reduce energy consumption (Bjarløv et al., 2015)(Hansen, 2019). However, Vereecken & Roels (2014)(2016) and Hansen (2019) state that the hygrothermal behaviour of an existing façade will change significantly after internal insulation is applied, which might result in frost damage, interstitial condensation, mould growth, and other damage forms. In addition, the change in hygrothermal behaviour is also dependent on the type of internal insulation system. The three internal insulation systems that can be distinguished are vapour-tight; vapour-open, capillary active; and vapour-open, non-capillary active (Stappers, 2020).

Nowadays, vapour-tight and vapour-open, capillary active, internal insulation systems are mostly used for historic buildings. Disadvantages of both systems are their demand for precise workmanship during the application to ensure risk-free performance and an increase of the indoor relative humidity after application might be possible if no extra ventilation is added (Zhao et al., 2017)(Vereecken & Roels, 2016)(Toman et al., 2009). For the third internal insulation system, vapour-open, non-capillary active, there seems to be a conflict about the recommendation of this internal insulation system for historic buildings between the practice and theoretical point of view.

Theoretically, the vapour-open, non-capillary active, internal insulation system is not recommended due to expected damage, especially for the critical points with moisture-sensitive wooden elements. However, from the conservation-practice point of view vapour-open, non-capillary active, internal insulation systems might be preferred since this system is less sensitive to errors in application to the historic brick masonry wall and user behaviour after application of the system. Nevertheless, this system is often only applied under strict boundary conditions and is sensitive to small modifications in the finishing layer since the desired performance of a vapour-open, non-capillary active system is only working if the interior finishing coat is also vapour-open. In addition, there is still uncertainty about the application of this system in combination with wooden elements such as beam ends, floors and window frames (M. Stappers (Dutch Cultural Heritage Agency) & R. Pater (Archivolt Architecten), personal communication, 11 January 2023).

This disagreement seems to emerge from a lack of knowledge about the hygrothermal behaviour of vapour-open, non-capillary active, internal insulation for historic buildings from both practical and theoretical perspectives, which goes hand in hand with a missing link between the perspectives. This is partly due to the fact that there seems to be a mismatch between the damage experienced in practice, which does not seem to be present, and the outcome of simulation software, which guarantees damage. This mismatch results from the fact that practice-related research on this subject in general is difficult. Not many vapour-open, non-capillary active, internally insulated historical buildings are known since post-insulation is often done privately by house owners. This is also the case for the other two internal insulation systems for historic buildings. This results in a lack of monitoring of the behaviour of internally insulated historic buildings. More research is conducted on vapour-tight and vapour-open, capillary active, internal insulation systems for historic buildings, but there is more to learn here.

House Reuversweerd is an example of a historic residential building which is post-insulated with vapour-open, capillary active insulation. In this building, there are some attempts to monitor the post-insulated situation but there are no consistent results for a thorough comparison between theory and practice. Therefore, this research focuses on the theoretical approach, while the case study House Reuversweerd provides a see-through of practical obstacles and possible solutions.

Fig 1. Case study House Reuversweerd (Erfgoedcentrum Zutphen, n.d.).

1.1 Problem statement

The main problem is found in the conflict between theory and practice about the recommendation of vapour open, non-capillary internal insulation for historic buildings. This problem consists of several sub-problems which need to be solved first. Therefore, the scope of this thesis is narrowed down to contribute to solving the main problem by addressing a sub-problem.

The main problem of the research that will be tackled is t*he lack of knowledge about the hygrothermal behaviour and risks of vapour-open, non-capillary active, internally insulated solid brick masonry for historic residential buildings.*

1.2 Objectives

The aim of this research is t*o gain insight into the most influential hygrothermal properties of vapour-open, non-capillary active, internally insulated historic solid brick masonry.*

Within the research scope, several sub-objectives are set to achieve the main objective. These sub-objectives are:

1 - *Providing insight into the challenges of applying internal insulation for historic buildings.*

2 - *Giving an understanding of the hygrothermal behaviour and risks of vapour-open, non-capillary active, internally insulated historic solid brick masonry by looking at the factors that influence this hygrothermal behaviour separately.*

3 - *Defining prerequisites for a risk-free hygrothermal performance of vapour-open, non-capillary active, internally insulated historic solid brick masonry.*

4 - *Defining factors that need to be taken into account to gain insight into the influence of hygrothermal properties of vapour-open, non-capillary active, internally insulated solid brick masonry.*

The final product of this research consists of recommendations about dealing with the most influential hygrothermal property in practice and what information is needed to validate Heat, Air and Moisture simulation software to gain insight into the mismatch between theory and practice. In addition, guidelines within what range of values of the hygrothermal properties and loads a risk-hygrothermal performance of a vapour-open, non-capillary active, internal insulation of historic residential buildings can be ensured are provided.

1.3 Research questions

The main and sub-questions that will be tackled in this research are as follows:

What hygrothermal property of vapour-open, non-capillary active, internally insulated solid brick masonry for historic residential buildings influences the hygrothermal behaviour of this façade most?

Sub-questions:

1 – *What factors influence the hygrothermal behaviour of vapour-open, non-capillary active, internally insulated historic solid brick masonry?*

Supported by background questions:

1. What is hygrothermal behaviour?
2. What problems are found in the application of internal insulation of solid brick masonry for residential buildings?
3. What historic solid brick masonry types can be found in the Netherlands?
4. What is a vapour-open, non-capillary active, insulation system?
5. How can the hygrothermal loads from the indoor and outdoor environment be classified?

2 – *Under what conditions is the hygrothermal performance of vapour-open, non-capillary active, internally insulated historic solid brick masonry risk-free?*

Supported by background questions:

6. What simulation software can be used to study the hygrothermal behaviour of a building component?
7. What models are used to identify hygrothermal risks and thus assess if the hygrothermal performance is risk-free?

3 – *What factors should be considered to gain insight into the influence of hygrothermal properties on the hygrothermal behaviour in the case of vapour-open, non-capillary active, internally insulated solid brick masonry for historic residential buildings?*

Supported by background questions:

8. What hygrothermal properties should be taken into account for each layer of the building component separately?
9. To focus on only the influence of hygrothermal properties of the wall, what outdoor environment needs to be chosen?
10. What indoor environment fits historic residential buildings according to building regulations?

1.4 Outline

This research consists of nine chapters, starting with the introduction. The second chapter elaborates on the scope of the thesis and places the research into the context of energy reduction for historic buildings to reduce carbon emissions in the building sector. Furthermore, the historic building stock and historic solid brick masonry are defined. In addition, the size of the historic residential building stock is shown. Finally, the contribution of post-insulation of historic solid brick masonry on energy reduction in historic residential buildings is described.

The third chapter presents background information on the hygrothermal behaviour of vapour-open, non-capillary active internal insulation of historic solid brick masonry, which is obtained through literature research. First, the term hygrothermal behaviour is defined. Then, the challenges of applying internal insulation for historic buildings including the suitability of historic solid brick masonry, the hygrothermal risks, the critical details, and the modifications of the wall structure are elaborated. In this chapter, a side step is taken by introducing the case study House Reuversweerd. Characteristics of the building illustrate the challenges that are found for post-insulation of historic buildings. Furthermore, the different factors that influence the hygrothermal behaviour of vapour-open, non-capillary active internal insulation of historic solid brick masonry are explored. The exploration starts with a study on historic solid brick masonry including types of bricks, mortar, pattern bonds and construction thickness. In addition, background information on a vapour-open, non-capillary active insulation system is described. The chapter finishes with a determination of the classification of hygrothermal loads of the indoor and outdoor environments.

The fourth chapter presents prerequisites for the risk-free hygrothermal performance of a vapour-open, non-capillary active, internally insulated historic solid brick masonry wall. First, an in-depth study of hygric behaviour is described by explaining moisture storage characteristics and moisture transport phenomena in porous building materials. In addition, HAM-simulation software WUFI 2D.4 is explored to study hygrothermal behaviour. Finally, assessment models for hygrothermal performance are explored and boundary conditions for risk-free hygrothermal performance within the scope of the research are defined.

The fifth chapter describes a parameter study through HAM-simulation software WUFI 2D.4 on the influence of hygrothermal properties on the hygrothermal behaviour of vapour-open, non-capillary active, internally insulated solid brick masonry of historic residential buildings. First, the input of the parameter study including the materials and boundary conditions is defined. Furthermore, the parameters and range of values are determined and subsequently, the results of the parameter study are described. Finally, a prediction method of the hygrothermal performance of a building component and its results are described.

The research concludes with the conclusion, discussion and recommendations.

2 Context

In this chapter, the scope of the research is explained and placed in the context of energy reduction for historic buildings to reduce carbon emissions in the buildings sector. The research focuses on the post-insulation of solid brick masonry of historic residential buildings. First, the range of the historic residential building stock with solid brick masonry is shown. Secondly, the contribution of post-insulation of historic solid brick masonry to the energy reduction of the historic residential building stock is described. Finally, the improvement of the energy performance by the application of post-insulation of solid brick masonry of historic residential buildings is assessed.

The scope of the research is narrowed down to residential buildings since the Dutch existing building stock consists of circa 9 million buildings, of which 87% are residential buildings (8 million) (CBS Statline, 2022). The development of the existing residential building stock is influenced by essential building periods, events in the past and building regulations, which are highlighted in figure 2. Background about the timeline is given in APPENDIX A.

In The Netherlands, the solid brick masonry wall was the primary construction method for buildings until the cavity wall was introduced around the mid-twentieth century (Van Hunen, 2012)(Stenvert, 2012). Almost a quarter of the Dutch existing residential building stock (23%) is built before 1955. Figure 3 shows the existing residential building stock as a function of the year of construction (CBS Statline, 2022).

Fig 3. Historic residential building stock (dark brown) as part of the Dutch existing residential building stock (CBS, 2022).

By comparing figure 2 and figure 3, explanations for the status of the historic building stock are found. For instance, it is found that less than 25% of the existing residential building stock was built before 1955, which can be clarified by periods of war and demolition that preceded this.

In the context of energy efficiency, only a small part of the existing residential building stock has an energy label. For residential buildings, circa 2 million energy labels are registered since 2011 as it is not mandatory for existing buildings to have an energy label, but only upon completion, sale or rental of the building (Rijksoverheid, 2020)(CBS, 2016). Nevertheless, the energy labels that are registered still highlight the need to reduce energy consumption, especially in historic buildings with solid brick masonry, as shown in figure 4. From this graph, as expected, the historic residential buildings built before 1945 mainly have energy labels E, F or G, and only a small percentage have energy labels A or B.

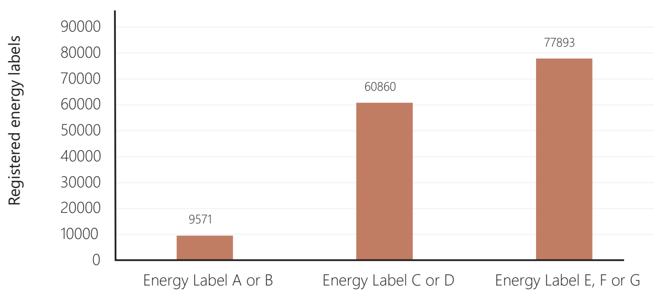

Fig 4. Registered energy labels residential buildings built begore 1945 (CBS, 2016)

Thermally improving a building's façade is one of the six steps to obtain a better energy label, for the building. This is confirmed by a study conducted in 2021 by Nieman. The study showed that an uninsulated solid brick masonry façade with a thermal performance of 0.19 m²K/W (Rc-value) has the largest share in the heat losses of a building. Therefore, thermally upgrading an uninsulated façade with 2.0 m²K/W has a significant effect and results in improving one energy label. Hence, post-insulation has a significant effect on reducing energy consumption for historic buildings.

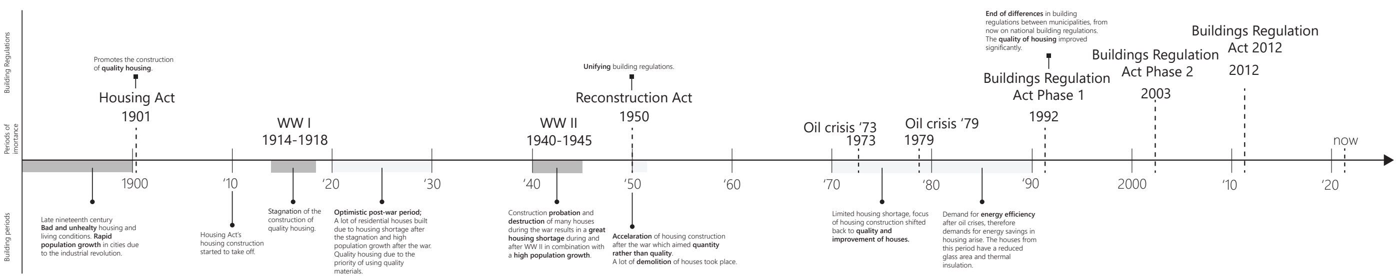

Fig 2. Timelime of the building regulations, building periods and important events influencing the development of the Dutch residential building stock.

Further elaboration is provided on the impact of post-insulation of the historic building stock with solid brick masonry facades on the reduction of energy consumption. The historic residential building stock with solid brick masonry consists of circa 2 million buildings since 23% of the existing residential building stock is built before 1955 (23% of 8 million). Furthermore, 96% of the registered energy labels for historic buildings are C or lower, meaning that 1.9 million historic residential buildings have an energy label of C or lower (96% of 2 million). The improvement of one energy label equals saving circa 38 kWh/m² of energy. According to research based on the WoON Energiemodule 2018, the average insulated façade surface of a Dutch residential building is 50 m² (Stuart-Fox et al., 2019). Therefore, applying thermal insulation to solid brick masonry for historic residential buildings can save almost 3.61 billion kWh of energy (1.9 million historic buildings * 50 m² * 38 kWh/m²). This converts to circa 1.73 billion kg CO_2 emission saved (fossil emission factor of 0.480-0.484 kg CO_2/kWh over 2019) (Cappellen et al., 2021).

To offset these CO_2 emissions, it would require the growth of 86.6 million trees over the course of a year (50 trees take up 1000 kg CO_2 over the course of one year). Alternatively, the amount of CO_2 emissions saved is equivalent to 2.2 million people choosing a vegetarian lifestyle for a year (a vegetarian diet for one week saves 15.4 kg CO_2 * 52 weeks = 800 kg CO_2 per year) or approximately 27.000 persons maintaining a vegetarian lifestyle their entire lives (average life expectancy in the Netherlands is 81 years * 800 kg CO_2 = 64800 kg CO_2 per life).

3 Background Research - hygrothermal behaviour

This chapter gives background information about the challenges regarding the hygrothermal behaviour which the application of internal insulation to historic solid brick masonry and about the factors that influence the hygrothermal behaviour of a vapour-open, non-capillary active, internally insulted historic solid brick masonry wall by addressing the first sub-question:

What factors influence the hygrothermal behaviour of vapour-open, non-capillary active, internally insulated solid brick masonry in historic residential buildings?

First, understanding the definition of hygrothermal behaviour and the factors that influence this behaviour is needed. The term hygrothermal refers to the movement of heat and moisture through buildings, building elements and/or materials. Therefore, the hygrothermal behaviour of a material can be defined as "the change in a material's physical properties as a result of the simultaneous absorption, storage and release of both heat and moisture" (Hall & Casey, 2012). The hygrothermal loads in a building envelope may be thermal or hygric and are experienced on both internal and external aspects, as shown in the figure below (Hall & Casey, 2012).

Figure 5 shows the influences of the thermal and hygric loads, particularly the indoor and outdoor environments. These affect the hygrothermal behaviour of the building envelope. However, buildings have varying building envelopes constructed from different materials, showing different hygrothermal behaviour because the physical properties of each material are different. Therefore every (type of) building envelope experiences a different change of physical properties and thus shows different hygrothermal behaviour.

So, for the scope of this research, this means that the hygrothermal behaviour of vapour-open, non-capillary active, internally insulated solid brick masonry for historic residential buildings is determined by three crucial factors:

- The hygrothermal properties of historic solid brick masonry;
- The hygrothermal properties of vapour open, non-capillary active, internal insulation; and
- The boundary conditions, the indoor environment of a residential building and the Dutch outdoor environment.

These factors will be discussed separately in the following paragraphs together with the challenges that arise for the application of internal insulation for historic buildings.

3.1 Challenges internal insulation of historic buildings

It may seem conflicting to preserve historic, cultural and aesthetical values while also enhancing the energy efficiency of historic buildings. It is correct that due to the preservation of the historic façade, thermal insulation cannot be applied to the external wall. However, internal insulation measures can be considered to enhance energy efficiency in historic buildings, which currently are the most difficult retrofit measure in historic buildings (Blumberga et al., 2015). The application of internal insulation for historic buildings brings a couple of challenges regarding hygrothermal performance and conservation of heritage value, which will be highlighted in this paragraph. First, the suitability of the historic

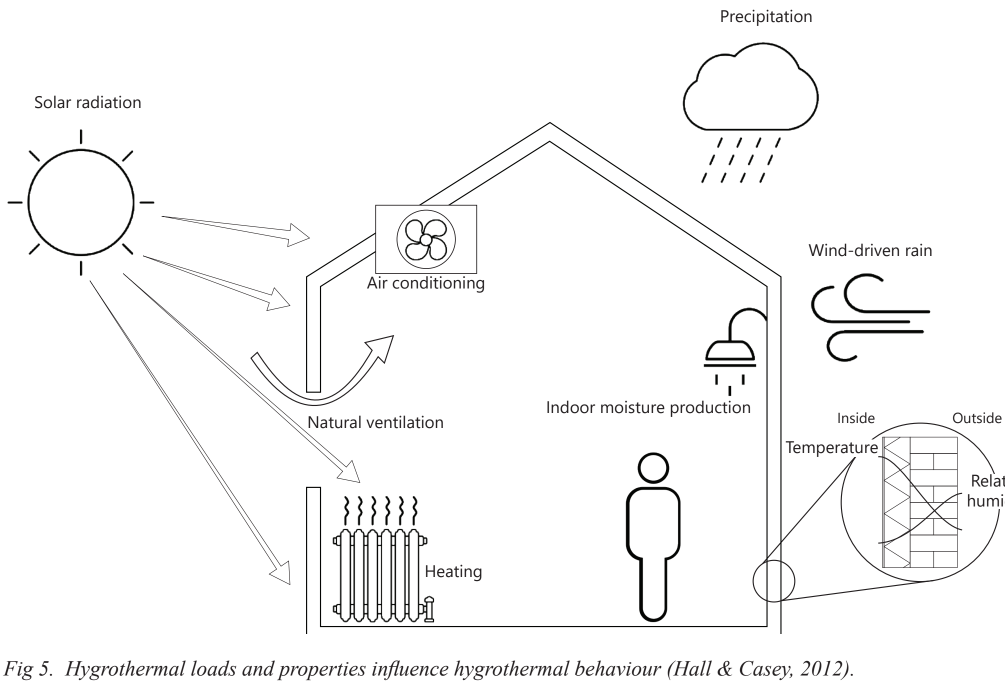

Fig 5. Hygrothermal loads and properties influence hygrothermal behaviour (Hall & Casey, 2012).

building, especially the suitability of solid brick masonry, before applying an internal insulation system will be addressed since this can bring a couple of challenges and attention points. Secondly, as mentioned before, applying internal insulation might induce hygrothermal risks and, therefore, will be discussed. Thirdly, internal insulation raises thermal bridges, causing critical details in historic buildings and, therefore, will be pointed out. Finally, modifications of the wall structure after the application of vapour-open, non-capillary active, internal insulation will be discussed since this can affect the hygrothermal behaviour leading to damage.

3.1.1 Retrofit historic buildings - suitability

Applying internal insulation in retrofitting historic buildings can pose challenges in terms of balancing the preservation of heritage value and mitigating potential hygrothermal risks that may arise from the application of internal insulation (Blumberga & De Place Hansen, 2015).

The process of determining whether to apply internal insulation in historic buildings is complex since it involves multiple factors that can be either independent or interlinked, which define whether the historic building is suitable for the application of internal insulation. These factors are hygrothermal properties of existing and applied building materials and hygrothermal loads from the indoor and outdoor environment. Additional factors such as human behaviour, occupation levels, HVAC systems, environmental impact, heritage value and many more also influence the suitability of the historic building for the application of internal insulation as a retrofit measure. Whether to apply internal insulation depends on the goal of the retrofit. The aim of the retrofit may consist of a single criterion or multiple combined criteria (Blumberga & De Place Hansen, 2015).

Several objectives can defined for the application of internal insulation in historic buildings such as reducing energy consumption, improving indoor climate conditions or minimizing environmental impact. However, it is essential to accomplish these goals goals while ensuring a risk-free hygrothermal performance and preserving the heritage value of the historic building (Blumberga & De Place Hansen, 2015).

Internal insulation can be applied for most historic facades while conserving the historic, cultural and aesthetic value of the historic façade. In that case, the next step is to determine whether the historic building is suitable for the application of internal insulation while avoiding hygrothermal risks. First, a visual assessment of a building needs to be carried out to determine whether there are any important constraints regarding the application of internal insulation since external walls deteriorate when exposed to the environment. Hence, prior to the application of internal insulation, it is crucial that the historic facade and adjacent structures are in a statisfactory condition, ensuring the absence of cracks, signs of moisture damage, or the presence of salt. Furthermore, it is essential to understand

	Interior insulation is applicable	Applicability interior insulation is unknown	Applicability interior insulation is **not** recommended
Visible damage	No visible damage (traces of moisture in the interior/exterior finish, such as irregularities, stains) or moisture sources.	No visible damage, however, presence of moisture sources (for example rising damp) which may lead to moisture problems and damage after installing the insulation.	Presence of moisture (stains, moisture ingress, efflorescence of salts, algae, cracks, irregularities).
Material properties of the existing masonry wall	**Exterior finish**		
	No exterior finish or an exterior finish which has a good condition, has a good quality, and is vapour-open.		Exterior finish which has not a good condition, and/or contains damages; Vapour retarding exterior finish such as varnished bricks, tiles, mosaic, vapour-retarding paint.
	Bricks		
	In accordance with NBN 771, very resistant to frost damage in accordance with NBN B27-009/A2 or DIN 52252-1.	No visible frost damage.	Visible frost damage; Brick susceptible to frost damage.
	Mortar joints		
	In accordance with NBN 771, very resistant to frost damage in accordance with NBN B27-009/A2 or DIN 52252-1.	No visible frost damage; Lime mortar.	Visible frost damage, mortar susceptible to frost damage (for example mortar containing sandy clay).
	Interior finish		
	No visible damage; No irregularities or loose parts; Smooth, non-structured surface.	Irregularities and/or loose parts; Very structured/irregular surface; Interior finish which is susceptible to moisture (damage); Vapour retarding interior finish.	Visible damage (for example cracks, paint which is flaking off, degraded plaster).

Fig 6. Visual evaluation tool for determining the suitability of a historic facade for the application of internal insulation, considering factors such as the visual condition of the masonry wall and material properties of the existing masonry wall (Blumberga & De Place Hansen, 2015).

the previous condition of the building, especially if the building has been damage-free (Blumberga & De Place Hansen, 2015). Figure 6 summarises the visual assessment of the damage of historic facades.

According to Blumberga and De Place Hansen (2015), the identification and elimination of moisture sources in historic buildings is essential if the visual assessment indicates moisture damage. The internal insulation system can only be applied after the elimination of the moisture source to avoid further moisture penetration into the construction. Damage can also be caused by anything other than moisture, such as war damage. It is necessary to replace or treat damage parts and adjecent structures, such as wooden beams supporting the floors should be replaced or treated. Furthermore, Blumberga and De Place Hansen (2015) state that “internal insulation can never be used to ‘hide’ previous damage” (Blumberga & De Place Hansen, 2015).

However, repairing damaged parts of brick masonry is challenging. Damaged bricks in the façade need to be replaced with the same type of brick as the damaged one, thereby mimicking the aesthetic and physical properties of the damaged brick. The same accounts for the mortar replacement (Blumberga & De Place Hansen, 2015). However, the hygrothermal properties of bricks and mortar can vary significantly, which will be described in paragraph 3.2. Therefore replacing brick masonry is very difficult and might result in differences in hygrothermal behaviour within the brick masonry wall. The differences in material properties quickly becomes noticeable at the facade, resulting in damage due to differences in moisture absorption (Blumberga & De Place Hansen, 2015).

Case Study - House Reuversweerd

As an example, war damage and its consequences are shown through a case study to assess the suitability of solid brick masonry for the application of internal insulation. House Reuversweerd is used as a case study where evident war damage influences the preservation of the historic, cultural and aesthetic value of the building and, on the other hand, the hygrothermal performance of the historic façade. First, an introduction will be given about the case study through the historical development of House Reuversweerd. Furthermore, the impact of the war damage is shown and assessed whether the state of the brick masonry wall is suitable for the application of internal insualtion.

Fig 7. House Reuversweerd (Erfgoedcentrum Zutphen, n.d.).

Historical Development

Little is known about the Reuversweerd estate before the 18th century. The estate is located in flood area of the river the IJssel. In 1700 there will have been only a few buildings since the area was still undiked. From the 18th century onwards, the estate is known to have an agricultural function and the farm is called ‘the house Reuversweerd’. In 1750 the construction of the banddyke, now called old dyke, was completed and around ca. 1800 the original farmhouse was built next to the farm. In 1813. The farmhouse and surrounding land were bought by F.C. Colenbrander, where he immediately started renovating the farmhouse.

Around 1850, the new House Reuversweerd was built. Historical data on the construction of the house are scarce. It is only known that two stucco reliefs were added in 1852 by Tiroler stuccoer Johann Martijn Rieff, and the stucco ceilings in the representative rooms were also works from by him. The newly built house Reuversweerd consisted of a rectangular building block. The building has a basement at the back (north-east side) and a lowered corridor was built along the north-east façade, providing daylight to the rooms of the basement.

A refurbishment of house Reuversweerd took place in 1921, led by architect Heineman. The reason for the refurbishment is not known, but it is possibly related to the flooding a year earlier, when the banddyke failed and the entire area was flooded. Another reason can be traced from the main intervention of the refurbishment, which is the addition of a new service wing with offices and staff rooms at the back (north-east side). The primary reason for this addition will have been the need to provide the staff with better living quarters. In the existing house no

Fig 8. Overview different building periods House Reuversweerd (BBA, 2019).

major changes were made in the structure, only the entire interior finish is refurbished since almost all the wall coverings date from after 1921 and a third stucco relief was applied in 1923 by, probably, the servant of Rieff.

During World War II the estate of Reuversweerd played in an important role and the war had a great impact on the house. In the time shortly before World War II, the IJssel Line was constructed along the river with the help of a large number of casemates. Defences were also built around the estate of Reuversweerd.

Fighting took place around the estate during the May Days, signigicantly damaging the house. The house served as an observation post for the Germans. The Canadian shelling of house Reuversweerd with armoured-defence shells started on 4 April 1945. The shelling continued at intervals until 14 April. On 9 and 11 April, the house was badly hit. The house Reuversweerd was liberated by the Canadians on Sunday 15 April 1945.
Right at the end of the war, the family Colenbrander started emergency repairs on the house. What was damaged and the extent of the damage is unknown. Especially the north-east side of the house suffered a lot of damage in April 1945. Only a small area at the east side is used for residential purposes and some of the office space are brought back into use after World War II.

In 1975, the estate of Reuversweerd was designated a national monument. The furnishings were removed from the house in 1979, after which the house became vacant (BBA, 2019).

War damage - suitability

The effects of war damage remain as House Reuversweerd was left unprotected from the weather for years, after inadequate, improvised repairs have been carried out. The war damage and immediate restoration are a clear reminder of the events at the end of the war, not only for the estate of Reuversweerd but also for the Netherlands. These events of 1945 are well recognized both internally and externally and are currently the most dominant layer in the building in cultural-historical terms (BBA, 2019).

Fig 9. War damage north-east facade House Reuversweerd (BBA, 2019).

Fig 10. Highlighted immediate repairs of the war damage (BBA, 2019).

The figures show the immediate repairs of the historic brick masonry. The emergency repair was carried out using only bricks due to a lack of mortar availability. The orange line shows the border of the emergency repairs. The left figure shows gaps in the masonry due to a lack of mortar. The right figure shows a turned brick in the wall (BBA, 2019).

From the retrofit point of view, the historic building House Reuversweerd is unsuitable for applying internal insulation, since this will probably lead to more moisture-related damage. Therefore, first, the war damage to the building must be restored to retrofit the historic building by applying internal insulation. However, this conflicts with the conservation of the war damage since the damage to the house is one of the last places in the Netherlands where the traces of the war are still evident. This results in a high rarity value and therefore a high cultural-historical value. However, due to the character of the damage, these traces are very dominant and partly interfere with the building's other qualities and cultural-historical values (BBA, 2019).

Fig 11. Details immediate repairs of the war damage (BBA, 2019).

3.1.2 Hygrothermal risks

Applying internal insulation will reduce heat loss through the wall reducing energy consumption and increasing thermal comfort. However, it will also significantly modify the hygrothermal performance of the wall assembly, which might result in a number of hygrothermal risks such as frost damage, decay on wooden beam ends, interstitial condensation, and surface condensation (Vereecken et al., 2015)(Vereecken & Roels, 2019).

The extra vapour diffusion resistance caused by an internal insulation system hinders an inward drying of the masonry. Additionally, the application of internal insulation results in a lower temperature of the masonry, causing a reduced drying potential towards the exterior. Furthermore, the lower temperature will increase the likelihood of moisture condensation within the wall, increasing the moisture content. Hence, the moisture content in the masonry due to outdoor moisture sources, such as wind-driven rain, will increase by applying interior insulation (Vereecken & Roels, 2019)(Hansen, 2019). Figure 12 shows the hygrothermal behaviour before the application of internal insulation and figure 13 shows the change in hygrothermal behaviour due to the application of internal insulation.

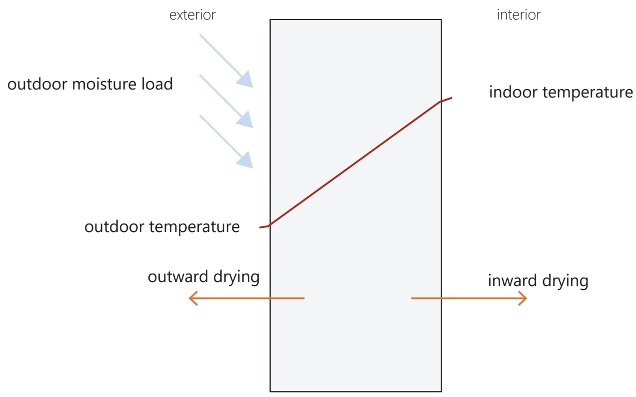

Fig 12. Hygrothermal behaviour before application of internal insulation.

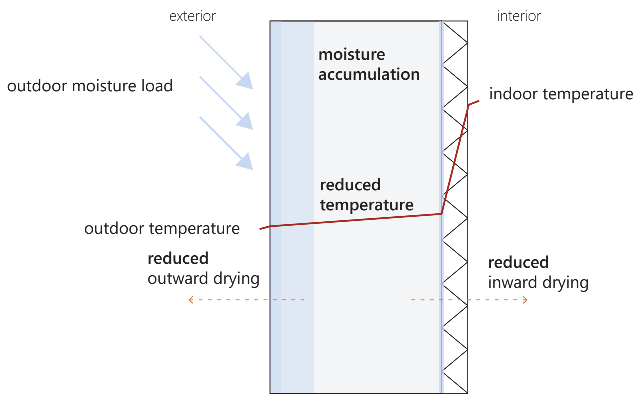

Fig 13. Hygrothermal behaviour after application of internal insulation.

The increased moisture content of the brick masonry, in combination with lower outdoor temperatures due to the application of internal insulation, results in an enlarged risk of frost damage in the brick masonry (1) which results in scalling of the exterior layer of the brick masonry. In addition, the increased moisture content in the masonry wall might damage wooden beam ends in the construction (2), which are common constructions in historic buildings (Vereecken et al., 2015). Wood decay of wooden beam ends threats the load-bearing structure of the historic building since rot attack of wooden beam ends results in reduced strength, which might induce a collapse of the wooden load-bearing construction (Blumberga & De Place Hansen, 2015). Moreover, the lower temperature of the masonry increases the risk of interstitial condensation (3) between the construction layers (Blumberga et al., 2016). This can lead to mould growth and deterioration of the wall structure. Furthermore, applying internal insulation might induce surface condensation due to too high relative humidity at the surface (4), which entails a risk of mould growth, which affects the health of the building occupants and the building itself. Finally, the influence of internal insulation on the indoor relative humidity (5) should be taken into account, since it can affect the comfort and health of building occupants (Vereecken & Roels, 2015). The hygrothermal risks that might be induced due to the application of internal insulation are highlighted in figure 14 below.

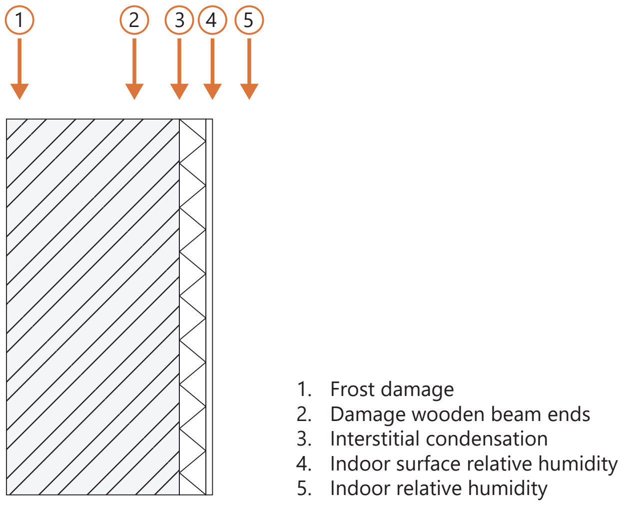

Fig 14. Hygrothermal risks after application of internal insulation.

The extent of hygrothermal risks of the application of internal insulation depends on the type of insulation system with its characteristic hygrothermal properties.

Three different insulation systems can be distinguished: vapour-tight, vapour-open capillary active and vapour-open, non-capillary active. The tightness of a vapour-tight internal insulation system blocks the inward drying out of the construction. The system is, therefore, very sensitive to high moisture loads from the outside, such as wind-driven rain, and other additional loads leading to a moisture increase, especially in the underlying masonry (Zhao et al., 2017)(Blumberga et al., 2016). Moreover, tightening the interior increases the demand for efficient ventilation to preserve a comfortable indoor environment (Toman et al., 2009).

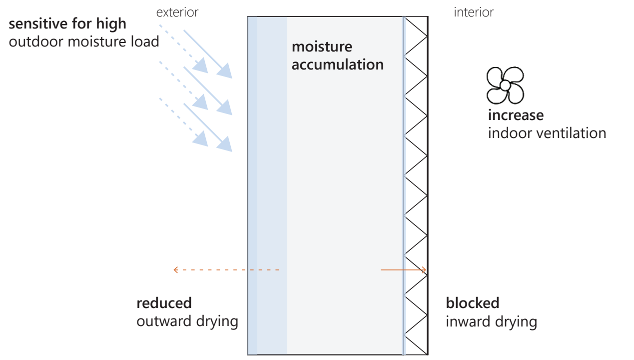

Fig 15. Vapour-tight internal insulation system.

In contrast, for both vapour open systems, capillary and non-capillary, inwards and outwards drying out of the construction is unhindered since the vapour diffusion resistance is low. However, due to this low resistance, there is a higher risk of interstitial condensation at the critical point where masonry and insulation meet (Blumberga et al., 2016). If sufficient contact between the brick masonry wall and the insulation is provided, the capillary active system can buffer the interstitial condensation and redistribute the moisture resulting in higher moisture content in the construction, especially in the insulation layer (Vereecken & Roels, 2015). The non-capillary active system is incapable of buffering the interstitial condensation. Therefore, brick masonry mainly absorbs moisture for this system, resulting in higher moisture content peaks in the construction.

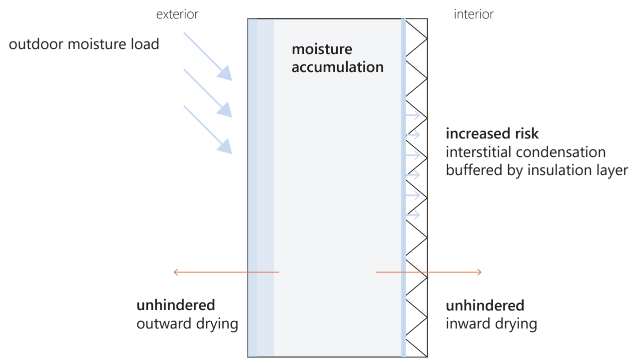

Fig 16. Vapour-open, capillary active internal insulation system.

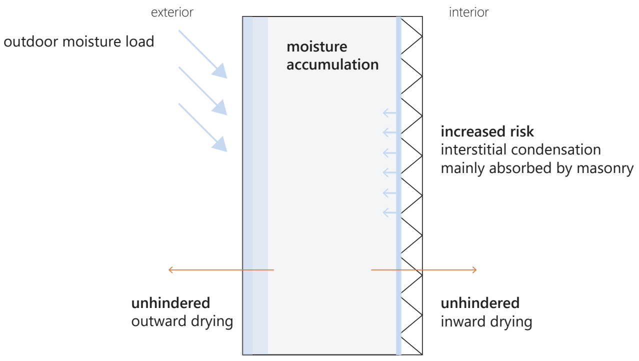

Fig 17. Vapour-open, non-capillary active internal insulation system.

Drying periods are necessary for both vapour-open systems to avoid moisture accumulation and associated risks (Blumberga et al., 2016).

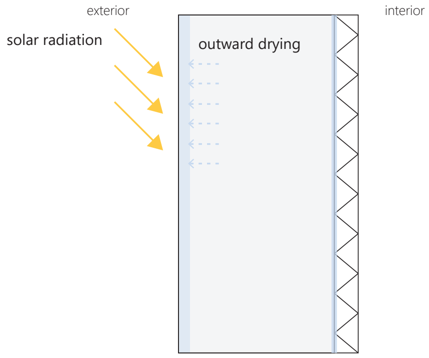

Fig 18. Solar radiation results in outward drying of brick masonry.

After all, the moisture content in the construction after the application of internal insulation is higher for all three systems. Vapour-tight insulation system yields a higher moisture content in the brick masonry layer. In contrast, the vapour-open, capillary active system yields a higher moisture content in the insulation layer and the vapour-open, non-capillary active system yields a higher moisture content peaks in the construction.

3.1.3 Critical details - thermal bridges

In historic buildings, wooden window frames are commonly found, and wooden beams are almost always used to span rooms and to support roof and floor structures and their incidental loads (Van Hemert, 2013)(Zwiers, 1920). The use of wooden beam ends dates back to around 1300 when beam constructions were introduced. Beam construction from the nineteenth century onwards were singular beam constructions [NL: eenvoudige balklagen]. The beams are arranged parallel to each other as much as possible and have the same beam distance between them (Van Hemert, 2013). Both ends of the beam find support in the masonry wall (Zwiers, 1920). Other types of beam constructions can be found in buildings built before 1800.

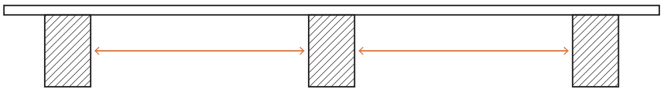

Fig 19. Singular beam construction (Van Hemert, 2013).

Sometimes the beams were loaded to the extent that they needed support from a triangular construction. This structure was placed below the beam ends and strengthened the beams, preventing the bending of the beams and buckling of brick masonry walls. The triangular timber construction consisted of a corbel, wall mullion, corbelling stone, and key piece. Wooden wall mullions [NL: muurstijlen] were partly constructed in the masonry wall and rested on a corbelling stone. Corbelling stones are also embedded in the masonry wall and partly protrude (Van Hemert, 2013). Different triangular structures can be found in historic buildings, an example is shown in figure 20.

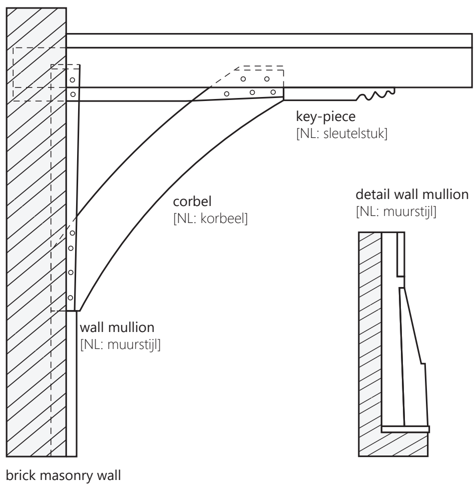

Fig 20. Triangular corbel construction with detail of wall mullion partly embedded in the solid brick masonry wall (Van Hemert, 2013).

For heavy brick masonry walls, a corbel construction is not necessary. However, transitions from beam to wall were still constructed as consoles, corbelling stones or a short key-piece (Van Hemert, 2013). Two examples are shown in figure 21 below.

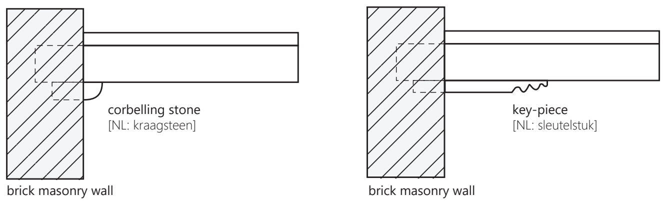

Fig 21. Transition by a corbelling stone (left) and a short key-piece (right)\ (Van Hemert, 2013).

In the case of triangular timber constructions or corbelling stones, applying internal insulation will cause aesthetic problems and will reduce the historic, cultural and aesthetic value of the historic building. In addition, thermal bridges for the wooden details will arise due to the application of internal insulation resulting in reduced surface temperatures and, consequently, excessive relative humidity. This might imply hygrothermal risks such as mould growth and wood decay, especially at critical points where the wooden elements and insulation meet (Blumberga et al., 2016)(Vereecken & Roels, 2017).

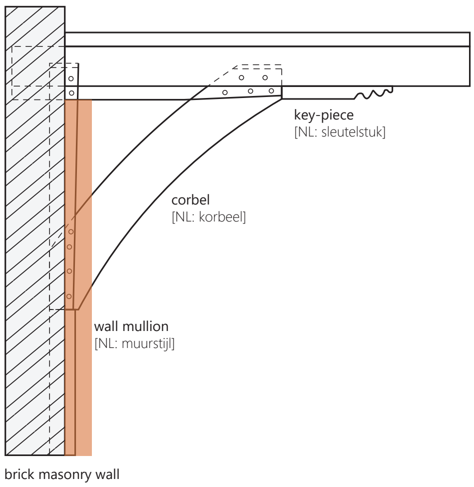

Fig 22. Aesthetic problems and thermal bridges after application of internal insulation.

In historic buildings, the support is the part of the beam that rests on the masonry wall. For wooden beams, this support is at least half a brick (Van Hemert, 2013)(Wattjes, 1934). If the support of the beams is too long, this would weigh down the wall too much, and, if the beam deflects, the beam end would be lifted too much, causing tensile stress in the masonry which might cause cracking of the brick masonry (Wattjes, 1934). Furthermore, the beam supports for solid walls are cut at an angle, making the upper end slightly shorter than the lower end. Cutting at an angle gives the masonry as much thickness as possible at the wooden beam ends, this way, a proper connection between the masonry and the beams can be achieved (Van Hemert, 2013)(Zwiers, 1920)(Wattjes, 1934). In the case of heavier solid brick masonry walls exceeding one-stone thickness, cutting beam ends at an angle is unnecessary because the pattern bond can continue around the beam support (Van Hemert, 2013).

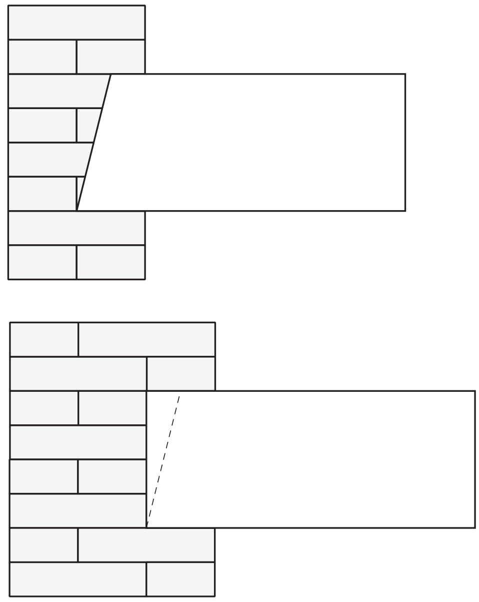

Fig 23. Beam supports in one-stone and one-and-a-half-stone solid brick masonry wall (Van Hemert, 2013).

Special care needs to be given to the embedded wooden beam ends concerning the application of internal insulation since the risk of mould growth and wood decay is possible. However, in the past, without the application of internal insulation, special attention to the wooden beam ends was already given since the ends of the beam are subjected to rotting or suffocation first. Therefore, the bottom of the beam rests on a tile with mortar to elevate the beam to the correct height and prevent the bottom from rotting due to moisture penetration. The beam heads were also painted with stain [NL: menie] to prevent moisture penetration. Furthermore, in eighteenth-century brick masonry, sometimes a narrow strip of lead was placed along the entire length of the wall to cover the beam ends and ensure that the moisture present in the wall is redistributed to the exterior (Van Hemert, 2013).

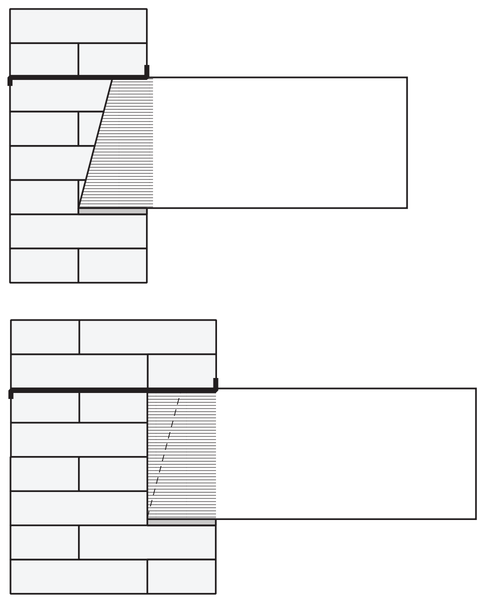

Fig 24. Lead strip in solid brick masonry and beam heads painted with stain and resting on a tile to protect the beam head against moisture penetration (Van Hemert, 2013).

From the thirteenth century, when the thickness of solid brick masonry walls was reduced, it became mandatory for residential buildings to attach the wooden beam ends to the brick masonry wall with forged anchors, see figure 25. However, these anchors bring challenges to the brick masonry. First, the anchors act as a thermal bridge which aggravates by the application of internal insulation (Blumberga & De Place Hansen, 2015). Furthermore, due to environmental loads, the anchors may corrode and expand, causing damage to the brick masonry, such as crack formation, which makes the historic building unsuitable for the application of internal insulation (Van Hemert, 2013).

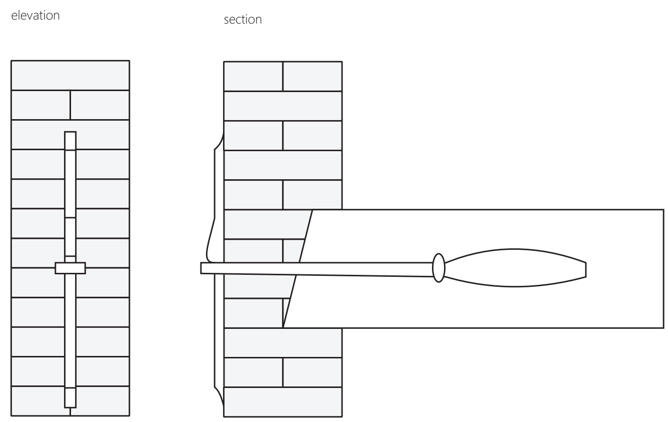

Fig 25. Front view and section of forged lap anchor (Van Hemert, 2013).

All in all, the wooden beam ends in brick masonry constructions bring a couple of challenges since these are most sensitive to damage in the construction. The supports of a beam in the brick masonry walls usually rot before the rest of the beam. (Zwiers, 1920). The damage to wooden beams can be caused by various factors, such as leakage, suffocation of the wood, renovations, restorations, thermal bridges and wood infestation (Van Hemert, 2013). Therefore, special care should be taken for wooden beam ends, especially, in combination with internal insulation which causes thermal bridges at the most moisture-sensitive parts of the building.

However, there is no consensus on whether interior insulation is applicable in combination with wooden beam ends in historic buildings. The same accounts for the recommended type of interior insulation system in combination with wooden beam ends in historic buildings (Vereecken & Roels, 2017). The first internal insulation system, the vapour-tight system, entails some challenges during the application. The system demands proper workmanship during the application stage and proper user behaviour in the operation stage to ensure perfect tightness of the system (Zhao et al., 2017). However, ensuring perfect tightness during these stages, especially for critical details, such as wooden beam ends, is time-consuming, expensive and risky since vapour barriers are sensitive to mechanical damage, which could result, in a long-term perspective, in water vapour condensation in the insulation layer (Toman et al., 2009). In addition, unintended leakages at wooden beam ends due to imperfect tightening can cause moisture damage to the historic building, as described before in paragraphs 3.1.1 and 3.1.2. In contrast, for example, from the experience of Archivolt Architecten no precise workmanship is required for the vapour open, non-capillary active, internal insulation systems since these systems are less sensitive to errors in application to the historic brick masonry wall (R. Pater, personal conversation, 11 January 2023). However, if the drying periods are inadequate, excess moisture can still transfer and accumulate in a more moisture-sensitive building component such as a wooden beam or wooden floor element. This can cause damage such as mould growth and wood decay due to rotting or corrosion of wall anchors (Stappers, 2021)(Blumberga et al., 2016).

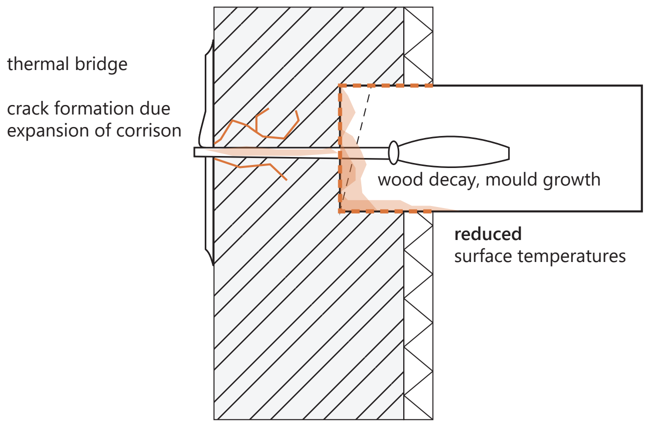

Fig 26. Possible damage at critical detail due to the application of internal insulation.

In conclusion, special attention is required for thermal bridges at wooden beam ends and wooden window frame connections in historic buildings with internal thermal insulation (Van Hemert, 2013).

3.1.4 Modifications

The vapour-open, capillary or non-capillary active, internal insulation system is sensitive to minor modifications of the wall structure because it influences the hygrothermal behaviour of the system. For example, hydrophobation of the exterior of the brick masonry wall makes the facade water-repellent while maintaining vapour permeability, resulting in a facade which prevents wetting due to wind-driven rain and, consequently, drying due to solar radiation. This treatment is safe if proper use of products and applications is guaranteed. If not, this treatment can result in several hygrothermal risks since the transport of liquid moisture, including salts, to the wall surfaces is blocked, resulting in an increased amount of salt behind the hydrophobized zone. The salt will crystallize causing the outer layer of the brick to crack away. Furthermore, the applied hydrophobation degrades due to environmental loads such as solar radiation. Therefore, this treatment requires a lot of maintenance to ensure proper performance (Van der Helm et al., 2007).

Furthermore, according to Vereecken and Roels (2015), especially the interior finishing layer of the system has a significant influence on a vapour-open internal insulation system since the desired hygrothermal performance of a vapour-open system is only working if the interior finishing layer is also vapour-open. However, it should be taken into account that historic buildings can have many different interior finishing layers, especially if the historic interior finishing, with historic, cultural and aesthetic value elements, is restored during the retrofit.

Case Study - House Reuversweerd

The case study House Reuversweerd is used as an example to highlight the many different modifications of the facade that can occur due to the interior finishing layer.

Modifications - finishing layers

In House Reuversweerd different finishing layers and elements can be recognized for the same exterior wall since the historic, cultural and astheatic values of the interior are conserved or replaced. Furthermore, different built-ups of external walls with the same finishing layers and elements can be found in the building. So, House Reuversweerd recognizes several different external walls with its characteristic modifications. Two different facades are highlighted in figure 28.

For both external walls, different finishing layers are found: decorative stucco, vertical wooden panels with wallpaper, low wooden wainscoting [NL: lambrisering], and window sills in the form of wooden benches, shown in figure 29. The four different finishing elements, with each differing hygrothermal properties, influence the hygrothermal performance of the external wall simultaneously. Even though Vereecken and Roels (2015) state that the finishing layer should be vapour-open to ensure the desired hygrothermal performance of a vapour-open internal insualtion system, it is still uncertain if different finishing layers that are vapour-open ensure the guaranteed hygrothermal performance simultaneously as well.

Fig 27. House Reuversweerd (Erfgoedcentrum Zutphen, n.d.).

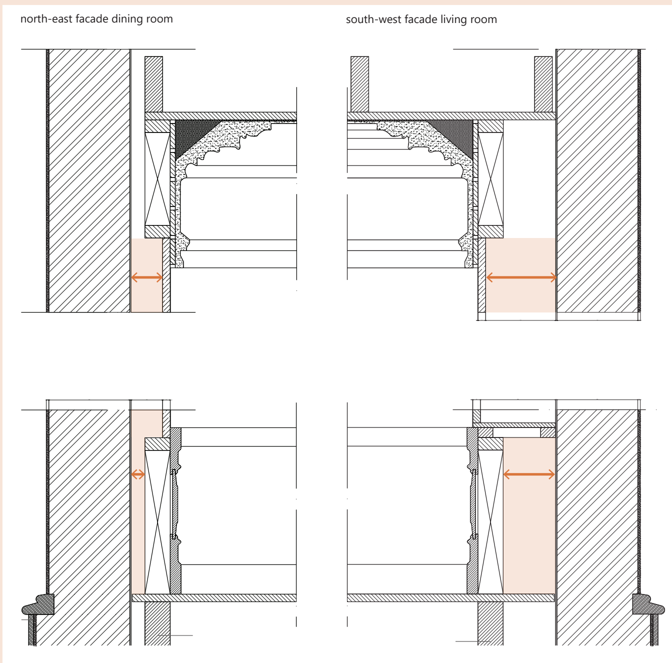

Fig 28. Different built-ups of the external walls in House Reuversweerd

Fig 29. Different finishing layers in House Reuversweerd: decorative stucco, vertical wooden panels with wallpaper, low wooden wainscoting [NL: lambrisering], and window sills in the form of wooden benches.

In House Reuversweerd, different historic finsishing layers are found for each facade and per facade, the finishing layers vary. Furthermore, the built up of each facade is also different. This results in varying hygrothermal properties within one facade.

Therefore, it should be taken into account that if a vapour-open internal insulation system is considered, the hygrothermal behaviour for every part in the facade needs to be considered before the applicaton. It should not be the case to take average values for the different parts in the facade, resulting in a general approach for the application of internal insulation in the historic building since this might result in hygrothermal risks at the less-performing parts of the facade. In other words, risk-free hygrothermal performance needs to be ensured for every part within one facade.

3.2 Historic solid brick masonry

In Europe, the facades constructed in historic buildings are typically brick masonry (Blumberga et al., 2015). Historic brick masonry can take different forms due to construction type, thickness and pattern bond differences. Solid or cavity brick masonry walls are two main brick masonry construction types that can be distinguished (Van Hunen, 2012). For residential buildings built before 1950, solid brick masonry is the most common type of brick masonry (Van Hunen, 2012)(Stenvert, 2012). This paragraph describes historic solid brick masonry, including types of bricks, mortar, pattern bonds and construction thickness.

3.2.1 Bricks

The earliest use of bricks in the Netherlands dates back to Roman times. At the end of the twelfth century, the production of bricks started in northern Europe including the Netherlands. At that time, masonry was built up using mainly peat stones. In the late twelfth and early thirteenth centuries, many combinations of peat stone and brick can be found. During the thirteenth century, the use of peat bricks was slowly replaced by the use of large bricks (about 30 x 14.5 x 9 cm). From the fourteenth century, bricks reduced in size, and many regional differences in sizes can be found. In the northern part of the Netherlands, larger bricks remained common much longer. The smaller-sized bricks had more advantages in the production process since these were moulded faster, easier and with less force and also dried and baked faster.

As a result, there were fewer mis-baked bricks and a more uniform structure was found for the smaller-sized bricks. Furthermore, with the emergence of smaller-sized bricks, the ideal ratio of 4:2:1 (l x w x h) evolved (Stenvert & Tussenbroek, 2007)(Hunen, 2012).

From the nineteenth century onwards more standardisations in brick production took place, which is closely related to innovations in the baking and moulding process of bricks. Field kilns [NL: veldbrandovens] were replaced by ring kilns [NL: ringovens] (1869), zigzag kilns [NL: zigzagovens] (1911), and the tunnel kiln [NL: tunneloven] (1916). Innovations in the moulding process took off in the mid-nineteenth century, when the strand press [NL: strengpers] (1858) appeared, which pressed bricks into strand press bricks [NL: strengpersstenen]. The strand press also made it possible to press hollow bricks (1870). The moulding press [NL: vormbakpers] (1867) also emerged, which was used to machine-form bricks into moulded bricks [NL: vormbakstenen]. After 1935, with the rise of expressionism, hand-formed bricks [NL: handvormstenen] again dominated brick masonry in the Netherlands (Stenvert & Tussenbroek, 2007)(Hunen, 2012).

Due to all developments in the production of bricks in the Netherlands, many different brick types can be found (Stenvert & Tussenbroek, 2007)(Van Hunen, 2012). The different brick types can be distinguished according to four characteristics: origin, size, hardness and moulding process. The first characteristic, place of origin, is related to the type of clay and the colour of the brick. Secondly, many different brick sizes were and are produced and used in the Netherlands, which is shown in table 1.

Thirdly, the hardness is influenced by kiln heat and primarily divided into clinkers [NL: klinkers], hard gray [NL: hardgrauw], peasant gray [NL: boerengrauw] and red [NL: rood] (Sirag & Wiedijk, 1950). Due to uneven heating in the kilns, many differences in brick colour and quality occurred. The final baking temperature determines the quality of the bricks:

- 800 - 900 °C: soft red brick quality;
- 900 - 1080 °C: tougher grayer brick quality, peasant and hard gray; and
- 1080 – 1125 °C: hard-baked clinker quality.

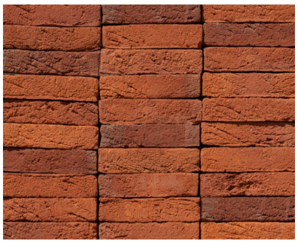


Fig 30. soft brick quality (left) and thougher brick quality (right), (Vogelensangh).

The final characteristic that can be distinguished is the moulding process of the brick. A distinction can be made between hand-moulded brick [NL: handvormbaksteen], (machine-)moulded brick [NL: vormbaksteen], or strand press brick [NL: strengperssteen] (Stenvert & Tussenbroek, 2007)(Sirag & Wiedijk, 1950).

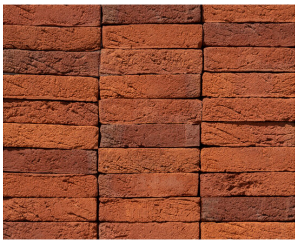


Fig 31. hand-moulded brick (left) and (machine-)moulded brick (right), (Vogelensangh).

Name	Size [mm]	Name	Size [mm]
Waalformaat	210 x 100 x 50	Friese drieling	184 x 80 x 40
Waaldikformaat	210 x 100 x 65	Friese mop	217 x 103 x 45
Vechtformaat	210 x 100 x 40	Groninger steen	240 x 120 x 60
Rijnformaat	180 x 87 x 91	Romeins formaat	240 x 115 x 42
Rijnformaat drieling	175/187 x 84/90 x 44/48	Lilliput I	160 x 75 x 35
IJsselformaat	160 x 78 x 41	Lilliput II	150 x 70 x 30
Hilversumformaat	225 x 105 x 42	Kathedraal I	240 x 115 x 65
Dordtse steen	180 x 88 x 43	Kathedraal II	270 x 105 x 55
Gendtse steen	155 x 72 x 53	Kloostermop	280 x 105 x 80
Limburgse steen	240 x 120 x 65	Kloostermop II	320 x 130 x 80
Brabantse steen	180 x 88 x 53	F5	230 x 110 x 57

Table 1. Overview of sizes of most common bricks produced in the Netherlands (Lubelli, 2017).

There are different clays, moulding processes, sizes and firing processes, resulting in an unlimited amount of brick types in the Netherlands.

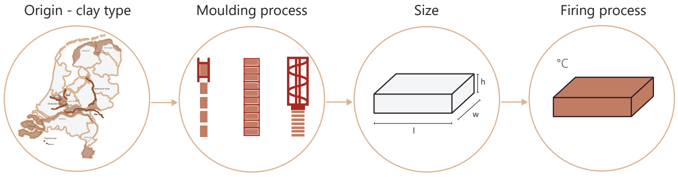

Fig 32. Overview characteristics that determine the type of brick.

The combination of clay, moulding, and firing process results in a product with characteristic properties. The pore system of the brick affects hygric properties. These include the total porosity, pore size or diameter distribution, open and closed porosity, capillary contacts between them, and the tortuosity of the pores. The firing process, especially firing temperature, influences the hygric properties. During the firing process, a significant change occurs in the pore system of the clay. The total porosity increases and as the product reaches the highest firing temperature, the pores start to rearrange and small pores merge into larger pores. The total porosity decreases with further temperature increase. Thus, the higher the firing temperature, the harder the brick, and the lower the porosity of the brick (Van Hunen, 2012).

Every type of brick has its characteristic properties, resulting in different pore systems for each type of brick. The figures below show two different schematic pore systems of bricks and highlights the different hygric properties per brick type.

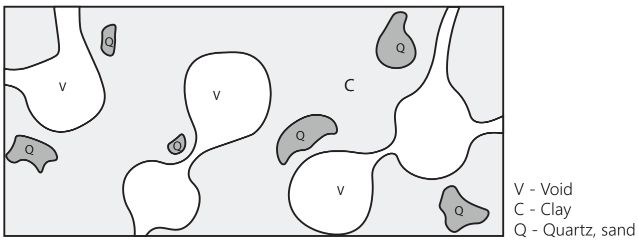

Fig 33. Schematic pore structure brick I based on Groot & Gunneweg (2007).

The pore structure of brick I, shown in figure 33, resembles a hard brick that has been fired at a high temperature, such as a clinker or a hard gray brick. In the pore structure, large closed pores are found, which are almost isolated, resulting in little capillary contacts between the pores. Furthermore, the skin is almost closed, leading to a poorly absorbing brick. During a period of rain, little moisture will penetrate the brick, only the outer layer of the brick will absorb moisture. Therefore, the brick has a relatively short drying period (Groot & Gunneweg, 2007).

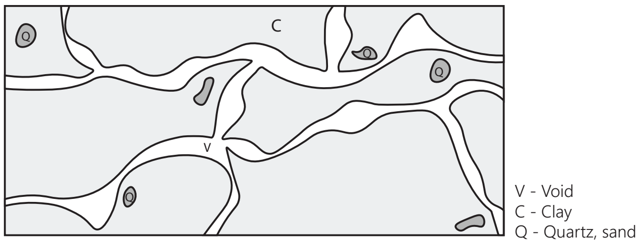

Fig 34. Schematic pore structure brick II based on Groot & Gunneweg (2007).

In figure 34, the pore structure of brick II is shown, which corresponds with a softer brick that has been fired at a lower temperature, such as a red brick. In the pore structure, a network of fine open pores with capillary contacts is recognized, making the brick strongly absorbent. During a period of rain, the brick will absorb moisture deep into the brick. Therefore, the brick needs long drying periods and is more sensitive to frost damage in comparison with the brick type I (Groot & Gunneweg, 2007).

3.2.2 Mortar

Mortar is the material needed to build one layer of bricks on top of another, creating petrification and turning stone and mortar into one (Zwiers & Mieras, 1918). Mortar can be defined as a material composed of one or more inorganic binders (such as lime or cement), aggregates (such as sand), water and optional aggregates.

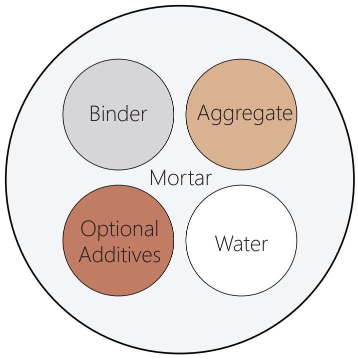

Fig 35. Components of mortar, based on Van Hunen (2012).

The main applications of mortar are laying mortar and pointing mortar in brick masonry (Van Hunen, 2012).

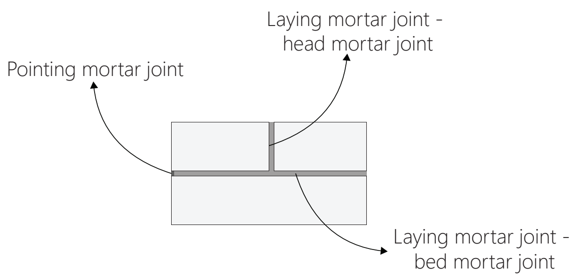

Fig 36. Main applications of mortar in brick masonry shown in vertical cross-section of brick masonry.

In historic masonry constructions, lime is the primary binding agent for the mortar to construct brick masonry. From the late nineteenth century, the primary mortar type shifted to cement mortar. In the Netherlands, cement lime mortars were used as the primary mortar type throughout the twentieth century. In modern brick masonry constructions, Portland cement is the main binder for mortar. Even though these developments, lime mortar is the main type of mortar found in historic brick masonry until 1950 (Van Hunen, 2012).
The lime is mixed as a binding agent with an aggregate in a lime mortar. The lime provides binding with bricks, and the aggregate provides volume and prevents the pure lime from shrinking too much and tearing loose from the brick. There are two types of lime as a binding agent in lime mortar, hydraulic lime and aerated lime. In aerated lime, the lime hardens and thus bonds through a reaction between the free lime in the mortar and carbon acid from the air. In hydraulic lime, the lime is hardened and thus bonded by a chemical reaction with water. Lime mortar with natural hydraulic properties was mostly used in historic masonry. The principal aggregate used in the Netherlands is sand. The function of sand in a mortar is to make the mortar less greasy, which also reduces the formation of cracks due to shrinkage during drying and hardening. Secondly, the sand provides strength, hardness and porosity to the mortar. Before lime was manufactured as a (pre)industrial product, it contained additional components such as trass and stone dust. These additional components contributed to the reaction and quality of the hardened mortar (Van Hunen, 2012).

Hardened mortar consists of three components; inert aggregate (sand), the matrix (lime or cement stone) that holds the sand grain together, and pores. The grain size distribution of the aggregate has a significant influence on the total porosity and pore size distribution of the mortar. A high lime or lime-cement paste content in comparison with sand and hollow space reduces the porosity, which is primarily determined by the content of hollow space in the mortar. The presence of different grain sizes (fine to course) leads to a lower porosity than, the use of the coarse sand grain of the same diameter. The binder, lime or lime-cement, fills the open space between the sand grains. In a mortar with a low binder-to-sand ratio, large pores occur in the space between sand grains that Is not completely filled by the binder. A mortar with smaller pores is able to absorb more moisture than a mortar with larger pores. The structure of hardened mortar is one of the most important factors influencing the hygric behaviour of brick masonry (Van Hunen, 2012)(Brocken, 1998). Figure 37 shows different pore structures of hardened mortar and thereby different hygric properties.

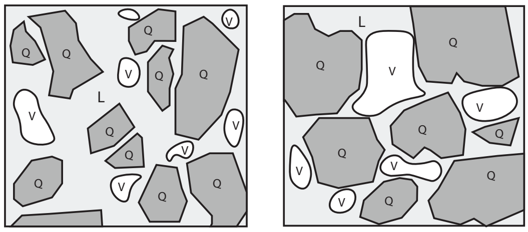

Fig 37. Meso-structure mortar I (left) and mortar II (right) based Van Hunen (2012) Groot & Gunneweg (2007) and Brocken (1998).

Mortar I has a higher lime paste content and contains different grain sizes in comparison with mortar II which leads to lower porosity and smaller pores in mortar I than in mortar II. Therefore, mortar I is able to absorb more moisture than mortar II.

3.2.3 Pattern bonds

Bricks are layered with mortar according to a pattern bond into brick masonry, making brick masonry an inhomogeneous wall construction. Resulting in different hygrothermal performances on a smaller scale within the brick masonry wall since the hygric behaviour of multi-layered building elements can differ from the behaviour found for the combination of single material elements (Vereecken & Roels, 2013). Different pattern bonds for brick masonry were and are commonly used and can result in different masonry thicknesses. According to Stenvert (2012) and Wattjes (1942) there are seven common pattern bonds for brick masonry in the Netherlands, which are:

- Flemish bond [NL: Vlaams verband]
- Chain bond [NL: kettingverband]
- English bond [NL: staand verband]
- Cross bond [NL: kruisverband]
- Head bond [NL: koppenverband/patijtsverband]
- Stretcher bond [NL: halfsteensverband]

The Flemish, English, Cross, Head and Stretcher bond are shown in figure 38.

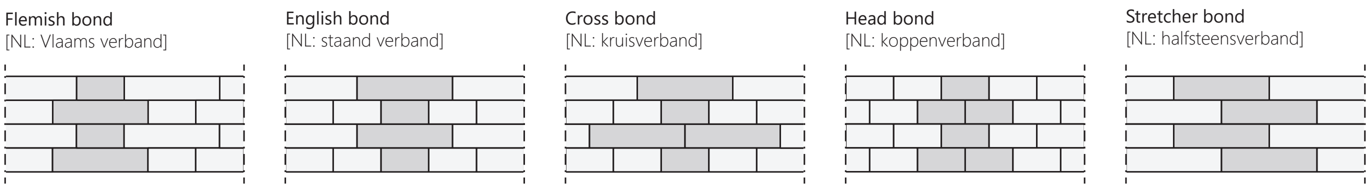

Fig 38. Six common pattern bonds for brick masonry in the Netherlands. From left to right: Flemish, English, Cross, Head and Streatcher bond (Stenvert, 2012) (Wattjes, 1942).

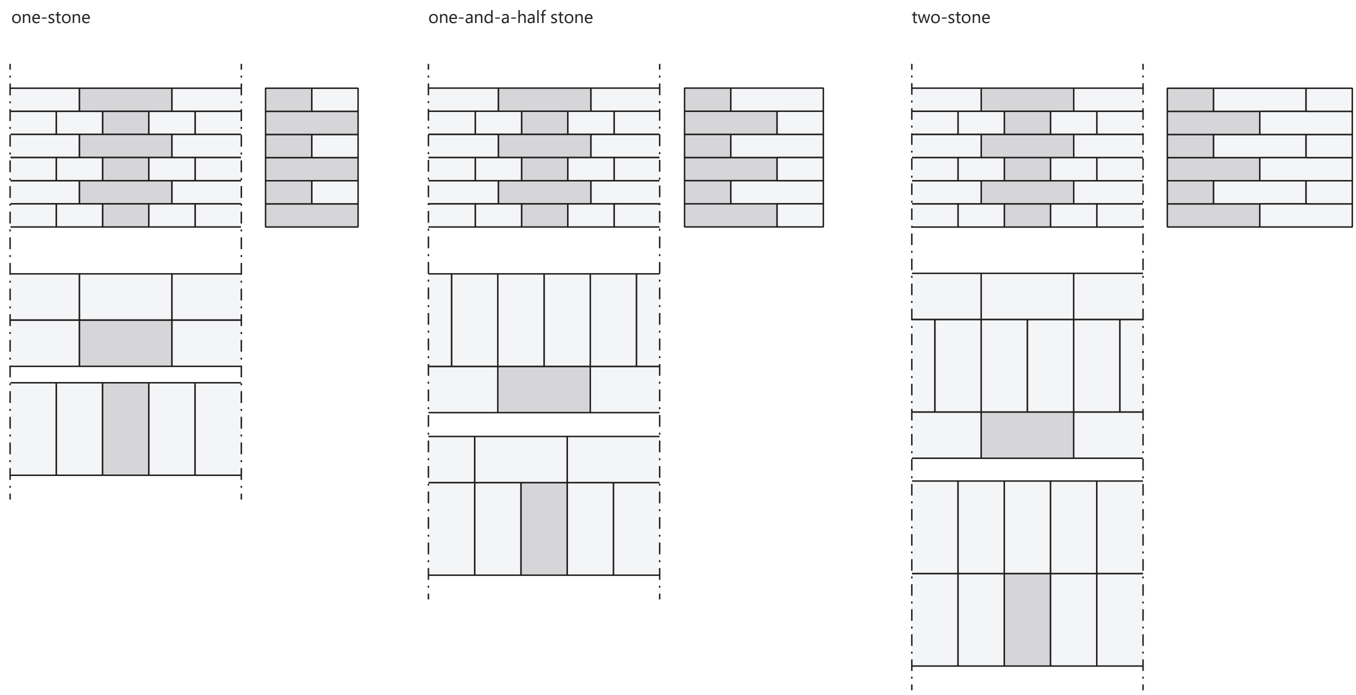

Fig 39. Front view, vertical cross-section and horizontal cross-section of the English bond in one-stone, one-and-a-half-stone and two-stone thickness. (Stenvert, 2012)(Wattjes, 1942)(Zwiers & Mieras, 1918).

Brick masonry wall constructions are three-dimensional, making the pattern bonds strongly related to the thickness and type of construction. Therefore, pattern bonds, thickness, and type of construction of brick masonry depend on one another. Brick masonry constructions, length and thickness, are measured in multiples of the brick size such as one-stone or two-stone walls (Van Hunen, 2012). Solid brick masonry walls have at least a thickness of one-stone and can also have a thickness of one-and-a-half-stone, two-stone, or sometimes even two-and-a-half stone (Wattjes, 1942)(Stenvert, 2012)(Zwiers & Mieras, 1918). Due to different brick types with varying brick sizes, the thickness of solid brick masonry walls varies which results in differing hygrothermal performances. Figure 39 shows the the vertical and horizontal cross-section of the English pattern bond with one-stone, one-and-a-half-stone and, two-stone construction thickness.

The figure shows that each pattern bond has different orientations of bricks (headers or stretchers) and mortar joints in the brick masonry. The orientation of bricks and mortar joints varies with different construction thicknesses within the same pattern bond. Thus, the pattern bond and construction thickness are interdependent, defining the orientation of the bricks and mortar joint and, consequently, the ratio of bricks to mortar in the brick masonry wall. As the brick masonry wall thickness increases, the wall becomes increasingly inhomogeneous, demonstrating a greater diversity for the orientations of brick and mortar to one another and for the ratios of brick and mortar joints.

Considering a smaller scale, figure 40 and 41, the three-dimensional construction of one-and-a-half-stone solid brick masonry reveals various forms of the relation between brick and mortar due to different orientations and ratios. In the vertical and horizontal cross-sections, the orientation and ratio of brick and mortar can adopt multiple configurations. Furthermore, considering different types of mortar in solid brick masonry, the pointing and laying mortar can be recognized which have varying hygrothermal properties.

In the vertical cross-section two different orientations for the laying mortar joint can be found, the bed mortar joint and head mortar joint. As shown in figure 40, three different orientations and ratio's of bricks and mortar joints can be found in the vertical cross-section:

1. Brick (stretcher) - head mortar joint - brick (header);
2. Pointing mortar joint - bed mortar joint; and
3. Brick (header) - head mortar joint - brick (stretcher).

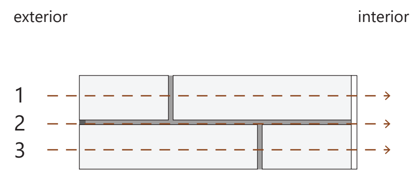

Fig 40. Three different orientations and ratio's of bricks and mortar joints in the vertical cross-section of a solid brick masonry wall in English bond.

In the horizontal cross-section, again two different orientations of the brick can be found, the header and stretcher. Also, two different orientations of the head mortar joint can be found, parallel or perpendicular. As shown in figure 41, five different orientations and ratio's of bricks and mortar joints can be found in the horizontal cross-section:

1. Pointing mortar joint - head mortar joint (parallel);
2. Brick (stretcher) - head mortar joint (perpendicular) - brick (header);
3. Brick (stretcher) - head mortar joint (parallel);
4. Pointing mortar joint head mortar joint (parallel) - brick (stretcher); and
5. Brick (header) - head mortar joint (perpendicular) - brick (stretcher).

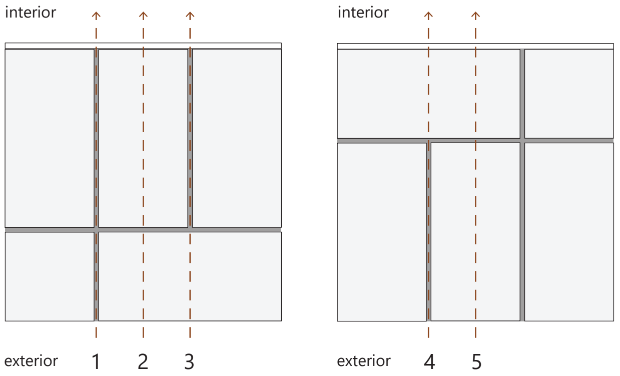

Fig 41. Five different orientations and ratio's of bricks and mortar joints in the horizontal cross-section of a solid brick masonry wall in English bond.

Finally, as mortar joints cure between bricks, a compacted boundary layer forms between the brick and mortar joint. The brick absorbs moisture from the moist mortar, causing the smallest dissolvable mortar base particles to accumulate against the brick in a compacted bond (Van Hunen, 2012). Consequently, looking in more detail at the cross-section of brick masonry, the interface can be distinguished as a third layer next to the brick and mortar joint in brick masonry. The three different layers are shown in figure 42.

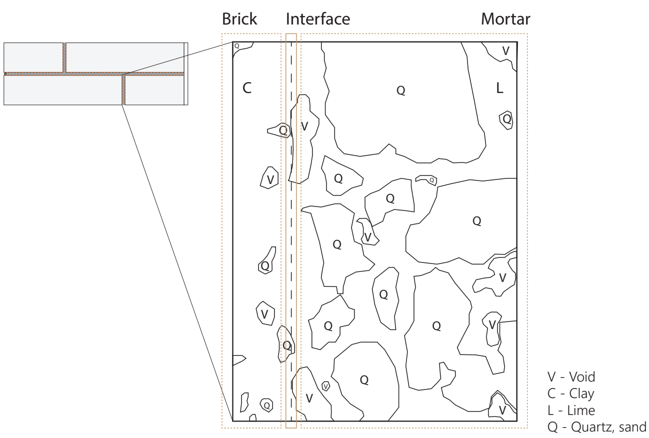

Fig 42. Interface between brick and mortar due to curing of mortar as third layer in the cross-section of brick masonry (Brocken, 1998)(Van Hunen, 2012)

The distinct configurations of brick and mortar in solid brick masonry significantly influence the hygric behaviour of the wall since the hygric behaviour of multi-layered building elements may deviate from that of the combination of individual material elements. This difference results from a different hygric behaviour across the material interface between brick and mortar (Vereecken & Roels, 2013).

Vereecken and Roels (2013) conducted a study comparing the hygric behaviour of homogeneous brick and mortar layers with that of an inhomogeneous brick masonry layer. The findings of the study, shown in figure 43, indicate that in the inhomogeneous brick masonry layer, the progression of the waterfront in the brick is slower compared to that in the homogeneous brick layer. Furthermore, the moisture content in the mortar joint of the inhomogeneous brick masonry layer is higher when compared to the moisture content in the homogeneous mortar layer.

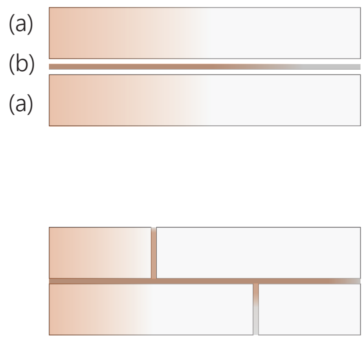

Fig 43. Progression of waterfront in homogeneous brick (a) and mortar (b) layer (top) compared to an inhomogeneous brick masonry layer (bottom), based on Vereecken and Roels (2013).

This difference in moisture content could be clarified by the fact that the finer pores of the mortar absorb moisture from the courser pores of the bricks. The study also observed that the brick layer tends to dry out faster, while to mortar layer shows slower drying, which is primarily due to the differences in pore sizes. Consequently, only the exterior surface experiences some drying of the mortar layer, while most of the moisture is redistributed towards the interior. As a result, the study obtained an accumulation of moisture within the mortar joint.

Despite the mortar having a lower capillary absorption coefficient compared to brick, during alternating wetting and drying periods, the mortar joint functions as the primary path for moisture infiltration.

So, the hygric behaviour of the mortar joint in an inhomogeneous brick masonry layer is more critical than in a homogeneous mortar layer. On the other hand, the hygric behaviour of the bricks is less critical in an inhomogeneous brick masonry layer than in a homogeneous brick layer.

For the inhomogeneous solid brick masonry construction this means that depending on the orientation and ratio of bricks and mortar in the construction, some construction show a more critical hygrothermal behaviour in comparison to others. First, a higher ratio of mortar results in more moisture accumulation in the brick masonry and more redistribution towards the interior. Secondly, solid brick masonry walls with mortar joints that are not intercepted by bricks, and thus connect from the exterior to the interior, show a more critical hygrothermal behaviour than solid brick masonry walls without these mortar joints.

In summary, this paragraph highlights the wide variety of historic solid brick masonry and, consequently, the variety of hygrothermal properties of historic solid brick masonry in the Netherlands. First, many types of bricks and mortar, with differing hygrothermal properties, can be found in historic solid brick masonry. Secondly, solid brick masonry is a three-dimensional wall construction, which can adopt many forms due to varying pattern bonds and thicknesses, influencing the orientation of the bricks and mortar joints and, consequently, the ratio of bricks to mortar in the brick masonry wall. Resulting in an inhomogeneous wall which shows a hygric behaviour that may deviate from that of the combination of individual material elements. For inhomogeneous solid brick masonry, this means that the mortar joint shows a more critical hygrothermal behaviour in the inhomogeneous brick masonry construction than in a homogeneous mortar layer. Therefore, the mortar joint defines the primary path of moisture flux in solid brick masonry. The orientations and ratios of mortar joints are different for each pattern bond and construction thickness showing different hygrothermal performances per type of solid brick masonry wall.

3.3 Vapour-open, non-capillary active insulation

Applying internal insulation will change the hygrothermal behaviour of an existing façade, which might result in several types of damage (Vereecken & Roels, 2014)(Hansen, 2019)(Vereecken & Roels, 2016). This paragraph highlights background information on vapour-open, non-capillary active insulation.

There are three main insulation systems:

1. Vapour-tight system;
2. Vapour-open, capillary active; and
3. Vapour-open, non-capillary active.

The three insulation systems can be distinguished by their material properties. The thermal conductivity (λ), vapour diffusion resistance factor (μ), water absorption coefficient (A) and sorption isotherm are hygrothermal properties of materials (Blumberga et al., 2016)(Künzel, 1995)(Krus, 1996). The vapour diffusion resistance factor indicates the relative hindrance of a material to the passage of water vapour. Considering the thickness of an insulation layer, the vapour diffusion equivalent air layer thickness, μd-value (product of μ and layer thickness), is used to classify insulation materials as a vapour-open or vapour-tight material (Blumberga et al., 2016). Table 2 is adopted from Stichting ERM (2021) as a guideline to classify vapour-open and vapour-tight insulation layers.

System	μd-value
Vapour-open	μd < 0.2 m
Vapour permeable	0.2 m < μd < 3 m
Vapour-tight	μd > 3 m

Table 2. Classification different insulation systems (Stichting ERM, 2021).

The water absorption coefficient (A) and sorption isotherm of an insulation material determine if an insulation layer is capillary active or not since capillary action refers to the capability of certain materials to absorb liquid water through capillary suction and distribute it throughout the material (Blumberga et al., 2016)(Vereecken & Roels, 2016). The sorption isotherm of a material and classification of a material as capillary active or non-capillary active is discussed in detail in Chapter 4.

Furthermore, tables 3 and 4 are adopted from the Dutch Cultural Heritage Agency as a reference to distinguish the three types of insulation materials.

System	Thermal conductivity coefficient (λ) [W/mK]	Vapour diffusion resistance factor (μ) [-]	Water absorption coefficient (A) [kg/m²√s]
Vapour-tight	Low, λ = 0.03 - 0.04 W/mK	Very high, due to application of vapour retarder, μ > 60000	-
Vapour-open, non-capillary active	Low, λ = 0.03 - 0.04 W/mK	Low, μ = 5 - 50	-
Vapour-open, capillary active	Medium, λ = 0.06 - 0.065 W/mK	Low, μ = 5 - 15	High, A > 0.2 kg/m

Table 3. Hygrothermal properties according to type of insulation system (Stappers, 2020)(Stappers, 2021).

Material		Thermal conductivity coefficient (λ) [W/mK]	Vapour diffusion resistance factor (μ) [-]	Water absorption coefficient (A) [kg/m²√s]
Traditional *these materials can be part of a vapour-tight or vapour-open. non-capillary active system.*	Cork	0.040 - 0.045	5 - 30	-
	Cellullar glass	0.042	5000 - 7000	-
	Glasswool	0.040	1.2	0
	Rockwool	0.040	1.5	0
	EPS	0.035	15 - 200	0.00001
	XPS	0.030	200 - 250	0
	PUR/PIR	0.030	60 - 80	0
Modern	Aerogel	0.013	3 - 5	0
	Vacuum panel	0.007	1500000	0.000008
Vapour-open, capillary active	Calcium silicate	0.060	6 - 9	0.8 - 1.1
	Wood fibre board	0045	10 - 16	0.2 - 0.3

Table 4. Common insulation materials with their hygrothermal properties (Stappers, 2020)(Stappers, 2021).

The vapour-open, non-capillary active systems are vapour-open, meaning that they have a low vapour diffusion resistance (μ) given only by the insulation material itself. In addition, the systems are non-capillary active, meaning that the system's water absorption coefficient (A) is zero or very low, and the moisture storage capacity is low. Mineral wool (glass wool, rock wool) is an example of a vapour-open, non-capillary active insulation material. It should be noted that a vapour-open, non-capillary active insulation material does not directly imply that the system is vapour-open since this depends on the thickness of the material layer as well as the vapour diffusion resistance of the material.

3.4 Hygrothermal loads - outdoor and indoor environment

The hygrothermal behaviour of a building envelope is influenced by the hygrothermal loads acting on the building envelope. The indoor environment is protected from the outdoor environment by the building envelope. The heat and moisture fluxes that generate hygrothermal loads on the building envelope can change direction, from interior to exterior and vice versa, as the air temperature and relative humidity change throughout the day and across the season in the outdoor and indoor environments. The principal hygrothermal loads experienced by the envelope, therefore, come from the indoor and outdoor environment (Hall & Casey, 2012). The hygrothermal loads acting on a building facade are visualised in figure 44.

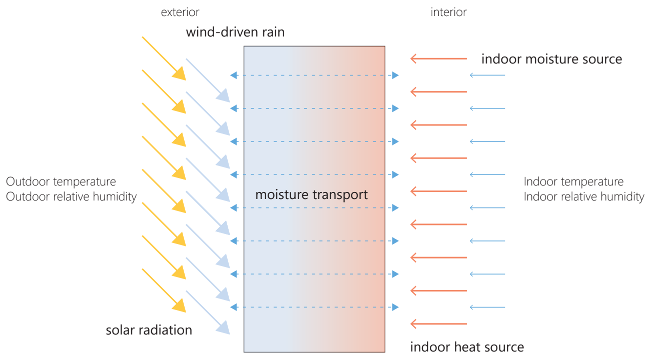

Fig 44. Hygrothermal fluxes through a building facade due to hygrothermal loads from the indoor and outdoor environment.

3.4.1 Outdoor environment

The main hygrothermal loads from the outdoor environment experienced by buildings are the outdoor temperature and relative humidity which are determined by solar radiation, precipitation and wind-driven rain. According to the WTA Guideline 6-2, "the external climate conditions on the building envelope are determined by external temperature, radiation, external humidity and precipitation."

The solar radiation and precipitation for building envelopes depend on the inclination and orientation (WTA Guideline 6-2). According to Hansen (2019) the orientation of the building envelope, and consequently the solar radiation and wind-driven rain on the building significantly influence the hygrothermal behaviour of a façade. Therefore, the outdoor hygrothermal loads are different per building envelope and need to be considered separately.

3.4.2 Indoor environment

Nowadays, historic buildings have another indoor climate compared to their original situation. For instance, the occupancy has changed, mainly due to an increased living space per person across all building types and a tendency for higher and more stable indoor air temperatures. These changes reduce the risk of high indoor air relative humidity. Another new habit that changed the indoor environment is an increased area of moist rooms and an increased number of moisture sources in buildings, compared to decades ago, with shared bathrooms on each floor, and joint washing and drying rooms in the basement. The impact of these changes is unknown and strongly depends on interaction with tenants in the building (Freudenberg, 2019).

The indoor climate conditions are determined by the indoor temperature and relative humidity or vapour pressure (NEN-EN-ISO 13788). The HVAC system and moisture production due to user behaviour and occupancy substantially impact the internal air humidity (WTA Guideline 6-2).

3.4.2.1 Indoor environment - NEN-EN-ISO 13788

According to Dutch building regulations (NEN-EN-ISO 13788) the indoor environment for heated residential buildings can be determined by an approach based on the external air temperature. Internal humidity load can be described by five humidity classes and is ordered according to the differences between indoor and outdoor vapour pressure, this is shown in table 5 and figure 45.

Humidity class	Building
1	Unoccupied buildings, storage of dry goods
2	Offices, dwellings with normal occupancy and ventilation
3	Buildings with unknown occupancy
4	Sports halls, kitchens, canteens
5	Special buildings, e.g. laundry, brewery, swimming pool

Table 5. Internal humidity classes (NEN-EN-ISO 13788).

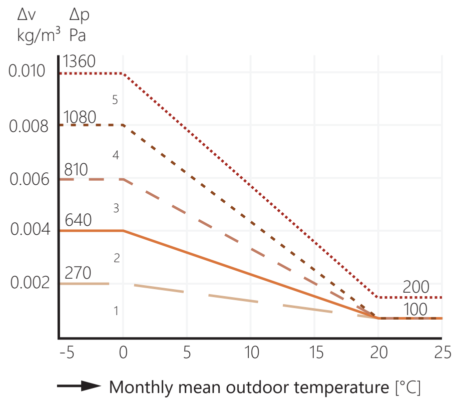

Fig 45. The indoor climate classes are an ordering of the difference between indoor and outdoor vapour pressure (NEN-EN-ISO 13788).

However, this regulation does not define the internal temperature and relative humidity and, therefore, does not entirely define the indoor climate of residential buildings.

3.4.2.2 Indoor environment - WTA Guideline 6-2

In contrast, the German WTA 6-2 Guideline for the indoor climate is more adequate in defining the indoor environment. In Germany, the indoor climate classes are also distinguished according to the moisture load in a building. According to WTA guidelines 6-2, the internal climate is, contrary to the external climate, substantially impacted by user behaviour and HVAC systems (moisture production, manual ventilations, mechanical ventilation or air-conditioning systems). The daily and seasonal fluctuations are lower than in the external environment since the heat and moisture storage capacities of interior building components, and furnishings usually ensure that temperature and relative humidity changes are relatively slow. Consequently, hourly measuring values of internal climate are only required for special situations.

As well as in the Dutch regulation, a distinction of moisture loads in buildings is made in Germany. Using table 6 and figures 46 and 47, the WTA Guideline 6-2 derives the internal air temperature and humidity level from the external air temperature's daily mean value.

Level of moisture load	Application type of building
high moisture load	Buildings with an extraordinarly high occupancy.
normal moisture laod +5%	Houses, normal situations, but with desired additional safeguards.
normal moisture load	Houses, normal situations, including kitchens and bathrooms.
low moisture load	Buildings with rooms such as offices, classrooms, sales premises. Approach does not include any safeguard and limits future changes of use.

Table 6. Indoor climate classes according to moisture load (WTA Guideline 6-2).

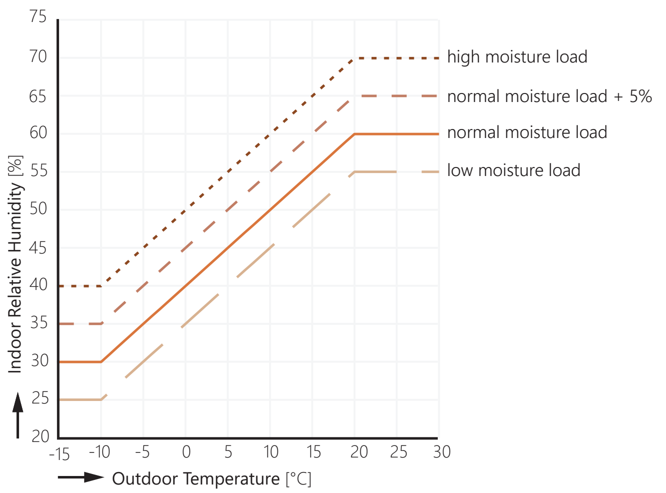

Fig 46. Deriviation of the internal relative humidity in buildings depending on the external daily mean air temperature and type of building (WTA Guideline 6-2).

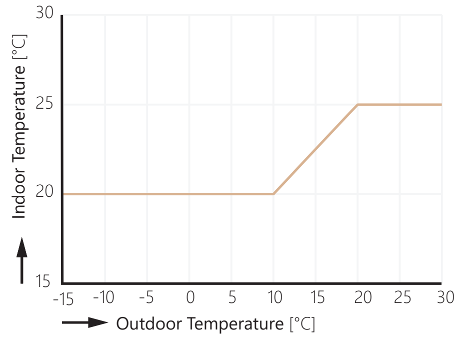

Fig 47. Deriviation of the internal temperature in buildings depending on the external daily mean air temperature (WTA Guideline 6-2).

Summarising, this chapter gave background information about the challenges that the application of internal insulation for historic buildings brings with regard to the hygrothermal performance and about the factors influencing the hygrothermal behaviour of a vapour-open, non-capillary active, internally insulted historic solid brick masonry wall. Resulting in insight into the complexity of the topic and a gain background knowledge that will assist in decision-making towards unfolding what hygrothermal properties influence the hygrothermal behaviour of this type of façade most.

From this chapter, it can be stated that applying internal insulation brings a couple of challenges regarding the suitability of brick masonry, the hygrothermal risks, the critical details causing thermal bridges and the modifications of the wall structure which all affect the hygrothermal performance. Special attention is required for thermal bridges at beam ends and window frame connections in buildings with internal thermal insulation (Van Hemert, 2013), since these cause aesthetic and hygrothermal problems which decrease the historic, cultural and aesthetic value of the historic building and the hygrothermal performance of the historic internally insulated solid brick masonry wall.

Furthermore, many types of historic solid brick masonry walls can be found in the Netherlands since this wall construction can vary in brick type, mortar type and construction type (thickness and pattern bond). The three factors that influence the hygrothermal behaviour of a historic brick masonry wall are independent and interlinked. Resulting in an inhomogeneous wall construction which shows a hygric behaviour that may deviate from that of the combination of individual material elements. For inhomogeneous solid brick masonry, this means that the mortar joint shows a more critical hygrothermal behaviour in the inhomogeneous brick masonry construction than in a homogeneous mortar layer and, therefore, defines the primary path of moisture flux in solid brick masonry.

In addition, the vapour-open, non-capillary active systems are vapour-open and non-capillary active, meaning that these systems have a low vapour diffusion resistance (μ) which is given only by the insulation material itself and have a very low or no water absorption coefficient (A) resulting in a very low moisture storage capacity.

Finally, the hygrothermal loads from the outdoor environment are defined as external temperature and relative humidity, which are different per orientation of the building envelope and determined by solar radiation and wind-driven rain. The loads from the indoor environment are defined as indoor temperature and relative humidity or vapour pressure. German regulations most adequately determine the indoor environment (WTA Guideline 6-2), which divides the indoor environment into classes mainly based on indoor moisture load and partly based on the outdoor environment, defining the indoor relative humidity and temperature.

4 Assessment hygrothermal performance

Assessing the hygrothermal behaviour of a building component is essential to ensure a risk-free hygrothermal performance. The hygrothermal behaviour can be studied employing Heat, Air and Moisture simulations. Other models can be used to assess the hygrothermal performance to ensure a risk-free performance. However, to understand the different programs and models, insight into the theory of moisture transport and storage must first be gained. The moisture theory will be addressed with regard to HAM-simulation software WUFI 2D.4. In this chapter, the prerequisites will be determined to asses a risk-free hygrothermal performance of a building component by addressing the second sub-question:

Under what conditions is the hygrothermal performance of vapour-open, non-capillary active, internally insulated solid brick masonry for residential buildings risk-free?

4.1 Theory of moisture in porous building materials

Moisture can affect a building component in liquid form as rain or rising damp, on the other hand, it can do so in the form of water vapour condensing on the surface or inside the component. Increased moisture content can also be caused during the formation process of a component, for example by mixing water for mortar or during the production of bricks (Künzel, 1995). Figure 48 shows four ways in which moisture can affect a building component.

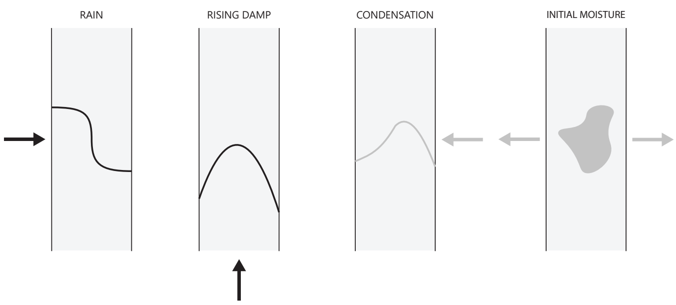

Fig 48. The effect and distribution of mositure in an external wall caused by rain, rising damp, condensation, initial moisture (Künzel, 1995).

Non-hygroscopic materials remain dry when in contact with moist air. In contrast, **hygroscopic** materials absorb water molecules at the inner surfaces of their pore system until their water content reaches equilibrium with the humidity of the surrounding air. A building material is considered capillary-active if it absorbs moisture by capillary suction. If it does not, it is considered hydrophobic (Künzel, 1995)(Künzel et al., 2001).

The moisture balance in porous materials is determined by the **moisture storage characteristics** and the **moisture transport phenomena** taking place in the material in liquid and gaseous phases (Krus, 1996). Depending on environmental conditions, moisture can take three different physical states, which are solid, liquid or vaporous. The sum of the total moisture in a building material is used since it is difficult to determine the different physical states separately by measuring, and since the ratio of individual states constantly changes under natural conditions (Künzel, 1995). This sum is total water content w.

Moisture is considered a mass, and the mass balance is as follows:

$$-\nabla \cdot g = \frac{\partial w}{\partial t} \qquad (1)$$

Where,

g = density of moisture or mass flow rate, [kg/m²s];
w = moisture content, [kg/m³];
t = time in hours, [h].

(De Wit, 2009)

The left part of the equation is the moisture transfer part and the right side is the moisture storage function.

4.1.1 Moisture storage in porous materials

Theoretically, a porous building material can take up moisture until all its pores are filled with moisture. However, this provides no information about the moisture storage capacity of the material under natural conditions. Therefore, it is essential to define a connection between the moisture content of a building material and the ambient conditions. The moisture storage capacity of a building material is shown by the function of the moisture content in relation to the relative humidity. To derive the function, three moisture storage regions can be distinguished in porous building materials: the **region of sorption moisture**, the **capillary moisture region** and the **region of supersaturation** (Künzel, 1995). The three moisture storage regions are shown in figure 49.

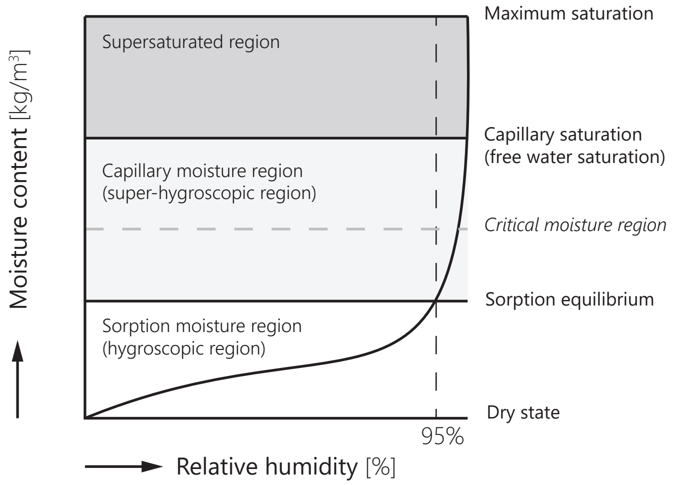

Fig 49. Diagram of the moisture storage fucntion of a hygroscopic capillary active building material (Künzel, 1995).

The **sorption moisture region**, the hygroscopic region, is defined as sorption from the surrounding moist air until a state of equilibrium is reached. This equilibrium is called the sorption equilibrium, which is reached around 95% relative humidity. The relationship between the accumulated moisture content and the relative humidity in a porous building material is described by the sorption isotherm, see figure 50. Sorption isotherms often show a hysteresis effect between adsorption and desorption of moisture. However, for most porous building materials, this effect is minimal, so the adsorption isotherm is sufficient to characterize the sorption moisture region (Krus, 1996)(Künzel, 1995)(Künzel et al., 2001).

The sorption isotherm can be divided into three areas. The lower area up to about 15% relative humidity is identified as the monomolecular layer, followed by the multimolecular layer ending at about 50% relative humidity. The third area is described as capillary condensation (Krus, 1996).

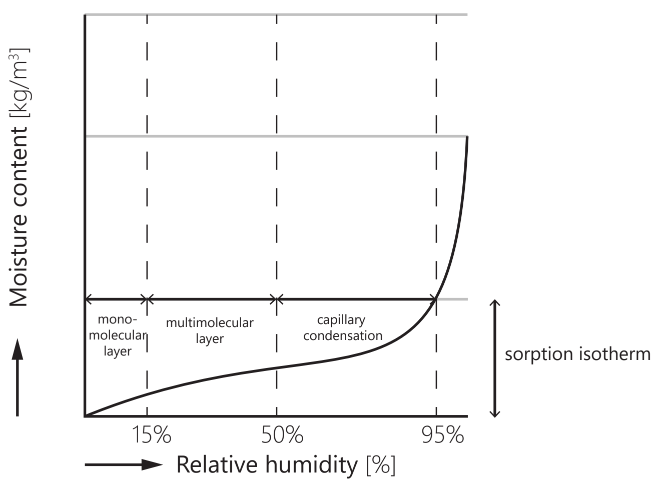

Fig 50. Diagram of the three areas within the sorption isotherm.

At relative humidities above 95% the sorption isotherm rises very sharply. Here, the **capillary moisture region**, frequently also called the superhygroscopic region, starts. The capillary moisture region is marked by the ability of capillary-active porous materials to absorb moisture until capillary saturation (free water saturation) is reached. Capillary saturation is reached through natural absorption without the influence of exterior forces. For capillary-porous building materials, capillary saturation is always below the water content possible from open pore space since not all pore space is filled due to the presence of entrapped air, see figure 51 (Künzel, 1995).

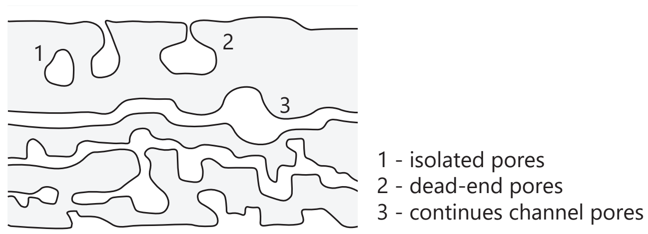

Fig 51. Different pore types and shapes in porous building materials (Künzel et al., 2001).

Thus, from a relative humidity above 95% a distinction between capillary and non-capillary active materials can be made. This results in a major difference in the moisture content at capillary saturation (free saturation). A capillary active material has a higher moisture storage capacity since the capillaries in these materials are able to absorb more moisture. This is shown by means of sorption isotherms of the building materials mineral wool and calcium silicate in figures 52 and 53.

To a certain extent, all porous materials are a little capillary active, but a significant difference can be found between mineral wool and calcium silicate.

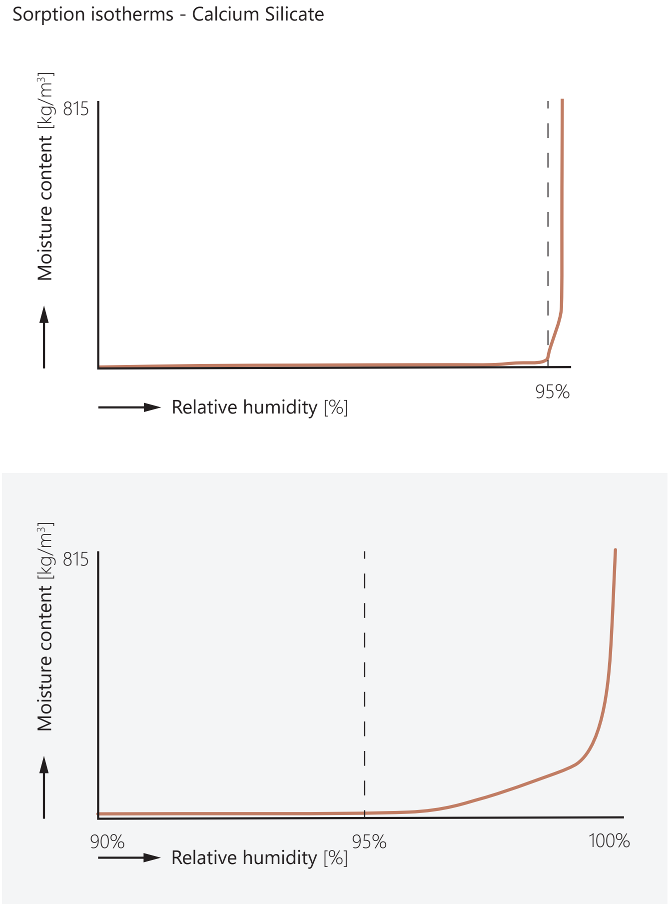

Fig 52. Sorption isotherms insulation material calcium cilicate starting from 0% relative humidity (top) and 90% relative humidity (bottom) adopted from WUFI 2D.4 Material Database.

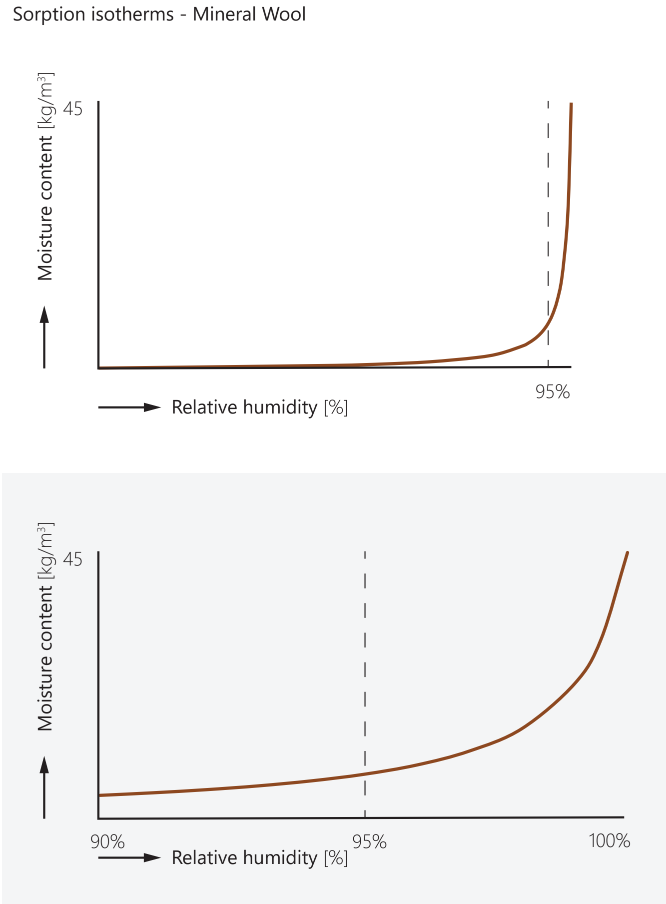

Fig 53. Sorption isotherms insulation material mineral wool starting from 0% relative humidity (top) and 90% relative humidity (bottom) adopted from WUFI 2D.4 Material Database.

The capillary phenomena can be described by the simple model of a cylindrical capillary, see figure 54. In a partially filled capillary, the moisture surface (meniscus) bends due to the surface tension of the liquid and the interfacial tension between the liquid and the wall of the capillary. The curved surface of the liquid creates a pressure directed towards the centre of the curve, this pressure is called capillary pressure. Depending on the wetting angle this capillary pressure is responsible for the rise (capillary ascension) or drop (capillary depression) of the meniscus in a capillary. If capillaries of different radii connect to one another, the smaller ones will continue to draw moisture out of the larger capillaries (Krus, 1996).

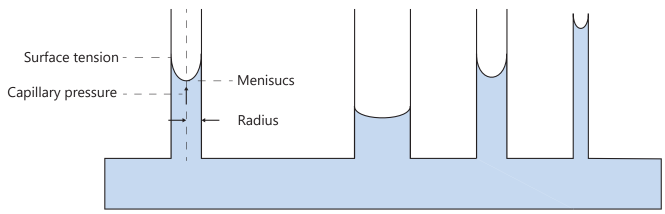

Fig 54. Diagram of cylindrical capillary showing the ability of smaller capillaries to draw moisture deeper, based on Krus (1996).

In the capillary moisture region, the moisture storage function is called the water retention curve, which describes the relationship between water content and capillary pressure in the relative humidity range between 95% and 100%. (De Wit, 2009), see figure 55. The capillary pressure can also be referred to as the suction pressure.

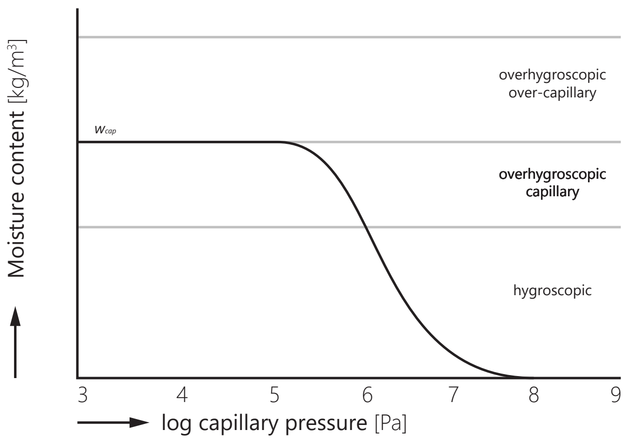

Fig 55. Water retention curve (De Wit, 2009).

Within the capillary moisture region, the critical moisture content can be recognized. The critical moisture content is higher than the moisture content at sorption equilibrium and lower than the free water saturation, see figure 49. The critical moisture content affects the different types of moisture transport which will be discussed in paragraph 4.1.2.

The **region of supersaturation** is reached after the capillary moisture region. Capillary saturation can only be exceeded by the application of external pressure. No moisture equilibrium is reached through capillary transport between supersaturated and capillary-saturated regions (Krus, 1996). Therefore, this region is out of scope and not further discussed.

The accurate determination of the moisture storage function is necessary in the case of building component layers with a direct capillary connection, in which the moisture transport from layer to layer plays an important role (Künzel, 1995). The moisture storage of a porous building material is measured by the moisture content. This potential can for example be derived from the weight increase of a porous building material due to moisture (De Wit, 2009). According to De Wit (2009), the following equation can be used for the moisture content:

$$\frac{\partial w}{\partial t} = \nabla \cdot D_w \nabla w \qquad (2)$$

Where,

w = moisture content, [kg/m³];
t = time in hours, [h];
D_w = liquid transport coefficient, [m²/s].

According to De Wit (2009) the change in moisture content can be written as:

$$\frac{\partial w}{\partial t} = \frac{dw}{d\varphi}\frac{\partial \varphi}{\partial t} \qquad (3)$$

Where the $\frac{dw}{d\varphi} = \xi$, which is the tangent of the sorption isotherm of a porous building material.

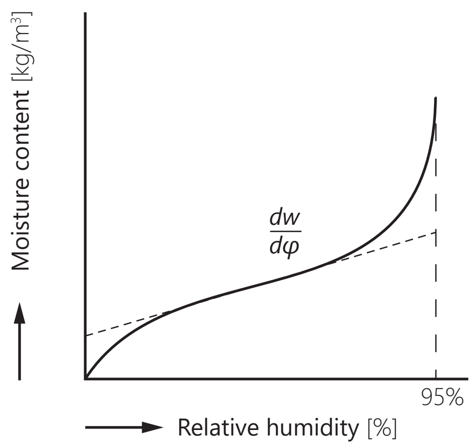

Fig 56. Tangent of sorption isotherm of a porous building material.

This results in the following formula for the change in moisture content:

$$\frac{\partial w}{\partial t} = \frac{dw}{d\varphi}\frac{\partial \varphi}{\partial t} = \xi \frac{\partial \varphi}{\partial t} \qquad (4)$$

Where,

w = moisture content, [kg/m³];
t = time in hours, [h];
φ = relative humidity, [%].

4.1.2 Moisture transport in porous materials

Under practical physical conditions of building and construction, moisture transport occurs as liquid and gaseous transport with different driving potentials. For liquid transport capillary conductivity and surface diffusion are found and for vapour transport vapour diffusion and effusion (or Knudsen transport) are found, see figure 57. Below the critical moisture content vapour transport dominates and above this liquid transport (Krus, 1996)(Künzel, 1995). In reality, there is no clear breakpoint but rather a transition regime between vapour and liquid transport (De Wit, 2009).

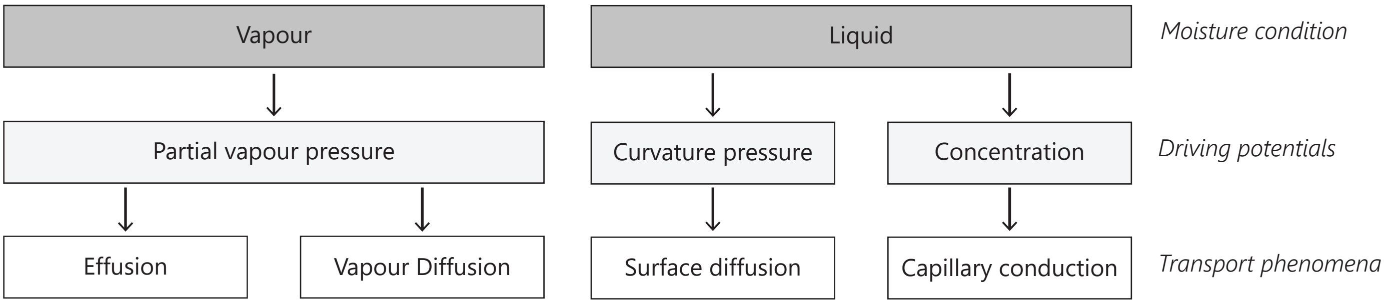

Fig 57. Overview of the moisture transport phenoma investigated in this research (Krus, 1996).

Moisture transport in building materials takes place from the inside to the outside and vice versa. Vapour and liquid transport do not influence each other, they act independently. This assumption applies in the sorption moisture region of most building materials, since vapour diffusion takes place mainly in the larger pores, while liquid transport takes place via the micropores and on the pore walls, see figure 58 (Künzel, 1995).

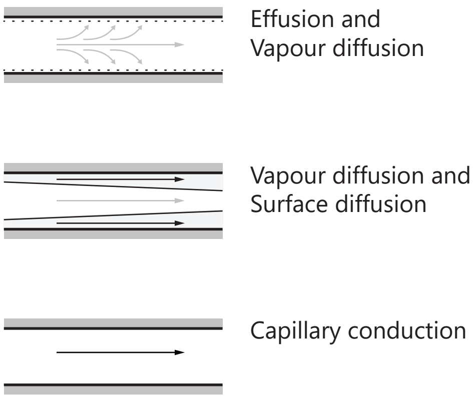

Fig 58. Diagram showing the moisture transport in a pore of a porous hygroscopic building material with vapour and liquid transport occuring simultaneously (Künzel, 1995)(Krus, 1996).

4.1.2.1 Vapour transport

There are two types of vapour transport: **effusion** and **vapour diffusion**. The driving potential of vapour transport is partial vapour pressure. During the heating season, the partial vapour pressure is higher on the interior side, resulting in vapour transfer through the building material from the indoor to the outdoor, seeking equilibrium. For **effusion** (or Knudsen transport), transport is marked by collisions of the water molecules with the pore wall. Therefore, effusion only takes place in the micropore region of a porous building material. If transport is marked by collisions of the water molecules with one another, the transport is known as **vapour diffusion**. In the intervening transition zone, the two transport mechanisms occur intermixed. A clear distinction of the vapour transport phenomena is almost impossible since most porous building materials have a pore size spectrum. Therefore a standard diffusion coefficient (Dv) can be used to describe both effusion and water vapour diffusion in building materials (Krus, 1996)(Künzel, 1995).

Diffusion flow has to overcome an increased resistance when vapour diffuses through porous material layers. This is because of the pore structure's tortuous path, cross-sectional changes in the pore ducts, and the ratio of the area occupied by the pores of the total cross-section area (porosity). These phenomena are incorporated by the water vapour diffusion resistance factor (μ). This factor represents the difference between the diffusion resistance of a material layer and that of air of the same thickness. The degree to which a porous material limits the vapour diffusion is defined by the vapour diffusion resistance factor. This factor is always larger than one (>1) for porous medium. The water vapour diffusion resistance factor of air is 1 (Krus, 1996)(Künzel, 1995).

Vapour diffusion in porous materials is, like vapour transfer in air, according to Fick's law.

$$g_v = -\frac{D_v}{\mu}\nabla\rho_v = -\frac{D_v}{\mu R_v T}\nabla p_v = -\frac{\delta_a}{\mu}\nabla p_v \qquad (5)$$

Where,

g_v = mass flux rate of vapour flow, [kg/m²s];
D_v = duffusion coefficient of water vapour in air, (≈2,5 $\cdot 10^{-5}$ m²/s at 20 °C);
μ = vapour diffusion resistance factor, [-];
ρ_v = partial vapour concentration in air, [kg/m³];
p_v = partial vapour pressure, [Pa];
R_v = universal gas constant, (8,314 J/molK)
T = absolute temperature, [K];
δ_a = vapour permeability of air, [kg/msPa].

(De Wit, 2009)(Krus, 1996).

The vapour permeability coefficient of air undergoes a resistance in porous materials, resulting in the following vapour permeability coefficient:

$$\delta_p = \frac{\delta_a}{\mu} \qquad (6)$$

Where,

δ_a = vapour permeability of air, [kg/msPa];
μ = vapour diffusion resistance factor, [-].

Ingluding equation (6), Fick's law for vapour transfer in porous materials can be written as:

$$g_v = -\delta_p \nabla p_v \quad (7)$$

Where,

g_v = mass flux rate of vapour flow, [kg/m²s];
δ_p = vapour permeability of a porous material, [kg/msPa];
μ = vapour diffusion resistance factor, [-];
p_v = partial vapour pressure, [Pa].

(De Wit, 2009) (Künzel et al., 2001).

4.1.2.2 Liquid transport

For liquid transport it is necessary to distinguish the sorption moisture region and the capillary water region. This is because **surface diffusion** takes place in the sorption moisture region, while **capillary action** takes place in the capillary water region in hygroscopic porous building materials (Krus, 1996), see figure 59.

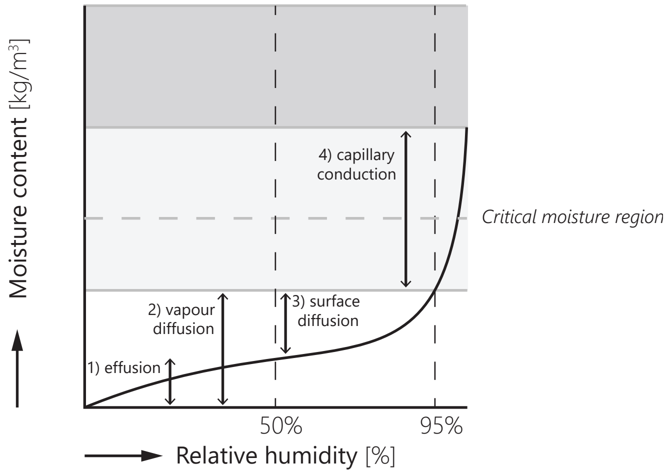

Fig 59. Diagram showing the different transport phenomena in the different moisture storage regions.

Surface diffusion is defined "as moisture transport in the water molecule layers absorbed at the pore walls of hygroscopic materials and in micro-capillaries" (Künzel, 1995). A sorptive film arises due to the absorption of water molecules on the inner surfaces of the pore walls, which increases in thickness with rising relative humidity (Krus, 1996).

Only at water contents above the critical moisture **capillary conduction** occurs. However, in the microcapillaries, this form of liquid transport already takes place significantly below the critical moisture content. Therefore, similarly to vapour transport, capillary conduction and surface diffusion take palce simultaneously in liquid transport (Künzel, 1995).

According to Künzel (1995), the liquid transport in porous building materials can be described with the liquid conduction coefficient (D_φ) and relative humidity (φ). The equation for the liquid transport is then as follows:

$$g_w = -D_\varphi \nabla \varphi \quad (8)$$

Where,

g_w = liquid transport flux density, [kg/m²s];
D_φ = liquid conduction coefficient, [m²/s];
φ = relative humidity, [%].

4.1.2.3 Moisture transport

For calculation of the moisture transport, both vapour and liquid transport, in porous building materials, the equations for vapour (7) and liquid (8) transfer can be substituted into the mass balance (1).

Mass balance:

$$-\nabla \cdot g = \frac{\partial w}{\partial t} \quad (1)$$

$$-\nabla \cdot (g_v + g_w) = \frac{\partial w}{\partial t} \quad (9)$$

Vapour transport equation:

$$g_v = -\delta_p \nabla p_v \quad (7)$$

And liquid transport equation:

$$g_w = -D_\varphi \nabla \varphi \quad (8)$$

Leads to the following transient differential equation that can be used for the moisutre transport (Künzel, 1995):

$$\frac{\partial w}{\partial t} = \nabla \cdot \left(\delta_p \nabla p_v + D_\varphi \nabla \varphi\right) \quad (10)$$

Where,

w = water content, [kg/m³];
t = time in hours, [h];
δ_p = vapour permeability porous material, [kg/msPa];
p_v = partial vapour pressure, [Pa];
D_φ = liquid conduction coefficient, [kg/ms];
φ = relative humidity, [%].

4.1.2.4 Moisture balance

The moisture balance is found with the equations for moisture storage (3) and transport (10).

Moisture storage characteristics, the change in moisture content:

$$\frac{\partial w}{\partial t} = \frac{dw}{d\varphi}\frac{\partial \varphi}{\partial t} \quad (3)$$

And moisture transport:

$$\frac{\partial w}{\partial t} = \nabla \cdot \left(\delta_p \nabla p_v + D_\varphi \nabla \varphi\right) \quad (10)$$

Leading to the following equation for the moisture balance:

$$\frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \nabla \cdot \left(\delta_p \nabla p_v + D_\varphi \nabla \varphi\right) \quad (11)$$

Where,

w = water content, [kg/m³];
φ = relative humidity, [%]
t = time in hours, [h];
δ_p = vapour permeability porous material, [kg/msPa];
p_v = partial vapour pressure, [Pa];
D_φ = liquid conduction coefficient, [kg/ms].

4.2 Hygrothermal simulation software

Simulation software that can be used to study hygrothermal behaviour is WUFI 2D 4.2. This is an advanced simulation model developed as a hygrothermal design tool for architects and engineers. The software is developed to assist architects and engineers during the design stage to optimize the heat and moisture performance of the envelope. The program is based on the state-of-the-art understanding of building physics regarding sorption and suction isotherms, vapour diffusion, liquid transport, and phase changes (Künzel et al., 2001). WUFI is developed for the computation of simultaneous heat and moisture transport in one- or two-dimensional multi-layered building components in the building envelope (Blumberga & De Place Hansen, 2015).

The governing equations employed in the WUFI model for mass and energy transfer are:

$$\frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \nabla \cdot \left(\delta_p \nabla p_v + D_\varphi \nabla \varphi\right) \quad (11)$$

$$\frac{\partial H}{\partial T}\frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + h_v \nabla \cdot \left(\delta_p \nabla (\varphi\, p_{sat})\right) \quad (12)$$

Where,

w = water content, [kg/m³];
φ = relative humidity, [%];
t = time in hours, [h];
δ_p = vapour permeability porous material, [kg/msPa];
p_v = partial vapour pressure, [Pa];
D_φ = liquid conduction coefficient, [kg/ms];
H = total enthalpy, [J/m³];
T = temperature, [K];
λ = thermal conductivity [W/mK];
h_v = latent heat of phase change, [J/kg];
p_{sat} = saturation vapour pressure, [Pa].

On the left-hand side of the mass equation (11) are the storage terms. The fluxes on the right-hand side are influenced by moisture (Künzel et al., 2001). The transfer equations show that each hygrothermal flux does not act independently but is interdependent and occurs simultaneously in a complex manner (Hall & Casey, 2012).

The governing mass transfer equation (11) is in line with the equation described in the previous paragraph. The energy transfer calculation (12) will not be further discussed since this research mainly focuses on the hygric behaviour including the building component's moisture transfer phenomena and storage characteristics, however, this calculation is of importance since it shows the thermal aspect of the behaviour. Furthermore, the simulation software neglects several transport phenomena such as air flow in the building component and the uptake of groundwater. Both are not studied in this research.

To solve above stated equations (11) (12) and obtain results, input is needed. The calculation procedure including the necessary input and the obtainable results are demonstrated in figure 60, showing the calculation technique on which the WUFI 2D.4 software is based.

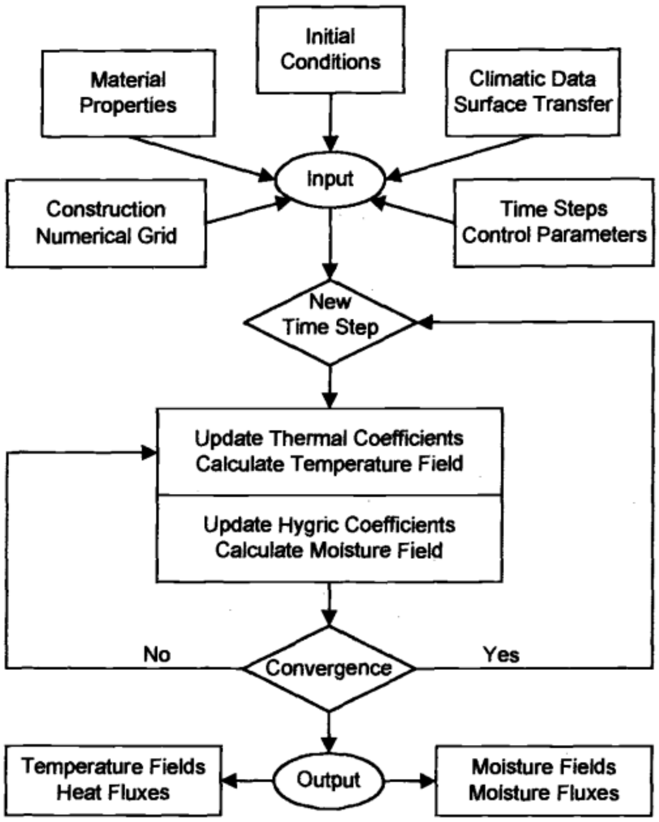

Fig 60. Flow chart of the solution procedure in WUFI 2D.4 (Künzel et al., 2001).

4.2.1 Input simulation software WUFI 2D.4

The input data consists of two types of input. First, input that influences the hygrothermal behaviour of the simulated construction. Secondly, input that influences the accuracy of the simulation. The numerical grid, the time steps and the numerical control parameters are input data that influence the accuracy of the output of the simulation. The geometry and composition of the building assembly; the hygrothermal properties of the relevant building materials; and the climatic indoor and outdoor boundary conditions are input data of the simulation that influence the hygrothermal behaviour of the simulated building component. This will be elaborated further below. (Künzel et al., 2001).

4.2.1.1 Material properties

First, the material properties are needed to solve the moisture and energy equations. According to Künzel et al. (2001), the minimum material properties required for the simulation are:

- Bulk density [kg/m³]
- Porosity [m³/m³]
- Heat capacity [kJ/kgK]
- Heat conductivity dry [W/mK]
- Diffusion resistance factor dry [-]
- Sorption/suction isotherms [kg/m³]
- Liquid diffusivity [m²/s]

4.2.1.2 Initial conditions

WUFI calculates the evolution of the temperature and moisture distributions within the building component at each time step starting from the specified initial conditions. The heat and moisture exchange with the indoor and outdoor environment as well as the underlying transport equations influence the evolution of the temperature and moisture distributions within the building component (Künzel et al., 2001).

The initial conditions are defined as the temperature, water content and relative humidity. The initial conditions in WUFI are set at 20 °C for the temperature and 80% for the relative humidity. The initial conditions for the water content are material dependent and related to the water content in the material at 80% relative humidity. The initial conditions can be changed, but this affects the results of the simulation. According to Künzel et al. (2001) the initial conditions are based either on measurements or derived from previous calculations.

4.2.1.3 Outdoor boundary condition

In WUFI, meteorological parameters such as temperature, relative humidity, solar radiation, wind speed and orientation, horizontal precipitation, cloud cover and more are used to define the outdoor environment. Hourly weather data is available for complete years, but it should be noted that the years have been selected to represent years that are more appropriate for moisture design purposes than average weather years for energy design. In addition, the model also includes the effects of wind-driven rain. User-defined weather files can also be used for the outdoor environment (Künzel et al., 2001). Furthermore, the program asks for the inclination and orientation of the building component.

4.2.1.3 Indoor boundary condition

In general, the indoor environment, defined as the interior temperature and relative humidity, of different-conditioned buildings, shows slight variations. Therefore the software differentiates four different interior climates: heating conditions, cooling conditions, mixed conditions, and constantly controlled conditions (Künzel et al., 2001). The software also includes the indoor environmental classes in accordance with EN 15026/DIN 4108/WTA 6-2, ISO 13788 and ASHRAE 160. The indoor environments according to the above-mentioned guidelines are based on the Reference Year used for the outdoor environment. For all three guidelines, the indoor environment can be changed and user-defined to a certain level.

4.2.2 Output simulation software WUFI 2D.4

As output data, the simulation software presents the calculated temperature and moisture fields as well as the heat and moisture fluxes at the surfaces of the building component (Künzel et al., 2001).

4.3 Assessment models hygrothermal performance

As mentioned in the background research, vapour-open, non-capillary active, internally insulating historic solid brick masonry entails hygrothermal risks. Even though all hygrothermal risks are important and need to be considered, this research focuses on the risk of mould growth due to interstitial condensation after applying internal insulation. Mould growth does not only damage a building component but also affects the health of the occupants of the building (Hansen, 2019). Several hygrothermal risk assessment models for mould growth prediction are available such as the VTT-model, the isopleth-model and biohygrothermal IBP model (Viitanen et al., 2015)(Sedlbauer, 2001). These models are used to determine risk of mould occurring on the surface behind the interior insulation (Odgaard et al., 2018).

This research focuses on the one-dimensional behaviour of the building component after the application of internal insulation, therefore a two- or three-dimensional situation such as wooden window frames or wooden beam ends is outside the scope of this research. However, as explained in paragraph 3.1.3, the critical details are most sensitive for damage in the construction since the supports of a beam in a brick masonry wall usually rot before the rest of the beam (Zwiers, 1920), see figure 61. It is essential to consider this sensitivity while assessing the hygrothermal performance of a building component.

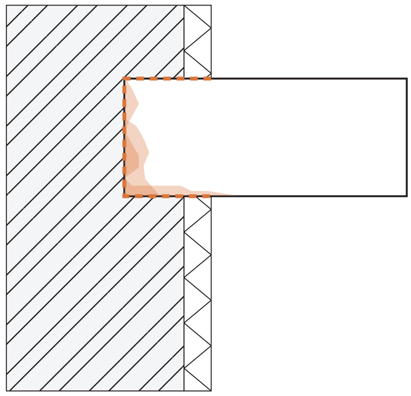

Fig 61. Diagram showing most critical point of a wooden beam end in a solid brick masonry wall, based on Zwiers (1920).

Therefore, the hygrothermal behaviour of a one-dimensional building component after the application of internal insulation will be assessed with an assessment model that is also sufficient for determining wood-decay and mould growth at wooden beam ends, as shown in figure 61. Resulting in a comprehensive hygrothermal assessment model that is adequate for all areas in a building component that need to be assessed on hygrothermal risks. The assessment model for wood-destroying fungi according to WTA Guideline 6-8 is most adeqaute for this approach.

For a one-dimensional building component after the application of internal insulation, the risk on mould growth due to interstitial condensation at the interface between insulation and brick masonry is assumed to be most significant. Considering this and the assessment model for wood-destroying fungi according to WTA Guideline 6-8, a one-dimensional building component after the application of internal insulation will be assessed as if there is a wooden beam end. This results in an interface between the masonry, insulation and wooden beam end, shown in figure 62, where the risk on mould growth due to interstitial condensation is assumed to be most significant.

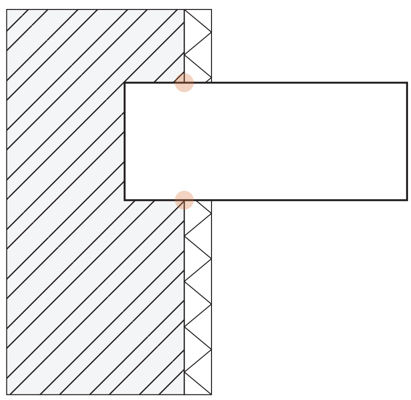

Fig 62. Diagram showing interface between solid brick masonry, internal insulation and a wooden beam end.

4.3.1 WTA Guideline 6-8

The risk of mould growth is governed by temperature, relative humidity, exposure time and material. Mould risk can be assessed mathematically based on monitored relative humidity and temperature or on-site measurements (Odgaard et al., 2018). According to Sedlbauer (2001) is besides the humidity and temperature, the nutrient content of the substrate on which mould grows, the most important factor for mould fungus formation. Small amounts of organic additives in building materials are enough to make microbiological growth possible. (Sedlbauer, 2001).

According to the WTA Guideline 6-8, the assessment with regard to wood-destroying fungi is carried out through the average pore air humidity of the critical layer of 10 mm. The relative pore humidity must not exceed 95% at 0 °C and 86% at 20 °C on a daily average. These conditions result in the limit curve shown in figure 63.

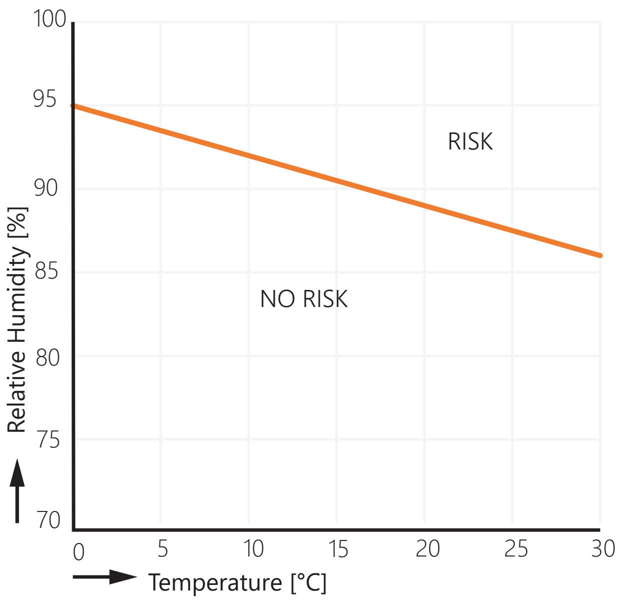

Fig 63. Limit curve of the relative pore air humdity in relation to the temperature, which must not be exceeded as daily average (WTA Guideline 6-2).

In summary, the hygric behaviour of building components is determined by the moisture balance of the building component, which is determined by the moisture storage characteristics and the moisture transport characteristics. It is essential to define the moisture storage characteristics of a material in case building component layers have a direct capillary connection, in which moisture transport from layer to layer plays an important role. Moisture transport distinguishes vapour and liquid transport. Vapour diffusion, a form of vapour transport, in a building component has to overcome an increased resistance due to the porosity and tortuosity of materials, defined by the vapour diffusion resistance factor. Moisture storage and transport are expressed in one equation that determines the moisture balance of a porous building material. Furthermore, HAM-simulation software WUFI 2D.4 can be used to study the hygrothermal behaviour of a building component. The input determines the hygrothermal behaviour of the simulated building component and, therefore, the input needs to be defined accurately to obtain expected results. Finally, the WTA Guideline 6-8 can be used to assess hygrothermal performance. In doing so, the assessment criteria for critical points for historic buildings, such as wooden beams, are considered.

This results in an approach sufficient for one-dimensional and two- or three-dimensional situations. A risk-free hygrothermal performance is achieved if the daily mean relative pore humidity and temperature in the construction do not exceed the limit curve.

5 Parameter study

The background research, chapter 3, shows that hygrothermal behaviour is influenced by three factors simultaneously: hygrothermal hygrothermal loads from the indoor and outdoor environment and hygrothermal properties. However, the main objective is to gain insight into the most influential hygrothermal properties of vapour-open, non-capillary active, internally insulated historic solid brick masonry on the hygrothermal behaviour.

This chapter describes a parameter study that has been carried out through simulations in WUFI 2D.4, to gain insight into the most influential hygrothermal property. Therefore, the input for the parameter study needs to be defined to obtain the most influential hygrothermal material properties of the building component. The factors (hygrothermal properties and loads) that influence the hygrothermal behaviour of the construction are determined by addressing the third sub-question:

What factors should be considered to gain insight into the influence of hygrothermal properties of vapour-open, non-capillary active, internally insulated solid brick masonry for historic residential buildings on the hygrothermal behaviour?

Furthermore, this chapter presents a prediction method to assess the hygrothermal performance of a building component without conducting advanced HAM-simulations. The prediction method can be a useful tool if HAM-simulation software is not available.

The parameter study adopts a reference system for the building component and materials. The study varies the input for this reference system to determine the influence of hygrothermal properties on the hygrothermal behaviour of a vapour-open, non-cappilary active, internally insulated solid brick masonry wall. The performance indicator for the parameter study is set to the number of exceedances of the limit curve from the WTA Guideline 6-8, at the interface of the brick masonry layer and insulation layer meet. The limit curve is exceeded if the daily average temperature and relative humidity at the interface are too high.

Brick, mortar and plaster are the primary materials in external walls of historic buildings (Blumberga & De Place Hansen, 2015). Therefore, a reference system of solid brick masonry, internal insulation and a finishing layer is defined, serving as a premise for the parameter study. The reference system is shown in figure 64.

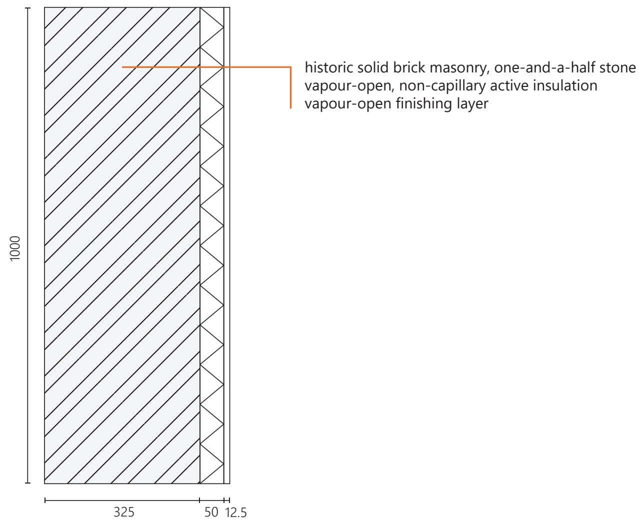

Fig 64. Diagram of reference buidlign component with solid brick masonry, internal insulation and finishing layer.

According to Blumberga et al. (2015) solid brick masonry walls for historic residential buildings were usually constructed in one-and-a-half-stone thickness. The thickness of the insulation layer is typically defined as 50 mm for historic buildings due to historic, cultural and aesthetic values (Stapprers, 2020). Therefore, the thickness of solid brick masonry is defined as one-and-a-half-stone and the thickness of the internal insulation layer is defined as 50 mm in the reference system. The thickness of the finishing layer complies with the commonly used gypsum board as finishing. It is assumed that the brick masonry has no interior finishing plaster. Further analysis is required if interior finishing plaster is present.

5.1 Input

5.1.1 Materials

The input of the reference system is based on the materials from the WUFI 2D.4 HAM-software database, which are appointed to the different layers of the reference system. Table 7 shows the appointed materials.

Material	Hygrothermal properties											
	Thickness (t) [mm]	Water vapour diffusion resistance factor (μ) [-]	μd-value [m]	Moisture content at 80% relative humidity ($w_{80\%}$) [kg/m³]	Free water content (w_{free}) [kg/m³]	Thermal Conductivity (λ) [W/mK]	R_c-value [m²K/W]	Bulk density (ρ) [kg/m³]	Porosity [m³/m³]	Specific heat capacity (C) [J/kgK]	Water absorption coefficient (A) [kg/m²√s]	Typical built-in moisture [kg/m³]
Solid Brick, historical	325	15	4,88	9	230	0.60	0.54	1800	0.31	850	0.36	100
Mineral Wool	50	5.2	0.26	1.79	44.8	0.02	2.50	60	0.95	850	-	-
Gypsum board	12.5	8.3	0.104	6.3	400	0.2	0.0625	850	0.65	850	0.287	6.3

Table 7. Hygrothermal properties of the appointed materials from the WUFI 2D.4 Material Database for the parameter study.

The materials are determined in a way that these comply with a vapour-open, non-capillary active internal insulation system for historic solid brick masonry. Therefore, based on findings in the background research, mineral wool without a vapour barrier is appointed as insulation material since this is a vapour-open, non-capillary active insulation system. In addition, to study the hygrothermal performance of a vapour-open, non-capillary active internal insulation system, a vapour-open finishing layer needs to be appointed. Therefore, the material Gypsum Board is chosen as a vapour-open finishing layer. Finally, as brick masonry layer the Solid Brick, historical is chosen. The appointed materials are shown in figure 65.

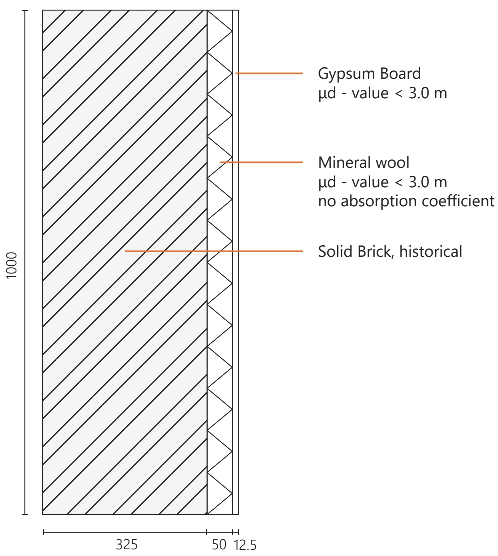

Fig 65. Appointed materials from the WUFI 2D.4 Material Database for the parameter study.

Furthermore, solid brick masonry is simulated as a homogeneous brick layer, neglecting the influence of the mortar joint as well as an interface resistance between mortar and brick. Research by Vereecken & Roels (2013) concluded that a simplification to a homogeneous brick layer is allowed for Heat, Air and Moisture simulations, meaning that it is allowed to only take the properties of bricks into account. However, attention needs to be paid to exceptional cases for instance rising damp, mortar-related damage and wooden beam ends. These are not studied in this research.

5.1.2 Outdoor boundary condition

To simplify the influence of the hygrothermal loads from the outdoor environment on the construction, only the temperature and relative humidity are taken into account. This means that solar radiation and wind-driven rain are excluded.

In doing so, the positive effect of faster drying of the brick masonry due to higher temperatures of the brick masonry by solar radiation is neglected. So, a more critical situation of a fully shaded exterior wall is analysed. However, by excluding wind-driven rain in the situation, the negative effect of wetting from the exterior is neglected, which resembles a situation where the outside surface is protected from wind-driven rain.

The simulation software WUFI offers several options to define the outdoor boundary condition for temperature and relative humidity. It was decided to use the default sine curves with a period of one year available in WUFI 2D.4, which have been derived from German Test Reference Years. These curves are illustrated in figure 66. The fluent running of these curves significantly reduces the simulation time. In comparison with the Dutch outdoor climate, these curves represent a very cold winter, with a monthly average temperature in January of about -1 °C.

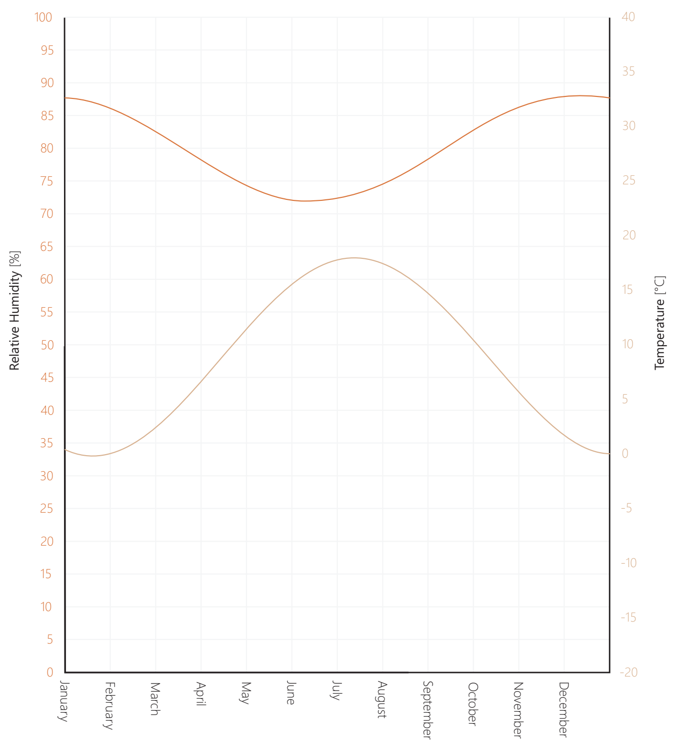

Fig 66. Input outdoor boundary condition with sine curves for the relative humidity and temerpature derived from German Test Reference Years for the outdoor relative humidity and temperature with a poriod of one year adopted from WUFI 2D.4.

5.1.3 Indoor boundary condition

Similar to the outdoor environment, the simulation software includes several options to define the indoor environment, this is also highlighted in Chapter 4. From the background research, chapter 3.4, it can be stated that the German WTA Guideline 6-2 is better suited in defining the indoor climate than the Dutch guideline, NEN-EN-ISO 13788. Therefore, the indoor boundary condition used as input for the parameter study is based on the WTA Guideline 6-2. The indoor climate is defined according to the indoor climate classes, which are based on the indoor moisture load and outdoor air temperature. The level of moisture load is defined as normal, which applies to 'houses, normal situations, including kitchens and bathrooms'. The outdoor air temperature is based on a Dutch reference year which is used for the determination of the energy performance in buildings in accordance with guideline NEN-EN 5060.

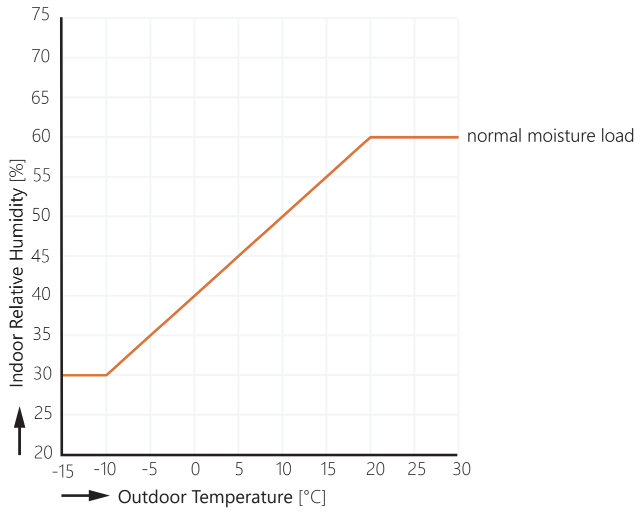

Fig 67. Deriviation of the internal relative humidity in a building with a normal moisture load depending on the external daily mean air temperature and type of building (WTA Guideline 6-2).

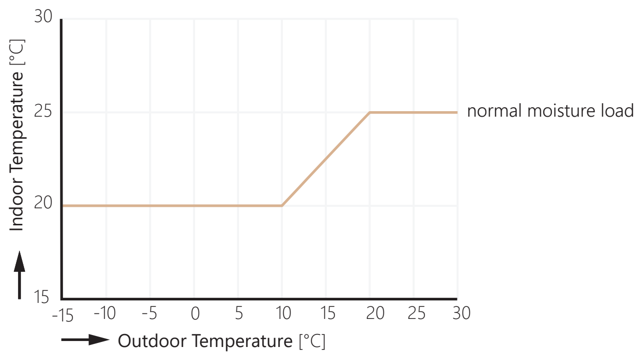

Fig 68. Deriviation of the internal temperature in a building with a normal moisture load depending on the external daily mean air temperature and type of building (WTA Guideline 6-2).

The combination of the chosen WTA 6-2 indoor climate class (normal moisture load) and an outdoor environment based on a Dutch reference year results in the indoor temperature and relative humidity that fits a historic residential building. The indoor temperature and relative humidity for a year are shown in the graph from figure 69.

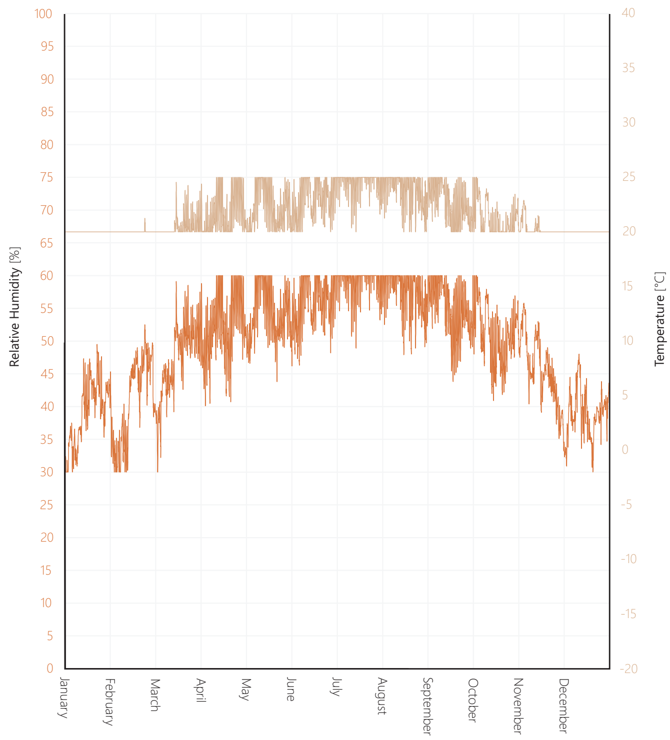

Fig 69. Input indoor boundary condition for the relative humidity and temerpature, derived from the WTA 6-2 'normal moisture load' and a Dutch reference yar as outdoor environment.

5.2 Parameters

In this paragraph, the parameters that will be varied in the parameter study will be defined. As mentioned in Chapter 3.2, thermal conductivity (λ), vapour diffusion resistance factor (μ), water absorption coefficient (A) and sorption isotherm are defined as hygrothermal properties of materials (Blumberga et al., 2016)(Künzel, 1995)(Krus, 1996). The vapour diffusion resistance factor (μ) and the vapour permeability of air determine the vapour permeability of a porous material. The moisture storage capacity is shown by the function of the moisture storage in relation to the relative humidity, the sorption isotherm (Künzel, 1995)(Krus, 1996).

In addition, these hygric properties also come forward in the moisture balance for porous materials, which also governs in the HAM-simulation software WUFI 2D.4. The simulation software also includes the energy balance, which is not discussed, including the above-mentioned thermal property. These properties are, amongst others, required to solve the moisture (mass) and energy balance in building components, see also paragraphs 4.1 and 4.2. Therefore, these properties need to be taken into account to determine the most influential hygrothermal property on the hygrothermal behaviour of a vapour-open, non-capillary active, internally insulated historic solid brick masonry façade.

A material obtains a thickness as a layer in a building component, which affects the material property. A material layer's vapour diffusion resistance depends on its thickness and vapour diffusion resistance factor. Taking this into account, the vapour diffusion resistance of a material layer is defined by the µd-value (product of µ and layer thickness), which is the vapour diffusion equivalent to air layer thickness. In addition, a material layer's thermal performance depends on the thermal conductivity and thickness. Therefore, the thermal performance of a material layer is defined by the thermal resistance (R_c-value) of a material layer.

As mentioned in chapter 3.3.4, vapour-open internal insulation systems should have vapour-open finishing layers to obtian the desired performance (Vereecken & Roels, 2015). The µd-value of a material layer classifies if a material is vapour-open or vapour-tight (Blumberga et al., 2016). Therefore, the µd-value of the finishing layer is an important hygrothermal property to take into account. The same applies to the insulation layer since the scope of the research focuses on a vapour-open, non-capillary active, internal insulation system. Therefore, the µd-value of the insulation layer is an important hygrothermal property to take into account to classify if the layer is vapour-open or not. In addition, the water absorption coefficient needs to be low or zero and the moisture storage capacity needs to be low. Furthermore, in the context of energy reduction for the historic residential building stock, the function of thermal insulation is to improve the thermal performance of the historic façade. For this reason, the thermal performance (R_c-value) of the insulation layer is an important hygrothermal property to take into account. Furthermore, the thermal performance of the finishing layer is not taken into account since this is low in comparison with the thermal performance of the insulation layer.

Finally, the moisture storage capacity of the construction influences the hygrothermal behaviour of a construction. The moisture content at 80% relative humidity is used as an indicator of the moisture storage capacity of a solid brick masonry layer. As shown in the table above, the moisture storage capacity is high for both gypsum board and solid brick masonry. However, to limit the amount of hygrothermal properties, only the moisture storage capacity of solid brick masonry is taken into account as this mainly affects the relative humidity at the interface between insulation and brick masonry.

This results in four hygrothermal properties that will be taken into account in the parameters to obtain the most influential hygrothermal material property of a vapour-open, non-capillary active, internally insulated historic solid brick masonry façade. The parameters are defined as the µd-value of the finishing layer (A1), the µd-value of the insulation layer (A2), the thermal performance of the insulation layer (A3) and the moisture storage capacity of solid brick masonry (A4).

The hygrothermal properties serving as parameters for the initial building component and appointed materials are shown in figure 70. Furthermore, table 8 summarizes the properties of the appointed materials.

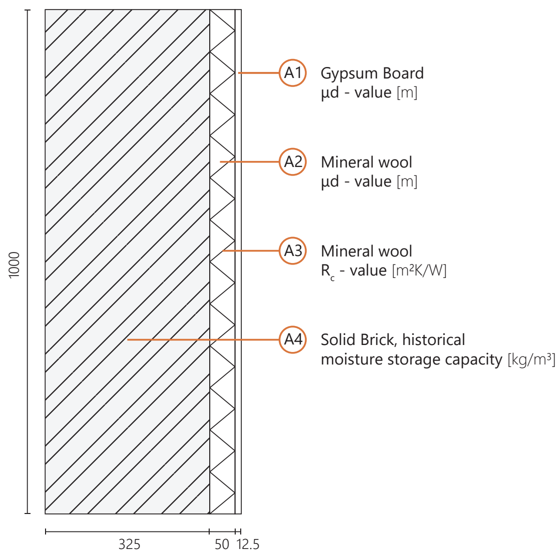

Fig 70. Overview four parameters for the parameter study.

Material	Hygrothermal properties											
	Thickness (t) [mm]	Water vapour diffusion resistance factor (µ) [-]	µd-value [m]	Moisture content at 80% relative humidity ($w_{80\%}$) [kg/m³]	Free water content (w_{free}) [kg/m³]	Thermal Conductivity (λ) [W/mK]	R_c-value [m²K/W]	Bulk density (ρ) [kg/m³]	Porosity [m³/m³]	Specific heat capacity (C) [J/kgK]	Water absorption coefficient (A) [kg/m²√s]	Typical built-in moisture [kg/m³]
Solid Brick, historical	325	15	4,88	9	230	0.60	0.54	1800	0.31	850	0.36	100
Mineral Wool	50	5.2	0.26	1.79	44.8	0.02	2.50	60	0.95	850	-	-
Gypsum board	12.5	8.3	0.104	6.3	400	0.2	0.0625	850	0.65	850	0.287	6.3

Table 8. Highlighting appointed hygrothermal properties as parameters.

It is assumed that the µd-value of the finishing layer (A1) influences the hygrothermal performance of a vapour-open internal insulation system the most. This is because the µd-value of the finishing layer determines the vapour resistance from the interior of the building component. An increase in the µd-value and thus an increase in the vapour resistance of the building component might result in a reduced inward and outward drying of the masonry, which might cause an increase in the moisture accumulation in the brick masonry. This can result in several hygrothermal risks, which might also induce mould growth at the critical point where the brick masonry layer and insulation layer meet. Therefore, the µd-value of the finishing layer (A1) is appointed as the first variable assuming this hygrothermal property has the most influence on the performance indicator, being the number of exceedances of the limit curve from the WTA Guideline 6-8.

Furthermore, also the µd-value of the insulation layer influences the vapour resistance of the façade which might also induce mould growth at the critical point where the brick masonry layer and insulation layer meet. Therefore, the µd-value of the insulation layer (A2) is appointed as the second variable assuming this hygrothermal property influences the performance indicator, being the number of exceedances of the limit curve from the WTA Guideline 6-8, the most after the µd-value of the finishing layer.

In addition, the thermal performance of the insulation layer determines the heat transfer through the layer. An increase in thermal performance results in a reduced heat transfer resulting in a lower temperature in the brick masonry layer causing moisture accumulation which might induce mould growth. Therefore it is appointed as the third variable that influences the hygrothermal performance of a vapour-open, non-capillary active, internally insulated historic solid brick masonry façade.

Finally, the moisture storage capacity of the brick masonry layer influences the hygrothermal performance of the building component. However, it is assumed this property has the least influence and is therefore appointed as the fourth variable. The higher the moisture storage capacity, the more moisture can be absorbed by the layer, resulting in a higher moisture accumulation if drying periods are not sufficient enough.

Figure 71 defines the range of values of the parameters and their reference values.

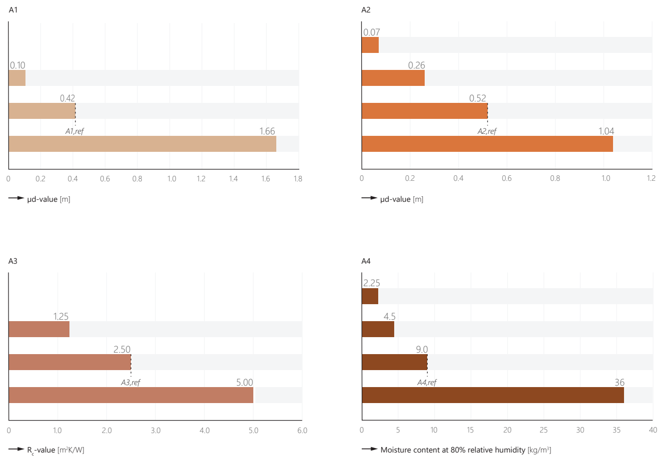

Fig 71. Range of values and reference values of parameters A1, A2, A3 and A4.

An increase in µd-value means that the vapour resistance increases resulting in a decrease in the vapour transfer into the construction, but also in a reduced inward and outward drying of the masonry. In addition, an increase in R_c-value means that the heat transfer in the building component is reduced, resulting in a lower temperature in the brick masonry layer. Furthermore, a higher moisture storage capacity of the solid brick masonry layer means that the layer can absorb more moisture.

Figure 72 shows the ranges of values in relation to other materials for the µd-values of the finishing (A1) and insulation layer (A2).

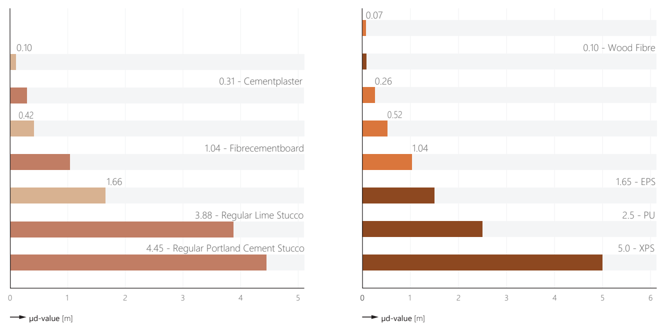

Fig 72. Relation between the µd-values of other finishing and insulation materials and the range of µd-values of the finishing layer (A1)(left) and insulation layer (A2)(right).

The values for the µd-value are determined by increasing the vapour diffusion resistances of the material properties instead of increasing the thickness of the material layers. The same accounts for the thermal performance (R_c-value), where the material property thermal conductivity is decreased. In doing so, the input for the geometry remains unchanged for the parameter study.

5.3 Results

5.3.1 Single variation of individual parameter

Single variation of the individual parameter involves varying one parameter within its range of values while the other parameters remain at reference values. The simulations are copmuted over a two-year period.

5.3.1.1 The µd-value of the finishing layer (A1)

The relation between an increase of the µd-value of the finishing layer and the number of exceedances of the limit curve of WTA Guideline 6-8, which is the performance indicator in this parameter study, is shown in figure 71.

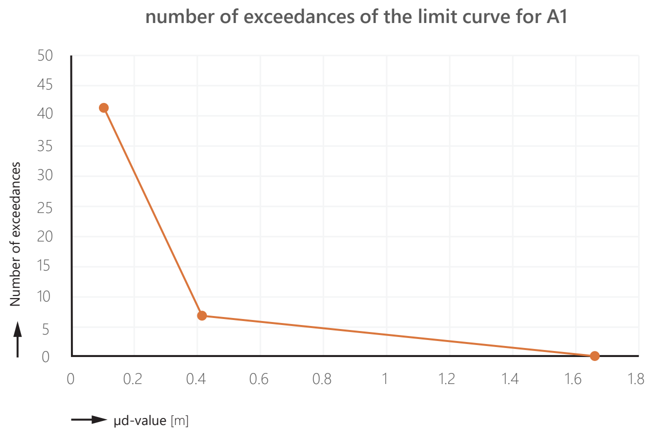

Fig 73. Relation between the number of exceedances of the limit curve from WTA Guideline 6-8 and µd-value of the finishing layer (A1).

The results show that the number of exceedances decreases with an increase in the µd-value of the finishing layer. In other words, less vapour reaches the critical point where the masonry and insulation layers meet due to an increased vapour resistance and therefore the daily mean relative humidity in the building component is lower.

5.3.1.2 The µd-value of the insulation layer (A2)

Figure 74 shows the relation between an increase of the µd-value of the insulation layer and the number of exceedances of the limit curve.

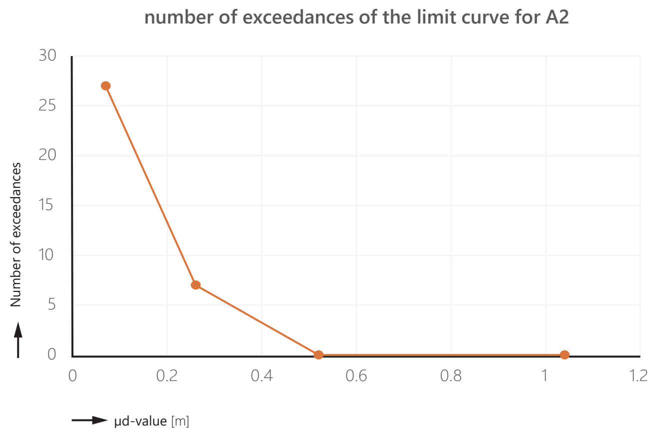

Fig 74. Relation between the number of exceedances of the limit curve from WTA Guideline 6-8 and µd-value of the insulation layer (A2).

The explanation is identical as for parameter A1, less vapour from the inside reaches the interface between masonry and insulation layer.

5.3.1.3 The R_c-value of the insulation layer (A3)

An increase in the R_c-value results in an increase in the number of exceedances of the limit curve from the WTA Guideline 6-8, which is the performance indicator in this parameter study. This is shown in figure 75.

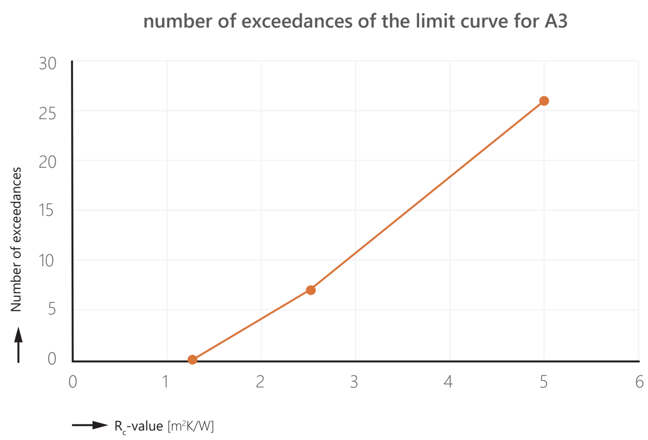

Fig 75. Relation betwen the number of exceedances of the limit curve from WTA Guideline 6-8 and R_c-value of the insulation layer (A3).

An increase in R_c-value means that the heat transfer in the building component is reduced, resulting in a lower temperature in the brick masonry layer. The lower temperature of the brick masonry layer might increase the likelihood of interstitial condensation at the critical point where the solid brick and insulation layer meet. The vapour transfer is not reduced due to an increase in Rc-value, which in combination with a reduced temperature of the brick masonry layer results in an increased risk of interstitial condensation in the building component. Resulting in a higher daily average relative humidity and lower daily average temperature in the building component causing a higher number of exceedances. The relation between the temperature and number of exceedances at the critical point in the building component where the brick masonry and insulation layers meet is shown in figure 76.

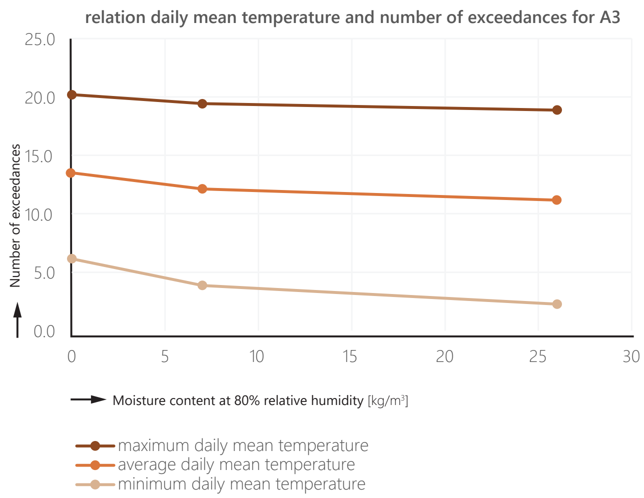

Fig 76. Relation between the daily mean temperature and number of exceedances of the limit curve from WTA Guideline 6-8 for parameter A3, the R_c-value of the insulation layer.

5.3.1.4 The moisture storage capacity of the solid brick masonry layer (A4)

Figure 77 shows the relation between an increase of the moisture storage capacity of the brick masonry layer and the number of exceedances of the limit curve.

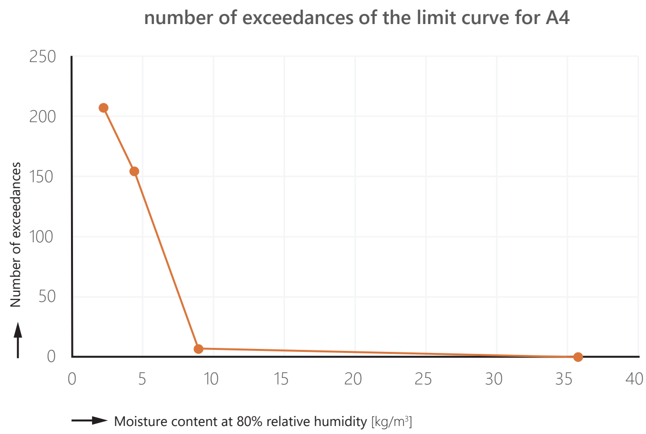

Fig 77. Relation between the number of exceedances of the limit curve from WTA Guideline 6-8 and the moisture content at 80% relative humidity (moisture storage capacity) (A4).

The interstitial condensation at the interface between the solid brick masonry and insulation layers is absorbed by the masonry layer since this porous material has a higher capillary activity than mineral wool due to a higher moisture absorption coefficient and storage capacity.

A higher moisture storage capacity of the solid brick masonry layer means that the layer can absorb more condensed moisture. This results in a lower daily average relative humidity at the interface between the brick masonry layer and insulation layer, resulting in a lower number of exceedances of the limit curve.

5.3.2 Combining parameters

Parameters A1 (µd-value finishing layer) and A2 (µd-value insulation layer) define the vapour resistance of the building component, which determines the vapour transport through the building component from the interior to the exterior. Therefore, these parameters may be combined into the variable a1 (a1 = A1 + A2). The range of values are shown in figure 78.

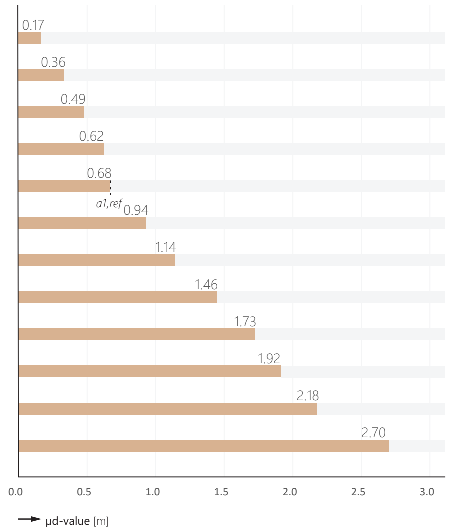

Fig 78. Range of values and reference values of parameter a1.

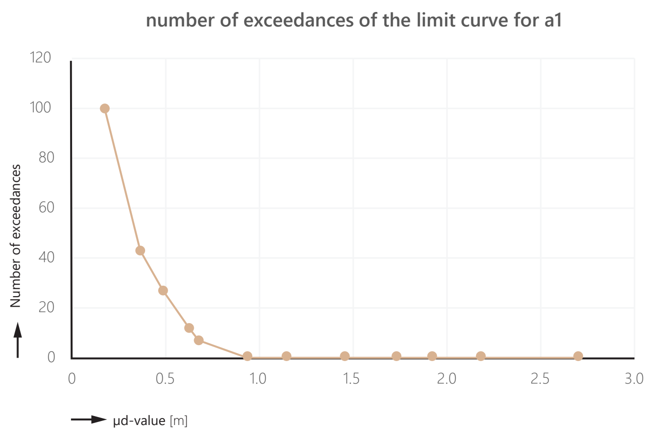

Fig 79. Relation between the number of exceedances of the limit curve from WTA Guideline 6-8 and the sum of the µd-value of the finishing and insulation layer (a1).

Figure 79 shows that the sum of A1 (µd-value finishing layer) and A2 (µd-value insulation layer) is a key parameter that determines the humidity at the interface between the brick masonry and insulation layers.

5.3.3 Variation of two parameters

Variation of two parameters involves varying one parameter within its range of values at different values of another parameter within its range of values while the other parameters remain at reference values. The parameters are sum of the µd-values of the finishing and insulation layers (a1), R_c-value of the insulation layer (a2) and moisture storage capacity of the solid brick masonry layer (a3). The range of values for parameters a2 and a3 are identical als parameter A3 and A4 for the single variation of the parameters. The simulations are copmuted over a two-year period.

5.3.3.1 The sum of the µd-value of the finishing and insulation layer (a1) and R_c-value of the insulation layer (a2)

The lower the sum of the µd-value of the finishing and insulation layer and the higher the R_c-value of the insulation layer, the higher the number of exceedances of the limit curve of the WTA Guideline 6-8. This is shown in the different graphs in figure 80, a higher R_c-value (5.0 m^2K/W) in combination with varying µd-values results in a higher number of exceedances in comparison with a lower R_c-value (1.25 m^2K/W) in combination with the same varying µd-values. The mostiure storage capacity of the brick masonry layer (a3) is at the reference value of 9 kg/m^3.

number of exceedances of the limit curve for a1 and a2

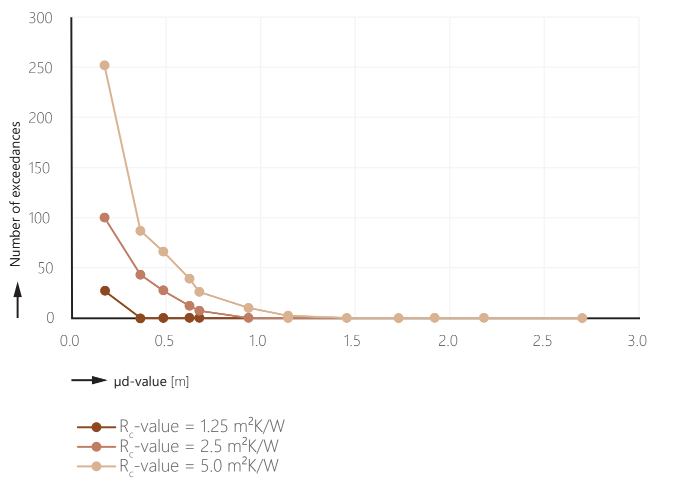

Fig 80. Relation between the number of exceedances of the limit curve from WTA Guideline 6-8 and parameters a1 (the sum of the µd-value of the finishing and insulation layer) and a2 (R_c-value of the insulation layer).

An increase in µd-value means that the vapour resistance increases resulting in a decrease in the vapour transfer into the construction, but also in a reduced inward and outward drying of the masonry. An increase in R_c-value means that the heat transfer in the building component is reduced, resulting in a lower temperature in the brick masonry layer. The lower temperature of the brick masonry increases interstitial condensation at the interface between solid brick masonry and insulation.

The combination of extremely low values of the µd-value with extremely high values for the R_c-value results in a very high number of exceedances of the limit curve.

Within the studied range of R_c-values, there are no exceedances if the sum of the µd-value of the finishing and insulation layer is higher than 1.46 m.

If the µd-value is 0.36 m or higher and the R_c-value is 1.25 W/m^2K, no exceedances of the limit curve are found.

5.3.3.2 The sum of the µd-value of the finishing and insulation layer (a1) and the moisture storage capacity of the solid brick masonry layer (a3)

The lower the µd-value of the finishing and insulation layer and the lower the moisture storage capacity of the brick masonry layer, the higher the number of exceedances. Figure 81 shows this in the different graphs, a lower moisture storage capacity (2.25 kg/m^3) in combination with varying µd-values results in a higher number of exceedances in comparison with a higher moisture storage capacity (36 kg/m^3) in combination with the same varying µd-values. The R_c-vlaue of the insulation layer (a2) is at the reference value of 2.5 m^2K/W.

number of exceedances of the limit curve for a1 and a3

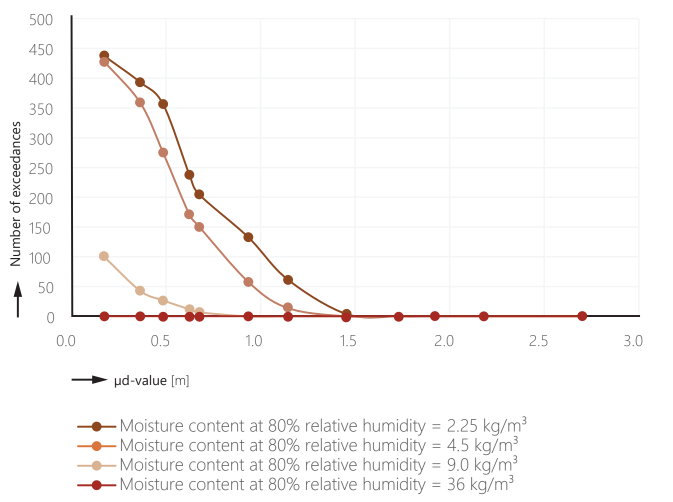

Fig 81. Relation between the number of exceedances of the limit curve from WTA Guideline 6-8 and parameters a1 (the sum of the µd-value of the finishing and insulation layer) and a3 (moisture content at 80% relative humidity).

A higher moisture storage capacity of the solid brick masonry layer means that the layer can absorb more moisture. This results in a lower daily average relative humidity at the interface between the brick masonry layer and insulation layer, resulting in a lower number of exceedances of the limit curve.

The combination of extreme values of the μd-value, meaning low μd-values, with extreme values for the moisture storage capacity, meaning a low storage capacity, results in a very high number of exceedances of the limit curve.

At a moisture storage capacity of 36 kg/m³ of the solid brick masonry layer, there are no exceedances of the limit curve for the studied range of values of the μd-value of the finishing and insulation layer.

For a higher μd-value than 1.46 m of the finishing and insulation layer, there are no exceedances of the limit curve, irrespective of the moisture storage capacity the solid brick masonry layer for the studied range.

5.3.3.3 The Rc-value of the insulation layer (a2) and the moisture storage capacity of the solid brick masonry layer (a3)

The higher the R_c-value of the insulation layer and the lower the moisture storage capacity of the brick masonry layer, the higher the number of exceedances. This is shown in the different graphs in figure 82, a lower moisture storage capacity (2.25 kg/m³) in combination with varying R_c-values results in a higher number of exceedances in comparison with a higher moisture storage capacity (36 kg/m³) in combination with the same varying Rc-values. The sum of the vapour diffusion resistances of the finishing and insulation layer (a1) is at the reference value of 0.68 m.

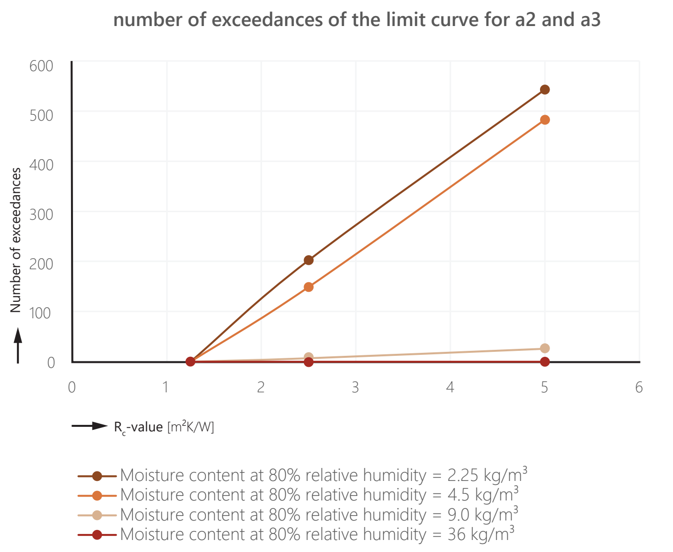

Fig 82. Relation between the number of exceedances of the limit curve from WTA Guideline 6-8 and parameters a2 (R_c-value of the insulation layer) and a3 (moisture content at 80% relative humidity).

At a moisture storage capacity of 36 kg/m³ of the solid brick masonry layer, there are no exceedances of the limit curve for the range of values of the Rc-value of the insulation layer.

For the R_c-value of 1.25 W/m²K of the insulation layer, there are no exceedances of the limit curve for the range of values of the moisture storage capacity of the solid brick masonry layer.

In summary, for the single variation of the parameters, the number of exceedances of the limit curve are highest for parameter A4, the moisture storage capacity of the solid brick masonry layer. In addition, for the variation of two parameters, the number of exceedances are the highest for the combination of a parameter with parameter a3, the moisture storage capacity of the solid brick masonry layer, which is identical to parameter A4 from the single variation of the parameter study. Therefore, it can be concluded that the moisture storage capacity of solid brick masonry has the most influence on the hygrothermal performance of a building component.

5.3.4 Relation between the number of exceedances and maximum relative humidity

Furthermore, the performance indicator, the limit curve of the WTA Guideline 6-8, shows the relation between the daily average temperature and relative humidity in the construction. Therefore, the relation between the number of exceedances of the limit curve and the maximum daily mean relative humidity in the building component at the interface between the brick masonry layer and insulation layers is reviewed in the paragraphs below.

The higher the maximum daily mean relative humidity in the building component at the critical point, the higher the number of exceedances, this is shown in figure 83.

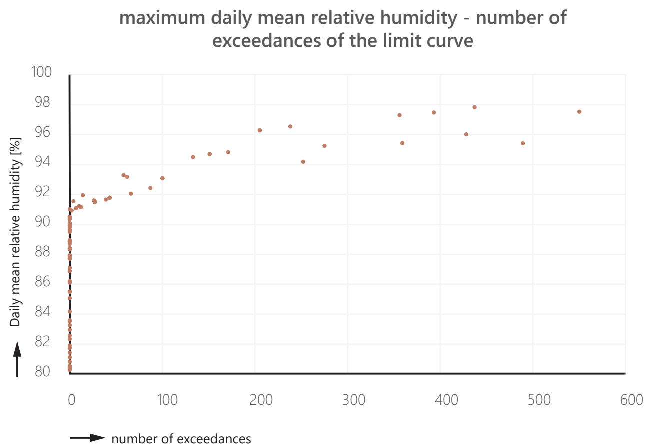

Fig 83. Relation between the maximum daily mean relative humidity and number of exceedances of the limit curve from WTA Guideline 6-8.

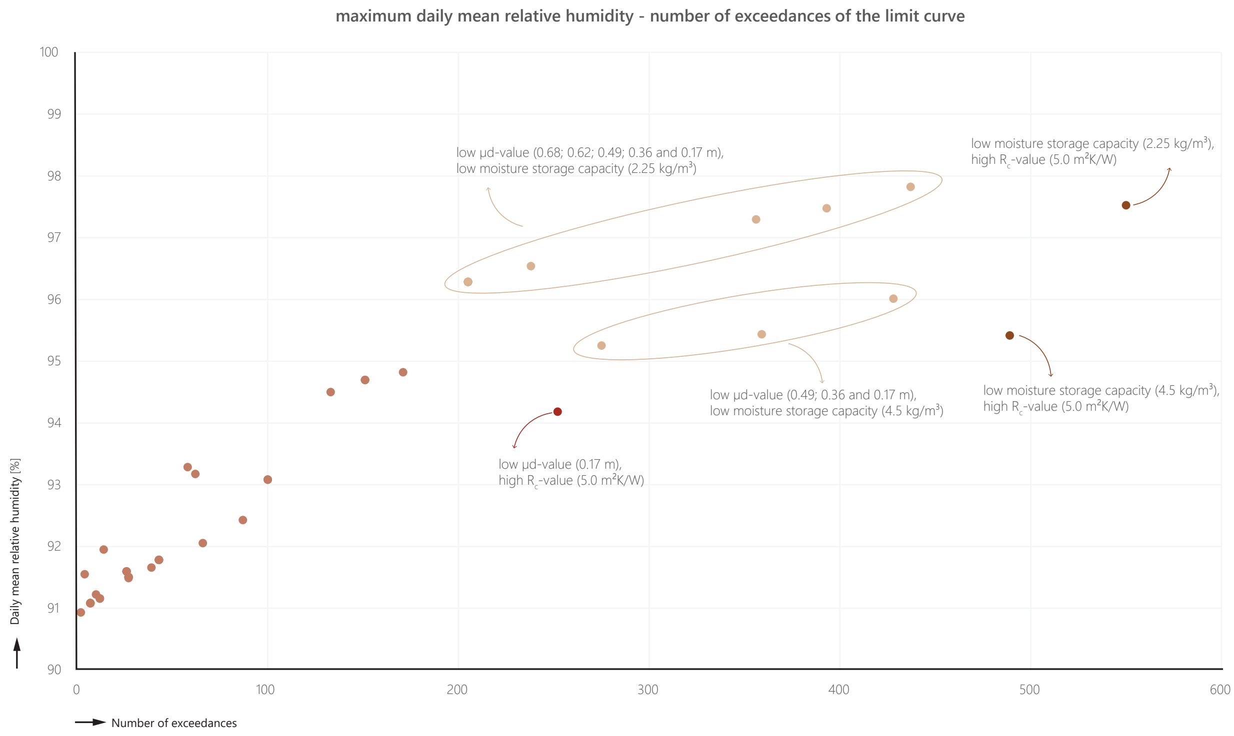

Fig 84. Graph highlighting outliers of the relation between the maximum daily mean relative humidity and number of exceedances of the limit curve from WTA Guideline 6-8, starting from a daily mean relative humidity of 91%.

From the graph in figure 83, it can be stated that if the maximum daily mean relative humidity in the building component at the critical point exceeds 91% the number of exceedances is larger than zero. Thus, if the maximum daily mean relative humidity in the building component at the interface between the insulation and solid brick masonry layer remains below 91%, no exceedances of the limit curve are found. Thus, no risk of wood decay and mould growth in the construction at the critical point. Furthermore, it can be stated that in general the higher the maximum daily mean relative humidity in the building component at the critical point, the higher the number of exceedances of the limit curve. However, some outliers with high number of exceedances are found, these are shown in figure 84.

5.3.5 Discussion

It remains uncertain within what range of values the hygrothermal performance of the building component is risk-free. However, for every parameter, it can be defined within what range of values the other two parameters need to be to ensure risk-free hygrothermal performance.

For the range of values of parameter a1 (sum µd-values of the finishing and insulation layers), the ranges of values for parameters a2 (R_c-value insulation layer) and a3 (moisture storage capacity solid brick masonry layer) are shown in table 9.

µd-value a1 [m]	Rc-value a2 [m²K/W]	MC at 80% a3 [kg/m³]
0.17 < a1 < 3.0	< 2.5	> 36
0.36 < a1 < 3.0	< 1.25	> 9
1.46 < a1 < 3.0	< 2.5	> 2.25
1.46 < a1 < 3.0	2.5 < a2 < 5	> 9
0.68 < a1 < 3.0	1.25 < a2 < 5	> 36
0.68 < a1 < 3.0	< 1.25	> 2.25

Table 9. Range of values within a risk-free hygrothermal preformance for the studied bulding compnent is ensured as an ordening range of values of parameter a1.

For the range of values of parameter a2 (R_c-value insulation layer), the ranges of values for parameters a1 (sum µd-values of the finishing and insulation layers) and a3 (moisture storage capacity solid brick masonry layer) are shown in table 10.

µd-value a1 [m]	Rc-value a2 [m²K/W]	MC at 80% a3 [kg/m³]
0.36 < a1 < 0.68	**< 1.25**	> 9
0.68 < a1 < 3.0	**< 1.25**	> 2.25
0.17 < a1 < 1.46	**< 2.5**	> 36
1.46 < a1 < 3.0	**< 2.5**	> 2.25
0.68 < a1 < 1.46	**< 5**	> 36
1.46 < a1 < 3.0	**< 5**	> 9

Table 10. Range of values within a risk-free hygrothermal preformance for the studied bulding compnent is ensured as an ordening range of values of parameter a2.

For the range of values of parameter a3 (moisture storage capacity solid brick masonry layer), the ranges of values for parameters a1 (sum µd-values of the finishing and insulation layers) and a2 (R_c-value insulation layer) are shown in table 11.

µd-value a1 [m]	Rc-value a2 [m²K/W]	MC at 80% a3 [kg/m³]
0.68 < a1 < 1.46	< 1.25	**> 2.25**
1.46 < a1 < 3.0	1.25 < a2 < 2.5	**> 2.25**
0.36 < a1 < 1.46	< 1.25	**> 9**
1.46 < a1 < 3.0	1.25 < a2 < 5	**> 9**
0.17 < a1 < 0.68	< 2.5	**> 36**
0.68 < a1 < 3.0	2.5 < a2 < 5	**> 36**

Table 11. Range of values within a risk-free hygrothermal preformance for the studied bulding compnent is ensured as an ordening range of values of parameter a3.

5.4 Prediction method

A prediction method can be a useful tool to quickly assess the hygrothermal performance of a building component, without conducting advanced Heat, Air and Moisture simulations which might not be available. Therefore, the aim of the prediction method is a simple methodology to assess the number of exceedances of the limit curve from the WTA Guideline 6-8 at the critical interface between the brick masonry layer and insulation layer, given the range of values for the parameters B1, A3 and A4. Furthermore, as previously shown, the maximum relative humidity within the building component is also a good indicator to assess the hygrothermal performance. Therefore, the maximum relative humidity can also be used as a prediction indicator, since above 91% relative humidity there is a risk of wood decay.

5.4.1 Methodology

It is assumed that the influence of a set of parameters, being a1, a2, and a3, on a performance indicator I can be written multiplicatively as:

$$I = I_0 * (a_{1n})^{n11} * (a_{2n})^{n22} * (a_{3n})^{n33} * (a_{1n})^{n12*(a2n-1)} * (a_{1n})^{n13*(a3n-1)} * (a_{2n})^{n23*(a3n-1)}$$

Where,

$a_{1n} = a_1/a_{1,ref}$;
$a_{2n} = a_2/a_{2,ref}$;
$a_{3n} = a_3/a_{3,ref}$;

n11, n22, n33, n12, n13 and n23 are fit parameters
$a_{i,ref}$ is a reference value for the parameter a_i

If all parameters are set at their reference values, the indicator I equals I_0. The term $(a_{in})^{nij}$ is the dependency of I on parameter a_i. The fit parameters nij (i,j = 1, 2, 3; i<j) can be found with the least-squares method by varying the parameters while keeping all other parameters at the reference values. The least-squares method can also be used to find the fit parameters nij (i<>j; i<j) of the cross terms.

5.4.2 Prediction number of exceedances

Table 12 shows the simulated and the predicted number of exceedances for the single variation of parameters. It should be noted that with all parameters at the reference value, the indicator I_0 must be larger than zero, otherwise the prediction will always be zero. Inherently, the regression equation always predicts a performance indicator I > 0.

	µd-value A1 [m]	µd-value A2 [m]	Rc-value A3 [m²K/W]	MC at 80% A4 [kg/m³]	Number of exceedances	Prediction
A1.1	0.10	0.26	2.5	9	43	43
A1.2	0.42	0.26	2.5	9	7	7
A1.3	1.66	0.26	2.5	9	0	1
A2.1	0.42	0.07	2.5	9	27	27
A2.2	0.42	0.26	2.5	9	7	7
A2.3	0.42	0.52	2.5	9	0	3
A2.4	0.42	1.04	2.5	9	0	2
A3.1	0.42	0.26	1.25	9	0	2
A3.2	0.42	0.26	2.5	9	7	7
A3.3	0.42	0.26	5	9	26	26
A4.1	0.42	0.26	2.5	2.25	205	215
A4.2	0.42	0.26	2.5	4.5	151	39
A4.3	0.42	0.26	2.5	9	7	7
A4.4	0.42	0.26	2.5	36	0	0

Table 12. Simulated and predicted number of exceedances for the single variation of parameters A1, A2, A3 and A4.

The predictions are correct to a certain extent. For the parameters A1, A2 and A3, the prediction of the number of exceedances is quite adequate since only small deviations are found if the simulated number of exceedances is zero. If the simulated number of exceedances are high, which are found for A4, then the prediction is not correct.

For the variation of two parameters, the prediction of the number of exceedances shows divergence. Table 13 shows the simulated number of exceedances and the predicted number of exceedances for the variation of two parameters.

	μd-value a1 [m]	Rc-value a2 [m²K/W]	MC at 80% a3 [kg/m³]	Number of exceedances	Prediction
a1.1	0.17	2.5	9	100	103
a1.2	0.36	2.5	9	43	24
a1.3	0.49	2.5	9	27	14
a1.4	0.62	2.5	9	12	8
a1.5	0.68	2.5	9	7	7
a1.6	0.94	2.5	9	0	4
a1.7	1.14	2.5	9	0	3
a1.8	1.46	2.5	9	0	2
a1.9	1.73	2.5	9	0	1
a1.10	1.92	2.5	9	0	1
a1.11	2.18	2.5	9	0	1
a1.12	2.70	2.5	9	0	1
a1.1/a2.1	0.17	1.25	9	27	26
a1.2/a2.1	0.36	1.25	9	0	6
a1.3/a2.1	0.49	1.25	9	0	4
a1.4/a2.1	0.62	1.25	9	0	2
a1.5/a2.1	0.68	1.25	9	0	2
a1.6/a2.1	0.94	1.25	9	0	1
a1.7/a2.1	1.14	1.25	9	0	1
a1.8/a2.1	1.46	1.25	9	0	0
a1.9/a2.1	1.73	1.25	9	0	0
a1.10/a2.1	1.92	1.25	9	0	0
a1.11/a2.1	2.18	1.25	9	0	0
a1.12/a2.1	2.70	1.25	9	0	0
a1.1/a2.2	0.17	2.5	9	100	103
a1.2/a2.2	0.36	2.5	9	43	24
a1.3/a2.2	0.49	2.5	9	27	14
a1.4/a2.2	0.62	2.5	9	12	8
a1.5/a2.2	0.68	2.5	9	7	7
a1.6/a2.2	0.94	2.5	9	0	4
a1.7/a2.2	1.14	2.5	9	0	3
a1.8/a2.2	1.46	2.5	9	0	2
a1.9/a2.2	1.73	2.5	9	0	1
a1.10/a2.2	1.92	2.5	9	0	1
a1.11/a2.2	2.18	2.5	9	0	1
a1.12/a2.2	2.70	2.5	9	0	1
a1.1/a2.3	0.17	5	9	252	417
a1.2/a2.3	0.36	5	9	87	92
a1.3/a2.3	0.49	5	9	66	51
a1.4/a2.3	0.62	5	9	39	31
a1.5/a2.3	0.68	5	9	26	26
a1.6/a2.3	0.94	5	9	10	13
a1.7/a2.3	1.14	5	9	2	9
a1.8/a2.3	1.46	5	9	0	5

a1.9/a2.3	1.73	5	9	0	4
a1.10/a2.3	1.92	5	9	0	3
a1.11/a2.3	2.18	5	9	0	2
a1.12/a2.3	2.70	5	9	0	2
a1.1/a3.1	0.17	2.5	2.25	437	475
a1.2/a3.1	0.36	2.5	2.25	393	309
a1.3/a3.1	0.49	2.5	2.25	356	262
a1.4/a3.1	0.62	2.5	2.25	238	226
a1.5/a3.1	0.68	2.5	2.25	205	216
a1.6/a3.1	0.94	2.5	2.25	133	179
a1.7/a3.1	1.14	2.5	2.25	62	159
a1.8/a3.1	1.46	2.5	2.25	4	138
a1.9/a3.1	1.73	2.5	2.25	0	125
a1.10/a3.1	1.92	2.5	2.25	0	118
a1.11/a3.1	2.18	2.5	2.25	0	109
a1.12/a3.1	2.70	2.5	2.25	0	97
a1.1/a3.4	0.17	2.5	4.5	428	162
a1.2/a3.4	0.36	2.5	4.5	359	75
a1.3/a3.4	0.49	2.5	4.5	275	55
a1.4/a3.4	0.62	2.5	4.5	171	43
a1.5/a3.4	0.68	2.5	4.5	151	39
a1.6/a3.4	0.94	2.5	4.5	58	28
a1.7/a3.4	1.14	2.5	4.5	14	23
a1.8/a3.4	1.46	2.5	4.5	0	18
a1.9/a3.4	1.73	2.5	4.5	0	15
a1.10/a3.4	1.92	2.5	4.5	0	13
a1.11/a3.4	2.18	2.5	4.5	0	12
a1.12/a3.4	2.70	2.5	4.5	0	9
a1.1/a3.2	0.17	2.5	9	100	104
a1.2/a3.2	0.36	2.5	9	43	24
a1.3/a3.2	0.49	2.5	9	27	14
a1.4/a3.2	0.62	2.5	9	12	8
a1.5/a3.2	0.68	2.5	9	7	7
a1.6/a3.2	0.94	2.5	9	0	4
a1.7/a3.2	1.14	2.5	9	0	3
a1.8/a3.2	1.46	2.5	9	0	2
a1.9/a3.2	1.73	2.5	9	0	1
a1.10/a3.2	1.92	2.5	9	0	1
a1.11/a3.2	2.18	2.5	9	0	1
a1.12/a3.2	2.70	2.5	9	0	1
a1.1/a3.3	0.17	2.5	36	0	6953
a1.2/a3.3	0.36	2.5	36	0	26
a1.3/a3.3	0.49	2.5	36	0	3
a1.4/a3.3	0.62	2.5	36	0	0
a1.5/a3.3	0.68	2.5	36	0	0
a1.6/a3.3	0.94	2.5	36	0	0
a1.7/a3.3	1.14	2.5	36	0	0
a1.8/a3.3	1.46	2.5	36	0	0
a1.9/a3.3	1.73	2.5	36	0	0
a1.10/a3.3	1.92	2.5	36	0	0
a1.11/a3.3	2.18	2.5	36	0	0
a1.12/a3.3	2.70	2.5	36	0	0
a2.1/a3.1	0.68	1.25	2.25	0	17
a2.1/a3.2	0.68	1.25	9	0	2

a2.1/a3.3	0.68	1.25	36	0	9
a2.1/a3.4	0.68	1.25	4.5	0	5
a2.2/a3.1	0.68	2.5	2.25	205	62
a2.2/a3.2	0.68	2.5	9	7	7
a2.2/a3.3	0.68	2.5	36	0	33
a2.2/a3.4	0.68	2.5	4.5	151	17
a2.3/a3.1	0.68	5	2.25	550	232
a2.3/a3.2	0.68	5	9	26	26
a2.3/a3.3	0.68	5	36	0	122
a2.3/a3.4	0.68	5	4.5	489	63

Table 13. Simulated and predicted number of exceedances for the variation of two parameters a1, a2 and a3.

The combination of extreme values of the µd-value (low), R_c-values (high) or the moisture storage capacity (low), results in a high number of exceedances of the limit curve for the simulated variations. The predictions of these calculations show great deviation. Furthermore, the combination of extremely low values of µd-value or high values of the R_c-values with extremely high values for the moisture storage capacity, results in no exceedances of the limit curve for the simulated variations. However, the prediction shows a higher number of exceedances of the limit curve.

It can be stated that the prediction method with the number of exceedances of the limit curve of the WTA Guideline 6-8 as the prediction indicator does not describe the hygrothermal behaviour sufficiently enough. This could be due to several reasons such as an insufficient prediction indicator, a limited number of values within the range of values and, a limited number of parameters.

5.4.3 Prediction maximum daily mean relative humidity

A relation is found between the maximum daily mean relative humidity in the building component and the number of exceedances of the limit curve of WTA Guideline 6-8, as described in paragraph 5.3.4. Therefore, it is researched if the maximum daily mean relative humidity could be used as a prediction indicator for the prediction method to assess whether or not the building component shows a risk-free hygrothermal performance without conducting advanced simulations.

Table 14 shows the maximum daily mean relative humidity in the building component for the simulated and the predicted maximum daily mean relative humidity for the single variation of parameters.

The prediction for the single variation is adequate since only small deviations are found between the simulated maximum daily mean relative humidity of the variations and the predicted maximum daily mean relative humidity of the variations. Furthermore, the prediction often shows a higher maximum daily mean relative humidity than the simulated maximum daily mean relative humidity.

As described in Chapter 4, exceedance of the limit curve results in hygrothermal risks, therefore the limit curve must not be exceeded. In paragraph 5.3.4 a relation is found between the maximum daily mean relative humidity in the building component and the number of exceedances of the limit curve. This relation shows that exceeding a maximum daily mean relative humidity of 91% in the building component results in a number of exceedances of the limit curve, meaning hygrothermal risk occurs in the building component. Therefore, it is researched if the simulated and predicted maximum daily mean relative humidity of the single variation of the parameters meet the measure of 91% as the maximum daily mean relative humidity in the building component.

	Maximum relative humidity		Prediction	
A1.1	91.8	TRUE	93.1	TRUE
A1.2	91.1	TRUE	91.1	TRUE
A1.3	87.7	FALSE	89.1	FALSE
A2.1	91.5	TRUE	92.4	TRUE
A2.2	91.1	TRUE	91.1	TRUE
A2.3	90.5	FALSE	90.4	FALSE
A2.4	88.9	FALSE	89.7	FALSE
A3.1	87.9	FALSE	89.3	FALSE
A3.2	91.1	TRUE	91.1	TRUE
A3.3	91.6	TRUE	92.9	TRUE
A4.1	96.3	TRUE	98.4	TRUE
A4.4	94.7	TRUE	94.7	TRUE
A4.2	91.1	TRUE	91.1	TRUE
A4.3	81.7	FALSE	84.3	FALSE

Table 15. XXX

If table 15 shows that if the simulated and predicted maximum relative humidity is higher than 91%, this is also predicted. Meaning that the prediction method with maximum relative humidity as the prediction indicator is a valid method to assess the hygrothermal risk in case of single variation of a parameter for its studied range. The other non-varied parameters must remain at their reference value.

	µd-value A1 [m]	µd-value A2 [m]	Rc-value A3 [m²K/W]	MC at 80% A4 [kg/m³]	Maximum relative humidity	Prediction
A1.1	0.10	0.26	2.5	9	91.8	93.1
A1.2	0.42	0.26	2.5	9	91.1	91.1
A1.3	1.66	0.26	2.5	9	87.7	89.1
A2.1	0.42	0.07	2.5	9	91.5	92.4
A2.2	0.42	0.26	2.5	9	91.1	91.1
A2.3	0.42	0.52	2.5	9	90.5	90.4
A2.4	0.42	1.04	2.5	9	88.9	89.7
A3.1	0.42	0.26	1.25	9	87.9	89.3
A3.2	0.42	0.26	2.5	9	91.1	91.1
A3.3	0.42	0.26	5	9	91.6	92.9
A4.1	0.42	0.26	2.5	2.25	96.3	98.4
A4.2	0.42	0.26	2.5	4.5	94.7	94.7
A4.3	0.42	0.26	2.5	9	91.1	91.1
A4.4	0.42	0.26	2.5	36	81.7	84.3

Table 14. Simulated and maximum daily mean relative humidity for the single variation of parameters A1, A2, A3 and A4.

For the variation of two parameters, the prediction of the maximum daily mean relative humidity in the building component shows divergence. Table 16 shows the maximum daily mean relative humidity in the building component for the simulated and the predicted maximum daily mean relative humidity for the variation of two parameters.

	µd-value a1 [m]	Rc-value a2 [m²K/W]	MC at 80% a3 [kg/m³]	Maximum relative humidity	Prediction
a1.1	0.17	2.5	9	93.1	95.0
a1.2	0.36	2.5	9	91.8	92.9
a1.3	0.49	2.5	9	91.5	92.0
a1.4	0.62	2.5	9	91.2	91.3
a1.5	0.68	2.5	9	91.1	91.1
a1.6	0.94	2.5	9	90.5	90.2
a1.7	1.14	2.5	9	89.9	89.6
a1.8	1.46	2.5	9	88.9	88.9
a1.9	1.73	2.5	9	88.4	88.5
a1.10	1.92	2.5	9	87.7	88.2
a1.11	2.18	2.5	9	86.9	87.8
a1.12	2.70	2.5	9	85.5	87.2
a1.1/a2.1	0.17	1.25	9	91.5	91.4
a1.2/a2.1	0.36	1.25	9	90.4	90.3
a1.3/a2.1	0.49	1.25	9	89.6	89.8
a1.4/a2.1	0.62	1.25	9	88.3	89.4
a1.5/a2.1	0.68	1.25	9	87.9	89.3
a1.6/a2.1	0.94	1.25	9	86.2	88.8
a1.7/a2.1	1.14	1.25	9	85.1	88.5
a1.8/a2.1	1.46	1.25	9	83.6	88.1
a1.9/a2.1	1.73	1.25	9	83.6	87.8
a1.10/a2.1	1.92	1.25	9	83.0	87.7
a1.11/a2.1	2.18	1.25	9	82.4	87.5
a1.12/a2.1	2.70	1.25	9	81.4	87.2
a1.1/a2.2	0.17	2.5	9	93.1	95.0
a1.2/a2.2	0.36	2.5	9	91.8	92.9
a1.3/a2.2	0.49	2.5	9	91.5	92.0
a1.4/a2.2	0.62	2.5	9	91.2	91.3
a1.5/a2.2	0.68	2.5	9	91.1	91.1
a1.6/a2.2	0.94	2.5	9	90.5	90.2
a1.7/a2.2	1.14	2.5	9	89.9	89.6
a1.8/a2.2	1.46	2.5	9	88.9	88.9
a1.9/a2.2	1.73	2.5	9	88.4	88.5
a1.10/a2.2	1.92	2.5	9	87.7	88.2
a1.11/a2.2	2.18	2.5	9	86.9	87.8
a1.12/a2.2	2.70	2.5	9	85.5	87.2
a1.1/a2.3	0.17	5	9	94.2	100.6
a1.2/a2.3	0.36	5	9	92.4	96.3
a1.3/a2.3	0.49	5	9	92.1	94.7
a1.4/a2.3	0.62	5	9	91.7	93.3
a1.5/a2.3	0.68	5	9	91.6	92.9
a1.6/a2.3	0.94	5	9	91.2	91.1
a1.7/a2.3	1.14	5	9	90.9	90.1
a1.8/a2.3	1.46	5	9	90.5	88.8

a1.9/a2.3	1.73	5	9	90.4	87.9
a1.10/a2.3	1.92	5	9	90.1	87.4
a1.11/a2.3	2.18	5	9	89.5	86.7
a1.12/a2.3	2.70	5	9	88.3	85.7
a1.1/a3.1	0.17	2.5	2.25	97.8	97.4
a1.2/a3.1	0.36	2.5	2.25	97.5	98.0
a1.3/a3.1	0.49	2.5	2.25	97.3	98.2
a1.4/a3.1	0.62	2.5	2.25	96.5	98.4
a1.5/a3.1	0.68	2.5	2.25	96.3	98.4
a1.6/a3.1	0.94	2.5	2.25	94.5	98.7
a1.7/a3.1	1.14	2.5	2.25	93.2	98.9
a1.8/a3.1	1.46	2.5	2.25	91.5	99.0
a1.9/a3.1	1.73	2.5	2.25	91.0	99.2
a1.10/a3.1	1.92	2.5	2.25	90.1	99.3
a1.11/a3.1	2.18	2.5	2.25	89.0	99.4
a1.12/a3.1	2.70	2.5	2.25	87.1	99.5
a1.1/a3.4	0.17	2.5	4.5	96.0	95.3
a1.2/a3.4	0.36	2.5	4.5	95.4	95.0
a1.3/a3.4	0.49	2.5	4.5	95.3	94.9
a1.4/a3.4	0.62	2.5	4.5	94.8	94.7
a1.5/a3.4	0.68	2.5	4.5	94.7	94.7
a1.6/a3.4	0.94	2.5	4.5	93.3	94.5
a1.7/a3.4	1.14	2.5	4.5	92.0	94.4
a1.8/a3.4	1.46	2.5	4.5	90.4	94.3
a1.9/a3.4	1.73	2.5	4.5	89.8	94.2
a1.10/a3.4	1.92	2.5	4.5	88.9	94.2
a1.11/a3.4	2.18	2.5	4.5	87.9	94.1
a1.12/a3.4	2.70	2.5	4.5	86.2	94.0
a1.1/a3.2	0.17	2.5	9	93.1	95.0
a1.2/a3.2	0.36	2.5	9	91.8	92.9
a1.3/a3.2	0.49	2.5	9	91.5	92.0
a1.4/a3.2	0.62	2.5	9	91.2	91.3
a1.5/a3.2	0.68	2.5	9	91.1	91.1
a1.6/a3.2	0.94	2.5	9	90.5	90.2
a1.7/a3.2	1.14	2.5	9	89.9	89.6
a1.8/a3.2	1.46	2.5	9	88.9	89.0
a1.9/a3.2	1.73	2.5	9	88.4	88.5
a1.10/a3.2	1.92	2.5	9	87.7	88.2
a1.11/a3.2	2.18	2.5	9	86.9	87.8
a1.12/a3.2	2.70	2.5	9	85.5	87.3
a1.1/a3.3	0.17	2.5	36	86.1	108.9
a1.2/a3.3	0.36	2.5	36	84.2	94.8
a1.3/a3.3	0.49	2.5	36	82.6	89.8
a1.4/a3.3	0.62	2.5	36	81.9	85.6
a1.5/a3.3	0.68	2.5	36	81.7	84.4
a1.6/a3.3	0.94	2.5	36	81.1	79.4
a1.7/a3.3	1.14	2.5	36	80.8	76.4
a1.8/a3.3	1.46	2.5	36	80.6	73.1
a1.9/a3.3	1.73	2.5	36	80.5	70.7
a1.10/a3.3	1.92	2.5	36	80.5	69.4
a1.11/a3.3	2.18	2.5	36	80.4	67.7
a1.12/a3.3	2.70	2.5	36	80.3	65.1
a2.1/a3.1	0.68	1.25	2.25	89.6	96.4
a2.1/a3.2	0.68	1.25	9	87.9	89.3

a2.1/a3.3	0.68	1.25	36	80.4	83.1
a2.1/a3.4	0.68	1.25	4.5	88.7	92.7
a2.2/a3.1	0.68	2.5	2.25	96.3	98.3
a2.2/a3.2	0.68	2.5	9	91.1	91.1
a2.2/a3.3	0.68	2.5	36	81.7	84.8
a2.2/a3.4	0.68	2.5	4.5	94.7	94.6
a2.3/a3.1	0.68	5	2.25	97.5	100.3
a2.3/a3.2	0.68	5	9	91.6	92.9
a2.3/a3.3	0.68	5	36	83.3	86.5
a2.3/a3.4	0.68	5	4.5	95.4	96.5

Table 16. Simulated and maximum daily mean relative humidity for the variation of two parameters a1, a2 and a3.

Table 16 shows that combinations of high values of the µd-value and low values of the moisture storage capacity of the brick layer result in large differences in the predicted and simulated maximum daily mean relative humidity. Furthermore, in contrast, the table shows that combinations of low values of the µd-value and high values of the moisture storage capacity of the brick layer result in large differences in the predicted and simulated maximum daily mean relative humidity. Also, combinations of low values of the R_c-value and low values of the moisture storage capacity of the brick layer result in large differences in the predicted and simulated maximum daily mean relative humidity.

5.4.4 Discussion

The presented prediction method with the number of exceedances of the limit curve or maximum daily mean relative humidity as a prediction indicator shows quite adequate predictions for the single variation of the parameters. The maximum daily mean relative humidity is more adequate since large deviations are found for parameter a3 (moisture storage capacity) using the number of exceedances of the limit curve as the prediction indicator.

For the variation of two parameters, the prediction method is not sufficient since large deviations are found. Therefore, advanced simulations are needed to assess the hygrothermal behaviour of a building component to ensure risk-free hygrothermal performance. The prediction indicator does not describe the hygrothermal behaviour sufficiently enough, this could be due to several reasons such as an insufficient prediction indicator, a limited number of values within the range of values and, a limited number of parameters.

For the studied set of parameters, an assessment can rely on the tables shown in paragraph 5.3.5.

6 Conclusion

This research is an exploration of the most influential hygrothermal properties of the one-dimensional hygrothermal performance of vapour-open, non-capillary active internal insulation for solid brick masonry of historic residential buildings. Sub-questions have been formulated as support to answer the main research question. The sub-questions are answered below.

1 – *What factors influence the hygrothermal behaviour of vapour-open, non-capillary active, internally insulated historic solid brick masonry?*

The factors that influence the hygrothermal behaviour of vapour-open, non-capillary active internally insulated historic solid brick masonry are the hygrothermal properties of solid brick masonry, vapour-open, non-capillary active internal insulation and the vapour-open finishing layer and the hygrothermal loads of the indoor and outdoor environment acting on the building component. Furthermore, other factors such as challenges before, during and after the application of internal insulation systems in historic buildings, influence the hygrothermal behaviour of the internally insulated historic solid brick masonry wall. These challenges involve the suitability of brick masonry, the hygrothermal risks, the critical details causing thermal bridges, and the modifications of the wall structure.

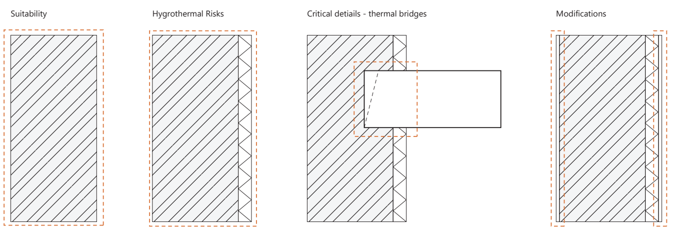

Fig 85. Diagram showing the challenges before, during and after the application of internal insulation for historic solid brick masonry.

The hygrothermal properties of historic solid brick masonry can vary a lot. Many types of historic solid brick masonry can emerge since masonry can vary in brick type, mortar type and construction type (thickness and pattern bond), resulting in an inhomogeneous wall which shows a hygric behaviour that may deviate from that of the combination of individual material elements. For inhomogeneous solid brick masonry, this means that the mortar joint shows a more critical hygrothermal behaviour in the inhomogeneous brick masonry construction than in a homogeneous mortar layer. Therefore, the mortar joint defines the primary path of the moisture flux in solid brick masonry. The orientations and ratios of mortar joints are different for each pattern bond and construction thickness showing different hygrothermal performances per type of solid brick masonry wall.

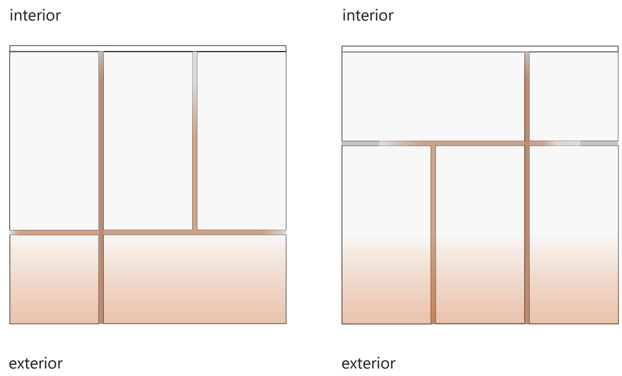

Fig 86. Diagram of the degree of saturation of the horizontal cross-section of a one-stone-and-a-half-stone solid brick masonry wall built up according to the English bond, showing that the inhomogenity (orientation and ratio of brick and mortar joint) of a brick masonry wall influences the moisture flux in the wall, based on Vereecken and Roels (2013).

Furthermore, the vapour diffusion resistance (μ), thermal conductivity (λ), adsorption coefficient (A) and moisture storage capacity can be recognized as basic hygrothermal material properties. For a vapour-open, non-capillary active insulation system, this means that the system has a vapour diffusion resistance which is only given by the material itself. The system has a vapour diffusion equivalent air layer thickness (μd-value) which is lower than 0.2 meters to be vapour-open or lower than 3.0 meters to be vapour permeable. Furthermore, the system has a very low or no water absorption coefficient (A) resulting in a very low moisture storage capacity.

System	Thermal conductivity coefficient (λ) [W/mK]	Vapour diffusion resistance factor (μ) [-]	Water absorption coefficient (A) [kg/m²√s]
Vapour-open, non-capillary active	λ = 0.03 - 0.04 W/mK	μ = 5 - 50 μd < 0.2 m	-
Vapour permeable, non-capillary active	λ = 0.03 - 0.04 W/mK	μ = 5 - 50 0.2 m < μd < 3.0 m	-

Table 17. Guideline defining hygrothermal material properties for vapour-open or vapour permeable, non-capillary active insulation systems, based on Stichting ERM (2021) and Stappers (2020)(2021).

Finally, the hygrothermal loads from the outdoor environment can be defined as external temperature and relative humidity, which are different per façade orientation and determined by solar radiation and wind-driven rain. The loads from the indoor environment can be defined as indoor temperature, relative humidity and vapour pressure. German regulations, the WTA Guideline 6-2, most adequately define the indoor environment, which divides the indoor environment into classes mainly based on indoor moisture load and partly based on the outdoor environment, defining the indoor relative humidity and temperature.

2 – Under what conditions is the hygrothermal performance of vapour-open, non-capillary active, internally insulated historic solid brick masonry risk-free?

The hygrothermal performance of a building component is risk-free if no hygrothermal risks, such as mould growth due to interstitial condensation, occur in the building component. Hygrothermal assessment models are used to determine the risk of mould occurring in building components. Mould growth is governed by temperature, relative humidity, exposure time and material sensitivity and are, therefore, considered as assessment criteria by hygrothermal assessment models. Furthermore, in the case of interior insulation in historic residential buildings, the critical points, such as thermal bridges at moisture-sensitive wooden beam ends, need to be considered in the assessment criteria of hygrothermal performance. Therefore, the German WTA Guideline 6-8 is most adequate to assess the hygrothermal performance of vapour-open, non-capillary active internal insulation of historic solid brick masonry. According to WTA Guideline 6-8, a risk-free hygrothermal performance is achieved if the daily average relative pore humidity and temperature in the building component do not exceed the limit curve. Therefore, the limit curve determines the boundary conditions for risk-free hygrothermal performance and defines the relationship between relative humidity and temperature in a wooden building. The boundary conditions are 95% relative humidity at 0 °C and 86% relative humidity at 20 °C as a daily average in the building component.

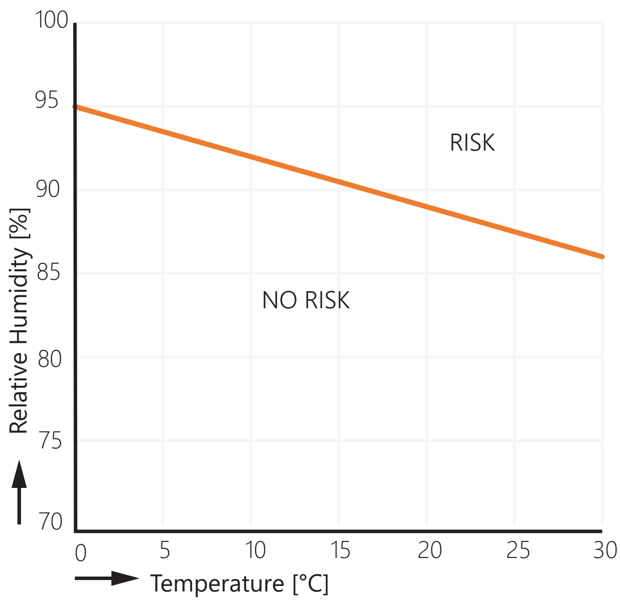

Fig 87. Limit curve of the relative pore air humdity in relation to the temperature, which must not be exceeded as daily average (WTA Guideline 6-2).

These boundary conditions result in an approach which is sufficient for one-dimensional and two- or three-dimensional situations including moisture-sensitive wooden elements. However, this approach does not imply that a risk-free performance of a one-dimensional building component also applies to a two- or three-dimensional situation.

3 – What factors should be considered to gain insight into the influence of hygrothermal properties on the hygrothermal behaviour in the case of vapour-open, non-capillary active, internally insulated solid brick masonry for historic residential buildings?

The hygrothermal behaviour of a building component is influenced by hygrothermal properties and hygrothermal loads from the indoor and outdoor environment. To gain insight into the influence of the hygrothermal properties of a building component on the hygrothermal performance, the influences from the hygrothermal loads from the outdoor environment need to be simplified. Therefore, only the external temperature and relative humidity need to be taken into account. This means that solar radiation and wind-driven rain need to be excluded.

In addition, the hygrothermal loads from the indoor environment should meet that of a residential building. The WTA Guideline 6-2 describes the indoor environment most adequately. The level of moisture load is defined as normal, which applies to 'houses, normal situations, including kitchens and bathrooms'.

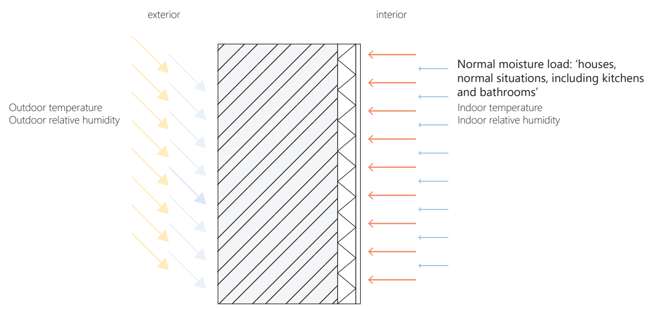

Fig 88. Diagram showing the boundary conditions of a building component for a simplified outdoor environment and a indoor environment for residential buildings.

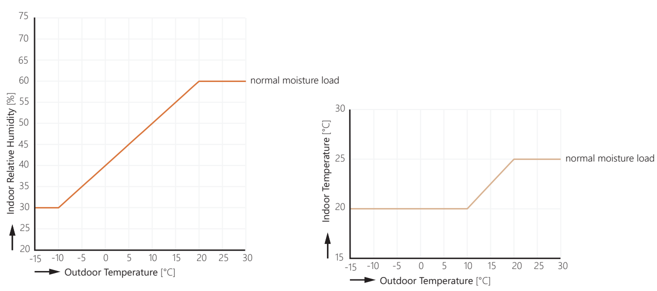

Fig 89. Deriviation of the internal temperature and relative humidity in a building with a normal moisture load depending on the external daily mean air temperature and type of building (WTA Guideline 6-2).

The main research question is as follows.

What hygrothermal property of vapour-open, non-capillary active, internally insulated solid brick masonry for historic residential buildings influences the hygrothermal behaviour of this façade most?

Different hygrothermal properties influence the hygrothermal behaviour in building components. Overall, vapour diffusion resistance (μ), thermal conductivity (λ), adsorption coefficient (A) and moisture storage capacity are important hygrothermal material properties. However, the thickness of a material layer also influences the material properties. Considering the material layer thickness, the vapour diffusion resistance of a material layer is defined by the μd-value and the thermal performance of a material layer is defined by the thermal resistance (R_c-value).

A parameter study through HAM-simulations in WUFI 2D.4 has been conducted to determine the most influential hygrothermal property. The influence of the moisture storage capacity of the brick masonry layer, the Rc-value and μd -value of the insulation layer and μd -value of the finishing layer were studied in studies for a single variation of parameters and for a variation of two parameters. The results of these studies showed that within the studied range of values, the moisture storage capacity of solid brick masonry is the most influential hygrothermal property that influences the hygrothermal behaviour in comparison to the R_c-value and μd-value of the insulation and finishing layer.

Therefore, to answer the main research question, it can be concluded that, within the studied range of values of the hygrothermal properties, the moisture storage capacity of historic solid brick masonry has the most influence on the hygrothermal behaviour of a vapour-open, non-capillary active internally insulated historic solid brick façade.

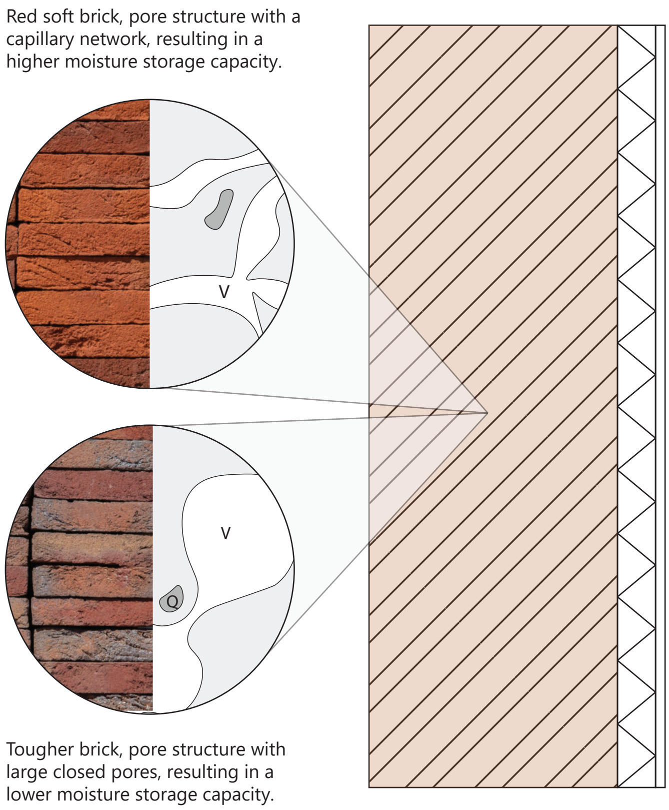

Fig 90. Schematic diagram highlighting the moisture storage capacity of solid brick masonry as most influential hygrothermal property of a vapour-open, non-capillary active, internally insulated solid brick masonry wall. The moisture storage capacity of soft bricks is higher than tougher bricks.

7 Discussion

7.1 Methods

The methods used in this research for the main research question that focuses on the influence of hygrothermal properties on hygrothermal behaviour of vapour-open, non-capillary active, internal insulation for historic solid brick masonry seem suitable to a certain extent since only research by simulations that were not validated against measurements from practice was used. Simulation results are dependent on the given input, showing the importance of validation of the simulations. Therefore, research by simulations for this specific topic could be improved by validation of the simulation software with measurements from practice since there is a mismatch between simulation software and measured data from the practice.

7.2 Parameter study

A parameter study was conducted to determine the influence of hygrothermal properties on the hygrothermal performance of a vapour-open, non-capillary active, internally insulated solid brick masonry wall. However, the study has several limitations which are described below.

7.2.1 Homogeneous brick layer

The parameter study has been carried out through HAM-simulations in WUFI 2D.4. For this research, it was decided to focus on one-dimensional simulations which significantly reduced the simulation time. By doing so, the inhomogeneous brick masonry layer is simulated as a homogeneous brick layer, neglecting the significant influence of the mortar joint on the moisture flux in the layer. Research by Vereecken & Roels (2013) on the influence of the mortar joint and interface between brick and mortar concluded that a simplification to a homogeneous brick layer is allowed for HAM-simulations, meaning that it is allowed to only take the properties of bricks into account. However, attention needs to be paid to exceptional cases for instance rising damp, mortar-related damage patterns and wooden beam ends.

The WUFI material database offers different materials for a homogeneous solid brick masonry layer. Brick materials as well as brick masonry materials in which the properties of bricks and mortar are combined are offered. A decision was made to appoint a brick material resulting in a homogeneous brick layer in the geometry of the simulated building component since the moisture storage capacity of this material is lower than the moisture storage capacity of the brick masonry option.

However, it should be noted that the influence of a one-dimensional brick masonry layer on the hygrothermal behaviour differs from the influence of a two- or three-dimensional brick masonry layer, due to a different hygric behaviour across the material interface between brick and mortar. Therefore, further analysis of the influence of hygrothermal properties on the hygrothermal performance of vapour-open, non-capillary active, internally insulated historic solid brick masonry could be carried out in two- or three-dimensional simulations to obtain more representative results.

7.2.2 Parameters

For the parameter study a limited number of hygrothermal properties were appointed as parameters in this research. However, more properties influence the hygrothermal performance of a building component. Furthermore, the parameter study is limited to a single variation of parameters and a variation of two parameters, resulting in an undefined range of values within a risk-free hygrothermal performance can be ensured. The next step for the parameter study could be a variation of all three defined parameters to define within what range of values a risk-free hygrothermal performance is guaranteed.

7.2.3 Range of values

For the process of defining the range of values for the parameters, due to limited time, some values were left out which led to significant gaps between the values. This could be improved by adding more values within the range to avoid large gaps leading to a more representative range of values.

7.2.4 Hydrophobation

This research focuses on the influence of hygrothermal properties on hygrothermal behaviour. To achieve this, the hygrothermal loads from the outdoor environment were simplified by excluding solar radiation and wind-driven rain. By doing so, a situation emerged that could be comparable to a hydrophobized facade since hydrophobation makes a façade water-repellent while maintaining vapour permeability, resulting in a facade which prevents wetting due to wind-driven rain and, consequently, drying due to solar radiation. For this treatment of the facade also a conflict between practice and theory arises. Different hydrophobation products with varying components and performances are known. In theory, this treatment is recognized as a safe treatment that performs well if proper use of products and application is guaranteed. In contrast, from experience in practice, this treatment is not recommended since the transport of liquid moisture, including salts, to the wall surfaces is blocked, resulting in an increased amount of salt behind the hydrophobized zone. The salt will crystallize causing the outer layer of the brick to crack away. Furthermore, the applied hydrophobation degrades due to environmental loads such as solar radiation. Therefore, this treatment requires a lot of maintenance to ensure proper performance. Moreover, hydrophobation of the building envelope is irreversible (Van der Helm et al., 2007). Although there is no consensus on this treatment, it is often not recommended. Therefore, further research on the influence of hygrothermal properties on the hygrothermal behaviour of vapour-open, non-capillary active, internal insulation of solid brick masonry should include the effects of a representative outdoor climate. In addition, the long term effects of hydrophobation in combination with vapour-open, non-capillary active internal insulation of historic solid brick masonry could be researched.

7.2.5 Prediction method

Furthermore, a prediction method was explored as a useful tool to quickly assess the hygrothermal performance of a building component, without conducting advanced Heat, Air and Moisture simulations which might not be available. The number of exceedances of the limit curve and the maximum daily mean relative humidity were explored as prediction indicators for the prediction method. The prediction method shows the most adequate results for the single variation of the parameters using the maximum daily mean relative humidity as the prediction indicator. For the variation of two parameters, the prediction method is not sufficient since large deviations are found. Therefore, advanced simulations are needed to assess the hygrothermal behaviour of a building component to ensure risk-free hygrothermal performance. The prediction indicator does not describe the hygrothermal behaviour sufficiently enough, this could be due to several reasons such as an insufficient prediction indicator, a limited number of values within the range of values and, a limited number of parameters.

7.3 Further research

Within the scope of this research, the next step for the parameter study could be a variation of all three defined parameters to define within what range of values a risk-free hygrothermal performance is ensured.

Furthermore, research on the influence of hygrothermal properties on the hygrothermal behaviour of vapour-open, non-capillary active, internal insulation of solid brick masonry could be including the effects of a representative outdoor climate.

Moreover, the next step could be taken by two- and three-dimensional situations including inhomogeneous solid brick masonry and moisture-sensitive wooden elements since most uncertainty in practice and theory and expected damage is found for these critical details in combination with internal insulation systems.

Finally, long-term research could be executed to gain insight into the mismatch between simulations and measurements in practice.

8 Recommendations

From the research it is concluded that the moisture storage capacity of historic solid brick masonry influences the hygrothermal performance most as hygrothermal property in the case of a vapour-open, non-capillary active internally insulated historic solid brick masonry façade. This means that before the application of vapour-open, non-capillary active, internal insulation in historic residential buildings the moisture storage capacity of brick masonry needs to be determined. Within the research, the moisture storage capacity is defined by the moisture content at 80% relative humidity. Therefore, the sorption isotherm of the solid brick masonry wall needs to be known to determine the moisture storage capacity of solid brick masonry. It is not possible to determine the sorption isotherm of solid brick masonry directly in practice since sorption isotherms are determined by placing an initially dry sample in environments of increasing relative humidity until equilibrium is reached, which can only be conducted in a laboratory. This means that a sample from the historic residential building needs to be measured in a laboratory to define the moisture storage capacity and thereby, to what extent the solid brick masonry façade can influence the hygrothermal performance before the application of vapour-open, non-capillary active, internal insulation is considered.

Currently, the initial moisture absorption (kg/m^{2}min) of solid brick masonry walls is measured in practice by means of the Karsten Tube method. Therefore, it is recommended to include this hygrothermal property in further research to determine the most influential hygrothermal property on hygrothermal performance.

Even though the moisture storage capacity of historic solid brick masonry can not be measured directly on-site, still several other recommendations can be provided about a first judgement of a historic solid brick masonry wall to determine if the wall has a high or low moisture storage capacity based on brick type, mortar type and construction thickness. A high moisture storage capacity results in a lower chance on hygrothermal risks in the case of exclusion of solar radiation and wind-driven rain.

A solid brick masonry wall has a higher moisture storage capacity if it is built up with softer red bricks than thougher gray bricks or clinkers since a red brick has a higher moisture storage capacity. In addition, a brick masonry wall with lime mortar joints shows a higher moisture storage capacity than a brick masonry wall with cement mortar joints. A thicker solid brick masonry wall also shows a lower risk on mould growth due to interstitial condensation. Firgure 91 shows the brick type, mortar type and construction thickness that show a lower chance on hygrothermal risks in the case of exclusion of solar radiation and wind-driven rain.

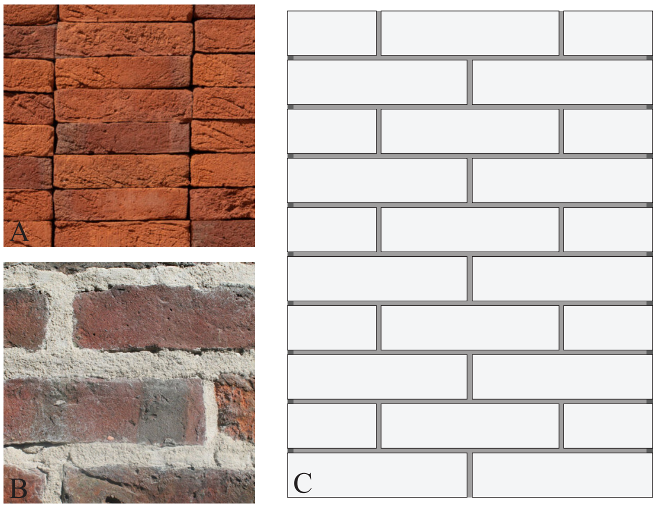

Fig 91. Soft red brick (A), lime mortar in brick masonry (B) and two-stone solid brick masonry wall built up in English bond (C).

In historic buildings built before 1950, often lime mortar joints and softer bricks are found. Therefore, it is recommended to have a visual assessment of the brick masonry wall to estimate if the moisture storage capacity of the historic solid brick masonry wall might be high based on the brick type, mortar type and construction thickness. Before starting more demanding measurements of the solid brick masonry are conducted to define the definitive moisture storage capacity of solid brick masonry.

Furthermore it is still uncertain within what range of values of the hygrothermal properties a risk-free hygrothermal performance can be ensured. However, recommendations can still be provided, based on the results from the parameter study. For the studied building component, three hygrothermal properties and the indoor and outdoor environment can be recognized as parameters. The sum of the µd-values of the finishing and insulation layers (a1), the R_c-value of the insulation layer (a2) and the moisture storage capacity solid brick masonry layer (a3) are three parameters that were explored in this research. The outdoor (B2) and indoor (B2) environment are two parameters that were set as boundary conditions in this reaserch and were not varied in the parameter study. These five parameters are shown in figure 92.

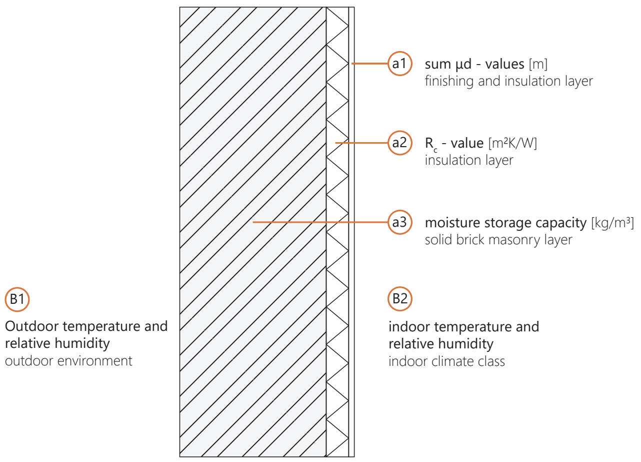

Fig 92. Schematic diagram showing five parameters: the sum of the µd-values of the finishing and insulation layers (a1), the R_c-value of the insulation layer (a2), the moisture storage capacity solid brick masonry layer (a3) and, the outdoor (B2) and indoor (B2) environment.

If the combination of values for parameters a1, a2 and a3 guarantee a risk-free hygrothermal performance, this also accounts for a lower indoor climate class from the WTA Guideline 6-2, which is low moisture load and applies to 'buildings with rooms such as offices, classrooms and sales premises'. In addition, this also accounts for a less severe outdoor climate where solar radiation and wind-driven rain are also excluded.

If two hygrothermal properties and boundary conditions for the indoor and outdoor environment are fixed for the studied building component, recommendations can be given about the range of values for the third studied hygrothermal property. These ranges are shown in tables 18, 19 and 20 and can serve as a guideline to take the first step towards a risk-free hygrothermal performance of a vapour-open, non-capillary active, internally insulated solid brick masonry wall.

µd-value a1 [m]	Rc-value a2 [m^2K/W]	MC at 80% a3 [kg/m^3]
0.17 < a1 < 3.0	< 2.5	> 36
0.36 < a1 < 3.0	< 1.25	> 9
1.46 < a1 < 3.0	< 2.5	> 2.25
1.46 < a1 < 3.0	2.5 < a2 < 5	> 9
0.68 < a1 < 3.0	1.25 < a2 < 5	> 36
0.68 < a1 < 3.0	< 1.25	> 2.25

Table 18. Range of values within a risk-free hygrothermal preformance for the studied bulding compnent is ensured as an ordening range of values of parameter a1.

µd-value a1 [m]	Rc-value a2 [m^2K/W]	MC at 80% a3 [kg/m^3]
0.36 < a1 < 0.68	**< 1.25**	> 9
0.68 < a1 < 3.0	**< 1.25**	> 2.25
0.17 < a1 < 1.46	**< 2.5**	> 36
1.46 < a1 < 3.0	**< 2.5**	> 2.25
0.68 < a1 < 1.46	**< 5**	> 36
1.46 < a1 < 3.0	**< 5**	> 9

Table 19. Range of values within a risk-free hygrothermal preformance for the studied bulding compnent is ensured as an ordening range of values of parameter a2.

µd-value a1 [m]	Rc-value a2 [m^2K/W]	MC at 80% a3 [kg/m^3]
0.68 < a1 < 1.46	< 1.25	**> 2.25**
1.46 < a1 < 3.0	1.25 < a2 < 2.5	**> 2.25**
0.36 < a1 < 1.46	< 1.25	**> 9**
1.46 < a1 < 3.0	1.25 < a2 < 5	**> 9**
0.17 < a1 < 0.68	< 2.5	**> 36**
0.68 < a1 < 3.0	2.5 < a2 < 5	**> 36**

Table 20. Range of values within a risk-free hygrothermal preformance for the studied bulding compnent is ensured as an ordening range of values of parameter a3.

The initial approach of the research was to gain insight into the mismatch between simulation software and measurements from practice through the validation of the simulation software with measurements from a case study. However, due to some shortcomings, it was not possible to execute this approach. Still, a lot of lessons were learned and insight was gained into what is needed to understand and eventually solve this mismatch. This starts with the information about the building where the conditions in an internally insulated historic building are monitored. This information must consist of:

- The properties of the existing and new façade materials. For the existing materials, the brick masonry, this is difficult but samples can be taken and measured. The properties of new materials are often known.
- In the historic building, relative humidity and temperature must be monitored hourly at the critical point, between masonry and insulation layers, for all façade orientations since the relative humidity and temperature are the most important factors that determine hygrothermal risks regarding mould growth in the building component. Furthermore, significant differences in relative humidity and temperature between different façade orientations can occur due to differences in influences of wind-driven rain and solar radiation.
- Hourly monitoring of the relative humidity and temperature of the indoor environment.
- Hourly monitoring of the outdoor environment, including temperature, relative humidity, wind-driven rain, solar radiation and precipitation.
- Monitoring for longer than one year in a building in use.

Figure 93 shows a roadmap to validate simulation software and measurements as a first step towards solving the mismatch between practice and theory.

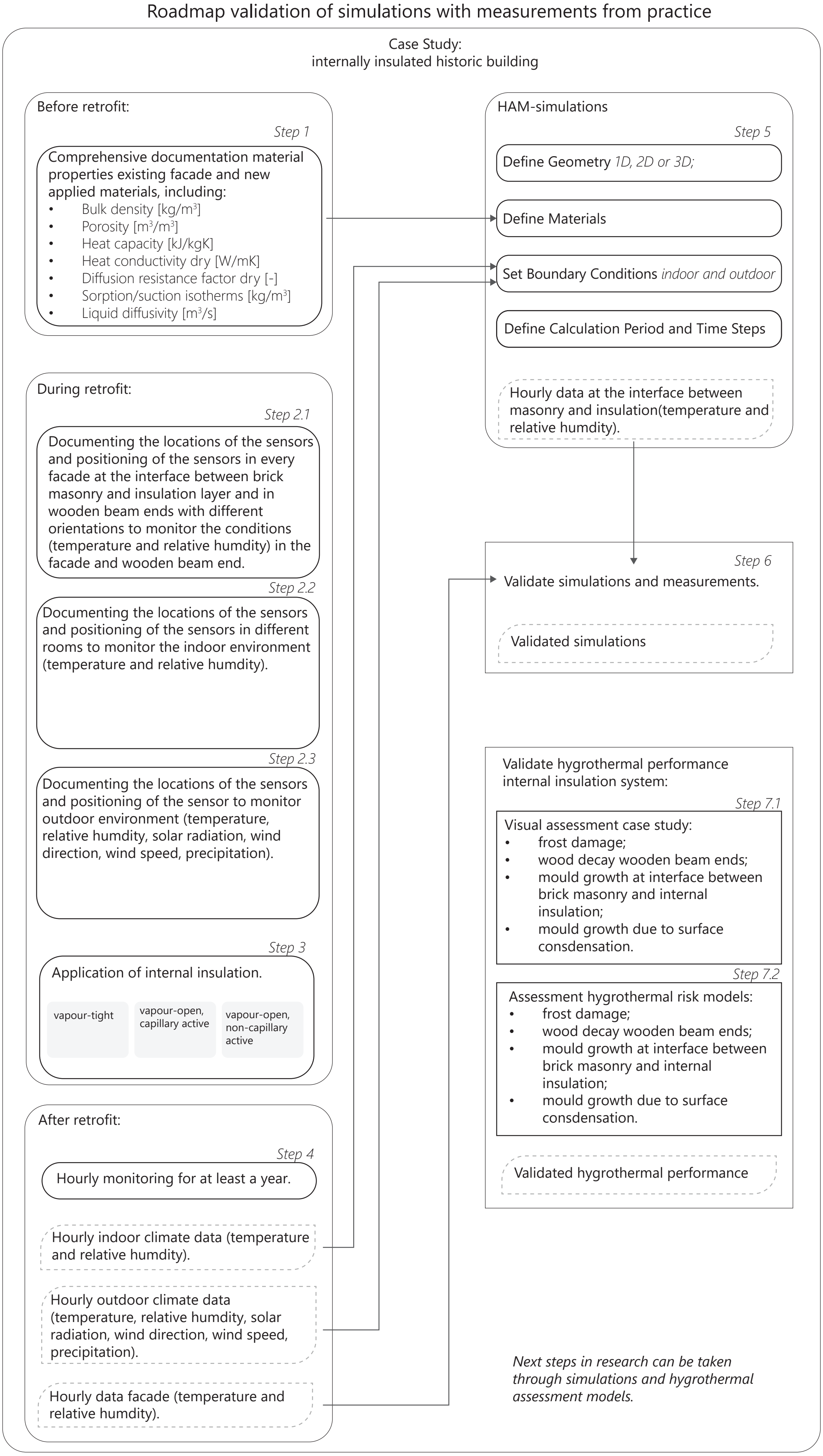

Fig 93. Roadmap to validate simulation software and measurements.

9 Reflection

The approach of the research aimed to determine the influential hygrothermal properties of vapour-open, non-capillary active internal insulation for historic solid brick masonry through simulations. The objective was to gain knowledge about the hygrothermal behaviour of such insulation systems in historic buildings and support in bridging the gap between theory and practice. However, initially, the scope and approach were broader. The focus was two-fold, validating simulations with measurements from a case study and exploring factors influencing the hygrothermal behaviour of a vapour-open, non-capillary active internal insulation for historic solid brick masonry. However, case studies that monitor the conditions of an internally insulated historic façade for at least one year are scarce. After finding and analysing a case study, it became clear that there were too many shortcomings to achieve reliable validation. Consequently, this approach was abandoned. Nevertheless, valuable insights were gained regarding the requirements for reliable validation and understanding of the mismatch between practice and theory. These lessons highlight the need for monitoring of internally insulated historic buildings and comprehensive documentation of material properties in historic buildings to facilitate reliable validation.

The methods employed to determine the most influential hygrothermal property were adequate to a certain extent. The literature review and expert consultations were sufficient since these provided background knowledge and insights into practice-related challenges. Although the available research primarily focused on vapour-tight and capillary active internal insulation systems, it still provided sufficient research on the hygrothermal behaviour of internally insulated historic solid brick masonry facades. The expert consultations were particularly useful in gaining an understanding of the practical challenges associated with internal insulation in historic buildings. For studying the hygrothermal behaviour of building components, the Heat, Air and Moisture simulation software WUFI 2D.4 proved to be suitable. It offered accessibility compared to the more advanced Delphin software, which is designed for advanced users, but allows for three-dimensional simulations. However, three-dimensional simulations were out of scope for this research, WUFI 2D.4 was considered sufficient for the research.

However, it is important to acknowledge that relying solely on simulations as a method to study hygrothermal behaviour is not fully comprehensive. Since there exists a known mismatch between the expected hygrothermal risks predicted by simulations and experienced in practice. Therefore, using simulations, that are not validated, is not sufficient to understand the complete behaviour of building components. However, comparing simulation studies with practice-related studies is challenging due to the limited monitoring of internally insulated historic buildings, as mentioned previously.

A prediction method as a tool to quickly assess the hygrothermal performance of a building component, witout using advanced HAM-simulation software, was explored. This showed quite adequate predictions for the single variation of the parameters. The method fell short for the predictions of the variation of two parameters.

During the research process, the feedback from mentors guided the research back to its objectives. Furthermore, several times the building technology and heritage perspective needed to be regained in the research. Initially, this perspective was provided through a case study, therefore, abandoning the case study also felt like losing the building technology and heritage perspective. Through feedback from the mentors, a way was found to include this perspective again in the research.

This graduation topic provided academic and personal growth. It allowed for the exploration of a new area of study, expanding knowledge on hygrothermal behaviour in building components. While I gained knowledge in this area, I also discovered the tendency to get absorbed in a subject and lose sight of the objective. Therefore, I learned the importance of maintaining focus and staying aligned with the research goals. Furthermore, the research also expanded my knowledge of historic buildings and their architectural details, emphasizing the challenges faced in improving sustainability within this sector. Engaging with experts resulted in gaining knowledge about the practical aspects and in what way this research can contribute to tackling practical issues. Additionally, I have experienced that abandoning a certain plan allows for new opportunities.

Throughout the process, I have also experienced personal growth. I have come to appreciate the value of teamwork, as the lack of a discussion partner in the graduation studio often left me with doubts and difficulties in decision-making. Recognizing this, I understand the significance of collaborative work and the benefits of discussions. Additionally, my ability to plan has improved, partly due to the more regular progress meetings with my supervisors. This has enabled me to better assess the tasks and determine the direction to proceed.

Relation of graduation project to Msc AUBS and master track Building Technology

The graduation project shares common principles with the master programme Architecture, Urbanism and Building Sciences, such as retrofit of the existing building stock, reduction of energy consumption and reduction of carbon emissions, aiming for a more sustainable built environment. The project relates to the Building Technology master track by combining perspectives from building physics and heritage and technology. Within the Building Technology track, Heritage and Technology explores possible solutions for restoration and transformation tasks from the perspective of technology, which aligns with the graduation project which explores a solution to reduce the energy consumption for historic buildings as a restoration measure. Building Physics and Services explore innovative insulation techniques to improve the thermal performance and indoor environment, which is in line with the graduation project which explores an insulation system to improve the thermal performance and indoor environment of historic buildings.

Academic and societal value, scope and implication of graduation project

The academic value of the graduation project is based on translating a theoretical approach into recommendations that are applicable to practice. The value of the graduation project from a societal perspective is that this project aims at an interlinked relation between the conservation and energy retrofits of historic buildings to preserve the architectural heritage and keep these buildings in use. It is necessary to make conservation upgrades in order to extend the lifespan of historic buildings. Therefore, the preservation of architectural heritage entails supporting effective measures for energy reduction to reduce climate change and keep historic buildings in use. Furthermore, the scope in which the graduation project is valuable is the preservation of historic and monumental buildings, sustainability measures in historic buildings while preserving cultural, historic and aesthetic value, and research on vapour-open, non-capillary active internal insulation systems.

Influence research on recommendations

The research influenced the recommendations since it first determined the factors that influence hygrothermal behaviour, from which the hygrothermal properties were further studied to define the most influential. Furthermore, through research, insight was gained into the challenges in practice, which affected the recommendations by making them more practice-related.

Value of approach

The value of the approach and methods is based on the accessibility of the tools and resources which is reasonable in this research. The literature review and simulation software are accessible. However, for further research, the use of simulation software Delphin needs to be considered since the hygrothermal behaviour of three-dimensional building components, such as wooden beam ends and window frames, can be studied in this software. Furthermore, a long-term approach also needs to be considered to achieve a reliable outcome of simulations through validation with measurements in practice.

Value of transferability of the graduation project

The value of transferability of this graduation project is reasonable. The recommendations and conclusions from this research are the most transferable, these form the basis for further research since this project only forms a small part of a lot of research that still needs to be conducted to gain insight into the lack of knowledge about vapour-open, non-capillary active internal insulation for historic solid brick masonry.

Environmental impact

The environmental impact of the application of vapour-open, non-capillary active thermal insulation for historic buildings is low. The buildings are kept in use, expanding their lifespan, reducing the reliance on new materials for new buildings and reduce energy use in manufacturing processes. Furthermore, vapour-open insulation materials can have a natural origin, and, therefore, have a lower environmental impact than vapour-tight insulation systems.

Climate change – extreme climate conditions

The hygrothermal behaviour of a building component is partly determined by hygrothermal loads from the outdoor environment. In this research the indoor and outdoor climate are simplified by excluding wind-driven rain and solar radiation to focus on the influence of hygrothermal properties on the hygrothermal behaviour. However, it should be taken into account that wind-driven rain and solar radiation have a significant influence on the hygrothermal behaviour of the building component. Therefore, taking climate change into account, it should be considered that the hygrothermal loads from the outdoor environment will be more extreme, with more and longer periods of rain, colder winters and hotter summers. This will also result in an indoor environment with larger fluctuation. This has a significant effect on the hygrothermal behaviour of a vapour-open, non-capillary active internal insulation system.

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Appendix

Appendix A - Historic building stock

In the late nineteenth century the living conditions, especially for people in the lower working class, were bad and unhealthy. Many people from the lower working class lived in rapidly built slums, with poor to no facilities. At the same time, the population in cities was increasing significantly due to the industrial revolution. The bad living conditions came to an end with the advent of the Housing Act [NL: Woningwet] in 1901, which aimed to make the construction of bad housing impossible by promoting the construction of quality housing. It was not until 1910 that the Housing Act's housing construction started to take off. However, this came to stagnation during World War I (1914-1918). Nevertheless, this was followed by an optimistic post-war period in which many residential houses were built (1920-1930) to cover the housing shortage after the stagnation during and high population growth after World War I. The houses constructed in this period were of good quality since the use of good quality materials was a priority. The Housing Act started to pay off as it sets these quality requirements. However, this is good period is followed by a lesser one due to World War II (1940-1945). A construction probation and destruction of many houses during WW II resulted in a great housing shortage and high population growth during and after World War II. As a result, the construction of houses accelerated around the 1950s and the Reconstruction Act [NL: Wederopbouwwet] was introduced in 1950 to unify building regulations. Housing construction from this period aimed at quantity rather than quality. In addition, a lot of demolishing of houses took place. In the period from 1970 to 1980, there was a limited housing shortage, so the focus shifted back to quality and the improvement of houses. With the oil crisis of 1973 and 1979, demands for energy efficiency in housing emerged. This is reflected in the houses from 1980 to 1990, where energy savings was the focus. This resulted in houses with a reduced glass area and thermal insulation.

In 1992, Buildings Regulation Act Phase 1 was implemented and ended differences in building regulations between municipalities. The quality of housing increased significantly. In 2003, Buildings Regulation Act Phase 2 and Buildings Regulations Act 2012 were implemented in 2012.

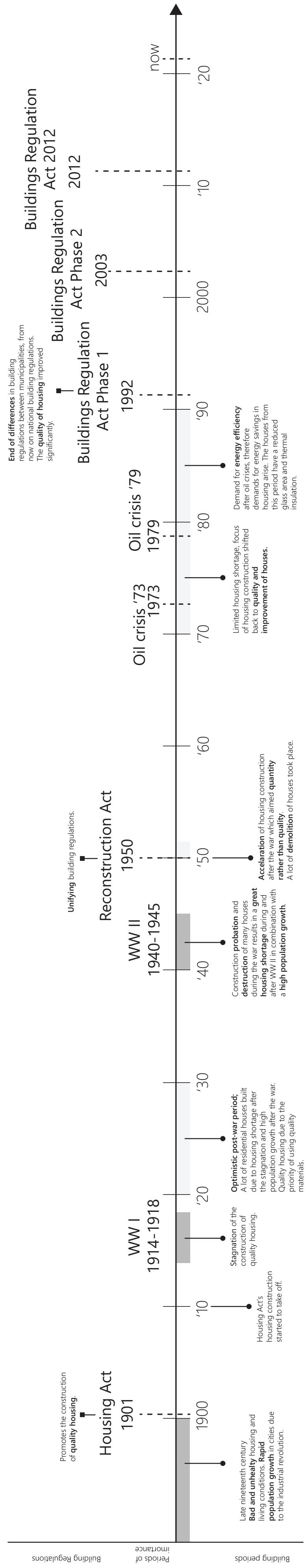

Fig A.1 Timelime of the building regulations, building periods and important events influencing the development of the Dutch residential building stock.

Appendix B - Parameter study: single variation parameters

B.1 Input materials

Material	Hygrothermal properties											
	Thickness (t) [mm]	Water vapour diffusion resistance factor (μ) [-]	μd-value [m]	Moisture content at 80% relative humidity ($w_{80\%}$) [kg/m³]	Free water content (w_{free}) [kg/m³]	Thermal Conductivity (λ) [W/mK]	R_c-value [m²K/W]	Bulk density (ρ) [kg/m³]	Porosity [m³/m³]	Specific heat capacity (C) [J/kgK]	Water absorption coefficient (A) [kg/m²√s]	Typical built-in moisture [kg/m³]
Solid Brick, historical	325	15	4,88	A4	230	0.60	0.54	1800	0.31	850	0.36	100
Mineral Wool	50	5.2	A2	1.79	44.8	0.02	A3	60	0.95	850	-	-
Gypsum board	12.5	8.3	A1	6.3	400	0.2	0.0625	850	0.65	850	0.287	6.3

Table B.1 Input materials properties of the conducted simulations for the single variation of parameters.

A1	μd-value [m]
A1.1	0.10
A1.2	0.42
A1.3	1.66
A1,ref	0.42

A2	μd-value [m]
A2.1	0.07
A2.2	0.26
A2.3	0.52
A2.4	1.04
A2,ref	0.26

A3	Rc-value [m²K/W]
A3.1	1.25
A3.2	2.5
A3.3	5
A3,ref	2.5

A4	MC at 80% [kg/m³]
A4.1	2.25
A4.4	4.5
A4.2	9
A4.3	36
A4,ref	9

Table B.2 Input hygrothermal properties of the appointed parameters of the conducted simulations for the single variation of parameters.

B.2 Overview simulations

A1	μd-value A1 [m]	μd-value A2,ref [m]	Rc-value A3,ref [m^2K/W]	MC at 80% A4,ref [kg/m^3]
A1.1	0.10	0.26	2.5	9
A1.2	0.42	0.26	2.5	9
A1.3	1.66	0.26	2.5	9

A2	μd-value A1,ref [m]	μd-value A2 [m]	Rc-value A3,ref [m^2K/W]	MC at 80% A4,ref [kg/m^3]
A2.1	0.42	0.07	2.5	9
A2.2	0.42	0.26	2.5	9
A2.3	0.42	0.52	2.5	9
A2.4	0.42	1.04	2.5	9

A3	μd-value A1,ref [m]	μd-value A2,ref [m]	Rc-value A3 [m^2K/W]	MC at 80% A4,ref [kg/m^3]
A3.1	0.42	0.26	1.25	9
A3.2	0.42	0.26	2.5	9
A3.3	0.42	0.26	5	9

A4	μd-value A1,ref [m]	μd-value A2,ref [m]	Rc-value A3,ref [m^2K/W]	MC at 80% A4 [kg/m^3]
A4.1	0.42	0.26	2.5	2.25
A4.4	0.42	0.26	2.5	4.5
A4.2	0.42	0.26	2.5	9
A4.3	0.42	0.26	2.5	36

Table B.3 Overview conducted simulations for the single variation of parameters.

Appendix C - Parameter study: combining parameters

C.1 Input materials

Material	Hygrothermal properties											
	Thickness (t) [mm]	Water vapour diffusion resistance factor (μ) [-]	μd-value [m]	Moisture content at 80% relative humidity ($w_{80\%}$) [kg/m³]	Free water content (w_{free}) [kg/m³]	Thermal Conductivity (λ) [W/mK]	R_c-value [m²K/W]	Bulk density (ρ) [kg/m³]	Porosity [m³/m³]	Specific heat capacity (C) [J/kgK]	Water absorption coefficient (A) [kg/m²√s]	Typical built-in moisture [kg/m³]
Solid Brick, historical	325	15	4,88	a3	230	0.60	0.54	1800	0.31	850	0.36	100
Mineral Wool	50	5.2	a1	1.79	44.8	0.02	a2	60	0.95	850	-	-
Gypsum board	12.5	8.3		6.3	400	0.2	0.0625	850	0.65	850	0.287	6.3

Table C.1 Input materials properties of the conducted simulations for the combination of parameters A1 and A2 into a1.

a1	μd-value [m]
a1.1	0.17
a1.2	0.36
a1.3	0.49
a1.4	0.62
a1.5	0.68
a1.6	0.94
a1.7	1.14
a1.8	1.46
a1.9	1.73
a1.10	1.92
a1.11	2.18
a1.12	2.70
a1,ref	0.68

a2	Rc-value [m²K/W]
a2.1	1.25
a2.2	2.5
a2.3	5
a2,ref	2.5

a3	MC at 80% [kg/m³]
a3.1	2.25
a3.2	4.5
a3.3	9
a3.4	36
a3,ref	9

Table C.2 Input hygrothermal properties of the appointed parameters of the conducted simulations for the combination of parameters A1 and A2 into a1.

C.2 Overview simulations

a1	μd-value a1 [m]	Rc-value a2,ref [m²K/W]	MC at 80% a3,ref [kg/m³]
a1.1	0.17	2.5	9
a1.2	0.36	2.5	9
a1.3	0.49	2.5	9
a1.4	0.62	2.5	9
a1.5	0.68	2.5	9
a1.6	0.94	2.5	9
a1.7	1.14	2.5	9
a1.8	1.46	2.5	9
a1.9	1.73	2.5	9
a1.10	1.92	2.5	9
a1.11	2.18	2.5	9
a1.12	2.70	2.5	9

Table C.3 Overview conducted simulations for the combination of parameters A1 and A2 into a1.

Appendix D - Parameter study: variation of two parameters

D.1 Input materials

Material	Hygrothermal properties											
	Thickness (t) [mm]	Water vapour diffusion resistance factor (μ) [-]	μd-value [m]	Moisture content at 80% relative humidity ($w_{80\%}$) [kg/m^3]	Free water content (w_{free}) [kg/m^3]	Thermal Conductivity (λ) [W/mK]	R_c-value [m^{2}K/W]	Bulk density (ρ) [kg/m^3]	Porosity [m^3/m^3]	Specific heat capacity (C) [J/kgK]	Water absorption coefficient (A) [kg/m^2√s]	Typical built-in moisture [kg/m^3]
Solid Brick, historical	325	15	4,88	a3	230	0.60	0.54	1800	0.31	850	0.36	100
Mineral Wool	50	5.2	a1	1.79	44.8	0.02	a2	60	0.95	850	-	-
Gypsum board	12.5	8.3		6.3	400	0.2	0.0625	850	0.65	850	0.287	6.3

Table D.1 Input materials properties of the conducted simulations for the variation of two parameters.

a1	μd-value [m]
a1.1	0.17
a1.2	0.36
a1.3	0.49
a1.4	0.62
a1.5	0.68
a1.6	0.94
a1.7	1.14
a1.8	1.46
a1.9	1.73
a1.10	1.92
a1.11	2.18
a1.12	2.70
a1,ref	0.68

a2	Rc-value [m^{2}K/W]
a2.1	1.25
a2.2	2.5
a2.3	5
a2,ref	2.5

a3	MC at 80% [kg/m^3]
a3.1	2.25
a3.2	4.5
a3.3	9
a3.4	36
a3,ref	9

Table D.2 Input hygrothermal properties of the appointed parameters of the conducted simulations for the variation of two parameters.

D.2 Overview simulations

a1/a2	µd-value a1 [m]	Rc-value a2 [m^2K/W]	MC at 80% a3,ref [kg/m^3]
a1.1/a2.1	0.17	1.25	9
a1.2/a2.1	0.36	1.25	9
a1.3/a2.1	0.49	1.25	9
a1.4/a2.1	0.62	1.25	9
a1.5/a2.1	0.68	1.25	9
a1.6/a2.1	0.94	1.25	9
a1.7/a2.1	1.14	1.25	9
a1.8/a2.1	1.46	1.25	9
a1.9/a2.1	1.73	1.25	9
a1.10/a2.1	1.92	1.25	9
a1.11/a2.1	2.18	1.25	9
a1.12/a2.1	2.70	1.25	9
a1.1/a2.2	0.17	2.5	9
a1.2/a2.2	0.36	2.5	9
a1.3/a2.2	0.49	2.5	9
a1.4/a2.2	0.62	2.5	9
a1.5/a2.2	0.68	2.5	9
a1.6/a2.2	0.94	2.5	9
a1.7/a2.2	1.14	2.5	9
a1.8/a2.2	1.46	2.5	9
a1.9/a2.2	1.73	2.5	9
a1.10/a2.2	1.92	2.5	9
a1.11/a2.2	2.18	2.5	9
a1.12/a2.2	2.70	2.5	9
a1.1/a2.3	0.17	5	9
a1.2/a2.3	0.36	5	9
a1.3/a2.3	0.49	5	9
a1.4/a2.3	0.62	5	9
a1.5/a2.3	0.68	5	9
a1.6/a2.3	0.94	5	9
a1.7/a2.3	1.14	5	9
a1.8/a2.3	1.46	5	9
a1.9/a2.3	1.73	5	9
a1.10/a2.3	1.92	5	9
a1.11/a2.3	2.18	5	9
a1.12/a2.3	2.70	5	9

Table D.3 Overview conducted simulations for the variation of parameters a1 and a2.

a1/a3	µd-value a1 [m]	Rc-value a2,ref [m²K/W]	MC at 80% a3 [kg/m³]
a1.1/a3.1	0.17	2.5	2.25
a1.2/a3.1	0.36	2.5	2.25
a1.3/a3.1	0.49	2.5	2.25
a1.4/a3.1	0.62	2.5	2.25
a1.5/a3.1	0.68	2.5	2.25
a1.6/a3.1	0.94	2.5	2.25
a1.7/a3.1	1.14	2.5	2.25
a1.8/a3.1	1.46	2.5	2.25
a1.9/a3.1	1.73	2.5	2.25
a1.10/a3.1	1.92	2.5	2.25
a1.11/a3.1	2.18	2.5	2.25
a1.12/a3.1	2.70	2.5	2.25
a1.1/a3.4	0.17	2.5	4.5
a1.2/a3.4	0.36	2.5	4.5
a1.3/a3.4	0.49	2.5	4.5
a1.4/a3.4	0.62	2.5	4.5
a1.5/a3.4	0.68	2.5	4.5
a1.6/a3.4	0.94	2.5	4.5
a1.7/a3.4	1.14	2.5	4.5
a1.8/a3.4	1.46	2.5	4.5
a1.9/a3.4	1.73	2.5	4.5
a1.10/a3.4	1.92	2.5	4.5
a1.11/a3.4	2.18	2.5	4.5
a1.12/a3.4	2.70	2.5	4.5
a1.1/a3.2	0.17	2.5	9
a1.2/a3.2	0.36	2.5	9
a1.3/a3.2	0.49	2.5	9
a1.4/a3.2	0.62	2.5	9
a1.5/a3.2	0.68	2.5	9
a1.6/a3.2	0.94	2.5	9
a1.7/a3.2	1.14	2.5	9
a1.8/a3.2	1.46	2.5	9
a1.9/a3.2	1.73	2.5	9
a1.10/a3.2	1.92	2.5	9
a1.11/a3.2	2.18	2.5	9
a1.12/a3.2	2.70	2.5	9

Table D.4 Overview conducted simulations for the variation of parameters a1 and a3.

a1.1/a3.3	0.17	2.5	36
a1.2/a3.3	0.36	2.5	36
a1.3/a3.3	0.49	2.5	36
a1.4/a3.3	0.62	2.5	36
a1.5/a3.3	0.68	2.5	36
a1.6/a3.3	0.94	2.5	36
a1.7/a3.3	1.14	2.5	36
a1.8/a3.3	1.46	2.5	36
a1.9/a3.3	1.73	2.5	36
a1.10/a3.3	1.92	2.5	36
a1.11/a3.3	2.18	2.5	36
a1.12/a3.3	2.70	2.5	36

Table D.5 Continuation Table D.4 Overview conducted simulations for the variation of parameters a1 and a3.

a2/a3	**μd-value a1,ref** [m]	**Rc-value a2** [m^2K/W]	**MC at 80% a3** [kg/m^3]
a2.1/a3.1	0.68	1.25	2.25
a2.1/a3.2	0.68	1.25	9
a2.1/a3.3	0.68	1.25	36
a2.1/a3.4	0.68	1.25	4.5
a2.2/a3.1	0.68	2.5	2.25
a2.2/a3.2	0.68	2.5	9
a2.2/a3.3	0.68	2.5	36
a2.2/a3.4	0.68	2.5	4.5
a2.3/a3.1	0.68	5	2.25
a2.3/a3.2	0.68	5	9
a2.3/a3.3	0.68	5	36
a2.3/a3.4	0.68	5	4.5

Table D.6 Overview conducted simulations for the variation of parameters a2 and a3.

Appendix E - Prediction method

E.1 Fit parameters: Single variation

Performance Indicator:

$I = I_0 * (A_{1n})^{n11} * (A_{2n})^{n22} * (A_{3n})^{n33} * (A_{4n})^{n44}$

Where,

$A_{1n} = A_1/A_{1,ref}$;
$A_{2n} = A_2/A_{2,ref}$;
$A_{3n} = A_3/A_{3,ref}$;
$A_{4n} = A_4/A_{4,ref}$;

n11, n22, n33 and n44 are fit parameters.

E.1.1 Normalised values A_{in}

A1	µd-value [m]
A1n1	0.25
A1n2	1
A1n3	4
A1,ref	0.42

A2	µd-value [m]
A2n1	0.27
A2n2	1
A2n3	2
A2n4	4
A2,ref	0.26

A3	Rc-value [m^2K/W]
A3n1	0.5
A3n2	1
A3n3	2
A3,ref	2.5

A4	MC at 80% [kg/m^3]
A4n1	0.25
A4n4	0.5
A4n2	1
A4n3	4
A4,ref	9

Table E.1 Overview normalised values for the prediction of the single variation of parameters.

E.1.2 Fit parameters n_{ij}

fit parameter nij	
n11	-1,31
n22	-1,03
n33	1,90
n44	-2,47

Table E.2 Fit parameters for the prediction of the single variation of parameters.

E.2 Fit parameters: variation of two parameters

Performance Indicator:

$$I = I_0 * (a_{1n})^{n11} * (a_{2n})^{n22} * (a_{3n})^{n33} * (a_{1n})^{n12*(a2n-1)} * (a_{1n})^{n13*(a3n-1)} * (a_{2n})^{n23*(a3n-1)}$$

Where,

$a_{1n} = a_1/a_{1,ref}$;
$a_{2n} = a_2/a_{2,ref}$;
$a_{3n} = a_3/a_{3,ref}$;

n11, n22, n33, n12, n13 and n23 are fit parameters
$a_{i,ref}$ is a reference value for the parameter a_i

E.2.1 Normalised values a_{in}

a1	μd-value [m]
a1n1	0.26
a1n2	0.54
a1n3	0.72
a1n4	0.92
a1n5	1.00
a1n6	1.39
a1n7	1.69
a1n8	2.16
a1n9	2.56
a1n10	2.84
a1n11	3.23
a1n12	4
a1,ref	0.68

a2	Rc-value [m^2K/W]
a2n1	0.5
a2n2	1
a2n3	2
a2,ref	2.5

a3	MC at 80% [kg/m^3]
a3n1	0.25
a3n2	0.5
a3n3	1
a3n4	4
a3,ref	9

Table E.3 Overview normalised values for the prediction of the variation of two parameters.

E.2.2 Fit parameters n_{ij}

fit parameter nij	
n11	-1,98
n22	1,90
n33	-2,47
n12	-0,07
n13	-1,86
n23	-1,26

Table E.2 Fit parameters for the prediction of the variation of two parameters.

Ninah Hubregtse
Master Thesis

Msc Architecture, Urbanism & Building Sciences
Master track: Building Technology