KU LEUVEN
FACULTEIT INGENIEURSWETENSCHAPPEN

Hempcrete as a sustainable material for heritage storage; applicability and transition

Niels Poelmans

Thesis voorgedragen tot het behalen
van de graad van Master of Science
in de ingenieurswetenschappen:
bouwkunde, optie
Gebouwentechniek

Promotoren:
Prof. dr. ir. K. Van Balen
Prof. dr. ir. S. Roels

Academiejaar 2015 – 2016

Master of Science in de ingenieurswetenschappen: bouwkunde

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Preface

The choice of this subject was impossible without the input of Prof. K. Van Balen. His proposal to investigate the transition and the application of hempcrete was a challenge which I gratefully accepted. It was a great opportunity to do scientific research on a new sustainable building material and to determine its transition within a case study, called *Depot Rato*. It was an honor to follow up the proceedings of the design of this project by attending the weekly meetings in Mechelen. Therefor I would like to thank the whole design team: Anouk Stulens, Wim Vervoort, Nick Torfs, Bart Stroobants and Sven Cuyt.
Additionally, they made it possible to take active part in the research of the applicability of hempcrete for the design. Additional tests are done to investigate the similarity in strength of the different manufacturing methods in order to obtain an approval for their usage. This involved the manufacturing of several samples according the design and the effective strength test. Those tests were done out of the region of this subject but it helped to map the path of transition.
To determine the material properties, I could count on the support of the staff of the laboratory. Therefor I would like to thank Willem Bertels and Jimmy Van Criekingen. I would like to thank Jelle Langmans, Evy Vereecken and Prof. H. Janssen for their support during the composition of the simulation tool.
Several interviews are done in order to get a clear image of the current path of transition of hempcrete. Therefor I would especially like to thank the following people: Elke De Beukelaer of Pulse; Sébastien Ernotte of ChanvrECO; Hilde Vanwildemeersh of Woonder; Steven Camertijn of BASBouwen; Caroline Lorenzen of Isohemp; Sara Korte of BBRI; Mathieu Hendricks of Hemp in a Box and all the other people I've interviewed but did not mentioned.
To compare analyse the behaviour in case of construction with the box-in-box principle, climate data was needed. I would like to thank Marta Leskard from the University of Bath for her input.
I would also like to thank my parents and friends for their support during the completion of this thesis.

Niels Poelmans

Contents

Abstract

In this thesis, the transition and application of hempcrete as a sustainable material for heritage conservation is described. A new heritage storage in Mechelen, called *Depot Rato*, is the leading subject of this research because in this specific case the design is based on the hygrothermal performances of hempcrete and its carbon dioxide negative character. The description of the current path of transition of hempcrete is based on interviews of professionals, contractors and producers of hempcrete. The transition within the design of the case study *Depot Rato* is highlighted. Based on those experiences, several hygrothermal properties of hempcrete are investigated. The needed hygrothermal properties which are needed as an input for simulations are determined, those are the thermal conductivity, heat capacity, vapour diffusion an sorption isotherm. These results will be used for simulations. To take into account the hygrothermal perfermances of hempcrete, a specific room model is composed. This is done to simulate the indoor climate conditions within a heritage storage room and to investigate the effect of hempcrete on the indoor climate. A final sensitivity analysis is made in order to compare the room model standard configuration with several deviations of the design. A final proposal is given related to the design and requirements of *Depot Rato*.

Samenvatting

Deze thesis handelt over de toepassing en transitie van kalkhennep als duurzaam materiaal voor erfgoed opslag, in het bijzonder voor het *Depot Rato*. Het *Depot Rato* is een project in Mechelen waarbij er een erfgoed depot gebouwd wordt met kalkhennep.
Erfgoed opslag vraagt een stabiel binnen klimaat zodat de verzamelingen niet aangetast kunnen worden door verscheidene factoren. Grote fluctuaties en hoge of lage waarden van de relatieve vochtigheid als van de temperuur kunnen lijden tot, of het bevorderen van, de aantasting van het opgeslagen erfgoed. Het is dus belangrijk om een stabiel binnenklimaat te garaderen binnenin een erfgoed depot. Voor zulke condities zijn voorschriften opgesteld die aangeven welke grenzen voor de fluctuaties, maxima en minima van de relatieve vochtheid en temperatuur er gesteld worden om bepaalde materialen en collecties te beschermen van aantastingen. Deze condities kunnen bekomen worden door een zeer luchtdichte, zware, bouwschil te voorzien waarvan het binnenklimaat geregeld wordt door een luchtbehandelingsinstallatie. Zo een constructie kan zorgen voor een uiterst stabiel binnenklimaat. Echter vraagt dit ook een grote hoeveelheid energie om de luchtbehandelingsinstallatie te voeden. Daarnaast is zo een constructie vaak onmilieu vriendelijk. Zulke constructies bestaan vaak uit materialen die bij de productie zeer veel koolstof dioxide uitstoten. Een voorbeeld hiervan is beton. Met de huidige nood naar een CO_2 arme samenleving is er dus nood aan een alternatief, een duurzaam alternatief.
Kalkhennep, dat een samenstelling is van kalk, hennep en water, kan hiervoor een oplossing bieden. Het materiaal neemt meer CO_2 op dan dat het afstaat tijdens het productie proces. Het materiaal is in staat om CO_2 op te nemen en te bufferen. Verder heeft het materiaal ook goede hygrothermische eigenschappen.
Kalkhennep is een materiaal dat al tientallen jaren bestaat, toch is het materiaal nog onbekend ondanks zijn vele voordelen. Het materiaal wordt reeds gepromoot door verschillende spelers op de markt. Toch blijkt de overschakeling van een traditioneel bouwmateriaal naar kalkhennep geen evidente zaak te zijn. Dit is typerend voor een materiaal dat zich in de begin fase van de transitie bevindt. Het overschakelen van een conservatie toestand naar een nieuwe toestand vraagt een volledige ommekeer van de huidige markt. Zo een proces duurt vaak erg lang en de kans op falen is reëel. De overschakeling naar duurzame materialen vergt zeer grote inspanningen.
Het grootste aandeel van de constructiematerialen markt wordt nog steeds vertegenwoordigd door de conservatieve, vaak zeer vervuilende, constructiematerialen. Toch blijft het moeilijk om gebruikers te overtuigen om duurzame materialen te

gebruiken. Een reden hiervoor is de onbekendheid van het materiaal. De uitspraak ”eerst zien, dan geloven” wordt zeer vaak gehanteerd om zich tot het gebruik van oude, conservatie, materialen te behouden. Er dienen dus eerst voordelen aangekaart te worden vooraleer men overtuigd geraakt van de effecten.
De gebruikers die niet wachten op deze bewijzen maar kiezen voor zulk een materiaal wanneer er nog maar een geringe kennis is, worden benoemd als de koplopers of pioniers. Deze mensen gaan aan de slag met het materiaal als er nog maar enkele voorbeelden voorhanden zijn.
Een pionier op dit vlak is de dienst Erfgoedontwikkeling van de stad Mechelen. In hun ontwerp van een nieuw depot, Depot Rato, wordt er gewerkt met kalkhennep. Zoals eerder vermeld zijn er op het vlak van erfgoed opslag strikte eisen op het vlak van klimaatbehandeling. Aan het begin van het ontwerp is er op zoek gegaan om te bekomen tot een duurzaam ontwerp. In hun zoektocht zijn ze geprikkeld door Hempcrete Museum Store (HMS). Dit is een erfgoeddepot in Bath, ten Westen van Londen. In dit ergoeddepot zijn de wanden opgebouwd uit kalkhennep. Uit meetresultaten van de temperatuur en relatieve vochtheid is hier al gebleken dat er kalkhennep zorgt voor een vrij stabiel binnen klimaat. Oorspronkelijk was er een luchtbehandelingsinstallatie voorzien die ontworpen was op basis van conventionele bouwmaterialen. Achteraf is gebleken dat deze installatie tot drie keer overgedimensioneerd was. Dit overtuigde het ontwerpteam van het Depot Rato om te kiezen voor kalkhennep.
Zoals reeds is aangehaald is er vaak bewijs nodig vooraleer er een overschakeling, een transitie, plaatsvindt.
Uit de analyse van de transitie van kalkhennep zijn enkele onderzoeksvragen naar boven gekomen, zo werd de vraag gesteld of latente warmte een grote invloed heeft op het warmte en vocht transport. Ook werd er gesuggereerd dat kalkzandsteen even goed zo presteren op hygrothermisch vlak als kalkhennep. In dit onderzoek is er getracht hierop een antwoord op te geven.
Om het effect van kalkhennep op het binnenklimaat te analyseren is de doelstelling om simuluties uit te voeren die de hygrothermische eigenschappen van het materiaal mee inrekening nemen. Omdat er voor de simulaties gegevens over het materiaal nodig zijn, zijn de eigenschappen van kalkhennep bepaald. Zo is de thermische geleidbaarheid, warmte capacitieit, dampdiffusie en sorptie isotherm bepaald.
De resultaten van de proeven met betrekking tot de dampdiffusie weerstand bleken niet overeen te stemmen met de verwachtingen uit de literatuur. Een mogelijke verklaring hiervoor is dat er Parrafine in het materiaal gedrongen is waardoor de het doorstroom oppervlak drastisch verminderd is.
Voor deze simulaties van start konden gaan is er een ′Roommodel′ opgesteld. Dit model is zo geschreven dat de temperatuur en relatieve vochtheid gekoppeld worden opgelost, hierdoor is het effect van latente warmte in rekening gebracht.
Het model is zo geschreven dat er na het doorlopen van het programma verschillende grafieken gegenereerd worden. Naast deze grafieken worden er ook matrices gegenereerd waarin info terug te vinden is over het binnenklimaat, de jaarlijkse warmte en vochtstromen door het materiaal, de nodige warmte en vochtbehandeling.
Met dit model zijn de simulaties van start gegaan. Er is onderzocht of de latente

warmte effectief een invloed heeft op de warmte en vocht doorstroom door het materiaal. Uit de simulaties is gebleken dat latente warmte een grote invloed heeft op het transport van warmte in het materiaal.
Daarnaast is er ook een gevoelheidsanalyse gebeurd. De reden hiertoe was om het effect te bepalen van verschillende situaties die zich kunnen voordoen als ook om enkele, frequent gebruikte, materialen te vergelijken met kalkhennep.
De resultaten die uit deze simulaties voortvloeienden tonen aan dat kalkhennep effectief goede hygrothermische eigenschappen heeft. Het materiaal is in staat een gunstiger binnen klimaat te behouden in vergelijking met cellenbeton of kalkzandsteen.
Uiteindelijk is er een voorstel gegeven voor een optimale wandopbouw. Hierbij is het buitenoppervlak bewerkt met een dampwerende coating. Het voordeel hiervan is dat er geen continue hoeveelheid vocht naar binnen kan stromen wanneer er voor lange tijd een zelfde dampdrukverschil over de wand heerst. De stabiliserende werking was vooral te merken op het vlak van de nodige hoeveelheid vocht die er aan de lucht moest onttrokken worden om binnen de grenzen van het aanvaardbare te blijven.
Het is raadzaam om in de toekomst het gedrag van de wand verder op de volgen. Niet enkel om de resultaten voor wetenschappelijke doeleinden te gebruiken, maar ook om een breder publiek aan te spreken die momenteel de stap naar duurzame materiaal nog niet gezet hebben. Met deze resultaten is de overtuigingskans aanzienlijk groter. Verder kan het simulatiemodel nog verder uitgebreid worden door de interactie met de aarde en het dak in rekening te brengen.

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Abbreviations

Symbols

b_m	Moisture effusivity	$kg/(Pam^2 s^{1/2})$
c	Heat capacity J/(kgK)	
d_b	Thickness buffer layer	m
d_p	Moisture penetration depth	m
h	heat surface transfer coefficient	
m	Mass	kg
m_0	Mass of dry material	kg
n	Air change rate	1/h
p	Vapour pressure	Pa
p_{sat}	Saturation vapour pressure	Pa
T	Temperature	K
t_p	Time period	s
u	Gravimetric water content	kg/kg
w	Water content	kg/m^3
w_m	Mono-molecular water content	kg/m^3
C_G	Fitting parameter GAB-Model	-
D_w	Moisture diffusivity	m^2/s
D_v^φ	relative humidity vapour coefficient	kg/(ms)
D_v^T	Temperature vapour coefficient	kg/(ms)
E_{stored}	Stored energy	J
G	Mass flow	kg/s
Q	Heat flow	W
Q_{vp}	Produced heat	W
R_v	Water vapour gasconstant	Nm/(kgK)
RH	Relativ humidity	%
Txiv	Temperature	K
T_b	Temperature buffer layer	K
V	Volume	m^3

β	vapour surface transfer coefficient	s/m
δ	Vapour diffusion permeability	kg/(msPa)
δ_{air}	Vapour diffusion permeability in air	kg/(msPa)
λ	Heat transfer coefficient	W/(mK)
μ	vapour diffusion resistance	-
π		
ρ	Density	kg/(m^3)
θ	Relative humidity ratio	-
ξ	Moisture capacity	kg/m^3

GAB	Guggenheim and Anderson and De Boer model	
HMS	Hempcrete Museum Store	
HVAC	Heat Ventilation and Aircoditioning	
LHC	Lime hemp concrete	
MBV	Moisture buffer value	g/(m^2%RH)
MHC	Mould hemp concrete	
SHC	Sprayed hemp concrete	
THC	Tetrahydrocannabinol	

Suffixes

air	Air
b	Buffering
buff	Buffering
dev	Part of divided wall
i	Interior
in	Inflowing
init	Initial
e	Exterior
fin	Final
l	Liquid
mat	Material
max	Maximum
min	Minimum
out	Outflowing
ref	reference
s	Solid
stored	Stored
v	Vapour
vp	Production
wall	Wall

Chapter 1

Introduction

The design of a heritage storage is a bipartite challenge. It has to meet the requirements for conservation and it has a social responsibility. Even if a heritage store is *just* a building where heritage is stored for a long time, it can and it must be a leader in the challenge to aspire a sustainable society. IT is an old fashioned thought to construct an air-tight building with heavy construction materials. Insulate it so hard that there is no interaction with the environment and treat the indoor air with an extensive air conditioning system belongs to the past. A new epoch has started where a balance between optimal conservation and a sustainable reliable design has to be found. To find that balance, a sustainable thought of the architect of a project isn′t enough. The promoter and all other participants related to the design must have the same vision, a sustainable vision.
Sustainability is often seen as a risk for heritage, since t has an high investment cost and limited rate of return. The department for heritage conservation of the village Mechelen wants to prove that a design can meet both sustainability and the conservation requirements. This is why they want to set an example by constructing a heritage storage, *Depot Rato*, with lime hemp concrete.
Lime hemp concrete, often called hempcrete, is a mixture of lime hemp and water. It has several hygrothermal privileges compared with other construction materials. Nevertheless, during the design of the new repository, several hazards needed to be overcome. In order to map those hazard and to prove the hygrothermal privileges, this research topic emerged. The transition to the usage of sustainable materials in heritage storages, in particular hempcrete, is determined by interviewing specialized people and by investigating the case study *Depot Rato*. One of the main hazards of this transition is a lack of information of the material and how to implement it in the dimension of an air conditioning system. In order to proof the benefits of hempcrete, hygrothermal performances are examined. This is done by determining the material properties, which are then used for the simulation of the hygrothermal behaviour of the wall and the indoor air conditioning requirements of a repository. For this specific case, a simulation model is constructed that takes into account the hygrothermal privileges.
Chapter 2 describes the requirements of heritage conservation. It highlights the

current descriptions of several standards and emphases the a balance between optimal conservation and sustainability.
Chapter 3 describes the case study Depot Rato. The design is highlighted and a description of the process of the composition of the Program Requirement is given.
Chapter 4 gives an image is the application of hempcrete. The different manufacturing techniques are highlighted and several existing hempcrete structures are described.
In chapter 5 the transition of hempcrete is analysed. The first part consists of a brief introduction of the need for a transition and the basic principles. The second part describes the transition, where the transition within the design of Depot Rato is highlighted.
Chapter 6 describes the properties hygrothermal principles which will be used to setup an simulation tool.
Chapter 7 handles the experimental investigation the hempcrete properties. The test methods are described together with an discussion of the results.
The roommodel, which is used for further simulations is highlighted in chapter 8. The composition of used the differential equations is described. Ad the end of the chapter a validation of the roommodel is made.
Chapter 9 analyses the dynamical behaviour of hempcrete based on simulations with the room model. The dynamical interaction between heat and mass flows is investigated, the moisture buffer value is determined and compared with other construction materials.
In Chapter 10, a sensitivity analysis is made. The influence of several deviations of the standard configuration, described in chapter 8, is analysed. At the end, a final proposal is given based on the results of the the previous chapters.

Chapter 2

Conservation of heritage

2.1 Heritage storage requirements

Heritage storage is more than only the storage of a bunch of objects in room. To have grip on the amount and the conditions of collections, a carefully considered management is necessary. This management relies on six, hardly inseparable, topics: information policy, different kinds of materials, different kinds of collections, conservation, storage and package and transport and handling.
Conservation of heritage for the future means that damage, in its broadest sense, needs to be prevented. In order to prevent damage by storage of heritage, at least ten risk factors need to be taken into account. These are: (i) Physical forces, (ii) theft and vandalism, (iii) fire, (iv) water, (v) pests and molds, (vi) pollution like dust or gasses and liquids, (vii) light and radiation, (viii) wrong temperatures and (xi) wrong relative humidities or high fluctuations and (x) loss of information. [31]
The chemical stability of objects in the collection of museums and storages is effected by temperature, moisture, reactive chemicals in the air and biological attack. The conservation of museum collections ask therefor a stable environment. The deterioration of articles is affected by the relative humidity, since this can change the size and shape of the exhibits. For example the cracking of wood when it's is dried after exposure to high a humidity [64]. In addition, the interstitial condensation inside the materials, together with the pollutants in the air, give rise to aggressive solutions that cause corrosion of the metals, discolouring of drawings on cottons, flaxes and so one, particular in the presence of light. Also the temperature affects the rate of deterioration by chemical reactions and changes in biological deterioration sources [41]. Research is done in order to determine an acceptable range of relative humidity to store most of the collection. This range appears to be between 5 % to 60 %. Temperatures below 20 °C are recommended. Further, pollution concentration; electromagnetic radiations coming from sources of natural and artificial light; vertical thermal transmission of air masses and velocity of the air in contact with the object influence the degradation process of artworks [39].

2.2 Standardization of climate requirements

Specifications and standards for heritage conservation are based on long-term average levels usually over one year, seasonal cycles and short-term fluctuations. From the 1970s, there are standards and specifications for temperature and humidity to preserve materials [53]. In 1999 American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc. (ASHRAE) subdivided storage specifications into five classes of climate quality, which is shown in table 2.2.

Table 2.1: ASHRAE Temperature and Relative Humidity Specifications for Museum, Library, and Archival Collections

Temperature °C	RH[%]			Remarks
	long-term average	seasonal sycle	short-term fluctuations	
15 to 25	50 or historical yearly average	No	±5	Class of control AA - No risk of mechanical damage to most artefacts and paintings
		No	±10	Class of Control A - Small risk of mechanical damage to high-vulnerability artefacts; no mechanical risks to most artefacts, paintings
		+ 10 in summer - 10 in winter	±5	
		+ 10 in summer - 10 in winter	±10	Class of Control B - Moderate risk of mechanical damage to high-vulnerability artefacts; tiny risk to most paintings
		25 to 27		Class of Control C - High risk of mechanical damage to high-vulnerability artefacts; moderate risk to most paintings
		Below 75		Class of Control D - High risk of sudden or cumuliative mechanical damage to most artefacts and paintings because of low-humidity fracture

This is based on the climate related risks that are avoided in each class and which are represented. The long term relative humidity was stated to be 50 % for international consistency or the local historic average relative humidity in the case of museums permanent collections [5].
The British standard 5454 recommends a fixed temperature and relative humidity. The relative humidity may vary between 45 and 60 %, the temperature must lie between 13 and 16 ℃ with minimal tolerances around these set-point, 5 % resp. 1 ℃.
A European Standard, EN 15757:2010 is less specific. For the temperature no specification is given. The historical yearly average was recommended for the relative humidity. The seasonal cycle was set to the historical seasonal cycle with a fluctuation of 10% RH (62).

2.3 Climate control

To obtain strict conditions in museums and museum storages it is common that extensive air conditioning is implemented. Which results in a case where the Heat Ventilation and Air conditioning (HVAC) system is often very energy consuming. In order to obtain low-energy museal spaces, it was suggested to use passive air conditioning. This could be satisfied by the use of a building envelope with a high thermal and hygric inertia, often the stored articles are taken into account as thermal and hygric buffer material. The desired conditions were merely satisfied when indirect heating was available or when particular ventilation strategies were applied. The ventilation strategies are based on natural ventilation by using outdoor air with low relative humidity to optimize the indoor conditions. For passive climate control, when pollutants are generated internally, it was suggested to recirculate the air through a pollutant filter [75]. This passive climate control is only possible when the outdoor conditions are right. However if the average relative humidity is too high, this way of climate control fails to get the desirable indoor conditions.

2.4 Optimal conservation

The definition of optimal conservation can be expressed as the storage of articles in a way that the hygrothermal conditions within the objects are kept constant, whereas in the previous the emphasis was placed on controlling the indoor climate. Evidence was found that even in highly controlled climates articles could be damaged, whereas in less controlled climates undamaged articles were found. An explanation can be found in the large moisture content of the stored objects compared with the relatively small moisture content of the indoor air. [67]
Measurements have shown that the water content in materials can vary despite a control of the indoor climate by air conditioning systems. To obtain an environment where objects can be stored in a way their hygrothermal equilibrium is guaranteed, high fluctuations of the indoor climate should be prevented and the buffering capacity of the materials should be used maximal. To minimize fluctuations, a compartment is

recommended in order to reduce air circulation. The reduction of fluctuations can by stimulated by building by a box-in-box principle. When conservation rooms are built within a space that is isolated from the exterior air, the intrusion of high fluctuations in the boxes can be reduced to a minimum. To prevent the arise of micro-climates, which occurs due to stagnant air and emitted pollution of the objects, a minimum air treatment is recommended. Typical ventilation folds are 0,1 air changes per hour (ACH). [32]

2.5 Climate control strategies proposed in literature

To fulfill the strict conditions, the air needs to be treated. There are several solution to manage this problem, one of them is the use of a dehumidifier. This application is used in the Museum Storage Building in Ribe (southwest Denmark), a heavily insulated building and nearly airtight. It appears that the dehumidification seems to succeed in obtaining a constant relative humidity. It was mentioned by T. Padfield et al. [61] that the energy demand of the dehumidifier is much lower compared with the one if the air was heated.
H. Janssen and J.E. Christensen [50] concluded the same after they studied the reliability of full passive conditioning for museum storages spaces. A simulation was done on a storage space in Denmark, which has a cold climate and a high relative humidity. Taking into account the heat transfer through the ground and the moisture buffering of stored objects, it was possible to obtain results that are reliable with the measured values. It was shown to be an illusion that full passive conditioning is possible, because an excessive relative indoor humidity was generated. It is straightforward that without any interior heat or moisture gains, the yearly average temperature and relative humidity will equilibrate with their exterior counterparts. Interior heat gains and solar radiation at the building surfaces can lead to more desirable values for the interior temperature and relative humidity in maritime and cold climates. But to ensure acceptable conditions, conservation heating or auxiliary dehumidification are still necessary. A main hazard in this kind of simulations is the complexity of a reliable quantification of the amount and nature of the objects that interacts with the interior air.
To reduce the economic and ecologic cost of conditioning, it was assessed by H. Janssen and J. E. Christensen [50] to use concentrated dehumidification. Because the highest moisture load occurs between 12.00 h and 18.00 h, dehumidification with set point 50% RH was employed in this interval, while the building was left in free-running from 18.00h till 12.00h. When taking into account the hygric interaction between the wall, which is built with light weight concrete, and the stored objects; the relative humidity only rises to 54.3%. For more air tight buildings, with a reduced air change rate of 0.01/h, it is possible to reduce the maximal relative humidity to 51%. So the interior conditions satisfied to the boundaries of ASHRAEs to conservation class AA, see Table 2.2. The use of light weight concrete in the museum storage in Denmark is a benefit for the fluctuations of the indoor relative humidity because it is a good moisture buffering material [71].

2.6 Balance between optimal conservation and sustainability

As mentioned in the introduction, the challenge in today′s design is the reach the indoor requirements and a sustainable design. A compromise has to be found between the high demands and a minimum energy consuming construction. In order to implement durability in heritage conservation, a transition path, needs be run through which rely on the principles of the circle of Deming: plan, do, check and act. It's necessary to take into account the special needs to make an expertise which is the most sustainable solution. Mostly this expertise comes to the conclusion that a sustainable solution is a one where no equipment is installed. In order to compromise the specific needs, a low-consuming equipment is provided. To do this, an attempt is done by constructing several models that rely on different theories like the *Denmark*- and the *Holland*-model. The *Denmark*-model is based on the thermal capacity of the earth. In order to take advantage of the heat buffering capacity, the building shell has to be isolated such that it is air-tight. The indoor temperature varies between 7 and 15 °C .[82] The *Holland*-model is based on concrete core activation. [46]
As mentioned before, another technique to reduce energy costs is the use of moisture buffering materials. Those materials are able to reduce fluctuations of the indoor relative humidity by absorbing and releasing moisture when the indoor relative humidity reaches high and low values. An indication of this ability is the moisture buffer value, which will be explained later on. Light weight concrete is classified as a good moisture buffering material, it has a moisture buffer value (MBV) of 1,0 $kg/(m^2\%RH)$. Another example is hempcrete, which has a moisture buffering value of 2.0 $kg/(m^2\%RH)$.

2.7 Hempcrete Museum Store in the UK

An example of an heritage storage where sustainable building materials are used in order to lower the energy costs is the Hempcrete Museum Store (HMS) in the United Kingdom. On a repurposed World War II airfield in Wroughton, a part of Wiltshire (west London), a large variety of objects from science, technology, industry etc. were collected and stored in hangars and brick buildings dating from the 1930s and 1940s. The old buildings required high ventilation costs to obtain a desired indoor climate for the storage of the heritage. In 2010 it was clear The Science Museum Group UK needed an environmentally-controlled yet sustainable repository. So it was decided to build a heritage store in an hangar for the following reasons: building a building within a building would assist in providing an improved level of environmental control and no planning permission was required. The Adnams brewery distribution warehouse, was a leading example for the design of the Hemcrete Museum Store. The team was convinced by the choice of hemp-lime as a building material with the aim of creating a passively controlled store. The construction consists of a steel frame and prefabricated Hemcrete, which are wall elements that were cast and dried before placing them. The HMS design team was convinced this would reduce the construction and drying times. The interior of the construction was finished with a permeable unpainted magnesium-silicate board. The ranges for the indoor air of 1518 °C and 45-55 % were specified. To maintain the indoor air parameters, an air handling system was provided. The software that calculated the dimensions of the system didnt accurately simulated the behaviour of the lime hemp, an additional modelling concluded a three-fold reduction in the design of the heating and ventilation system. The indoor conditions could be maintained by the use of dehumidifiers that turn on when the RH exceed 55 % to bring it back to 45 % [58].

Figure 2.1: The Hempcrete Museum Store (HMS) at Wrougthon

Chapter 3

Depot Rato: a new hempcrete museum store

3.1 Conception

In Mechelen, the collections of the city archives, the reserves of the library, the archeological finds and cultural heritage are currently stored at thirteen different locations in less ideal conservation conditions. To assemble the heritage collections and to conserve them in the required conditions, the local authorities started with the search of a better location. One of the buildings that belongs to the cultural heritage inventory of the city is the *Alstomsite*, located at Leuvensesteenweg 474 in Muizen, a sub-municipality of Mechelen.[74]

FIGURE 3.1: The Alstomsite as cultural heritage [74]

The Alstomsite has a rich history since 1902. In 1911 a workplace was built by Auguste Rateau for the construction of several pumps and ventilators. The Belgian coalmines were one of the main costumers. During the First and Second World War, the fabric was seriously damaged, each time the industrial sheds were restored. In the period after the Second World War, the company got specialized in the design and construction of turbines and centrifugal pumps. In 1976 the group Alstom was bought by Alstom Power Services in cooperation with Bombardier, they manufactured all double decker railway carriages for the NMBS. In 2014, the management of Alstom Power Services decided to restructure and close the factory in Mechelen. Since then, the Alstomsite is deserted and the industrial sheds are now reduced to large unused spaces. [78]

FIGURE 3.2: The Alstomsite [2]

The local policy decided to revive this area by an integral project called *Depot Rato*. The project is established due to a collaboration with the following partners: *RPD* as project developer, the city of Mechelen as founder, *Tecro & Krea* responsible for the architectural design and *Archimedes* responsible for the engineering design. The total area of this project is 15559 m^2. The oldest sheds, with an area of $2780m^2$, are readdressed for heritage storage. The remaining area will be used for the construction of a retail center and fifty eight residential accommodations. By such design, heritage isn′t stored somewhere in the back. In contrary, it gets a central spot in a blooming environment.

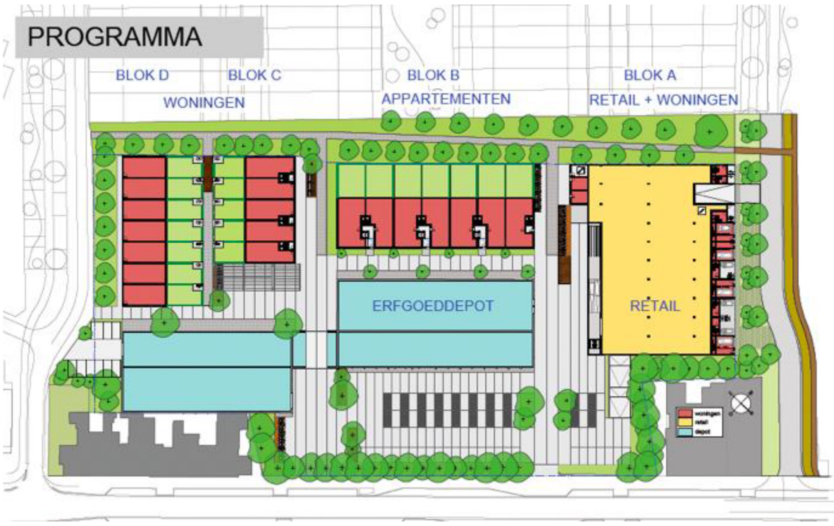

FIGURE 3.3: Plan integral project [74]

The design of the readdressed sheds, relies on the box-in-box principle. Two construction units will be built inside one of the sheds for the storage of heritage collections. This design kills two birds with one stone. The building, which is certified as cultural heritage, will be preserved and the collections can be stored inside in a safe way.
Sustainability is a value preached by local policies of Mechelen. This is why the aim was to design conservation units who answer to the requirements of conservation and are sustainable. In the search to a sustainable solution, the Hempcrete Museum Store of Wroughton emerged. With this information, the departments ′Gebouwen and Erfgoedontwikkeling′ started with the design of the project Depot Rato.

3.2 Heritage collections and their requirements

The heritage collections include a wide range of articles, books, going from books, paintings, glass plates, furniture, textile to human skeletons and DNA-samples. These articles consists of different kind of materials.
To guarantee a good conservation, the circumstances in which they will be stored must fulfill to the conservation requirements for each specific article. Due to the fact that the amount of specific requirements is considerably high, it would be inefficient to construct such an amount of areas so all articles with the same specific requirements can be stored together. In order to solve this problem, articles with slide differences in requirements can be stored together by adapting the way that they are stored. For example, articles who consist of materials who are vulnerable for acids, can be stored in acid-free boxes next to the ones that are less vulnerable for acids.
Requirements that are less manageable are temperature and relative humidity. So it is more efficient to group the objects and store them in function of their temperature

and relative humidity requirements. The department ′Erfgoedontwikkeling′ made an inventory of their collections. With this inventory and in the light of their requirements for conservation and handling of the articles, it appears that seven different climate zones need to be provided. These are summarized in table 3.1.

TABLE 3.1: Categorization of climate zones

Zone	Temperature [°C]	RH [%]
A	7 - 18	45 - 55
B	10 - 25	max 40
C	7 - 25	40 - 60
D	/	/
E	max 18	30 - 40
F	3 - 4	n/a
G	> 5	< 75

Examples that require the conditions of zone A are books, LP′s, textile, paintings, architectural fragments and gravestones.
Objects like archeological objects like pottery, human skeletons, dry materials such as wood or textile, and sieve samples require the conditions from zone B.
Climate zone C is the one with less stringent climate requirements. This is the climate condition for areas with functions like the processing of incoming articles, digitizing and scanning, quarantine, treatment and administration office. Areas for kitchen, toilet and changing room are areas with a low occupation and therefor categorized as zone D. Climate zone E is the area where audio articles will be stored, these have vary specific requirements and will be placed in a later stadium. The are, needed for these constructions, will be limited. Some articles need to be stored in refrigerators, they will be placed in zone F. Areas to store no heritage objects, like tools and service vehicles, are categorized as zone G.

3.3 Design

3.3.1 Provide climate controlled areas

The building shell of the industrial shed is already aged and doesn′′t fulfill the today′s isolation requirements, controlling the indoor climate of the shed is excluded. To create different climate zones, a compartmentalization of the available space and control of these compartments appeared to be the ultimate solution.
To suit the required climate conditions in each zone, an air conditioning strategy is necessary. This strategy will differ for each zone, related to their limitations. Obtaining a sustainable design means that each part of the design needs to be approached to fit the reasoning of sustainability. So a minimal energy requirement is the objective in the design of the air condition strategy.
To compromise these two contradictory requirements, it is preferred to create storage

boxes which will regard a relative humidity between 40 and 60% RH and a temperature between 10 and 25 °C. The heritage objects belonging to zone A and C will be stored within these storage boxes. The objects belonging in zone B an C, will be stored in a separate climate conditioned room. A refrigerator is included in the design for the storage of articles with requirements of zone F.
The design of such compartments includes the choice of appropriate construction materials. As mentioned, in the search to a sustainable design, hempcrete appears to fulfill both hygrothermal and sustainable requirements. So hempcrete will be used to build storage boxes for the objects that are currently categorised in zone A and C. The indoor climate will be set to a relative humidity between 40 and 60 % and a temperature between 10 and 25 °C.
Due to the fact that hempcrete is not a conventional building material, the implementation of the hygrothermal behaviour in the dimensioning of an air conditioning system is not a matter of course. The experiences of the Hempcrete Museum Store in Wroughton led to the finally decision to control the hempcrete boxes strategy that only contains a set of hot water air heaters and, if necessary, dehumidifiers. A permanent evaluation of the indoor conditions and, if required, an adjustment will be done to maintain the climate requirements.
To avoid that new incoming heritage objects can attack the stored collections, the incoming objects will be placed in quarantine for a certain time. Afterwords, they will be stored in an anoxy room which is a room with a low concentration of oxygen, for two weeks. Since contaminations within the objects are not able to survive in a low oxygen climates. In order to obtain a low oxygen concentration, the room will be filled with nitrogen. Because the air tightness of hempcrete is not well known, it is obtained to build the anoxy room with other materials.
The consultation zone is designed with port containers, where the needed HVAC equipment will be installed.

3.3.2 Dimensions of the storage boxes

To store the large amount of articles, movable shelves will be installed within the storage boxes. These shelves are made of perforated panels to prevent the appearance of micro climates. In the figure 3.4 and figure 3.5, the storage units are highlighted. Each unit is subdivided in several storage boxes. The upper unit consists of two storage boxes at the ground floor and four storage boxes at the first floor. The lower unit is subdivided in only two boxes, see figure 3.4 and 3.5.

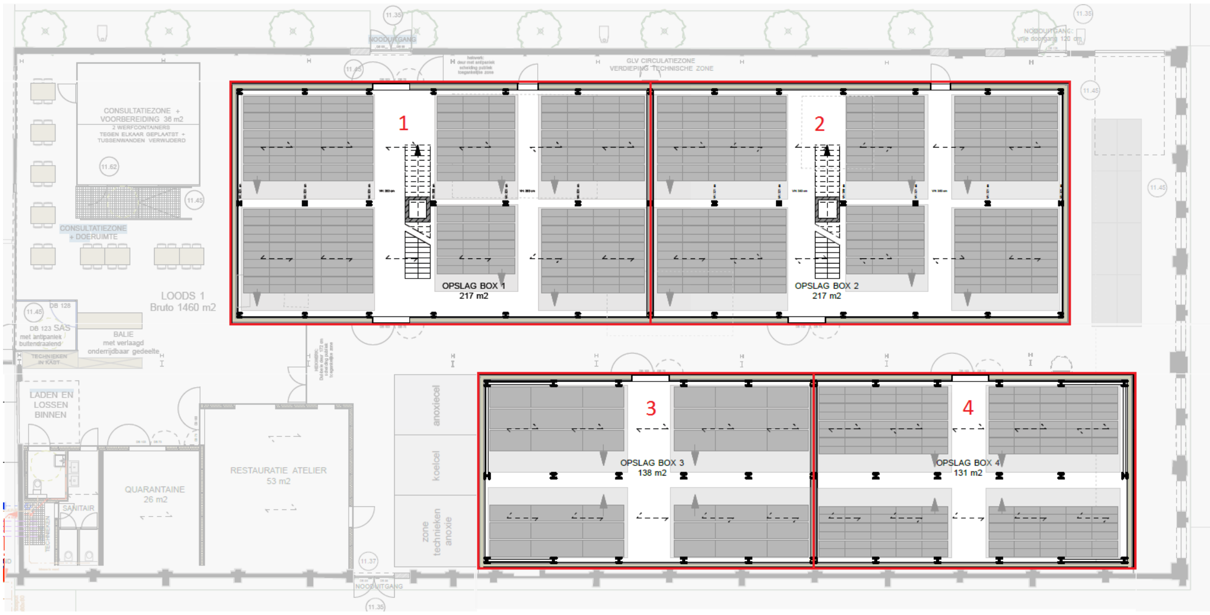

FIGURE 3.4: Top view of hempcrete boxes ground level

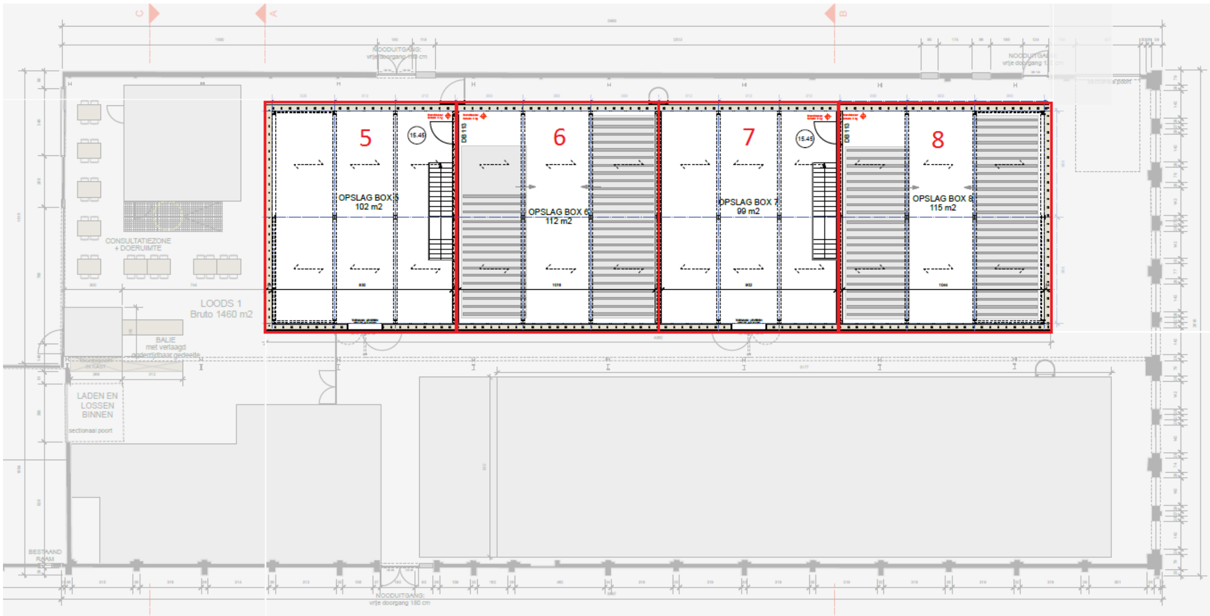

FIGURE 3.5: Top view of hempcrete boxes first level

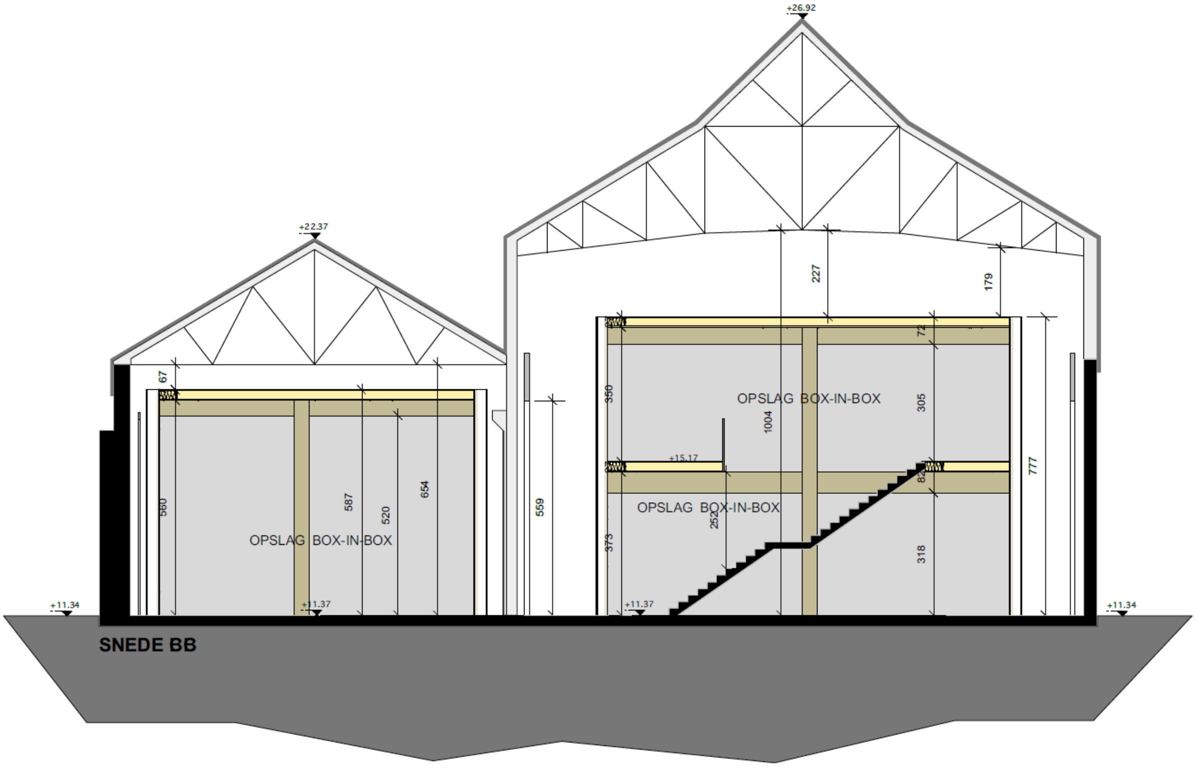

Figure 3.6: vertical cup of hempcrete boxes

In figure 3.6, a vertical cut is shown of the hempcrete conservation units. Due to the stairs, the climate in box 1 and box 5 and the climate in box 2 and 7 are the same, except the temperature can vary in height. The other boxes can be closed completely, so the indoor climate can be adapted. Boxes 5 and 7 will be used for future heritage objects. In table 3.3.2, the dimensions of the boxes are given.

Table 3.2: Dimensions of the heritage storage boxes

Box	1	2	3	4	5	6	7	8
width [m]	11	11	8.80	8.80	11	11	11	11
length [m]	19.99	19.99	15.19	15.94	9.49	9.82	9.36	10.29
area [m^2]	219.89	219.89	133.67	140.27	104.39	108.02	102.96	113.19
height [m]	3.83	3.83	5.8	5.8	3.74	3.74	3.74	3.74
volume [m^3]	838.35	838.35	775.29	813.57	525.06	403.99	385.07	423.14

3.3.3 Hempcrete walls

The walls of the storage boxes will be made out of hempcrete. To ensure a stable indoor climate, the thickness of the exterior walls is set at 300 mm. Due to the fact that lime hemp is not able to bear itself, a load bearing structure needs to be included. A wooden structure is foreseen within the hempcrete wall. The wooden grid consists of 100 mm by 50 mm beams with a center-to-center distance of 430 mm. A draft of a wall section is visualized in figure 3.7.
The finishing of the wall depends on the manner of manufacturing. If the walls are manufactured with the moulding- or projection-technique, they will be finished with a lime-based plaster. When precast elements are used, it depends of the design of the supplier. However, the finishing layers need to be vapour open to ensure the hygrothermal performance of the hempcrete wall.

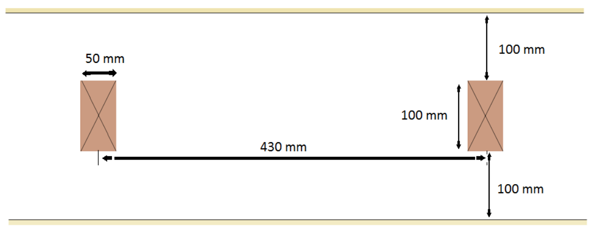

FIGURE 3.7: Indication of the position of the wooden frame within a hempcrete wall

The separation between two boxes will be a hempcrete wall with a thickness of 200 mm and with an analog built-up as exterior wall structure. This means that the wooden frame within the wall will be covered with 50 mm of hempcrete at both sides, whereas it was 100 mm for an exterior wall.
Because the height of the exterior wall is higher then the buckling length of the wooden beams, a laminated cornice girder will be placed at mid height of the wall. The floor and roof will be made out of a 150 mm thick autoclaved aerated concrete roof tiles. The roof tiles are isolated with 80 mm thick PIR isolation plates. To reduce the needed load bearing capacity of the wall, an external load bearing frame will be placed within the boxes to carry the load of the floot, wall and roof of the units.

3.4 The draft of Program Requirements

To do a call for tenders, a Program Requirements is required in order to inform interested attenders. Since the bidder is a governmental institution, it must be a public tender. To prescribe the construction method of the hempcrete wall, an extensive market research was done. It appeared that three different kind of wall constructions, which will be highlighted in Chapter 4, can be described. In order to address a broad public of attenders, all three methods are prescribed.

Due to the public character, each attenders needs to proof that his wall construction fulfills to the requirements concerning fire resistance. A fire resistance of $EI60$ needs to be obtained.
In order to approve a construction with two levels made out of hempcrete fulfills the requirements of fire and safety, a lot of effort was needed. The first hazard in this approval was to convince the local authorities themselves of the safety and applicability of hempcrete. To confirm the applicability, existing fire resistance certificates needed to be served.
To know which fabrication method and the relating density fulfills the conditions of fire safety, a *shear tension* test was done on samples with different density and with a different manufacturing methods.
It is clear that the draft of the Program of Requirements was not evident compared with the situation if conventional building materials were used. Several hazards needed be overcome, including the doubts about this material. These difficulties are typical for a material in transition. This is why the transition of hempcrete for heritage storage will be highlighted in Chapter 6

Chapter 4

The application of hempcrete

4.1 History

The history of hemp dates from 4000 years ago. It was cultivated and used by man in most ancient civilizations. From 1000 years after Christ it was used all over the world. Hemp fibers are utilized for the manufacturing of ropes, sails, clothing and paper. The grains are used for the production of cosmetics, food and medicines. After 1900, hemp products begin to be substituted within synthetic materials (plastics, nylon,etc). From 1960, the cultivation of hemp is reintroduced in several countries. The fibers are processed predominantly for use in paper and clothing and later in the automobile and plastic industry. Until 1990, the stem, after having been stripped of its fiber, had no functional meaning. Yves Kuhn, a French man, discovers the possibility of using the stem, as a building and insulation material. Its unusual high silica content makes it highly resistant to all kinds of climatic conditions, in particular humidity. When mixing it with lime, it crystallizes and will not rot or burn. The first houses were built entirely hemp materials. Other companies, started to build and insulate with hemp. Several Research and Development programs started and lot of research was done with various combinations of lime and other natural materials to optimize thermal effect of the end-products. In 2000, the use of hemp as building and insulation material spreads throughout Europe. Hemp associations are established both in Europe and North America. An example is the Hemp International located in Ireland.

Hempcrete can be applied as a finishing layer and as building material in a framework because it is a non-load bearing material. It performs good and has several advantages compared with ordinary brick. The ustainability and hygrothermal performances are the two main privileges of the implementation of lime hemp concrete (LHC), often called hempcrete.

4.2 Hempcrete as a building material

The appearance of hempcrete as a building material is similar to the one of concrete, it can be precasted, sprayed or moulded. The methods differ in the sequence that lime, hemp and water are added to the mixture and the stress that is applied during mixing.

4.2.1 Precast

Hempcrete can be precasted in blocks or in prefab-panels. The main advantage of this technique is that they can be installed after these elements are dried in the factory, so a finishing layer can be implied 5 days after the main core the wall is riced up, which reduces the construction time onside. Prefabricated panels with a thickness of 15 cm could dry in two days due to an enforced air passage. Hempcrete blocks or panels are formed with quicklime (CaO). The usage of additives differ. Some prefer to add none because they raise the thermal conductivity. Others add puzzolanic additives. The hydrated lime and hemp shivs are throw together in an mixer, whereafter the mixture is poured in moulds and blocks are formed by compaction in the moulds under vibration.
Like already mentioned, the hemp-blocks are not able to carry any load so the blocks are often used in post-and-beam structures. The blocks are placed between the wooden frame studwork. They are limed together with a lime basted mortar with a joint of 3 mm. The mortar consists of lime, sand and hydraulic binder. To avoid capillary uptake of water, a substructure with a height of 20 cm is recommended with a vapour impermeable membrane on top of it as visualised in figure 4.1 [48]. To obtain a passive wall construction, the wooden frame can be filled up with Hempwool. At both sides of the wooden frame, a wall of blocks is constructed to obtain a wall with a desirable thermal resistance. An example is given in Figure 4.1 , where a U-value of 0.13 W/m^2K is obtained.

Thickness [mm]	120	155	200	300
Sizes [mm]	600x300	600 x 300	600 x 300	600 x 200
Blocks per m² [-]	5.55	5.55	5.55	8.33
Density [kg/m³]	360	360	360	360
Thermal resistance [m²K/W]	1.6	2	2.6	4
Fase [h] (ISO 13786)	6.25	9.33	12.5	18.75
R_w [dB]	37	39	42	45
adsorptioncoefficient α[-]	0.8	0.8	0.8	0.8
Firebehaviour (NF EN 13501-1)	d0 – M1	d0 – M1	d0 – M1	d0 – M1

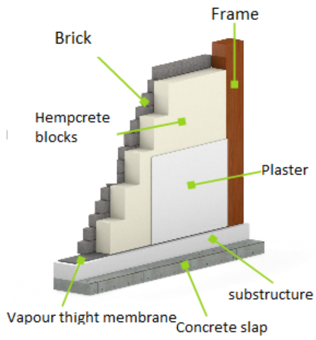

Figure 4.1: Properties of hempcrete blocks and a wall construction

An example of a prefabricated panel is given in Figure 4.2. The wall panel consists of a main loadbearing frame and an inner structure. The inner structure is built up with two loadbearing frames, the outer frame is filled with natural (wood) fibre isolation while the inner frame is filled with lime hemp concrete. The interior surface is a perforated hardboard with a thickness of 5 mm. According to the fabricant, this is done to let the hempcrete do his job as breathing material and to make it possible to adapt a finishing layer of clay, gyproc, natural plasters or wood. The exterior surface is a breathable membrane and can be finished with a plaster, wood or a brick. The thermal transmittance of a prefab lime hemp panel is equal to 0.15 W/m^2K.

4.2.2 sprayed

Another manufacturing method is thee projection of hempcrete, often called: Sprayed Hemp Concrete (SHC). It is a build-on-site technique where the components are projected on a shutter board or in a block mould. First the hemp shivs and the lime are mixed together. Then the dry mixture is conducted by air through a hose. Just before the end of the hose, pulverized water is added. Figure **??** shows the filling of samples with the projection technique. After filling, the surface is smoothed.

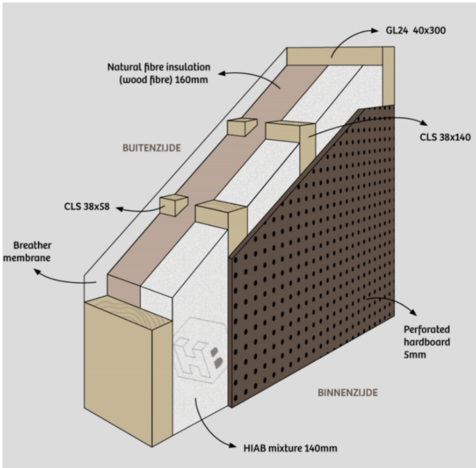

FIGURE 4.2: Example of a Prefab LHC panel

It is often cited that the main advantage of this technique is that less water is needed in the manufacturing, compared with a conventional method were everything is mixed in place. This is because in the conventional manufacturing method, hemp shivs are able to absorb a large amount of water. This is due to its highly porous structure and strong capillary effects. So in this case there is more water needed with respect to what is needed to slake the lime. This implies that the setting and drying times are in the order of several months to several years, which is not desirable. Another issue where conventional techniques need to deal with is that nearly no compaction under gravitational action is possible due to the light weight of hemp shivs. This results in highly porous structures.

4.2.3 moulded

The third method to construct lime hemp walls is the mould hemp concrete (MHC), which can be used on construction. First, fibred hemp shivs are mixed with a commercial lime-based binder in a mixer. Water content is adjusted to obtain fresh hempcrete with a satisfactory rheology. Moulds are filled with the mixture and the hemp concrete is slightly compacted. When using this method on side, it is necessary to use a mould which can be filled with the mixture. A possibility is to cast it between an existing wall

FIGURE 4.3: Moulding on-site

and a plate. It must be done in several steps in height because the mixture needs to dry before any load can be applied on it. There are several applications for MHC in the building industry. One of them is to use is an improvement of the thermal resistivity by placing a loadbearing frame against an existing wall and fill it up with lime hemp concrete. An example of this is visualised in 4.3. [1] It is also possible to use it in a post-and-beam structure by filling up a sliding formwork, and letting it dry till it has enough strength to construct a new layer on top of it.

4.3 Privileges of hempcrete

4.3.1 Sustainability

Hemp concrete is a mixture of hemp, lime and water. The curing of this paste involves the carbonation of hydrated lime. It needs carbon dioxide to form a calcium carbonate to form a solid mixture. The uptake of carbon dioxide makes it extremely attractive to use LHC in the building industry.
As mentioned, LHC is a non-load bearing material and is used in association with a framework, most of the time a wooden framework is applied. It is stated that the use of lime hemp concrete takes more carbon dioxide out of the air than it produces due to manufacturing. Manufacturers state that lime hemp concrete stocks 100 $kgCO_2/m^3$. As it is shown in figure 4.4 , it consumes more CO_2 than it produces [49].

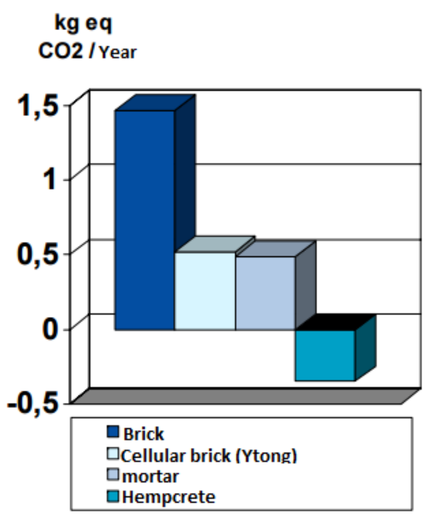

Figure 4.4: CO_2 production of several building materials

A life cycle analysis (LCA) was done by S. Pretot et al. [68] on a sprayed lime hemp concrete wall with a wooden frame structure. They investigated the effect of the thickness of the wall on the negative carbon dioxide character of the application. The outcome of the research is a graph that represents the impact on climate change, expressed as the emission of CO_2. Firstly it is worth to mention that the contribution of the emission during the production of the raw materials was included. The production of lime, which is formed by burning calcium carbonate into calcium oxide, involve an emission of CO_2. The end of life cycle of the wall isnt took into account because it wasnt investigated jet. This is shown in figure 4.5 for a LHC-wall with a thickness of 24 cm.

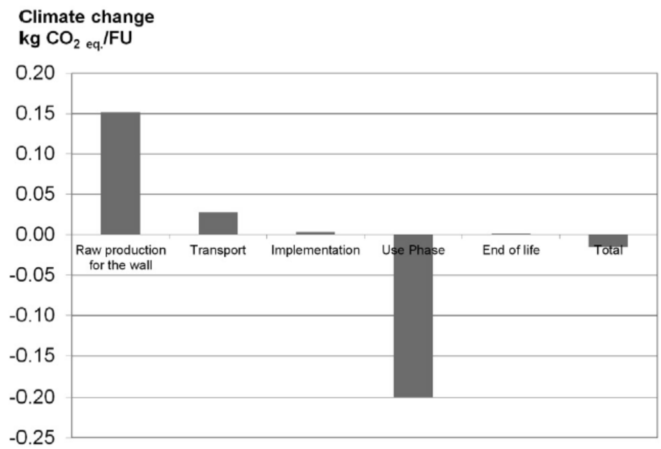

FIGURE 4.5: Impact on the climate changes for the different phases

Another observation they made was that the thickness of the wall has an effect on the climate change indicator. The indicator decreases with wall thickness. For a 20 cm thickness, the indicator is positive because the CO_2 uptake is lower than emissions. The balance becomes zero for a thickness equal to 0.22m [68].

4.3.2 Hygrothermal performances

A lot of research is done on the hygrothermal performance of hempcrete. One of the hygrothermal parameters, that is investigated, is the moisture buffer value (MBV). This value indicates if the material is able to take moisture out of the air when it is exposed to a high relative humidity and releases it when the relative humidity of the air has lowered to its original value. So, it indicates if a material is able to buffer moisture when a room is exposed to a sudden humidity increase. This could be of particular importance in rooms, such as museums or museum storages, where valuable artifacts and goods are stored which are sensitive to humidity shocks. Most of the museums and museum storages are constructed with an ordinary brick, which has a low moisture buffering value. To maintain a constant relative humidity, a high performance ventilation system is required. Because the main targets of current standards for buildings are the reduction of energy demand, moisture buffer value could be a solution. It appears that hempcrete is an excellent moisture buffering material. More details will be discussed in Chapter 6.

4.4 Today's hempcrete applications

4.4.1 City Council of *Villers-le-Bouillet*

In 2011, the city council of Villers-le-Bouillet, a community between Lié ge and Namur, was renovated by the use of hempcrete. It was financed for fifty percent by the government of Wallonia because the aim of the renovation was to fulfill the standards of passive public buildings. One of the requirements, at that time, was a maximal global insulation value of K45. To ensure such a degree of insulation, the building was encapsulated with a wooden frame and a 60 cm thick hempcrete layer, applied with the technique of projection, see figure 4.6 [22]. It appears that the building had a global insulation value of K12. The yearly energy needed for heating was reduced with 90 percent. It appears that the buffering capacity of hempcrete is able to manage daily fluctuations in temperature and humidity due to occupation. An air conditioning system is provided to assist when necessary. Because the structure is made air-tight to fulfill the passive requirements, the CO_2 concentration could increase when the occupation is high. To prevent such high concentrations, CO_2 sensors are installed to boot the air condition system to refresh the air. One of the difficulties appears to be the air-tightness of the construction. The passive standards requires an air change rate of 0.6/h. Several small adaptions were needed to reach this value. [33]

FIGURE 4.6: Encapsulation of city council of Villers-le-Bouillet

4.4.2 Adnams′ brewery distribution warehouse

One of the popular examples of the use of hempcrete is the Adnams distribution warehouse constructed in 2006 in the UK with a footprint of 4500 m^2. It consists of a steel load bearing frame. The facades of the walls are constructed of prefabricated hempcrete blocks, more than ninety thousand, while the inside is filled with lime hemp concrete, see figure 4.7. The wall has a U-value of 0.18 W/m^2K [55]. It appears that the indoor temperature remains naturally between 11 and 13 °C , which is desirable for the storage of thousands of bottles [60].

FIGURE 4.7: Hempcrete blocks filled with lime hemp concrete [81]

Chapter 5

Transition of hempcrete

5.1 The need for a transition to sustainable materials

The myth that's present in the current society is to pursue an economic growth. This thought is an overall vision, even in the highest political areas, for many decades. Since the fifties, the world economy has grown five time as big in Western countries and predictions say that it will evolve with the current economic model in the same way. The evolution let to an increase of the quality and expectancy of life. This is in sharp contrast of what happened in the rest of the world. The economic growth of the Western countries did not let to a worldwide growth.

One of the main parameters that is related to the economic growth is consumption, which in turn is directly related with the use of raw materials. If the economy will follow the same pattern as it did in history, so if it tends to increase, the increase of consumption of raw materials is unavoidable. There is one decisive element which states that this trend will lead to a worldwide failure. This is the biophysical impossibility of an unlimited worldwide economic growth. The permanent increase of consumption has an underestimated impact on the environment. Since the eighties, the environmental impact of the world transcends the capacity of the Earth, the so called overshoot. A simple translation of this problem is that this style of living, so the consumption of materials, asks for more materials than the Earth can produce. As a consequence an ecological debt is created. It is estimated that thecurrent world population consumes the equivalent of 1.6 times planet Earth. This trend will evolve to two planets by 2030 [13] .

The Ecosystem Earth is currently in a no-analogue state. This term refers to the fact that the speed and growth of the spatial scale of the human induced chances is unseen in the history of this planet. So there is no analogue case where the current period can be compared with. Diverse system parameters of the Ecosystem Earth are, as a consequence of the chances caused by human activity, no longer in the range of natural variability. Mankind is currently moving on a Terra Incognita. The continuation of the unsustainable consumption patterns of the worldwide consumption class will have implicit costs and consequences for the rest of the world and the next generations. No matter how seductive the Western growth-oriented development may be, it is fundamentally undemocratic because it can not be generalized into a total growing world. A welfare model that is only possible for a world minority, at the expense of an ecological catastrophic and social unacceptable, can not be a base for a justified society model [8].

As mentioned, the current economic model clashes with basic principles of a long lasting sustainable liveable world, business-as-usual isn't an anymore option. A gradually conversion of the world system is needed. This conversion can happen by external factors which impose it to us or we going to impose it ourselves. External shock factors are for example catastrophic and irreversible climate changes, financial implosions, etc. This would impose a abrupt transition. This would be accompanied with immensely social and ecological damage. When choosing for option two, so when mankind would impose a conversion, mankind would be able to dam the worst climatic consequences, to impose some stability in the world economic system, to obtain a stable and useful employment and a higher subjective level of welfare [12].

To obtain an ecological sustainable socially-justified and economical stable model is not an easy work to fulfil. Thats why mankind needs to begin with the search of solutions that fit in the current model. There are 3 main types of approaches. The first one is *Low hanging fruits*, which are problems that are immediately soluble. These problems are achievable when there is political willingness. An example of this type is the isolation of roofs. The main positive consequences are the reduction of the emission of CO_2 and the creation of jobs. The approach of type 2 deals with tougher problems. This is situated on the level of the current production and consumption patterns. Especially in terms of mobility, food, building and living, travelling and electrical supply. To make this regime sustainable, profound changes transition - are indispensable on the level of culture, political and economic structure. This is a process of medium timescale. One of the main difficulties of this type is the fact that there are powerful potential losers. Problems of type 3 are are soluble on the long run. Type 3 is dealing with meta-transition, a gradually reverse of the world system. This type of transition is needed to counteract with a fall of the quality of life and economic welfare. This type is accompanied with winners and a lot of powerful losers. There are no ready-made models available.

Tim Jackson [9] resumed it as follows. "More than ever there is a urgent need to develop a resilient and sustainable macro-economic model that is no longer based on an uninterrupted growth of consumption. The clearest message of the financial crisis of 2008 is that our model of economic success is fundamental unsound. For the highly developed economies in the Western world, a welfare without growth is no longer a utopic dream, but a financial and ecologic need. "

5.2 Basic principles

5.2.1 Transition path

In general, a transition can be defined as a radically societal changing process from an old to a new balance in sociotechnical regimes, where there are changes on the level of structures, culture and methods. Because in sociotechnical regimes, there is barely room for movement, these social regimes change very slowly. System components are optimized stepwise without hitting any fundamental statements of the system. These changes are called linear changes. In certain moments in history the development is non-linear. At that moment, everything is acceleration fast and with a high velocity. Existing sociotechnical regimes are changed by new regimes, a transition is happening at this stage. These changes will met several hazards on the way to a stable state. It lasts several years before a system is fundamentally changed. All transitions follow the same curve that exists of four stages. The first one is the development phase. In this stage, less visible changes take place, even if many new ideas are developed that break with the common regime. Pioneers are experimenting at the background with new concepts and ideas. At a certain critical point, the tipping point, the system starts to move. Under external pressure and by changes in landscape processes the future of the system is changing fundamentally in this take-off-phase. After this point, there is more social support for the changes and the developments start to amplify themselves. Thereafter, the transition comes in an accelerated phase. At this point, a real systematic turnover happens. Structural changes become very clear through a summation of small sociotechnical, economical, ecological and institutional changes who amplify each other. The last phase is the stabilisation phase. The system settles down in an equilibrium state [12]. This transition path is visualised in figure 5.1. Transition management occurs at a multi-level scale. Complex social

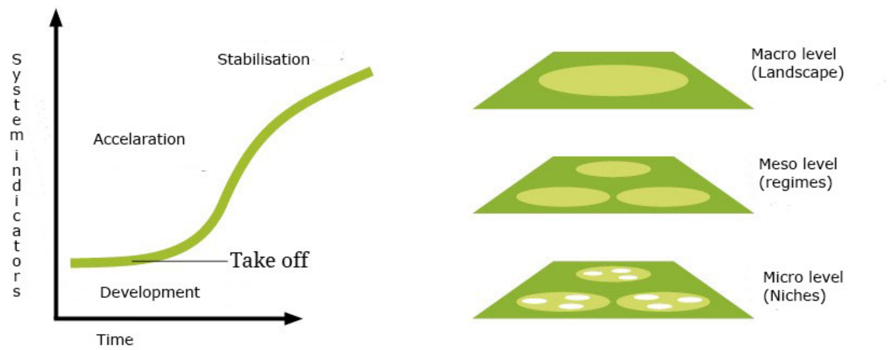

FIGURE 5.1: Curve of Transition and Multi-levels

systems need to be understood and piloted on 3 levels: the landscape level (macro), the sociotechnical level (meso) and the niches level (micro). Transitions need to be seen as the complex interaction between the three levels. The landscape level is the one that refers to the set of meta-factors that can not be controlled on a short period. They can have a stabilizing and destabilizing role in the dominant sociotechnical regimes. The meso-level consists of the dominant habits and systems that are imbedded in the society through a set of rules and institutions, for example the current mobility (which is based on the internal combustion engine, that needs highways). The micro-level is the lowest level. At this level, the pioneers are situated, who are already experimenting and innovating.

5.2.2 Transition management

Transition can not be managed like an ordinary company. It is impossible to set goals and to work them out in the way it happens in companies, an up-down-management would not make it. As mentioned, transition is the interaction of different processes which is hardly to rule. On the other hand, a transition can be pilot, due to change direction and speed of the transition. Transition management is the search on a small base to solutions for complex problems and learn from it. The pilot of transition happens in up-down and in down-up processes. "We cant solve problems by using the same kind of thinking we used when we created them." This is the saying of Albert Einstein. It is the line of thought that is needed for a transition. A transition can be fulfilled only when a system at macro level is destabilized, evolutions at all levels are available and are able to form a better option than before. The new solutions are better than the old methods, who dont satisfied anymore to the current social requirements. Because of the complexity and persistency of structural unsustainable problems, transitions only can succeed if all relevant actors are actively involved in the switch. This is compressed in the term multi-actor. It describes that the reciprocal dependent actors need to cooperate or negotiate to accomplish a certain achievement. This can be translated in the Triangle of change, which is presented in figure 5.2, which was a conclusion of the British Sustainable Development Commission.

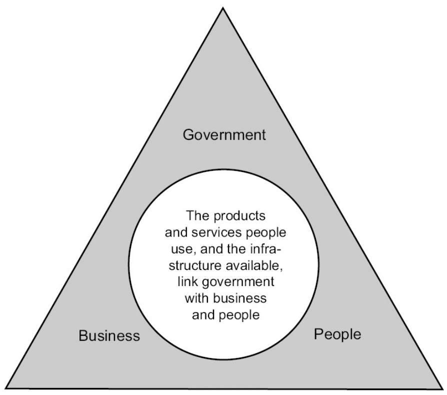

Figure 5.2: Triangle of change

The Triangle of Change refers to the fact that all parts of the triangle need to be involved in the search to a sustainable development. One element of the triangle of change is the government. The government has an important role in this process. It must enable the transition, preferably without creating a top-down an command-and-order procedure. It should act in a way that business and people have the ability to give their input. The most effective moment for the government is the development stage. It is crucial that the government promotes variation, gives opportunities at strategic niches, enables and supports experiments. The pro-activity of the government is of crucial importance. Not only the national governments play an important role, it also concern local or regional governments. Support from the political side is so important that a project depends of it to succeed or not. After the main perspectives are set at short, medium and long-term time scale, a transition path can be set. A transition path is the translation of the transition visions into a real time scheme. In this way it is possible to achieve the desired goals. At certain moments, there are set visions. The proportion between the visions is given and the resting barriers are systematically eliminated. Because of the big uncertainties, it is important to maintain several options, so adjustments can be made, as long as they fit in the main concept vision. The principle of a transition path is illustrated in Figure 5.3 [**?**].

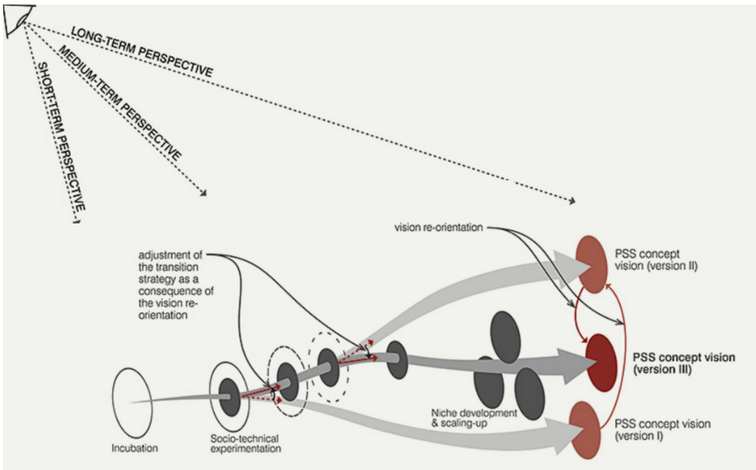

FIGURE 5.3: Strategy transition path

After the transition paths are drown, a vision is created of the possible areas where the transition can take place. Even at this point uncertainties remain. Several landscape factors, like climate changes, can have a great, still unknown, influence on the evolution of the concept vision during a transition. The next step in the transition management process consists of the definition and set up of transition experiments. These are set up to enforce or to replace certain regimes on the niches level. They need to contribute to the renewability of on the systems level. Because transition experiments have a high risk, the chance to succeed is relatively small. A successful experiment is an experiment which results in knowledge and where changes are the input for other areas. To increase the chance to success, it is important to set up educational goals and to involve the people who need to work with the results in an early stage. It is also important to follow up the changes, evaluate them and make changes if necessary. So the basic principles of transition management are: influence, adapt and correct [40].

5.2.3 Defra-model

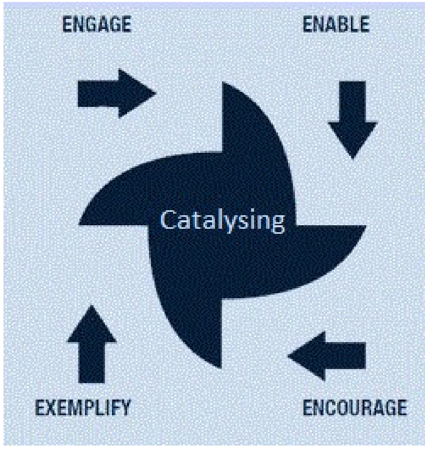

Figure 5.4: Defra 4 E's model

An effective strategy that encourages a behavioural change must introduce a mix of complementary instruments. The Defra-model expresses this with a windmill that is driven by the 4 Es: Enable, Encourage, Exemplify and Engage [69], see figure 5.4. Only the government got the recourses to simultaneously to deploy all Es. Nevertheless, all other actors in the society need to fulfill a role. The first E, enable, stands for the fact that the transition to sustainable behaviour and smart consumption above all needs to be enabled, access is determining. It includes to ensure an easy access to viable alternatives, provide facilities. The government to take care of the fact that not only the lone survivors will be motivated to try but that it is attractive for everybody to do. Sustainable alternatives just need to become simple and straightforward. The government has an important role to fulfill regarding choice editing. It means that the government imposes strict quality standards to producers and prevent that consumers are misled to inappropriate decisions. Which leads that only sustainable decisions are available. The government needs to set up a roadmap for the use of sustainable materials which indicates the sustainable alternatives [29].
The second E, encourage, takes into account that sustainable choices need to be encouraged on different ways, by providing incentives and disincentives: giving the right signals. The incentives have the aim to encourage and disincentives aim to ensure your target audience responds. At this stage, it is important to provide feedback. This could be done partly due to price signals and ask for a reversion of the current price forming. At this moment sustainable alternatives arent encouraged enough and are most of the time more expensive than the old fashioned methods.
The third E, exemplify, means that the government needs to lead as a prime example. Practice what you preach. The government is the biggest consumer in an economy. If they choose for sustainable green energy, it will be a stimulation for these new sectors in the economy.
The last E is engage. It states that it is important to get people involved in changing processes. The behaviour of people is meanly dominated by the ruling social norms. It is more effective to use insights to mobilise population groups than individuals. So the use of networks is important. Working with trusted intermediaries is another advantage. There are two forms of engaging: pull- and push-factors. Its useful to invest in pull-factors because it makes it more attractive, it plays with the emotions to accentuate the sustainable alternatives. Push-factors concentrate on the fact why change is needed, it emphasizes why mankind needs to go away from the unsustainable lifestyle.

5.3 Transition Path of Hempcrete

The current state of the transition to hempcrete can be situated in the development stage and nearly ready to take off. Ten years ago, the presence of the material on the building market was nearly invisible. Only individuals who were committed to nature were building with hempcrete. They were denoted as *fools* by outsiders. At that moment nearly no research was done on performances of the material. It was nearly unknown. Today, more and more individuals and contractors are building with hempcrete. The choice is often conscious because they want to contribute to a sustainable development due the rise in awareness that a global change is necessary. These people can be indicated as pioneers. They have the important role as representatives of sustainable materials, even if this wasnt their intention. Their construction and their experiences with hempcrete can be the key evidence that helps potential users to chose for such a sustainable building technique.
Those yet unconvinced people can be subdivided in two groups: the sceptics and the conservatives. The sceptics are those people who are aware of the need for transition, but till now they hadnt any urge to switch-over because they werent convinced of the reliability of sustainable materials or didnt simply known the existence of them. The conservatives have often no direct intentions to use sustainable materials. The persuasion rests mostly on multiple factors like the astonishment of the building, the workability of the material, the construction time and so on. The contribution of hempcrete to the transition to a sustainable development doesnt count for this group, some people even flinch by this. Not necessary that they have any objections but that they are, maybe unconsciously, influenced by the general view of sustainable materials is still too conservative. This latest may be one of the hardest problems to deal with in the transition to a sustainable development. One of thoughts that arise when presenting a new material is why would people change their habits and choices for this unknown material? Changing a habit is definitely not a short-time issue but requires a repeated, beaten persevere force by players in each level. The faith that costumers have in conservative materials, just because they are used to them, is used for marketing of the those materials. This is a privilege that hempcrete simply doesnt have, it should because it was already used in the past as building material. The relation of hempcrete to *Cannabis Sativa* is one of the reasons why it is less used then other sustainable materials. In the past, many leaflets and brochures contained an image of a hemp leaf, which is the same as the one of Cannabis Sativa, and were designed with mainly green colours. Today, more and more sellers and producers of the product are aware of this problem, still more work can be done to hide this relation.
A good example how to present hempcrete in the media is an article, *Renoveren met kalkhennep* , which was included in an appendix ”Duurzaam wonen” of a newspaper[85]. It described the renovation of a house with hempcrete. The owners did it by themselves and they told about their experiences. Beside of that, the hygrothermal advantage were mentioned in order to reach more people. As mentioned before, one of the privileges of hempcrete is that is a building material which can be moulded on side. So people themselves are able to do it. To be sure everything

is executed well, there are workshops on-side where they can practice and get instructions of professionals. The reliance with the material, that will be generalized during a workshop, is one of the main goals of these events. The participants will be indirectly encouraged to convince there environment to use hempcrete. Beside of the individuals, some contractors participate to polish their techniques and to make contacts with other contractors or individuals. These events happen at small scale but are an important factor in this state of transition. Such events can be organized by constructors, producers or even a union of constructors and producers. The main goal of the establishment of such a union is to assemble knowledge and experience. Another privilege for the attractors is the fact that they can compete a project together whereas individuals wouldnt have the capacity to do so.
In every herd, there are leaders and followers. In the hempcrete market, the leaders are a step-a-head. The leaders are dealing more properly with the stated problems. They have more experience which they use in their selling techniques. This is why they more professional appearance and convincing. The role of these professionals in the transition of hempcrete is important. They are able to present themselves on the market as true competitors other contractors and producers. There are several expositions, like Batibouw, where hempcrete is already represented by a producer. In the current division of the building market, hempcrete belongs to the sustainable materials, even it could also be part of building blocks or prefabricated panels hence the application. In this stadium of the transition, it would be better to be mixed between the other materials, just for lowering the threshold for less sustainable-minded people. Another privilege that the leaders have compared with the small contractors and producers is that they can invest more in research and development. This is why they will be constantly be ahead of the followers. But, like in every transition, this knowledge will be spread in time so even the followers can make use of the research that is done.
Since ten years ago, research has been done all over the world on the properties of hempcrete. Several researches have done parallel work. Still a lot of research can be done. This could be used as a prove of the hygrothermal performances that is stated by several small organisations. In order to use hempcrete in public buildings, a fire attestation is mandatory. For a wall construction, it is necessary to analyse the fire behaviour in several load conditions. For many contractors this is a threshold to compete a public tender because they need to finance this cost by themselves. The awareness starts to penetrate in the minds of more and more policymakers. Different organisations are founded with the intention to promote usage of sustainable building materials. It decreases the gap between potential customers and producers. In the passe, the thought ruled within the group of sustainable material producers that they were fighting a losing battle. These support actions could be helpfull to wash away that negative thought. Nevertheless, the durable policies of the government are lost effort without applying by themselves. The presence of hempcrete, and even durable building materials, in the public building market is nearly non-existent. When this large market would be stimulated and effectively use sustainable materials, in particular hempcrete, an acceleration of demand would be the consequence. It would be a take-off for transition of hempcrete. To disturb the current market and

flip to a new balanced sustainable material market, a lot of courage, effort and perseverance is needed from each branch of the government.

5.4 Transition management

5.4.1 Interreg Europe

At the level of Europe, Interreg Europe tries to bring all three corners of the Triangle of Change, see figure 5.2, together by creating an environment and opportunities for sharing solutions. They aim to ensure that government investments, innovation and implementation efforts lead to integrated and sustainable impact for people and place. By bringing ideas and experiences together, solutions can be generated. They assist public authorities, managing authorities, agencies, research institutes, thematic and non-profit organisations. The main goal of Interreg Europe is to create an added value in the development of European economy and environment with the thought "Do more with less". To do this they want to support by investing in research, innovating projects, Low-carbon economy, environment and resource efficiency. Interreg Europe relies on cooperation, collaboration and community engagement. These projects are financed by the European Regional Development Fund (ERDF). When partnerships are made between organisations from different countries in Europe, Interreg Europe is willing to co-finance up to 85% of project activities. As a partnership wants to be in the running for interregional cooperation projects, a proof of common interest is needed. They must produce an action plan, set up by a stakeholders group and participate in the Interreg Europe Policy Learning Platforms. Afterwards, a monitoring of the progress of the implementation is required in order to proof the effective application of the proposed goals. Such a cooperation has a timespan of three to five years. The interreg Europe Policy Learning Platforms are organised for organisations in order to optimize and improve their policies which they imply in the supported Interreg regions. Beside of the privilege to get a financing up to 85%, the organisations of the partnership will get many benefits as return. Due to participating, their workspace and network extend, even in foreign countries. One of the main advantages of an Interreg-project is that it actually can work from the bottom-up. The results of successful projects and their positive impact can be used as a prove why a change in national and international policies are required. This property can make Interreg-project very efficient.

5.4.2 Grow2build

An example of such an Interreg-project is Grow2build, which was active from 2012 till 2015 in nordwest Europe. It was a cooperation between eleven organisations from Belgium, France, the UK, Germany and the Netherlands, which aimed to bring the materials back on the market and to improve these building materials. The partnership consisted of members from academics as well as industrialists. [44] [6]. To create Development of sustainable and future oriented product chains of hemp and flax based building materials in Nord West Europe, an action plan was composed.

The targets were economy, creating an open transnational network with the focus on sharing knowledge on the possibilities and requirements of every link within the chain. Whereas calling attention to local and regional policy makers to initiate a favourable context for the development of a bio-based economy for hemp and flax based building materials, taking into account the specific bottlenecks and challenges of the product chains and the market development. In order to prove why the usage of hemp and flax in the current economy could make a change, research is done on the quality of hemp and flax products, related to the demand of the manufacturers of building materials. Relevant cultivation parameters are analysed to optimize the cultivation strategies. As mentioned before the hemp stem consists of fibres and shives, to optimize the performance of existing decortication methods several studies were done. By creating a database for innovating knowledge and technologies and expertise for mass production of hemp and flax, a larger public was obtained to reach, even after the end date of the Interreg-project [43].
To promote the end use of hemp and flax based building materials, Grow2Build disposed knowledge and information on hemp and flax building materials to costumers. This action involved the creation of a mobile demonstration tool, see Figure 5.5 [19]. It aimed to raise awareness for natural fibre based building material and was demonstrated at local events, building fairs, etc. all over the North West European region. Another way to promote the end use was increasing the confidence in and the use of existing labels for eco-building materials.

Figure 5.5: Modile demonstration tool Grow2Build

To gain confidence of the use of hemp and flax building materials and techniques for consumers, educational workshops were organized. Different groups, from individuals to high schools, participated and were organised onside and in demonstration rooms.

5.5 Hemp for heritage

Heritage storages belong to the government, so it could be thought that a transition to sustainable materials is evident. Even there, it isn′t an easy case. The need for a widespread support for sustainability is crucial. To engage such support, the government has founded Pulse. Pulse is a transition network for culture and heritage. All members of the network are active in that sector and want to contribute to a sustainable society. When a member starts with a sustainable project or an idea, Pulse helps to spread that knowledge within its network. All information of the

specific project or idea will be communicated online where all members get access to it easily. Frequently, meetings are organized where subjects are highlighted and members can share their knowledge and start a dialog. Bringing knowledge together could trigger new working points and even accelerate the transition of a subject. One of the advantages of the existence of such a network is direct communication with the government. They are able to engage transition in both ways, down-up and up-down.
An other organisation that supports sustainability for cultural heritage is Faro. It is a Flemish fund for cultural heritage. The main targets are increasing the social support for cultural heritage and the development of the cultural industries in Flanders. By sharing knowledge and advice, they want to give support to future projects. Another aim is to connect cultural heritage with other branches of governmental institutions like schools, tourism, science and so on. To spread knowledge, they organize public-oriented events and exemplify applications. An example of such an event was ′Goed begonnen is half gewonnen. Duurzaam (ver)bouwen van museum- en depotinfrastructuur′. Several subjects where highlighted in here, like the implementation of sustainability in a statement of requirement and specific material usage. One of the subjects was the use of hempcrete in the upcoming project *Depot Rato* by Bart Stroobants, a conservator of the Urban Musea Mechelen. Such presentations are important for the exemplifying of the applicability of hempcrete as a sustainable building material for heritage.

5.6 *Depot Rato*: handling transition

A case in which the government can be a pioneer in the usage of hempcrete is definitely the project *Depot Rato*. Despite a heritage storage is often seen as a bunker far from civilisation, the major privilege of this field case is its public character. It will be located in the center of a new residential area. On top of that, it could be a perfect illustration for other future museums and heritage stores. This was the driving force that inspired the design team of Depot Rato.
That the design wasn′t like walking on a smooth path, several hazards needed to be overcome. This was the most noticeable in the construction of the Program of Requirements, as mentioned before. The construction of a Program of Requirements is often based on the experiences of previous similar projects and the specific requirements belonging to a project. The establishment of such a document is in cooperation with all partners of the design team, where every partner has his responsibility on the content of the document. This responsibility includes informal items like the recording of the delivery date of a work post that needs to be accomplished by an exterior contractor. But also the composition of the technical requirements is a crucial element on this moment in the design. The draw up of the different components relies on the liability of the architects, engineers and founders, which want to give support to subjects of discussion. Especially when new building materials are proposed. The designers, both architects and engineers, have often no experiences with the application of the proposed material. This why they often

implement, sometimes large, additional safety factors in order to obtain a reliable design and to protect themselves from possible unexpected failures for which they can be responsible, relying on the principle of 10 year liability.
An example is the design of the air conditioning system in of the Hempcrete Museum Store. After several years, it appeared that the requirements were three times less then it was proposed for the design. Again, this was done because there was no experiences with hempcrete for cases with such specific climate requirements, so none can be blamed. This was quoted because the same phenomenon occurs in the early stage of the design of *Depot Rato*. Due to a lack of experiences, the air conditioning system was designed as the construction would be built with conventional building materials. Which resulted in a system with elements for cooling, heating, drying and humidification. With the experience of the Hempcrete Museum Store kept in mind, the design was adapted to a system which includes only a dehumidifier and a heating element.
The storage of heritage has several requirements that needs to be implemented in the design. One of them is the fire behaviour of the store. The government prescribes several requirements for such public constructions, one of themp is a fire resistance of EI60 of the wall construction. Within the process of the application of a project, the fire department and the local policies must give their approval, based on the design and fire resistance certifications. The use of hempcrete as building material to erect walls of that height in public projects is hardly unknown, it is difficult to prove the decision-makers the reliability of the material. When contractors want to compete a tender, they must proof that their wall structure fulfills the requirements of fire and safety. So the design of the construction must be such that there are contractors who can send an invitation to tender. In the case of hempcrete as a new building material, this is not evident because the amount of contracts that have such an fire attestation is very low.
A link can be made with the Defra-model. Previous adaptions of the design were only possible due to information of the experiences of the Hempcrete Museum Store as its prime example. By sharing the difficulties and experiences that they have with the application of hemcrete, the design team could use this information to form the fundamentals of their design. The positive outcome of such, as it is for others, an example has an encouraging effect. This is way pioneers, and in the way they handle with their information and communication, are so important to accelerate, or even to start a transition. As the Hempcrete Museum Store was a prime example for the design of Depot Rato, Depot Rato wants to be a prime example itself to encourage future projects.
An example of their dedication is the initiation that they took to investigated the shear tension behaviour of the several fabrication methods. This was necessary to compare the applicability of unattested fabrication methods with previous results from fire attestations from the United Kingdom. The reluctance from the concerned institutions was a high.
The persistence in the applicability of hempcrete by the design team is noticeable in many ways. As mentioned lot of effort and research has been done to accomplish a Program of Requirements in order to reach as many competitors as possible. But the

work goes on. The behaviour of and the experiences with the hempcrete store will be analysed in the future. The indoor climate will be recorded whereas the condition within the wall, in particular fluctuations of temperature and relative humidity. So beside an heritage store it will function as a full-scale test building. An example with such stringent climate conditions has a lot of opportunities. The behaviour of the constrution can be compared with the one of the Hempcrete Museum Store in Wroughton. The data can be to lower the hazards for implementing the hygrothermal properties of hempcrete in the calculations of the needed air condition treatment. There are several compartments with a different degree of heritage occupation so the effect of the heritage itself on the indoor climate can be investigated. Dependent on the manufacturing method of the wall, the drying can be analysed.
This project could be a state-of-the-art in an attempt to reach a sustainable environment. The way of dealing with this project, trail and error, will lead to fundamental information for future projects, even if the results were not as expected.

5.7 Small windmills can be powerfull

People have the attitude to wait and see what other people do and what is the profit of those actions. A nice example of a transition to sustainability is the rise of wind farms. First a lonely windmill appeared at the horizon. Now, more and more wind farms are constructed because the positive effects emerge. Those effects are not only sustainability but also, and often mainly, the fruits of such an investment. Authorities who were not yet convinced by the research of wind farms, but after reading about the positive outcome, invested in this green energy.
This could also be translated to the case of hempcrete. When more and more people are dealing with the material, more and more people could get convinced of the applicability of the material. The establishment of hempcrete working groups, organisations and so on could be the power that is needed to enhance transition.
An example of a hempcrete windmill is HempEcoSystems. HempEcoSystems is a Swizz company which promote the use of hempcrete by selling hempcrete. The difference between HempEcoSystems and other conventional building material distributors is the fact that HempEcosystems tries to have holdings in as many as possible countries. Jorgen Hempel tries to convince people by making aware the need for a transition to sustainable material and that hempcrete is one of the solutions. His aim is to reach as many as possible people by let them come in contact with the material at different ways. An example was the presence of hempcrete within an art gallery. The subject of the meeting was proportions of earth and nature. People who are interested in art are often people who are aware of the need for guarding the treasures of nature. One of the cites of Jorgen Hempel was: ”The aim is not to build a barrier between humans and nature, but in fact constructing a healthy breading link between humans and nature” [54].

Chapter 6

Properties of Hempcrete

6.1 Composition of Hempcrete

6.1.1 Proportions

Hemp concrete is a mixture of lime, hemp and water. The ratios are dependent of the manufacturing method. Several proportions [vol %], found in literature, are given in table 6.1.1.

Table 6.1: Proportions of lime mix, hemp and water volume

	Moulded [30]	Moulded [26]	Sprayed [34]
Lime mix	15.6	29	21.15
Hemp	62.5	47	58.63
Water	21.9	24	20.22

The hemp:water:binder ratio is also dependent of the diverse applications. It will differ for wall formation, roof insulation, insulating plasters and renders. Examples are given in mass % in table 6.1.1

Table 6.2: Proportions of lime mix, hemp and water volume

	Roof	Wall		floor		Render
	[15]	[23]	[15]	[23]	[15]	[15]
Lime mix	23.6	35 - 45	31.4	47	30.4	34.1
Hemp	28.0	17 - 23	18.6	20	14.4	9.1
Water	48.4	35 - 48	50	33	55.2	45.6

Studies revealed that a higher lime ratio in the mixture results in a higher thermal conductivity and higher specific heat capacity. A larger hemp ratio will give a lower thermal conductivity and heat capacity of the mixture. A higher lime ratio also implements a higher moisture transfer trough the material, especially at higher relative humidity [30] [73].

6.1.2 lime

To find an appropriate binder, several suggestions were tried out by practitioners. Cement and other hydraulic binders were investigated but none of them looked ideal. The major problem observed is that only few centimetres react properly on the surface of the drying material, the rest of its thickness powders. Mould growth was also encounter when introducing plaster material, like heated gypsum in binder mixture. It was found that rich lime is the most appropriate binder for the fabrication of hempcrete. There are several advantages that can be quoted: its thermal conductivity is lower than classical cement; its mechanical flexibility allows slight distortion without cracking and good toughness against shocks; its high pH protects hemp chips for a long time from mould growth or bacterial attack; its hardening is quite slow but its relatively high permeability to vapour allows thorough drying of the hemp chips; and its chemical reaction needs dissolved carbon dioxide which is gradually given back through water exchange with hemp chips. Chemical transformation of rich lime is quite slow compared to what is expected from nowadays building processes. This is why hydraulic of puzzolanic binders are added [38]. It appears that the use of puzzolans improves the workability of the lime mixtures, reduces the water requirement and improves the reaction of the binder. Lime reacts with silicates and aluminates in puzzolans in the presence of water to produces calcium silicate hydrate(CSH), in a process better known as hydraulic set. Puzzolans improve the hydraulic set of lime [47].
De Bruijn et al. [30] used 75 % slaked lime, 15 % natural hydraulic lime and 10% fly ash. These are also the proportions of the lime Tradical [59] PF 70, of the trade mark Tradical, where the proportions are given by 75% slaked lime, 15% hydraulic lime and 10% puzzolanic lime. Tradical PF 70 has a thermal conductivity of 0.189 W/mK, and is packed in bags of 22kg. As finishing layer, Tradical PF80 M could be used. It is a lime based of 35% mineral fillers and 65% Tradical PF80. The mineral fillers is composed of calcium carbonate. Tradical PF80 is a mixture of 85% slaked lime and 15% hydraulic lime. Another frequently used lime is SUPERCALCO 97 [21], which consist of 97.1% slaked lime and a hydrated mixture of CO_2, MgO, SO_3 and water.

6.1.3 Hemp

Hemp is a historical product in nordwest Europe. Till the 19th century, it was often used for the production of rope and textile. Due to the import of cheaper fibers, like cotton and synthetic materials in the 20th century, the demand for hemp vanished. And the cultivation of hemp was forbidden due to the spread and upswing of Cannabis Sativa. Nowadays, a revival of the use of hemp is visible. Due to the relation with the Cannabis sativa, the government has strict laws for the cultivation of hemp. Only those species hemp with a THC-content lower then 0,2 % are allowed.

[45]
Hemp is a fast growing vegetable, after a growth time of 120 days, they reach a, height of 1,5 to 4 meters. The stem consists of a woody core enrobed with a fibrous shell. Due to a special technique, the core and fibers can be separated. The product proportions are given in table 6.1.3. [7]

FIGURE 6.1: Indication of the hemp stem and fibers (left) [?] and hemp shivs (right)[?]

TABLE 6.3: Proportions of the crop

Part of straw	Proportions of crop
Shiv (stem core)	60 %
Bast fibres (strong fibers)	30 %
Fines (small pieces of bast fibre)	7 %
Dust	3 %

The fibers are mainly manufactured for insulation. Hemp insulation is damp open and bear up to an optimal living climate. It is available in bulk, in rolls and in panels for floor insulation. The woody core is cut into small pieces, better known as shivs. These are mainly used for the manufacturing of lime hemp concrete. They have the ability to absorption three to four times their one mass.
The applications of hemp are numerous. Henry Ford constructed in 1941 a car that was constructed with agriculture waste, hemp was a part of it. Today, hemp is still used in the car industry, mainly in pressed products. Further, parts of hemp are used in food, cosmetics, textile, fuels and so on [76].
The hemp shivs have a volume by mass varying between 100 and 130 kg/m^3. The shivs, used for construction applications, consists of particles with a size between 5 mm and 40 mm. A typical grading curve is given in figure 6.2.

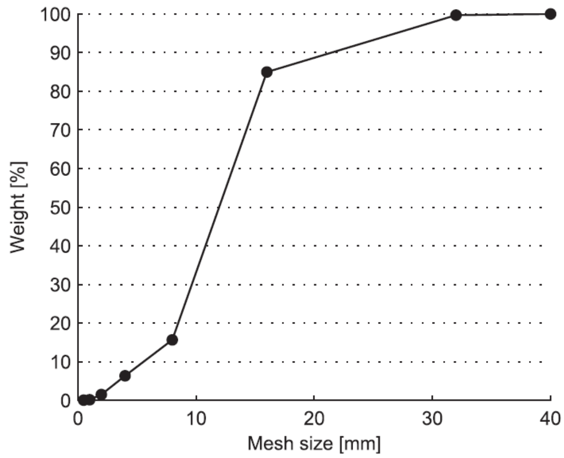

Figure 6.2: Grading curve of hemp shiv used for construction applications [73]

6.2 Curing

6.2.1 Formation

The curing of hempcrete occurs due to hydration and carbonation. An important role in the binding is played by water. Water can quickly be absorbed by the hemp shivs during mixing. The hydrophilic behaviour of the hemp shivs makes it tough to control the amount of water that is necessary for a correct binding during manufacturing and setting. The time sequence of adding water, hemp and lime together and the time that it takes, will influence the amount of water that is needed for a proper binding.
During settlement and hardening, water is necessary to ensure the hydration reaction. The chemical reactions occurring during curing are dependent of the chosen lime: hydrated lime or quicklime.
Dicalcium silicate (C_2S) and tricalcium silicate (C_3S), which are both contained in hydrated lime, react with water to form calcium silicate hydrate ($C-S-H$) and calcium hydroxide ($Ca(OH)_2$) according to:

$$2(2(CaO) \cdot SiO_2) + 4H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + Ca(OH)_2 \qquad (6.1)$$

The speed of the reaction kinetics of C_2S and C_3S are different. The reaction kinetics of C_3S happens in a range of a few hours, while the range for C_2S is a few days. The reaction kinetics of C_2S is the dominating phase in lime. The hydration reaction is enhanced under moisture conditions.
In the case of quicklime, calcium oxide will react water to form calcium hydroxide, according to

$$CaO + H_2O \rightarrow Ca(OH)_2 \qquad (6.2)$$

During hydration, a micro-porosity is created in the lime-binder and a strength within the material is developed.

The carbonation reaction is a much slower process compared with hydration and it occurs over several years. During this process, calcium hydroxide will react with carbon dioxide CO_2 to form calcium carbonate $CaCO_3$, according to

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{6.3}$$

Carbonation is a process that happens more easily under dry conditions or when exposed to high levels of carbon dioxide since both diffusion and dissolution of carbon dioxide is possible in the pore system. During this process, the mechanical properties are improved and pore size, water absorption surface and transport characteristics are reduced [56].
The presence of water within the composition is influenced by the amount of calcium hydroxide that is formed, but also by several transport phenomena. Water can migrate from the centre to the surface through diffusion and evaporated at the surface. This phenomena happens faster then the carbonation reaction and in competition with the hydration reaction.
When the curing conditions are too dry, carbonation occurs only in the lime surface whereas the center of the material has no consistency. The underlining reason for this phenomena is that, due to the lack of water, carbonation reaction prevails the hydration and will attack the hydrated phase. This effect is better known as the skin effect [23].

6.2.2 Drying

The way in which the hempcrete is fabricated influences the time that is needed to dry. Like already is cited, there are 3 different ways to fabric a hemp concrete wall. The difference between these methods is the amount of water that is added and the strength of tightening during implementation. It has shown that the strength during implementation has a great influence. The stronger the mixture was pressed, the slower it dried. The mixture dried also slower when more water is added, which is straightforward. A fast and violent mixing did not had a great influence [36].
The curing time of hempcrete, which is defined by reaching a constant density after composition, is dependent of the initial hemp shiv water content and the total content. It appears that the use of dry shivs results in lower curing times. The curing time for normal water contents, see table 6.1.1 and 6.1.1, varies between 60 and 100 days. During the curing of several samples of sprayed and moulded hempcrete, the mass was weighted weekly, the weight loss ratios are given in figure 6.3. In the case of the sprayed hempcrete sample, the left bar graph, less water was used and it was less pressed compared with the moulded hempcrete sample.
The exponential decrease of weight can be explained by the vapour transfer within the pores of the material. First free water forms a saturating or non-saturating continuous liquid phase and can be transported to the surface and evaporates until the critical water content is reached. After this point, liquid water exists in disconnected separate islands and water can only be removed via a slow vapour transport until the residual water content is reached [10].

Figure 6.3: Comparision of weight loss ratios over time for sprayed (left) and moulded (right) hempcrete

6.3 Mechanical behaviour

The use of hempcrete in the building industry is always in combination with an external load bearing construction. In order to avoid thermal bridges, the use of a wooden structure is recommended. The reason for this is the non-loadbearing property of hempcrete. It was found by several researches [34] that the compressive strength lies in a range of 0.180 MPa and 0.800 MPa for hemp concrete blocks with a density between 290 kg/m^3 and 480 kg/m^3. The amount of shivs in the mixture showed to have an inversely related influence on the compressive strength [15], [18], and [79]. It appears that the curing conditions strongly affect the mechanical behaviour of hemcrete. A high relative humidity is not suitable for the binder setting. This is well known for the air setting of a binder. The diffusion of carbon dioxide from the air through the pores of a lime mortar is hindered when the internal relative humidity is very high. A low relative humidity slows down very sharply the setting of hydraulic lime-based binders. A low and high relative humidity leads to extremely low compressive strengths, lower than 0.11 MPa. A maximal compressive strength can be reached after curing with 20 °C and 50 % RH. [15]. The compaction during fabrication significantly improves the compressive strength but does not change its stiffness [66].

6.4 Heat and moisture transport

As mentioned, the aim is to investigate the behaviour of a hempcrete wall. Due to the wall configuration, in particular the height, the heat and moisture transport are assumed to be one dimensional.

6.4.1 Heat transfer

Due the one dimensional assumption, the heat flow through a material can be described as

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right) \tag{6.4}$$

With ρ the density $[kg/m^3]$, c the heat capacity $[J/(kgK)]$, T the temperature $[K]$, λ the thermal conductivity $[W/(mK)]$, x the position $[m]$ within the material and t the time $[s]$.
The thermal conductivity is related to density of a material. The density of hempcrete vary for different manufacturing methods so does the thermal conductivity. The density of hempcrete is also related to the composition of hempcrete. This was noticed in several researches. [34] [18] [80]. The shiv/mixture ratio has an influence on the density, which is related to the thermal conductivity, and which has an nonlinear relation. An increase in shivs content leaded to an decrease in thermal conductivity and the slope decreased for increasing shivs content [18]. It appears that the binder type did not had an significant influence on the thermal conductivity whereas the binder hydraulicity reduces conductivity and increases heat capacity [80].
It was also noticed that thermal conductivity λ varied linearly related to relative humidity. The relation is given by [24]

$$\lambda = 0.1058 + 0.77 \cdot \theta \tag{6.5}$$

With θ [-] the relative humidity. This equation is derived for a hemp concrete with a density of 440 kg/m^3. In table , examples of researches are given.

	$\rho[kg/m^3]$	$\lambda[W/(mK)]$	c [J/(kgK)]
[25]	450	0.1	1000
[77]	413	0.1	1000
[17]	420	$0.1231 + 0.0465\ \varphi$	1560
[65]	325 (dry)	0.072	1600

TABLE 6.4: Fitting parameters of diffusion resistance found in literature

6.4.2 Moisture transport

Relative humidity

The hygrothermal behaviour of the wall is related to the vapour pressure, which in turn is related to the relative humidity RH [%], or φ [$-$] and the temperature T [K]. The relations relative humidity is given by:

$$RH = \frac{\rho}{\rho_{sat}} \cdot 100 \ , \ \varphi = \frac{\rho}{\rho_{sat}} \tag{6.6}$$

With ρ [kg/m^3] the vapour concentration and ρ_{sat} [kg/m^3] the saturation vapour concentration. These formulas can be rewritten in the form of vapour pressures due to the ideal gas law.

$$\rho_v = \frac{p_v}{R \cdot T} \tag{6.7}$$

This formula consists of p_v the vapour pressure [Pa], R the gasconstant [461.89 J/kgK] and T the temperature [K]. So the relative humidity can also be expressed as:

$$\varphi = \frac{p_v}{p_{v,sat}} \tag{6.8}$$

In the previous expression, the saturation pressure can be approached with:

$$p_{v,sat} = 288.68 \cdot (1.098 + \frac{\theta}{100})^{8.02} \tag{6.9}$$

Adsorption, desorption and the hysteresis effect

In function of the relative humidity, a material contains an certain amount of humidity. That amount can be described with the humidity concentration w [kg/m^3] or the water content u [kg/kg]:

$$w = \frac{m}{V} \tag{6.10}$$

$$u = \frac{m - m_0}{m_0} \tag{6.11}$$

With m the mass [kg], m_0 the mass of the dry material [kg] and V the volume of the dry material [m^3].
The equilibrium humidity concentration for a material is related to the relative humidity. These relations are often expressed by sorption-isotherms. Adsorption and desorption curves can differ due to an hysteresis effect, so the describing functions can differ. Moisture hysteresis can be explained as the phenomenon that a material can experience a different degree of moisture content at a certain relative humidity depending on its loading history. The phenomenon is the most noticeable in the range of high relive humidities. It is commonly explained as capillary condensation hysteresis, the contact angle hysteresis and the ink-bottle effect.
An example of a condition of exposure to an cyclic moisture load is the contact of a material like concrete with to environmental conditions. The material undergoes

a large number of sorption cycles. As hempcrete is an hygroscopic material, a significant hysteresis effect can be recognized in the sorption isotherm. Sorption and desorption curves for different hempcrete manufacturing methods are given in figure 6.4.

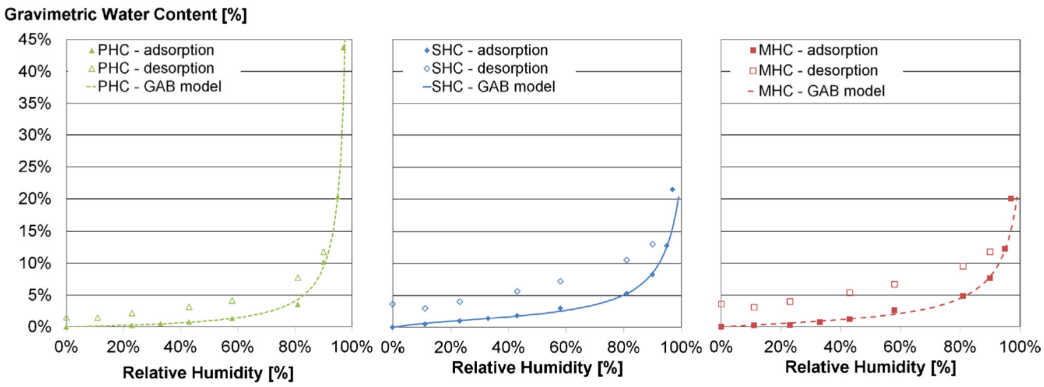

FIGURE 6.4: Sorption isotherms for hempcrete manufactured by three techniques [27]

The absorption and desorption branches are nearly parallel over a wide range of relative humidity for hemp concrete, but when high relative humidity the effect of hysteresis is clearly visible. It can be observed that the hysteresis of precasted hempcrete (PHC) is less than the one of sprayed (SHC) and moulded (MHC) hempcrete. This phenomenon can be explained by the different hemp/binder ratio. It was found that the hysteresis of pure hemp shiv is less than the one of lime hemp concrete. So a smaller hemp/binder ratio will lead to a larger hysteresis. T. collinart et al. [42] observed analogue curves for the absorption and desorption isotherms for sprayed hemp concrete. In the literature, several approaches for those sorption curves are used. The most frequent are given below.
One of the models that has been developed to describe the sorption curve is the GAB-model. This is a model developed by Guggenheim, Anderson and De Boer. [27] It relates the water content to the specific surface area of the material for multilayer sorption. It covers a wide range of relative humidity (0.05 to 0.8-0.9) and is convenient to fit experimental adsorption data all over the RH range. The model is translated in the following formula:

$$\frac{w}{w_m} = \frac{C_G \cdot k \cdot \varphi}{(1 - k \cdot \varphi) \cdot (1 - k \cdot \varphi + C_G \cdot \varphi)} \tag{6.12}$$

With w the water content $[kg/kg]$, w_m the mono-molecular water content $[kg/kg]$, C_G and k fitting parameters of the GAB model and φ the relative humidity $[-]$. Values of these fitting parameters, found in literature, are given in table 6.4.2. SHC_{ad} resp. SHC_{des} represents the values of sprayed hempcrete in ad- resp. desorption.

Table 6.5: Fitting parameters of GAB′s-moisture content model

Preparating Method	PHC [27]	SHC [27]	MHC [27]	SHC_{ad}[57]	SHC_{des}[57]
w_m	0.0104	0.0130	0.0124	0.02	0.06
C_G	0.8586	6.5615	2.1928	7	60
k	1.0021	0.9463	0.9499	0.86	0.68

Another way to describe the adsorption and desorption curves is proposed by Maalouv et Al. [62]. In this analytical model, the relation between the water content θ and the relative humidity φ is performed as:

$$ln\left(\frac{\theta}{\theta_s}\right) = a \cdot ln(\varphi) \cdot e^{b \cdot \varphi} \tag{6.13}$$

With a and b parameters determined experimentally. Results from researches are given in table

Table 6.6: Fitting parameters of GAB′s-moisture content model

	absorp. [62]	desorp. [62]	adsorp. [26]
a	1.1	0.75	1.1
b	2.3	2.3	2.1
θ_s	0.151	0.151	0.1185

For a relative humidity lower than 95% RH, the next equation appears to fit. [11]

$$w_H = \frac{\varphi}{a_H \cdot \varphi^2 + b_H \cdot \varphi + c_H} \tag{6.14}$$

with a_H, b_H and c_H constants that are material dependent.

Diffusion

The moisture transfer occurs through interconnected pores due to a vapour pressure gradient. In an isothermal case, Fick′s law states the relationship between the water vapour diffusion rate in air and the gradient of water vapour pressure:

$$g_v = -\delta_{air} \cdot \nabla p_v \tag{6.15}$$

With δ_{air}[kg/msPa] the water vapor diffusion permeability in air and p_v [Pa] the water vapor partial pressure. The porosity of building materials can differ in size. In larges pores, vapour diffusion can be compared with the diffusion of water vapour in air, while in small pores the collision between molecules and pore walls are more numerous than collisions between molecules. This mechanism is called effusion or

Knudsen transport. The effects of the pore structure can be described by water vapour diffusion resistance factor μ [-]. At macroscopic scale, moisture transfer under a vapour pressure gradient can be expressed as:

$$g_v = -\delta \cdot \nabla p_v \tag{6.16}$$

The vapour permeability δ is equal to water vapour permeability δ_{air} divided by the water vapour resistance factor μ. Under isothermal conditions and for one-dimensional transfer, the flux of moisture is equal to:

$$g_v = -\rho_0 \cdot D_w \cdot \frac{\partial w}{\partial x} = -\rho_0 \cdot D_w \cdot \frac{\partial w}{\partial \varphi} \cdot \frac{\partial \varphi}{\partial x} \tag{6.17}$$

De Vries theory states that the variation of moisture diffusivity D_w $[m^2/s]$ versus water content w evolves according to three phenomena: for low water content, moisture transfer is essentially due to vapour transport (diffusion and effusion). The condensed phase exists in the form of an absorbed film or in small islands of water. When water content increases, small islands of water increase in number or in size, the area for vapour flux decreases and moisture transfer occurs by mechanisms of condensation and evaporation at vapour-liquid interfaces. Then, for high water content, liquid transfer is predominant [27]. This phenomena is also observed by other researches, whith a relative constant value for the vapour diffusion factor is found for relative humidities upto 60% RH, with an average value of 6. When the relative humidity rises, the vapour resistance value decrease exponentially. This is presented in figure 6.5 [16]. Strong compression during manufacturing results in a higher resistance. [36]

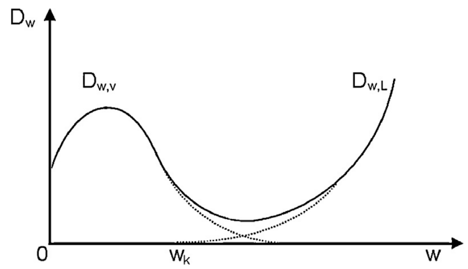

FIGURE 6.5: Moisture diffusivity in function of the water content according De Vries Theory

So the variability of the vapour diffusion in function of the relative humidity is a must to obtain a realistic behaviour of a material. The vapour resistance factor can be described as:[72]

$$\mu = \frac{1}{a + be^{c\varphi}} \tag{6.18}$$

with a, b and c material parameters. Fitting parameters are given in table 6.7.

Table 6.7: Fitting parameters of diffusion resistance factor found in literature

	[63]	[16]
a	0.177	$1.52 \cdot 10^{-1}$
b	$5.005 \cdot 10^{-3}$	$3.50 \cdot 10^{-5}$
c	3.4	11.5

The vapour permeability can be described as

$$\delta = A + B\varphi^C \tag{6.19}$$

With A, B and C fitting parameters. Previous researches on hempcrete, fabricated with different techniques, gave following fitting parameters for equation 6.19.

Table 6.8: Fitting parameters of vapour permeability of hempcrete found in literature

Preparating Method	PHC [27]	SHC [27]	SHC [28]
A	$2.52 \cdot 10^{-11}$	$3.19 \cdot 10^{-11}$	$2.31 \cdot 10^{-11}$
B	$2.24 \cdot 10^{-10}$	$5.18 \cdot 10^{-10}$	$5.25 \cdot 10^{-11}$
c	4.94	8.38	1.366

The values of table 6.7 and 6.8 are given in figure 6.6. The green curve is fitted on three measurement points, so it can be concluded that it is better to investigate the whole moisture range.

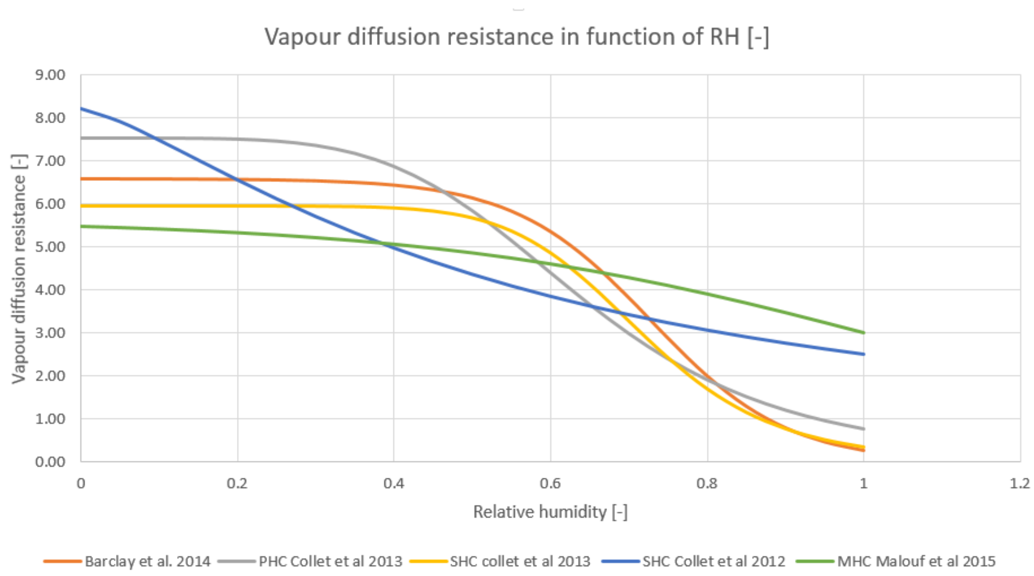

FIGURE 6.6: Vapour diffusion resistance factor found in literature

Moisture effusivity

The moisture buffer capacity on the material level is based on the heat-mass transfer analogy. In heat transport theory the thermal effusivity expresses the rate of heat transfer over the surface of a material when the surface temperature changes. It is defined as the square root of the product of material density, specific heat capacity and thermal conductivity. An analogue equation is present for the moisture effusivity b_m $[kg/(m^2 \cdot Pa \cdot s^{1/2})]$: [71]

$$b_m = \sqrt{\frac{\delta_p \cdot \rho_0 \cdot \frac{\partial u}{\partial \varphi}}{p_s}} \tag{6.20}$$

With δ_p,water vapour permeability $[kg/(m \cdot Pa \cdot s)]$; ρ_0 $[kg/m^3]$, dry density of the material; u $[kg/kg]$, moisture content; φ $[-]$, relative humidity; and p_s $[Pa]$, saturation vapor pressure. Except for the saturation vapor pressure, all the parameters are standard material properties. The moisture effusivity is therefore theoretical able to express the rate of moisture that can be absorbed by a particular material when it is subjected to a sudden increase in surface humidity.

Penetration depth

The penetration depth shows how deep vapour will penetrate in the material due to a variation of relative humidity during a certain period. This is given by:

$$p = \sqrt{\frac{t_p \cdot \delta_v \cdot p_{v,sat}(T_b)}{\pi \cdot \xi}} \tag{6.21}$$

With p_{vb} $[Pa]$ and T_b $[K]$ respectively vapour pressure and temperature in the buffer layer and δ_v $[s]$ and ξ $[kg/m^3]$ the water vapour permeability and moisture capacity of the buffering layer.

Moisture buffer value

Moisture buffering is the ability to moderate variations in the relative humidity. It has positive consequences for the interior air when there is an sudden increase of relative humidity, which also could lead to an smaller energy demand of the ventilation system. It is common to use the Nordtest Protocol to characterize the moisture buffer value of materials. The moisture load of this protocol is a cyclic step-change in relative humidity of the exposed air between high, 75 % RH, and low, 33%RH values for 8 and 16 hours respectively and a constant temperature of 23 ℃. In order to classify material according their ability of moisture buffering, a classification system was generated. It is based on the results of a Robin test on several materials. A material with a MBV-value of 0.2 $g/(m^2\%RH)$ and lower has a negligible effect on the building performance. A MBV-value of 2.0 $g/(m^2\%RH)$ and higher represents a very high efficiency moisture buffering material. This is shown in Figure 24.

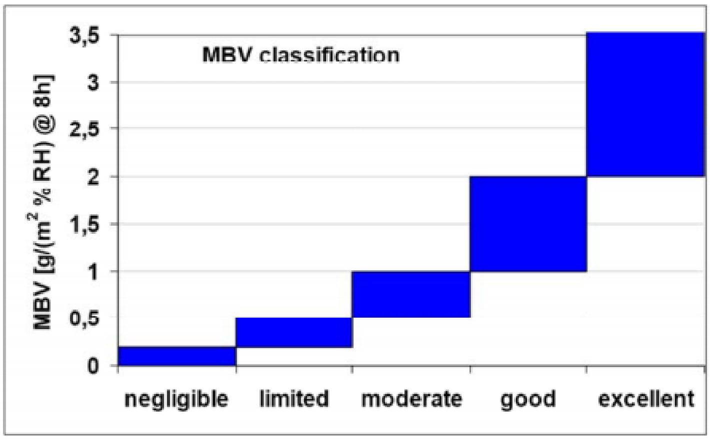

Figure 6.7: Classification of MBV

The moisture buffering potential of a room depends on the moisture capacities of each material combination and furniture in the room together with the moisture production, air change rate and the ratio between the material surface area and the air volume. On the next level, the system level, the MBV depends on the air velocity, area, and thickness of the sample. On the material level, there is a theoretical and a more physical definition of the moisture buffer value.

The practical moisture buffer value indicates the amount of water that is transported in or out of a material per open surface area, during a certain period of time, when it is subjected to variations in relative humidity of the surrounding air. When the moisture exchange during the period is reported per open surface area and per $\%RH$ variation, the result is $MBV_{practical}$ [70].This can be translated as:

$$MBV_{practical} = \frac{\Delta m}{A \cdot (RH_{high} - RH_{low})} \tag{6.22}$$

With MBV, moisture buffer value $[kg/(m^2\%RH)]$; Δm, moisture uptake/release during the period $[kg]$; A, open surface area $[m^2]$; $RH_{high/low}$, high/low relative humidity level [%].

The ideal moisture buffering value is derived of the heat transport theory. There, sudden changes in surface temperature are described. But also where the temperature varies according to a periodic function. Therefore, by using Fourier analysis, it is possible to describe these changes in other forms that are depended of the time variation of the surface conditions. This can also be done for the moisture transfer. In the case of the 8/16 hours regime, the moisture uptake can be transformed to:

$$G(t) = 0.568 \cdot p_s \cdot b_m \cdot \sqrt{t_p} \tag{6.23}$$

The moisture uptake within 8 hours corresponds to the moisture release within 16 hours. With t_p, time period $[s]$. The moisture buffer value, MBV, is a characteristic of the material based on the moisture uptake/release. It is expressed as the moisture uptake normalized with the change in surface relative humidity, ΔRH.

$$MBV_{ideal} = \frac{G(t)}{\Delta RH} = 0.00568 \cdot p_s \cdot b_m \cdot \sqrt{t_p} \tag{6.24}$$

Since the ideal experimental situation rarely exist, it is only an approximation. The ideal moisture buffering capacity is based on the assumption the materials studied have a thickness that exceeds the moisture penetration depth of the sample.

F. Collet et al [28] investigated the moisture buffering capacity of sprayed hemp concrete. They made several samples with different densities and different thicknesses. The conclusion of that investigation was that the variation of the thickness does not matter if the thickness was higher than the moisture penetration depth. The density varied from 410 $[kg/m^3]$ to 450 $[kg/m^3]$, in this range the MBV did not varied sufficient to see a clear change. The moisture buffer value had an average value of 2.15 $[kg/m^2\%RH]$ with a standard deviation of 0.06 $[kg/m^2\%RH]$.

Evrard and De Herde [37] analysed the transient hygrothermal performance of lime hemp assemblies by using the results of simulations with WUFI Pro 4.1. They compared seven wall assemblies that were oriented to the south. The definition of the wall assemblies is presented in Figure 25. The main building materials that are used are lime hemp (LH), spruce, radial (Wood), autoclaved aerated concrete (AAC), historical brick (Brick), mineral wool (MW), classical concrete and XPS, all material parameters are obtained from the database of WUFI Pro 4.1. The moisture buffering obtained by simulations is given in table 6.4.2.

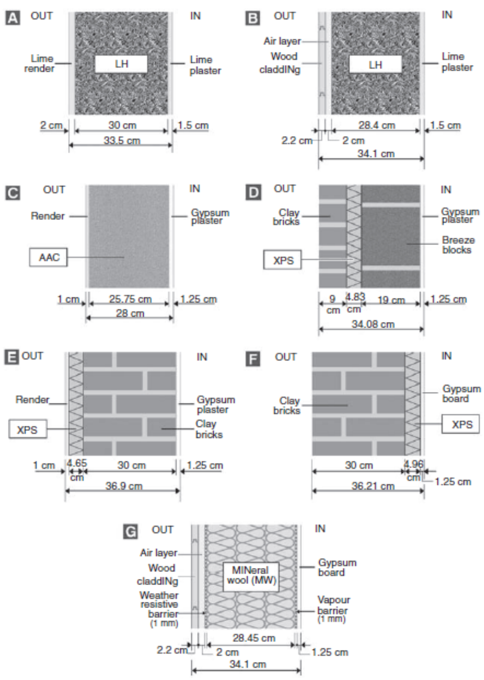

Figure 6.8: Simulated wall assemblies

Table 6.9: Moisture buffer value of assemblies

Wall assembly	MBV $[kg/m^2\%RH]$
A	2.11
B	2.11
C	1.02
D	1.04
E	1.01
F	0.96
G	0.93

It is clear that according the simulations the lime hemp wall assemblies A and B have the highest ability for moisture buffering. According the classification, they belong to the category Excellent.

6.5 Including hygrothermal properties within simulations

6.5.1 Importance of a whole building performance

To simulate the interior room conditions several simulation programs can be used such as WIFI Pro and EnergyPlus. To compare the and to analyse the differences found in the output of the programs, the BESTEST-project was set up. In the BESTEST-project, better known as the Building Energy Simulation Test project [3], a method was developed for systematically testing whole-building energy simulation programs and diagnosing the sources of predictive disagreement. M. Barclay et al. [16] made use of this project to simulate the performance of a building constructed with lime hemp. The BESTEST-building, which is shown in Figure 29, was modelled with a steady air exchange rate of 0.5 ACH and a humidity burst of 500 g/h during occupied hours (08:00-17:00). The walls of the building were simulated as 200 mm of lime hemp with and without humidity transport simulated with the HAMT model. The initial water content of the lime hemp wall is 0.09 kg/kg. M. Barclay et al. used some material properties of earlier researches, of Evrard, Evrard De Herde, Collet et al, together with own experimental data to get a full list of input data. As mentioned, two models are used, a ”close” model, with the wall constructions effectively closed to moisture, and a hygric model, which use the HAMT model and the full set of hygrothermal material properties are used to simulate combined heat and moisture transport. The external conditions were kept on a whether file with a constant temperature of 23 °C and a relative humidity of 20%. The internal relative humidity of the closed and hygric model of a period of one day are visualized in Figure 30. This indicates the weight of taking into account the hygroscopic properties of the building materials. The average result remains similar for both closed and hygric cases. The smaller fluctuation in internal relative humidity of the hygric case indicates the buffering performance of the building material. It must also be mentioned that the relative humidity after the moisture load remains higher for the hygric case compared with the closed case. So the hygric case is able to attenuate the peaks resulting in more stable internal conditions.

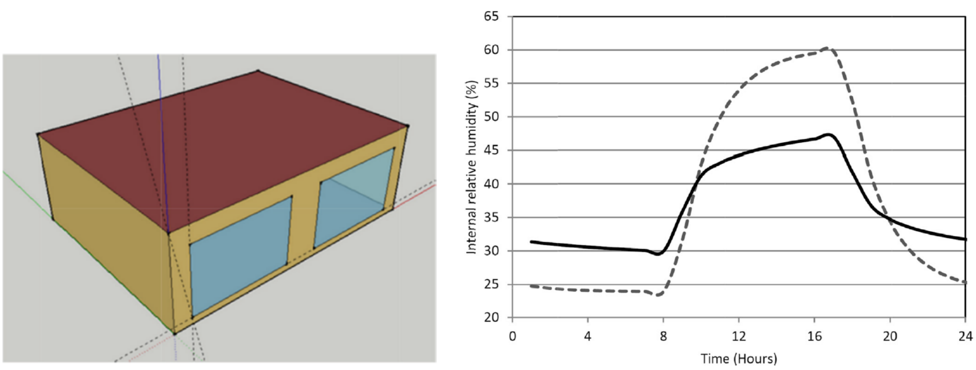

FIGURE 6.9: Bestest Building whole building performance

6.5.2 Effective moisture penetration depth model

The effective moisture penetration depth model (EMPD) [51] is based on the assumption that only a thin surface layer of the interior elements material contributes to the moisture buffering process. Moisture storage and transport in this buffer layer is described with a single control-surface equation. For a single buffer layer the G_{buf} can be formulated as:

$$G_{buf} = A \cdot \frac{p_{vi} - p_{vb}}{1/\beta + d_b/(2 \cdot \delta_v)} = A \cdot \xi \cdot d_b \cdot \frac{\partial}{\partial t}(\frac{p_{vb}}{p_{v,sat}(T_b)}) \tag{6.25}$$

With p_{vb} $[Pa]$ and T_b $[K]$ respectively vapour pressure and temperature in the buffer layer with thickness d_b $[m]$ and δ_v $[m]$ and ξ $[kg/m^3]$ the water vapour permeability and moisture capacity of the buffering layer. The thickness d_b of the buffering layer is related to the effective moisture penetration depth d_p $[m]$, which depends on the period of the humidity variations in the room, as:

$$d_b = a \cdot d_p = a \cdot \sqrt{\frac{t_p \cdot \delta \cdot p_{v,sat}(T_b)}{\pi \cdot \xi}} \tag{6.26}$$

With $a = min(d/d_p, 1)$ the adjustment factor taking into account the fact that the actual thickness d $[m]$ of the material may be below the effective moisture penetration depth d_p. This simplification just holds for cyclic humidity variations with a constant period. Because the EMPD method depends on the penetration depth, it is a very time consuming method because the material parameters δ and ξ needs to be measured. Another disadvantage is the fact that is that layer with thickness d_b is a homogeneous layer.

6.5.3 Effective capacitance model

The effective capacitance (EC) model is built up with the assumption the relative humidity in the active part of the room enclosure is at all times in equilibrium with the room air humidity. To take into account the hygric effect of the building material, an additional air volume could be added to the zone, this dilutes any moisture changes. Often it is characterized as a multiplier which multiplies the air volume, for example a multiplier 5 refers to a rise of the air volume by a factor 5. M. Barclay et al. [16] made use of this model, they found that in the case of the BESTEST-building a multiplier 5 results in a humidity peak that matched with the hygric case. This model does not take into account the effect of water content on the material thermal properties or moisture distribution within the materials.

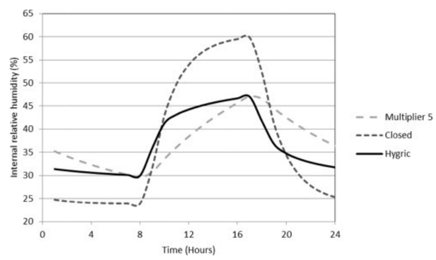

Figure 6.10: Comparing models for whole building moisture buffering

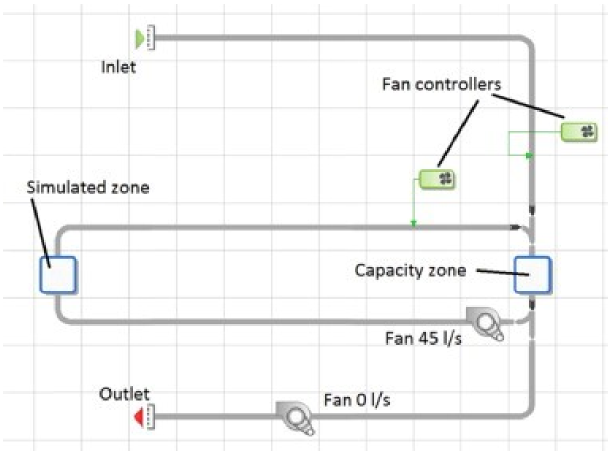

FIGURE 6.11: Comparison of the IES ECM moisture buffering performance

The EnergyPluss Zone capacitance multiplier object means the zone air has instant access to the extra capacitance and there is no resistance to moisture flow. In reality, hygric materials take time to absorb and release moisture. So when using additional HVAC equipment to the physical zones for controlling the access to the extra humidity capacity, the curve would be more realistic. This could be done by controlling the speed of the connecting fan. This is used by the software IES. The scheme is represented in figure 6.11. The results of the implementation of the effective capacitance model in the software IES is shown in figure 6.12. It is clear that EC model fits better with the hygric model curve.

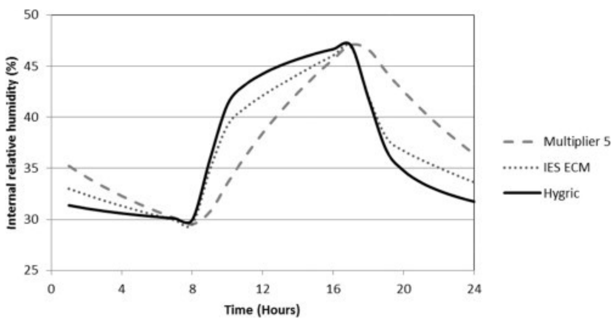

FIGURE 6.12: Comparison of the IES ECM moisture buffering performance

This is translated in the following equation:

$$M \cdot \frac{V}{R_v \cdot T_i} \frac{\partial p_{vi}}{\partial t} = (p_{ve} - p_{vi}) \frac{nV}{3600 R_v T_i} + G_{vp} \tag{6.27}$$

The factor M is a multiplication factor, sometimes called the effective capacitance EC that takes into account the room air moisture capacity. A larger M implies a larger potential for moisture buffering.

Several researches were done on the determination of the magnitude of the effective capacitance. In the following table, several magnitudes are suggested according the contents of the room which are used in an indoor humidity assessment tool[35].

Room contents	Effective capacity EC [-]
Library	15 - 25
Classrooms	10 - 20
Office	10 - 20

Table 6.10: Effective capacitance related to the room content

The mean conclusion found was that it is difficult to estimate this value, it was noticed that the effective capacitance is related to the duration and magnitude of the moisture load. The advantage of this model is its simple implementation. It response less realistic than the EMPD method but when its hard to estimate the duration of the vapour load and when the room content can not be determined properly, it seems to be good solution to implement the hygric effect [51] [35] [83].
Picking large values for the effective capacitance will lead to a more damping effect of peaks compared with low values. A low effective capacitance, for example 5, is more related to short-term buffering. It reacts better to high-frequence moisture loads, like the one coming from air conditioning systems. But it does not provide enough damping to low-frequency moisture loads like seasonal changes. Whereas a high effective capacitance, in the order of 45, fits better for low-frequency moisture loads and less with high-frequency moisture loads [84].

6.5.4 Taking into account the effect of hysteresis

To obtain a reliable simulation of a construction with hempcrete, the implementation of hysteresis can be a completion, which is the conclusion of several researches. Figure 6.13 shows a result of the investigation of a fast cycling test, in particular the effect of the Moisture Buffer Value . The approximation of Pendersen nor the one of Mualem predicted the sorption behaviour of hempcrete exactly [57]. The difference between both approximations is the effect of ′ pumping ′ , which refers to the accumulation phenomenon with the Pendersen approximation. In order to reduce this affect, Muelem′s model includes a scaling.
An experiment with scanning curve, shown in figure 6.13, revealed that the hygric behaviour of hempcrete is over estimated. The hysteresis effect has high impact on the uptake and release of moisture [14]. It appears that implying the Mualem′s model showed good agreement with hygric behaviour of a wall [57].

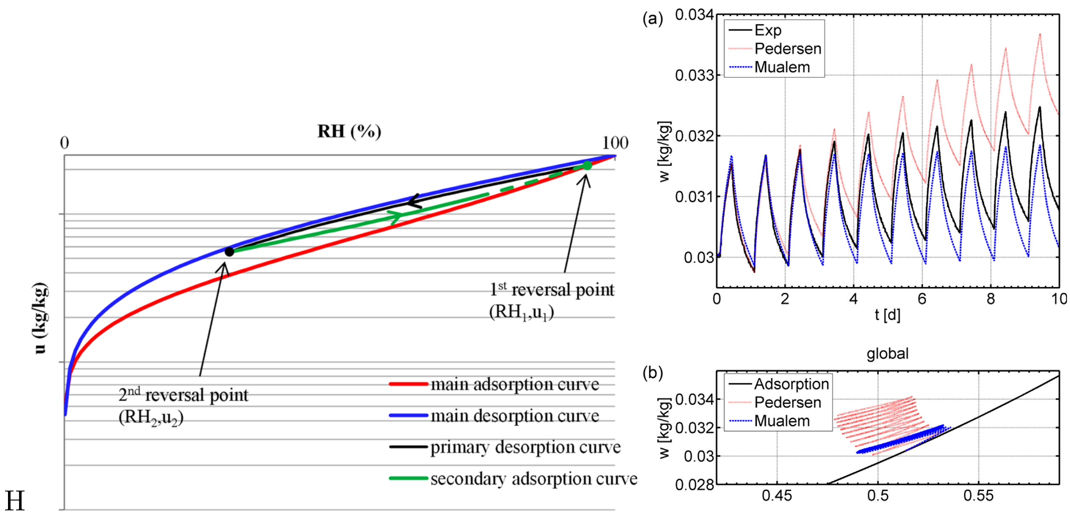

Figure 6.13: Left: An example of a scanning pattern. Right: An attempt to include the hysteresis effect

Chapter 7

Characterisation of specimens

In order to simulate the behaviour of a hempcrete wall, several material properties are needed for implementation. The essential properties for such an simulation are thermal conductivity, heat capacity, sorption isotherm and diffusion resistance. As mentioned before, the temperature and relative humidity in the heritage storage boxes will be limited due to the conservation requirements. The relative humidity will be kept between 45%RH and 60%RH, the temperature between 10℃ and 25℃. Because the interaction between the hempcrete wall and the indoor climate is a topic of interest, the accent in the determination of the material properties will be those in the ranges of temperature and relative humidity within the boxes.
For completeness and applicability for simulations, the material properties are also determined outside these ranges.
Three samples were provided by ChanvrECO. Those samples were fabricated by the MHC-technique. A mixture of hempcrete, with a hemp:binder:water ratio of 2:1:1, were poured into a mould and tightened with a stamper. When the samples were delivered, they had an age of six months, which mean that they had a decent time to gain strength. No information was given about the climate conditions during hardening. The samples were stored in the Laboratory of building Physics [1] where a constant temperature of 20 ℃ and a relative humidity of 50% is preserved.

7.1 Dimensions and densities

After a month of storage in the laboratory, the dimensions and mass were determined. The results are given in table 7.1.

[1] Afd. Bouwfysica, K.U.Leuven, Kasteelpark Arenberg 51, B3001 Heverlee

Sample	1	2	3
$b_x[mm]$	600	600	600
$l_y[mm]$	600	600	600
$h_z[mm]$	110	110	110
$mass_i[kg]$	20.108	13.487	19.943
$\rho_i[kg/m^3]$	507.77	340.58	503.61

Table 7.1: Dimensions and densities of tested samples

7.2 Thermal conductivity

The thermal conductivity is determined with a heat flux measuring apparatus according the method described in ISO 8302. This apparatus consist of a central hot plate between two cold plates, as is sketched in figure 7.1. Sensors, who register the heat flow, are placed on top of and at the bottom of the central plate, at the bottom of the upper plate and on top of the lower plate. [4]. Before a measurement, the heat

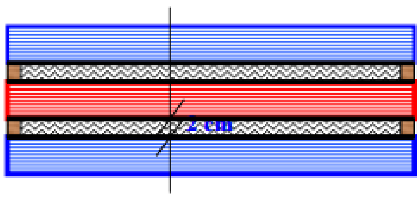

Figure 7.1: Configuration of test setup

flow sensors need to be recalibrated by using a calibration sample. Measurements are done with a temperature difference of 10 ℃ between the thermostatic plates who garden the temperature of the lower and upper plate and the thermostatic plate who gardens the temperature of the center plate. Ones a constant heat flow density and temperature are reached, the measured values are stored in a database, which can be used to determine the thermal conductivity and heat capacity. The follow formula is used to determine the thermal conductivity.

$$\lambda = \frac{d\,(C_1 E_1 + C_2 E2)}{2\Delta\Theta} \tag{7.1}$$

With d the thickness of the sample $[m]$, C_1 and C_2 calibration constants of the heat flow sensors $[W/(m^2.mV)]$, E_1 and E_2 the measured electric voltage difference across the heat flow sensors $[mV]$, Θ the temperature difference across the samples $[K]$ and λ the thermal conductivity of the sample $[W/(mK)]$

Two samples are tested, 2 and 3, each with their specific density. The result of those tests are given in figure 7.2. The relation between the thermal conductivity $\lambda[W/mK]$ and Temperature $T[K]$ for low density hempcrete is given by

$$\lambda = 0.0003T - 0.005 \tag{7.2}$$

For high density hempcrete this relation is given by

$$\lambda = 0.0003T - 0.0016 \tag{7.3}$$

Where the relation between the thermal conductivity and the density $\rho[kg/m^3]$ for 283.15 K is given by

$$\lambda = 0.00014\rho + 0.024 \tag{7.4}$$

And for 303.15 K this relation is equal to

$$\lambda = 0.00015\rho + 0.027 \tag{7.5}$$

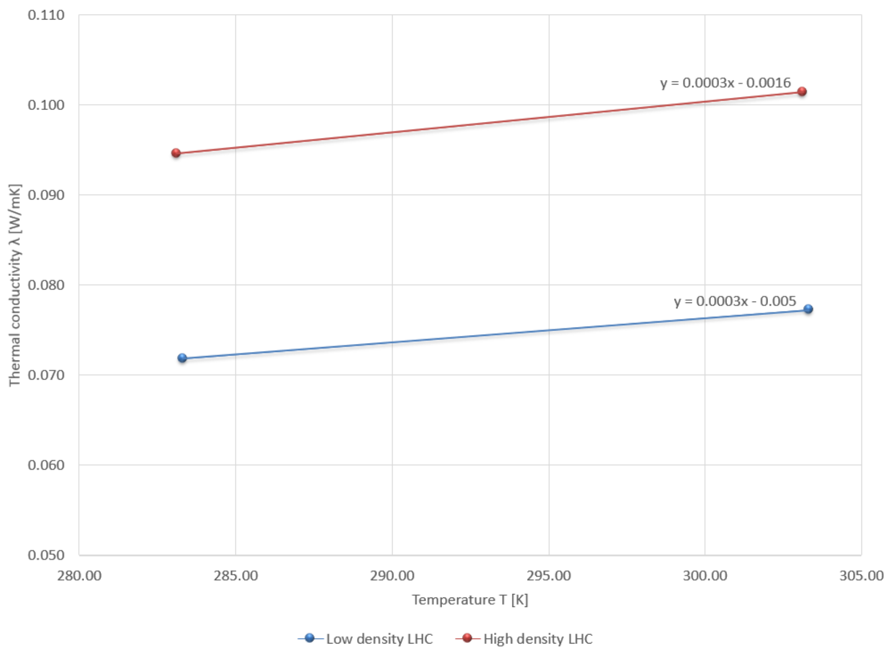

FIGURE 7.2: Thermal conductivity for low and high density LHC

7.3 Heat capacity

The determination of the heat capacity is done with the same configuration of the thermal conductivity, which is based on the following principle. Before testing, the temperature of the plates across which will be measured, are equal. The heat momentum on the known boundary temperatures will ensure that the sample will reach a new thermal equilibrium. The switch in equilibrium will happen with a time lag, due to the heat capacity of the specific sample.
Due to the fact that the samples are isolated such that only a one dimensional heat transfer occurs, formula 6.4 can be written as

$$\rho_c \frac{T^m - T^{mo}}{\Delta t} = \frac{T^k - T^m}{d/\lambda} + \frac{T^w - T^m}{d/\lambda} \tag{7.6}$$

With ρ_c the specific heat capacity $[J/(m^3K)]$, T^m resp. T^{mo} the new resp. previous temperature of the monster $[K]$ of a certain time step Δt $[s]$. And d represents the thickness of the sample $[m]$, whereas λ represents the thermal conductivity $[W/(mK)]$ at T^{mo}. T^w resp. T^k represents the temperature of the hot resp. cold plate.
With previous equation, $_s$ can be determined by inverse fitting.
Due to a lack at data, impossible to obtain a reliable result. Just one could be obtained, 1182 J/kgK. This is why the choice is made to use 1200 J/kgK in further calculations.

7.4 Sorption, desorption and scanning

To determine the sorption and desorption behaviour of hempcrete, eighteen cubic specimens were fabricated out of sample 1. The side of the cubic specimens varies between 50 and 60 mm. The were first dried in a furnace with a temperature of 50°C and 5%RH. The specimens are weighted before and after drying. More information about the specimens can be found in Appendix **??**.
To create an atmosphere where the relative humidity ratio of the measurement points are obtained, six hygroscopic desiccators are used. In each desiccator a cup was placed, filled with a saturated salt solution. In order to create an homogeneous climate in the desiccators, little ventilators are installed at the top of the desiccators.

Figure 7.3: A desiccator

To determine the sorption isotherm of hempcrete, seven different measurement points are chosen: 33%, 43%, 54%, 65%, 75%, 86% and 94%. The used salts are given in table 7.2. Firstly the sorption isotherm was determined in the range of 33% and 65% in order to see if the hysteresis effect occurs in the range of 40% and 60%, which are the limits for conservation. Secondly, the sorption isotherm was determined for the whole range because one side of the hempcrete wall is exposed to exterior climate conditions where higher relative humidity ratios dominate.

RH [%]	33	43	54	65	75	86	94
Salt	$MgCl_2 \cdot 6H_2O$	K_2CO_3	$Mg(NO_3)_2$	$NaNO_2$	NaCl	KCl	KNO_3

TABLE 7.2: Salts used for the determination of the sorption isotherms

7.4.1 Scanning

Objective

To determine the first range, the desiccators were filled strategic, see table 7.3. This is done to speed up the time of measurement because it made it easy to jump between two points.

RH [%]	33	43	54	65
Desiccator	1	2 3	4 5	6

TABLE 7.3: Salts used for the determination of the sorption isotherms

To obtain reliable results, the measurements were done with sets of three samples. The path of the samples is given in:

	Step 1	Step 2	Step 3
Set 1 (1-3)	33%	43%	54%
Set 2 (4-6)	43%	33%	43%
Set 3 (7-9)	43%	54%	65%
Set 4 (10-12)	54%	65%	54%
Set 5 (13-15)	54%	43%	33%
Set 6 (16 -18)	65%	54%	43%

TABLE 7.4: Path of samples

Results

The results are shown in figure **??**. This bar graph represents the gravimetric water content for each specimen after each step. Large deviations can be observed.

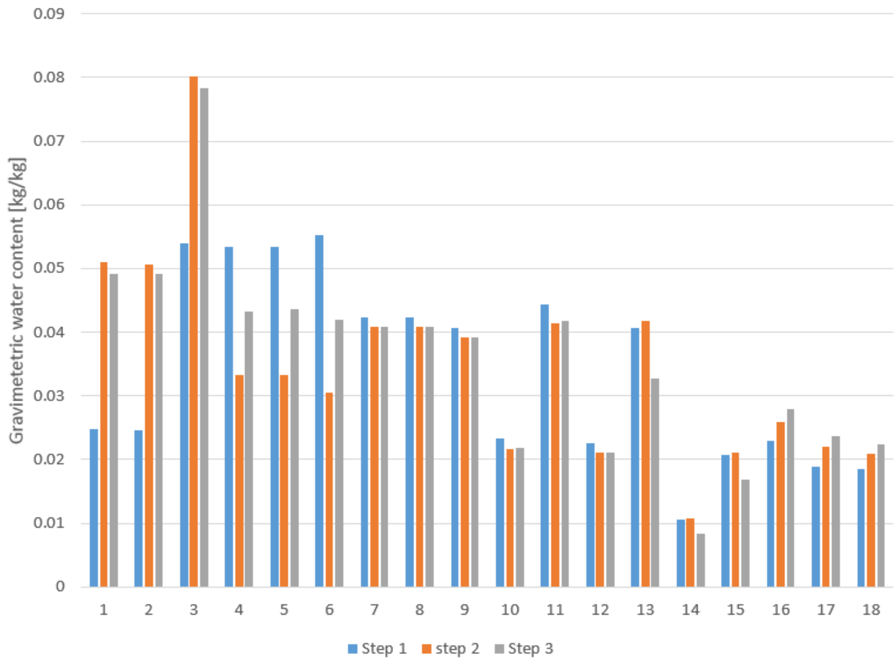

Figure 7.4: Gravimetric water content for each specimen after each scanning step

The moisture content of the specimes that were guarded in one of the desiccators with a relative humidity of 45 %RH appears to have a higher moisture content then the one who were guarded in the other desiccator with 45 %RH. They have even a higher moisture content then those who are weighted after being guarded in desiccators of 54 %RH. This can be noticed in figure 7.4.1, which represents the gravimetric moisture content after each step for the specimens of set 3. The other isotherms are given in APPENDIX X.

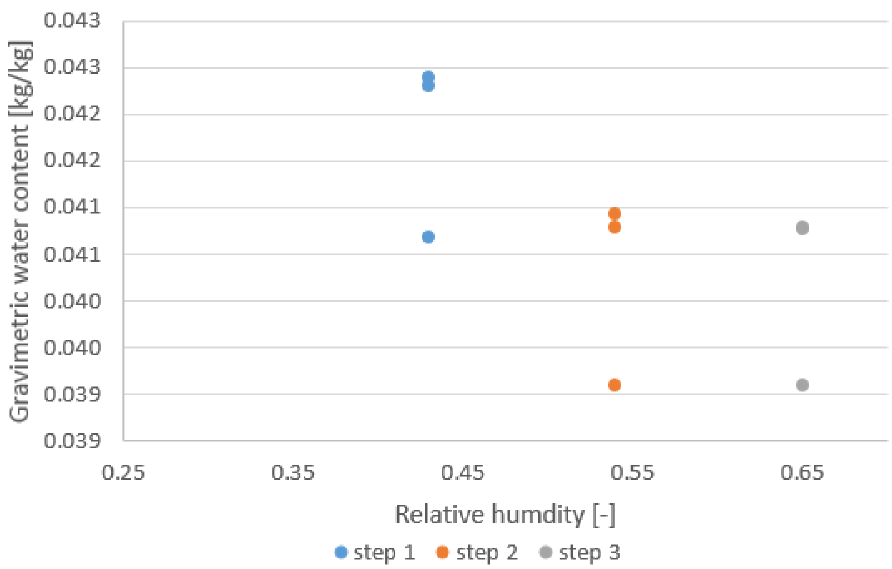

FIGURE 7.5: Gravimetric water content for each specimen after each scanning step

This result was already observed after step 1. At that moment, it was suggested that the differences in weight could be explained due to the frailty of the specimens. The small specimens fabricated by sawing sample 1 in small specimens. Due to the sawing, the strength of the material is affected, especially at the edges. Tiny fractions could have been felt during transport, even if the transport was done with prudence. During step 3, a HOBO-measurement tool was placed within two desiccators, 33 %RH and 45 %RH, to record the temperature and relative humidity. The relative humidity within the desiccator with a intended relative humidity of 43 %RH appears to be 52.6 %RH, which mean that the solution was not saturated anymore at that moment. This explains the observed pattern of figure 7.4.1. Regarding to specimens 1, 2 and 3, the height of the second bar should be between the bars of step 1 and step 3 since the humidity of step 2 lies between those of step 1 and step 3.
The relative humidity within the desiccator with a intended relative humidity of 33 %RH, which is used to determine the whole sorption isotherm, was equal to 32.2 %RH. Worth to mention is that the precision of the measurement tools was 1 % RH. At the moment at which the problem was stated, there was insufficient time to restart the tests.

7.4.2 Whole moisture range

The sorption isotherm is determined for the whole humidity range by using the salts mentioned in table 7.2. The results are given in figure 7.6, the values of the data points are given in Appendix A. A fitting curve is proposed by using equation 6.14, with a = -70, b = 61.5 and c = 10.

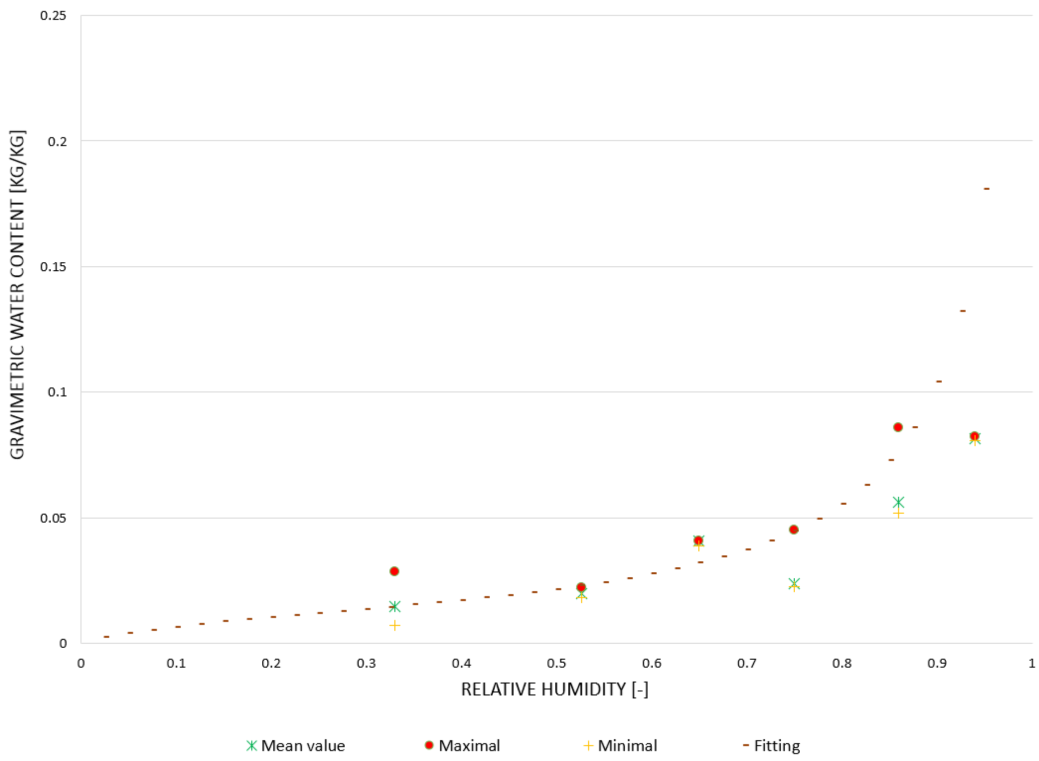

Figure 7.6: Values of sorption isotherm and a fitting curve

The description of the desportion curve is based on the measurements of the samples before and after the drying process, described in the beginning of this section. The samples were delivered in January. Based on the fact that the humidity in that period is high and that the specimens were never dried completely before, it is assumed that at the moment of delivery the water content could be described with a desorption curve. The data of the measurements can be found in Appendix **??**. It results in a mean gravimetric water content of 0.0416 kg/kg at a relative humidity of 50 %. A fitting curve, according equation 6.14, the next parameters are proposed: a = -31.5, b = 28.5 and c = 5. The determination of these fitting parameters can be found in Appendix **??**.

7.5 Diffusion resistance

The diffusion resistance of hempcrete is determined with the cup-test, according EN ISO 12572:2001. Is based on the change of mass by time. In order to do so, cups are filled with several salt solutions and are periodic, weekly, weighted.
As mentioned, the accent of these determinations relies on the behaviour of the wall in contact with the indoor climate of the heritage storage boxes. The cups are filled with different salt solutions in order to obtain a constant relative humidity within the cups. In order to ensure one dimensional vapour transport through the samples, the sides of the samples are made air-tight, see figure **??**. The conditions within the cups are set as shown in table 7.5. In order to obtain reliable results, nine samples were prepared, three for each condition. It appeared that for each condition only two cups were air-tight so the test are done with six samples. The cups are placed in an air conditioned room where the relative humidity is set at 54%RH and the temperature at 23°C.

FIGURE 7.7: Preparation of cup-test

RH_{cup}	RH_{Room}
33%	54%
43%	54%
65%	54%

TABLE 7.5: Test conditions for the cup-test

The change of mass by time can be determined with:

$$\frac{\Delta m_{12}}{\Delta t_{12}} = \frac{m_2 - m_1}{t_2 - t_1} \tag{7.7}$$

with m_1 resp. m_2 the mass of the samples $[kg]$ with $t_2 - t_1$ the duration between two consecutive measurements $[s]$. The moisture flow $g[kg/(m^2 s)]$ through the samples is given by

$$g = \frac{\Delta m_{12}}{A \cdot \Delta T_{12}} \tag{7.8}$$

with A the exposed surface $[m^2]$. The vapour permeability $W[m/s]$ is derived as

$$W = \frac{g}{\Delta p} \tag{7.9}$$

were Δp expresses the vapour pressure difference between the cup and the room. the vapour permeability is equal to

$$\delta = W \cdot d \tag{7.10}$$

with d the thickness of the sample [m].
The results are given in table 7.6. The measurement data are given in Appendix ??.

Specimen	1	2	4	5	8	9
RH [%]	33	33	43	43	65	65
$\mu[-]$	- 53.44	7.36	-33.45	-36.43		3.02

Table 7.6: Specimens and their diffusion resistance factor

Only two values are in the range of what was expected, those of specimens 2 and 6. A reason of these results could be found in the manufacturing of the test setup. To obtain a one dimensional vapour transport that only can happen through the material, Paraffine is used to cover the side edges as can be seen in figure 7.7. The use of this material is justified due to friable structure and the open porosity of hempcrete. One of the consequences could be that paraffine was absorbed by the hempcrete specimens which could block the vapour transport in such a way that very low mass differences are measured.
According the results that were found, a best fitting curve is suggested. When describing the vapour diffusivity with formula 6.19, a = $2.7{\cdot}10^{-11}$, b = $2.24{\cdot}10^{-11}$ and c = 4.94. The curve of the vapour diffusion resistance is given in figure 7.8.

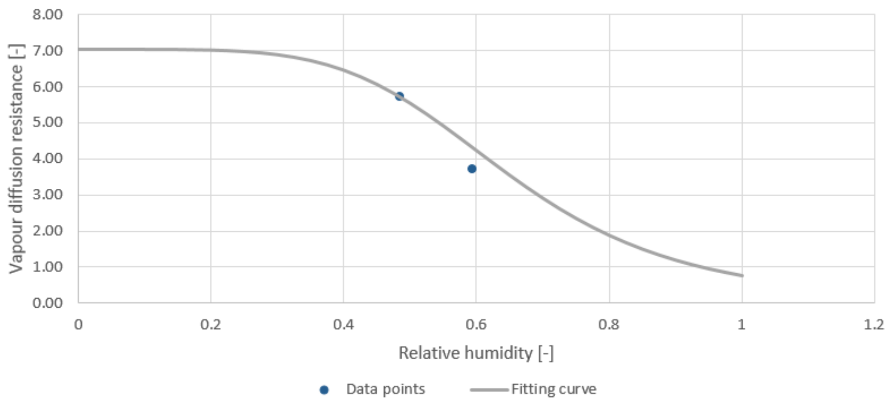

Figure 7.8: Fit of the moisture diffusivity resistance according the usefull data

Chapter 8

Design of a suitable room model

8.1 Assumptions and method

The upcoming model, that will describe the behaviour of the wall and the interior air conditions of a hempcrete store, is based on a one-dimensional heat and moisture flow. This is justified by the assumption that the floor and roof are seen as adiabatic surfaces. In reality their will be an interaction between the earth and the store. The heat and moisture flow through the roof are neglected. Even if this might be the case, the essence of this simulation is to validate the behaviour of a hempcrete wall and its effect on the indoor climate control. The simulation room is represented in figure 8.1 with the adiabatic planes coloured in red. As mentioned, no exterior air will be put in except by intruding air through voids, which is dependent of the air tightness of the construction. The air flow that occurs when visitors enter the room, will be neglected since automatic closing doors are included in the design. This is justified because the volume of the intruding air is small compared with the volume of the room. All heat resp. moisture gains within the room are implemented in one matrices Q_{prod} [W] resp. G_{vp} [kg/s], even possible gains from an air conditioning system.

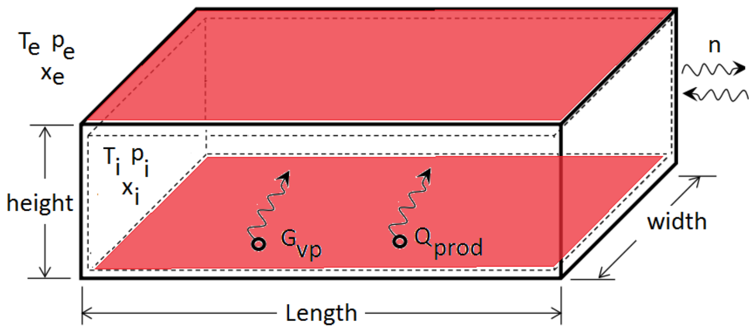

Figure 8.1: Roommodel with adiabatic planes indicated in red

To analyse the effect of an finishing layer, the wall is devided in two parts, which can differ in thickness and mesh size. The left part, indicated in blue, is in contact with the interior of the hempcrete box. It has a thickness $d_{wall,1}$ [m] and a mesh size $n_{dev,1}$. The right part is in contact with the exterior air within the shed. It has a thickness $d_{wall,2}$ [m] and a mesh size $n_dev, 2$. The thickness of each layer is given by

$$d_{b,1} = \frac{d_{wall,1}}{n_{dev,1}} \quad \text{and} \quad d_{b,2} = \frac{d_{wall,2}}{n_{dev,2}} \tag{8.1}$$

The wall setup is shown in figure 8.2. The direction is taken positive from inside to outside.

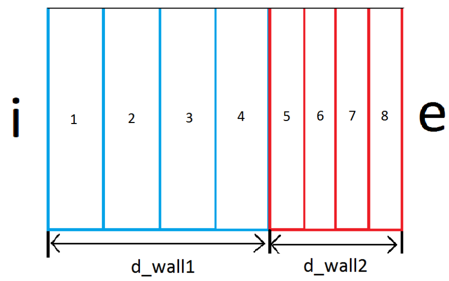

FIGURE 8.2: Sketch of the division of the wall

To set up such a model, there are several assumptions made. It assumed that the room air is well mixed, such that the relative humidity, air temperature are equal in the entire building zone. Their is no air transfer through the wall. The temperature remains well below boiling point. Local thermal equilibrium is assumed at every point of the material. The material is assumed to be homogeneous and stabilized (no internal chemical reactions).

8.2 Composition of differential equations

8.2.1 Heat and moisture balances of indoor air

Heat balance

Firstly, the heat balance for room air and enclosure will be formed. This balance is based on the main principles of thermodynamics, conservation of energy:

$$\frac{dE_{stored}}{dt} = \sum Q_{in} - \sum Q_{out} \tag{8.2}$$

Where the E_{stored} $[J]$, the stored energy in a certain object, is related to the mass M_mat $[kg]$, the heat capacity c_{mat} $[J/kgK]$ and the temperature T $[K]$ of the object. M_{mat} can be written as the product of the volume V_{mat} $[m^3]$ and density ρ_{mat} $[kg/m^3]$ of the material. This relation can be described as:

$$E_{stored} = M_{mat} c_{mat} T \tag{8.3}$$

Q_{in} resp. Q_{out} are the in resp. outgoing heat flows. There are five forms of heat transfer: conduction, convection, radiation, advection and latent heat flow. In this case radiation is neglected because the construction of the LHC-boxes is based on the box-in-box principle. This means that the LHC boxes arent exposed to radiation from the sun. Secondly the difference of temperature of the objects in the box and the wall are of that kind that radiation between the object can be neglected. The balance for the room air can be described as:

$$V_{air}\rho_{air}c_{air}\frac{dT_i}{dt} = \frac{\rho_{air}c_{air}nV}{3600}\cdot(T_i - T_e) + Q_{vp} - Q_{buf} \tag{8.4}$$

The first term on the right-hand side is the one that describes the advective heat transfer due to cracks and holes, which is related to the density of air ρ_{air} (1,25 kg/m^3), the heat capacity of air c_{air} (1000 J/kgK), the air change rate n [$1/h$], the volume of the enclosure V [m^3] and the interior resp. exterior room air temperature T_i resp. T_e. The second term, Q_{vp} [W], is the heat production of a source within the room, for example due to human activity. The third term, Q_{buf} [W] is the heat flow due to buffering. Q_{buf} of a single buffer layer of the wall is equal to:

$$Q_{buf} = A\cdot\frac{T_i - T_b}{1/h_i + d_b/(2\lambda)} \tag{8.5}$$

With A [m^2] the exposed surface, T_b [K] the temperature, d_b [m] the thickness and λ [W/mK] the thermal conductivity of the buffer layer, and h_i the convective transfer coefficient (8 W/m^2K). In order to solve the heat balance for the wall, the temperature of the buffer layer needs to be determined. This term is related to the heat flow due to conduction through the wall. So the next step will be to described the thermal behaviour of the wall.

Moisture balance for room air

In order to describe the moisture balances for room air and enclosure, there is a description needed. These are based on mass conservation.

$$\frac{dM_{stored}}{dt} = \sum G_{in} - \sum G_{out} \tag{8.6}$$

This leads to the following equation:

$$\frac{V}{R_v\cdot T_i}\frac{\partial p_{vi}}{\partial t} = (p_{ve} - p_{vi})\frac{nV}{3600R_vT_i} + G_{vp} - G_{buf} \tag{8.7}$$

The first term on the left, $V/(R_vT_i)$ [kg/Pa], is the moisture capacity of the zone air, $p_{vi/e}$ [Pa] the partial vapour pressure of interior/exterior air, n [$1/h$] the air change rate per hour, V the volume of the zone [m^3], R_v (462 $J/(kgK)$) the gas constant of water vapour, T_i [K] the interior air temperature, G_{vp} [kg/s] the interior moisture production and G_{buf} [kg/s] the moisture exchange between room air and room enclosure. This mass change can be expressed as:

$$\frac{\partial M}{\partial t} = A_b\cdot\frac{p_{v,i} - p_{v,1}}{1/\beta + d_b/(2\delta)} \tag{8.8}$$

With M the mass $[kg]$ of vapour in the room. β the surface vapour transfer coefficient $[s/m]$. And $p_{v,1}$ the vapour pressure $[Pa]$, δ moisture permeability $[s]$, d_b the thickness $[m]$, T_1 the temperature $[K]$ of the buffer layer.

Including hygrothermal effect of stored objects

In the previous room balances, the influence the stored objects in the room are neglected. To take this interaction into account, an adaption is needed. Regarding to the models that mentioned before, the effective capacitance model is the best way to implement the effect of the stored objects because it isnt period dependent like the EMPD model. The room balances can be rewritten as:

$$M_{heat} V_{air} \rho_{air} c_{air} \frac{dT_i}{dt} = \frac{\rho_{air} c_{air} n V}{3600} \cdot (T_i - T_e) + Q_{vp} - Q_{buf} \tag{8.9}$$

And

$$M_{moist} \frac{V}{R_v \cdot T_i} \frac{\partial p_{vi}}{\partial t} = \frac{nV}{3600 R_v T_i} \cdot (p_{ve} - p_{vi}) + G_{vp} - G_{buf} \tag{8.10}$$

With M_{heat} and M_{moist} the multipliers for the heat and moisture balance. The values will be discussed later on.

8.2.2 Heat and moisture balances within the wall

heat balances

As mentioned, the wall is divided in n_{dev} equally divided layers. For the outer layers of the wall, which are in contact with the interior resp. exterior air can be composed as:

$$V \rho\, c \frac{dT_1}{dt} = A \cdot \frac{T_i - T_1}{1/h_i + d_b/(2\lambda)} + A \cdot \lambda \cdot \frac{T_1 - T_2}{d_b} \tag{8.11}$$

and

$$V \rho\, c \frac{dT_{n_{dev}}}{dt} = A \cdot \lambda \cdot \frac{T_{n_{dev}-1} - T_{n_{dev}}}{d_b} + A \cdot \frac{T_{n_{dev}} - T_e}{1/h_e + d_b/(2\lambda)} \tag{8.12}$$

For the inner layers the balances can be expressed as:

$$V \rho\, c \frac{dT_i}{dt} = A \cdot \lambda \cdot \frac{T_{i-1} - T_i}{d_b} + A \cdot \lambda \cdot \frac{T_i - T_{i+1}}{d_b} \tag{8.13}$$

With V the volume of the layer $[m^3]$, which can be expressed as Ad_b so both sides of the equation can be divided by A. ρ is the density $[kg/m^3]$, c the heat capacity $[J/kgK]$ and λ the thermal conductivity $[W/mK]$ of hempcrete.

Moisture balances

Again, the principles to describe the moisture balances in the wall are based on mass conservation. The incoming and outgoing mass flows are based on diffusion. So the mass conservation law for the exterior layer that is in contact with the interior of the room can be expressed as:

$$\frac{\partial M}{\partial t} = A \cdot \frac{p_{v,i} - p_{v,1}}{1/\beta + d_b/(2\delta)} - A \cdot \delta \frac{p_{v,1} - p_{v,2}}{d_b} \tag{8.14}$$

With $p_{v,1\,resp\,2}$ the vapour pressures $[Pa]$ of layer 1 resp. 2. The change of mass can be expressed as:

$$\frac{\partial M}{\partial t} = V \frac{\partial w}{\partial t} \tag{8.15}$$

This can be rewritten as:

$$\frac{\partial M}{\partial t} = \frac{\partial w}{\partial \varphi} \frac{\partial \varphi}{\partial p_v} \frac{\partial p_v}{\partial t} \tag{8.16}$$

Coupled heat and moisture transport

Till here, the heat and moisture transport in the material was described uncoupled. In this section, the energy and moisture conservation equations will be constructed, taken into account the effect of latent heat. Because the interior prescriptions are expressed in terms of temperature T and the relative humidity φ, the conservation equations are derived in terms of these parameters. The energy conservation equation is written as:[57]

$$\begin{aligned} \rho_s(c_{p,s} + w c_{p,l}) \frac{\partial T}{\partial t} &= -\nabla \bullet (-\lambda \nabla T) \\ &+ \nabla \bullet (D_v^{\varphi} \nabla \varphi + D_v^T \nabla T) \times (L_v + (c_{p,v} - c_{p,l})(T - T_{ref}) \end{aligned} \tag{8.17}$$

$$\rho_s \theta \frac{\partial \varphi}{\partial t} = -\nabla \bullet (-(D_l^{\varphi} + D_v^{\varphi}) \nabla \varphi - D_v^T \nabla T) \tag{8.18}$$

With ρ_s the dry density, $c_{p,s}$ the heat capacity $[J/kgK]$, w the moisture content $[kg/kg]$ and $\theta = \partial w / \partial \phi$ the sorption capacity of the material. And $c_{p,l}$ resp. $c_{p,v}$ the heat capacity of liquid (4186 J/kgK) resp. vapour (1864 J/kgK). L_v, the heat of vapourisation, is equal to 2500 kJ/kg and the reference temperature T_{ref} is equal to 273.15 K. The vapour diffusion constants are:

$$D_v^{\varphi} = \frac{\delta_a}{\mu} p_v^{sat} \tag{8.19}$$

$$D_v^T = \frac{\delta_a}{\mu} \varphi \frac{dp_v^{sat}}{dT} \tag{8.20}$$

With δ_a the vapour permeability of air, equal to $1.9 \times 10^{-10} kg/(msPa)$. The liquid diffusion coefficient D_l^{φ} is described as:

$$D_l^{\varphi} = \theta e^{p_1 + p_2/w} \tag{8.21}$$

For more information about the setup of the differential equations can be found in Appendix **??**.

8.2.3 Determination of the HVAC requirements

With these set of differential equations, it is possible to determine the magnitudes of the needed heat, cooling, humidification and dehumidification. Limits are set for the indoor temperature and relative humidity. When these limits are reached, an external source, the HVAC-equipment, must perform so the indoor climate satisfies again the requirements. The necessary magnitudes of the HVAC-equipment can be divided into an amount of heat flow, which is positive resp. negative in the case of heating resp.cooling, and an amount of moisture flow, which is positive resp. in the case of humidification resp. dehumidification.
To determine the needed heat flow, the conditions must be set when the HVAC-equipment must turned on. These conditions are

$$\text{if } T_i \leq T_{min} \text{ and } dT_i < 0, \quad \text{or} \quad \text{if } T_i \geq T_{max} \text{ and } dT_i > 0 \tag{8.22}$$

At that moment the equipment must return a heat flow Q_{HVAC} $[W]$ such that the temperature doesn′t anymore, so the dT_i must set to zero. Using formula 8.4, the needed heat flow is equal to

$$Q_{HVAC} = -\left(\frac{\rho_{air} c_{air} n V}{3600} \cdot (T_i - T_e) + Q_{vp} - Q_{buf}\right) \tag{8.23}$$

The determination of the needed moisture flow relies on the same principles. The conditions are set to

$$\text{if } \varphi_i \leq \varphi_{min} \text{ and } d\varphi_i < 0, \quad \text{or} \quad \text{if } \varphi \geq \varphi_{max} \text{ and } d\varphi_i > 0 \tag{8.24}$$

The needed moisture flow G_{HVAC} $[kg/s]$ can be derived from equation 8.7 and is equal to

$$G_{HVAC} = -\left(\frac{nV}{3600 R_v T_i} \cdot (p_{ve} - p_{vi}) + G_{vp} - G_{buf}\right) \tag{8.25}$$

8.3 Solving the differential equations

The differential equations are solved with Matlab, a mathematical program which is able to solve differential equations. The Matlab application to solve this set of differential equations calls ODE45. It solves ordinary differential equations by using simultaneously fourth and fifth order Runge Khutta formula to estimate errors and to adjust time step accordingly. To get proper solutions, several options need to be set like absolute tolerance, relative tolerance, initial conditions and time step. The time step is set to 3600 seconds, so the differential equations will be solved in steps of one hour in the interval zero till *days*, where *days* is a positive natural number. The absolute and relative tolerance are both set to $1 \cdot 10^{-9}$.
To solve these equations, the approximation of several parameters need to be set. The water content is described by formula 6.14. The derivative is equal to

$$\frac{dw}{d\varphi} = \frac{c - a\varphi^2}{(a\varphi^2 + b\varphi + c)^2} \tag{8.26}$$

The thermal conductivity is implemented as a constant value. the values of the liquid diffusion coefficient, p_1 and p_2 are set as -13.5 and -1.2 in the case of hempcrete. [86] The vapour resistance factor μ is described with formula 6.19, with variable values according the implemented material.
The saturation vapour pressure is described by formula 6.9, where the derivative to the temperature T $[K]$ is equal to

$$\frac{dp_{v,sat}}{dT} = \frac{288.68 \cdot 8.02}{100} \left(1.098 + (T - 273.15)/100\right)^{7.02} \tag{8.27}$$

The exterior temperature, exterior relative humidity, internal heat sources, internal vapour sources and ventilation rate are implemented as matrices, consisting of one column, with on each row a value belonging to a specific hour. When running the program, they will be generated as separately matrices within the file where the Matlab-file Roommodel is located on your computer. The time step can be changed according the input climate data file, for example the climate data for simulating moisture buffering.
A manual of the simulation tool is included within Appendix **??**. It describes the needed inputparameters, what must be changed to obtain specific desired graphs and what is the output. In that input, all used climatic data is including, each in a separated sheet. The output consists of several matrices and graphs. Statisics, heat and moisture fluxes, the solved set of differential equations are given in separate matrices. Several graphs are made after solving the differential equations. Even a video of the behaviour of the vapour pressure within the wall can be generated. More information can be find in the manual.

8.4 Description of standard hempcrete configuration

For the simulation of a hempcrete store, it is obtained to simulate hempcrete storage box number 1 and 5, see figure 3.4 and 3.5. The reason of this choice is the exposed wall area to exterior conditions and the fact that box number 5 will be used for the storage of future heritage objects. The hempcrete wall is in the simulation constructed with the moulded technique, which is chosen because the hygrothermal properties are experimentally determined on moulded samples. In order to know if this was the most optimal choice, it will be compared with the other techniques, precast and sprayed hempcrete, later on. The effect will be investigated when starting on the sorption or on the desorption isotherm.
To integrate the building usage, it is assumed that two persons will work for one hour per week. Due to their activity within the building, their presence will be translated as a heat and vapour source Q_{prod} $[W]$ and G_{vp} $[kg/s]$. For this degree of occupation, Q_{prod} is set as $600W$ ($500W$ from peoples activity and $100W$ from lightning) and $4.58 \cdot 10^{-5}$ kg/s during occupations, otherwise they are set to zero. The occupation will happen each week at Friday from 9 till 10 o′clock.
The air change per hour n is determined by $n50$ and is set to $1/24$ $1/h$. This specific value is set because this is the air change rate that was measured for the Hemcrete

Museum Store in Wroughton.
The properties of the hempcrete store configuration are summarised in table **??** and 8.4.

Table 8.1: Thermal properties of hempcrete used for standard configuration

	$\lambda[W/(mK)]$	C [J/(kgK)]
	0.0814	1200

Table 8.2: Sorption isotherm and vapour diffusion parameters of hempcrete used for standard configuration

	a	b	c
adsorption	-70	61.5	10
Desorption	-31.5	28.5	5
δ	$2.7 \cdot 10^{-11}$	$2.24 \cdot 10^{-11}$	4.94

Table 8.3: Dimensions of hempcrete used for standard configuration

d [m]	$A_{exposed}[m^2]$	V [m^3]	$n_{dev}[-]$	$\rho[kg/m^3]$
0.34	307.38	1363.41	34	460

$c_{air}[J/(kgK)]$	$\rho_{air}[kg/m^3]$	$c_{vap}[J/(kgK)]$	$c_{liq}[J/(kgK)]$	$L_v[J/kg]$	$T_{ref}[K]$
1000	1.25	1864	4186	$2{,}50 \cdot 10^6$	273.15

Table 8.4: Air, vapour and liquid properties

Table 8.5: heat and moisture convective transfer parameters

$h_i[W/(m^2K)]$	$h_e[W/(m^2K)]$	$\beta_e[Pa/(m^2K)]$	$\beta_i[Pa/(m^2K)]$
10	10	$2 \cdot 10^{-8}$	$3 \cdot 10^{-8}$

8.5 Validating room model

To check the the output of the room model, a simulation is done where the interior and exterior relative humidity and temperature is set constant. To obtain an indoor climate which is constant, the minimal and maximal of relative humidity resp. temperature are set to a constant value. The air change rate is set to zero. An adaption witin the program was necessary to obtain a constant exterior climate.

When regarding the matlab-file *Roommodel* it will be clear how this is done. The temperature resp. relative humidity in each layer of the wall are set to one equal value. The conditions are represented in table 8.6. The Pressure and temperature profiles within the wall are are given in figure 8.3 and 8.4. The wall is subdivided in thirty parts. The midlayer is represented by layer 17.
Due to the fact that the vapour pressure and temperature difference across the wall is constant, the vapour pressure and temperature profile across the wall will be linear. The temperature resp. vapour pressure profile increase from the side with the lowest temperature resp. vapour pressure to the side with the highest temperature resp. vapour pressure. After a certain time, this profile can be observed in the upcoming graphs.

TABLE 8.6: Test conditions of interior, exterior and wall

	T[°C]	RH [%]
Indoor conditions	5	90
Wall conditions	15	55
exterior conditions	25	20

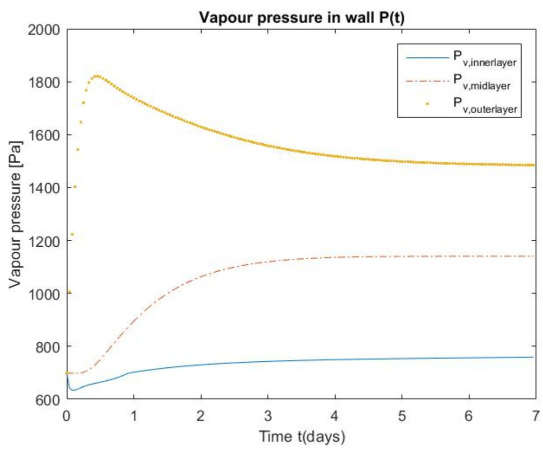

FIGURE 8.3: Vapour pressure profile within wall during validation

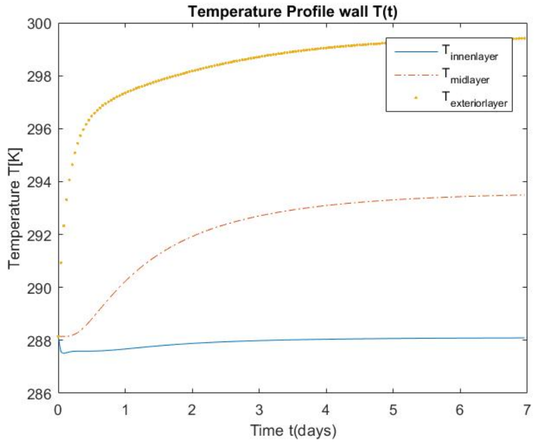

Figure 8.4: Behaviour of the Temperature within wall during validation

8.6 Exterior conditions

The climate restrictions are set on a relative humidity that may vary between 40 and 60 %RH and a temperature that may vary between 10 and 25°C, which are the limits which will be set. The exterior climate is first set to the climate of Uccle, where a weather station of Koninklijk Meteorologisch Instituut of Belgium (KMI) is located. The exact climate data used can be found within in the input file of the simulation tool. Secondly, the influence of the box-in-box principle is analysed by using a climate file which represents the climate with in the shed of the Hempcrete Museum Store. The weather data of Wiltshire, near Wroughton is included in table 8.8. Unfortunately, no exact climate data was presented.

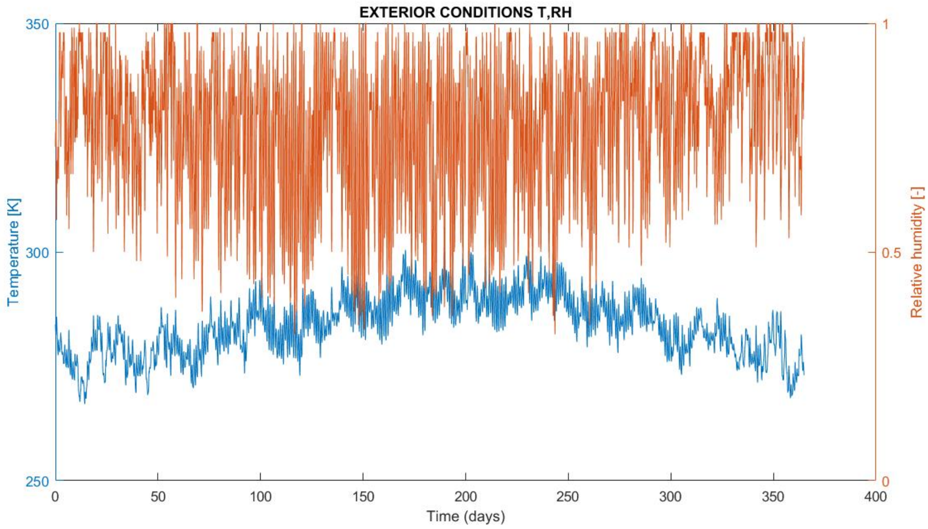

Figure 8.5: Temperature and relative humidity profile Uccle

Table 8.7: Statistics of the used climate file of Uccle

	T [°C]	RH [%]
Yearly average	11.03	77.09
Yearly minimum	-6.4	32
Yearly maximum	32.1	100
Maximal yearly variation	38.5	68
97.5 percentile year	23.9	99
2.5 percentile year	-1.41	44
Mean day variation	7.01	33.81
maximal day variation	15.06	68

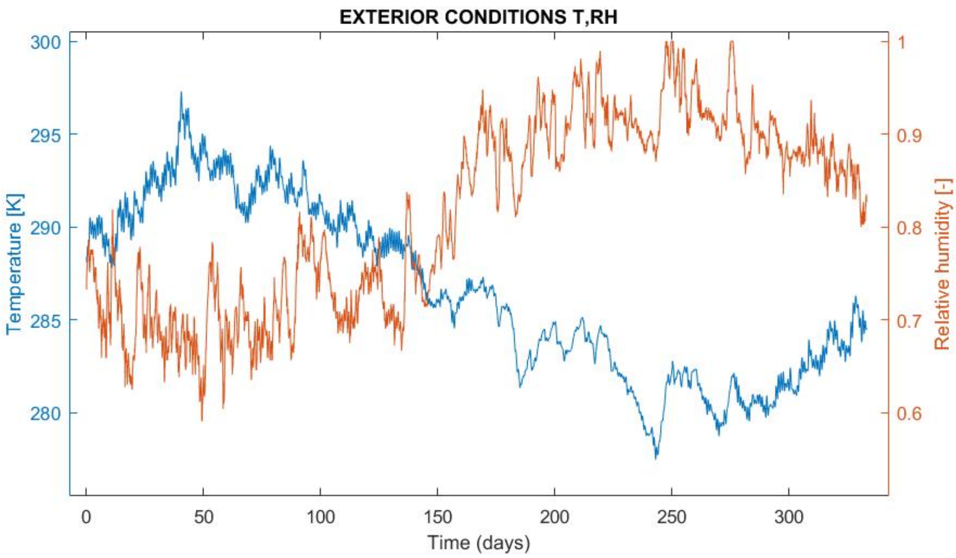

Figure 8.6: Temperature and relative humidity profile Wroughton

Table 8.8: Statistics of the used climate file of the indoor shed

	T [°C]		RH [%]	
	HMS	Wiltshire	HMS	Wiltshire
Yearly average	13.39	9.90	81.48	80
Yearly minimum	4.33	-1.5	59.13	32
Yearly maximum	24.14	26	100	100
Maximal yearly variation	19.81	27.5	40.87	68
97.5 percentile year	21.00	/	97.56	/
2.5 percentile year	6.13	/	65.398	/
Mean day variation	0.84	/	3.07	/
maximal day variation	1.94		/	11.69
/				

8.7 The implementation of an adsorption vs desorption isotherm

It is important to pick an appropriate isotherm. To choose the wright one, a comparison is done of simulations with both isotherms. The weather file of Uccle is used for these simulations. Figure 8.7 represents the behaviour of the relative humidity within the wall, for which the adsorption isotherm was implemented. Within the outer layer, which is exposed to weather conditions, the relative humidity rises up to 100 %. After reaching saturation, the relative humidity remains on this level and decreases only very slow at the end.

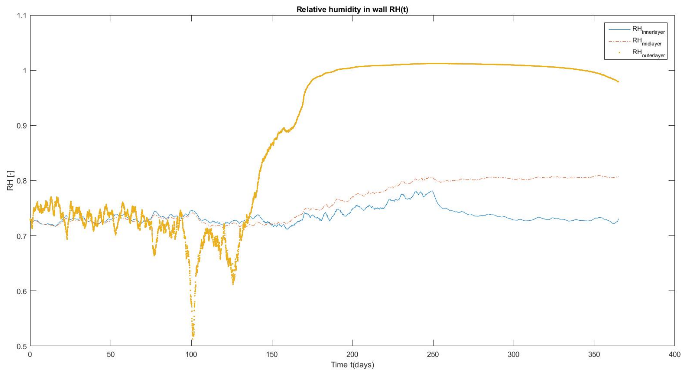

FIGURE 8.7: Behaviour of relative humidity within the wall

It is a remarkable phenomena. The outer layer of the wall remains saturated while the relative humidity of the exterior conditions variate between 65 and 100 %RH with a mean value of 78 % RH. An explanation could be found by the slow drying process of hempcrete. While drying, the relative humidity stays at a constant high level and a after a period of 60 till 120 days, depending on the manufacturing method, the relative humidity starts to decrease [23]. This behaviour will be highlighted later on. The reason why this happens is the fact that the behaviour of hempcrete at high humidity rates, near saturation, was not implemented in the composition of the fitting curves. Hempcrete is able to absorb more then its own mass. Previous researches investigated that samples of hempcrete, with a dry density of 320 kg/m^3 had a moisture content of 546 kg/m^3 [16]. So it is necessary to adapt both sorption isotherms. The results are given in table 8.7. At saturation level, both isotherms have an moisture content of 1 kg/kg. The fitting curves are given in APPENDIX X.The behaviour of the relative humidity and vapour pressure within the wall is given in figure 8.8 and **??**.

TABLE 8.9: Adapted sorption isotherm and vapour diffusion parameters of hempcrete used for standard configuration

	a	b	c
adsorption	-70	61	10
Desorption	-31.5	6.5	6

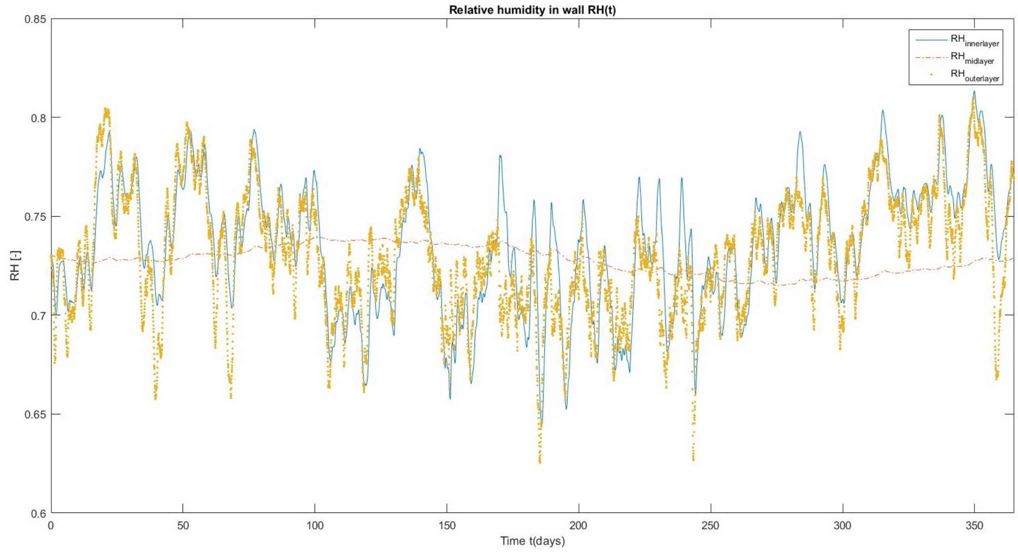

Figure 8.8: Behaviour of relative humidity within the wall with adapted sorption isotherm

The relative humidity rises to 80.97 %RH in the outer layer and to 81.34 %RH. In this region of high humidity ratios it is necessary to adapt the effect of hysteresis. Further simulations will be done by using the desorption isotherm, given in table 8.7. The chanc

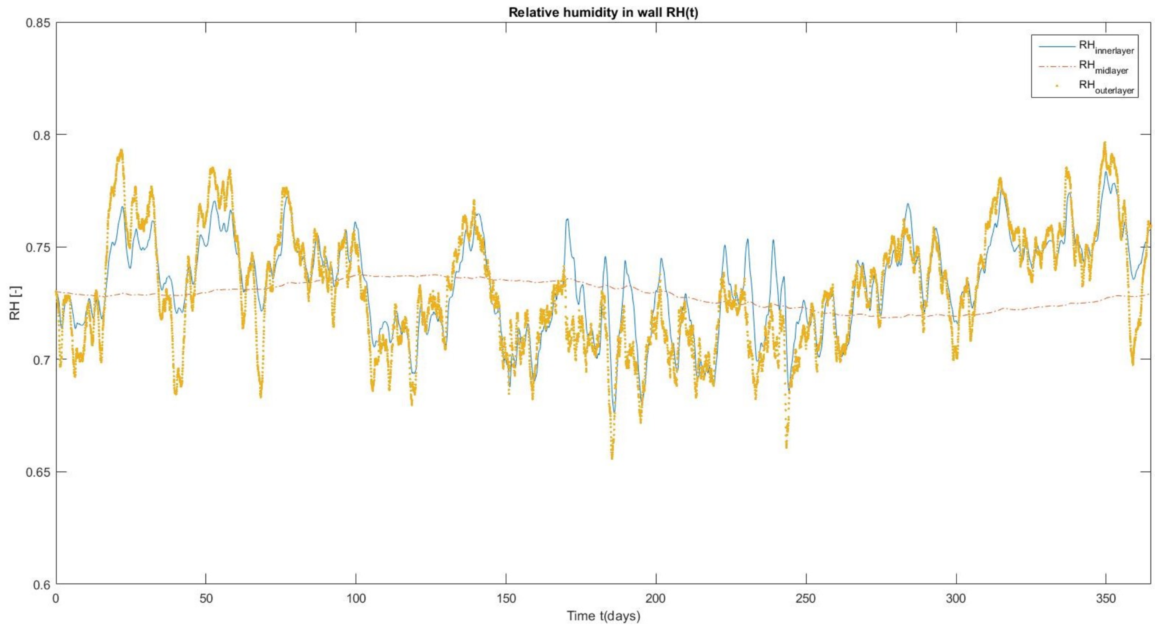

Figure 8.9: Behaviour of relative humidity within the wall with adapted desorption isotherm

8.8 Influence of effective capacitance

The next step will be the determination of the magnitude of the effective capacitance for heat and moisture. In order to analyse the effect of the magnitude, several cases are determined. First, the effective capacitance for heat and moisture are both set to 5, 10, 25 and 45. The relative humidity and temperature for each effective capacitance are given in figure 8.8. Secondly, a the effect of unequal values for the heat and moisture effective capacity will be analysed.

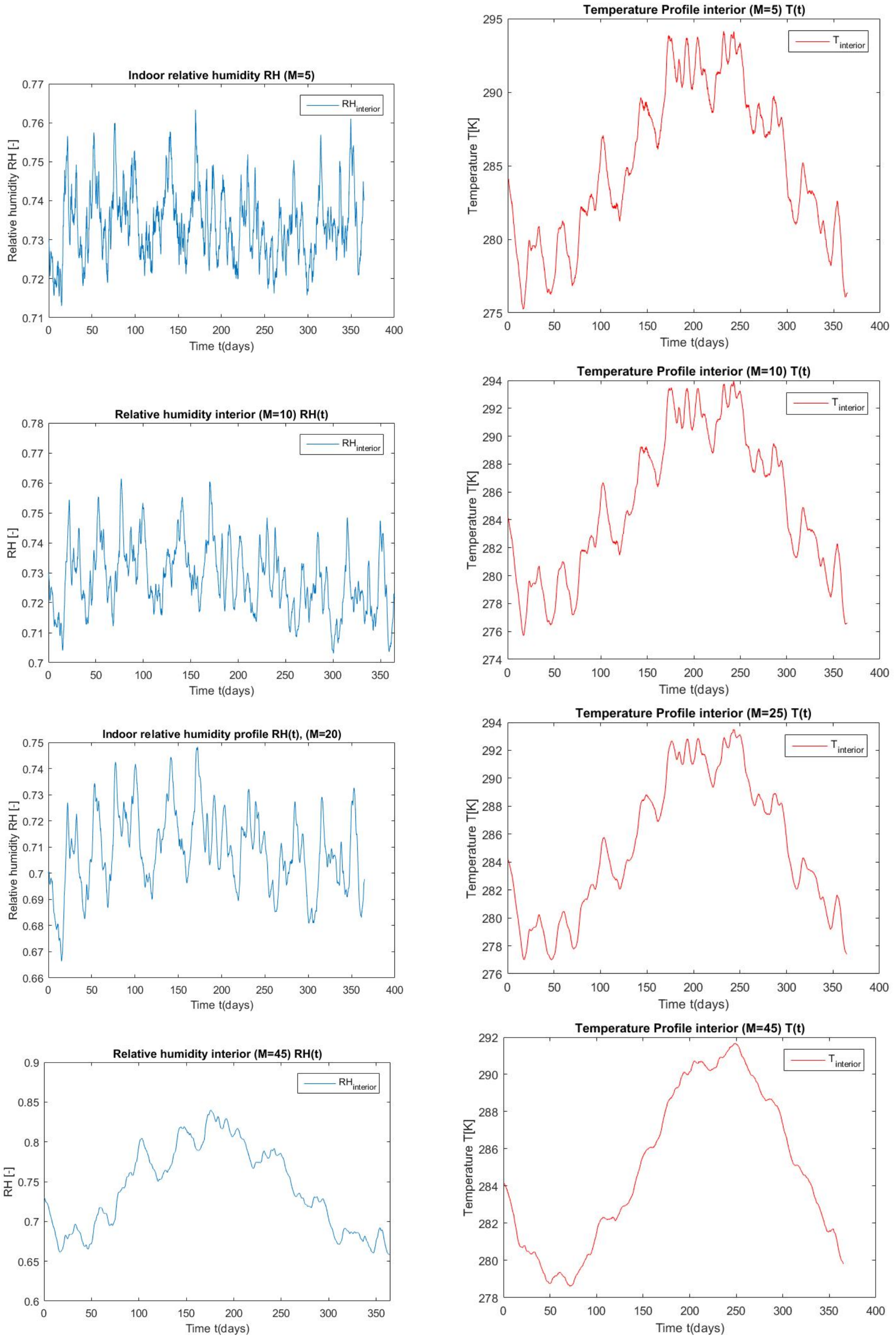

Figure 8.10: The effect of effective capacitance on indoor relative humidity (left) and temperature (right)

In the following figure, different values are set for the effective capacitance for heat and moisture capacity 8.8.

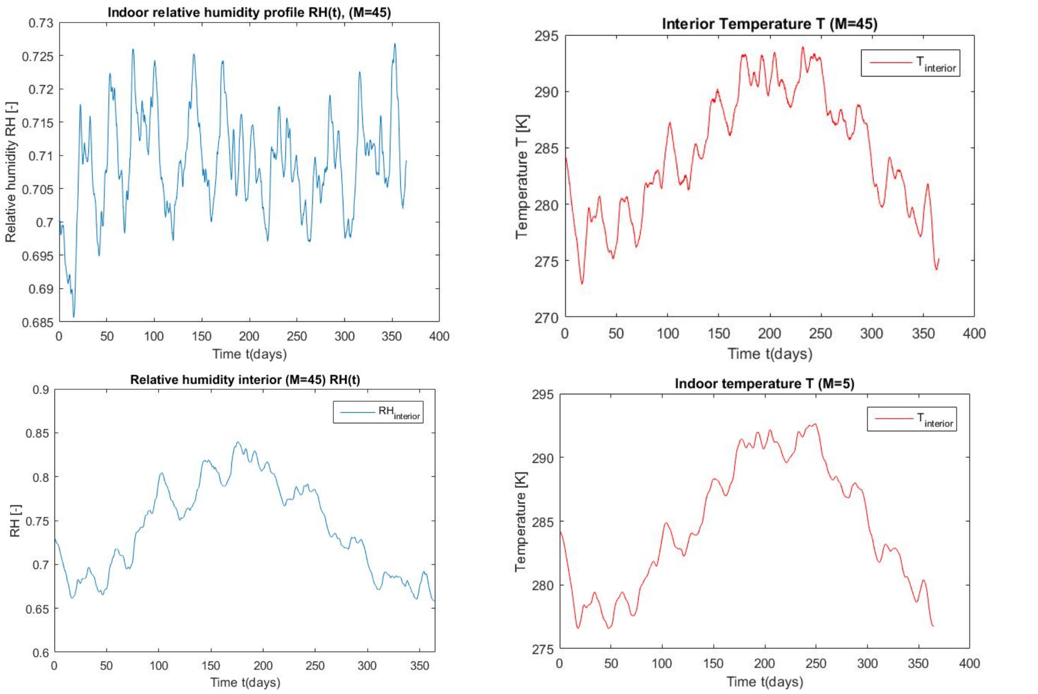

FIGURE 8.11: The effect of different effective capacitance on indoor and relative humidity (left) temperature (right)

To choice for the magnitude of the effective capacitance is based on previous results and on the kind of objects that will be stored within the room and the way they will be stored. Some vulnerable objects are guarded in separate boxes to protect them from possible harmful dusts or gasses coming from other objects. So regarding to table 6.10, a value of 15 seems appropriate for both heat and moisture effective capacitance.

8.9 Energy requirements of the standard configuration

The indoor temperature and relative humidity conditions will be analyses by a simulation. The energy requirements will be determined. The heating and cooling are represented in the same graph since they have the same unit. This will also be the case for the required humidification and dehumidification. Figure 8.12 shows the behaviour of the indoor temperature and relative humidity. The averages and deviations of those parameters are given in table 8.10. it can be remarked that the relative humidity is stable. Regarding to the ASHRAE-assessment, table 2.2, the relative humidity could be categorised as Class A. The temperature does not fulfill to any control class. So the air quality does not fulfill to any class. The energy requirements are given in table 8.11 and the needed HVAC strategy is given in figure 8.13 and 8.14.

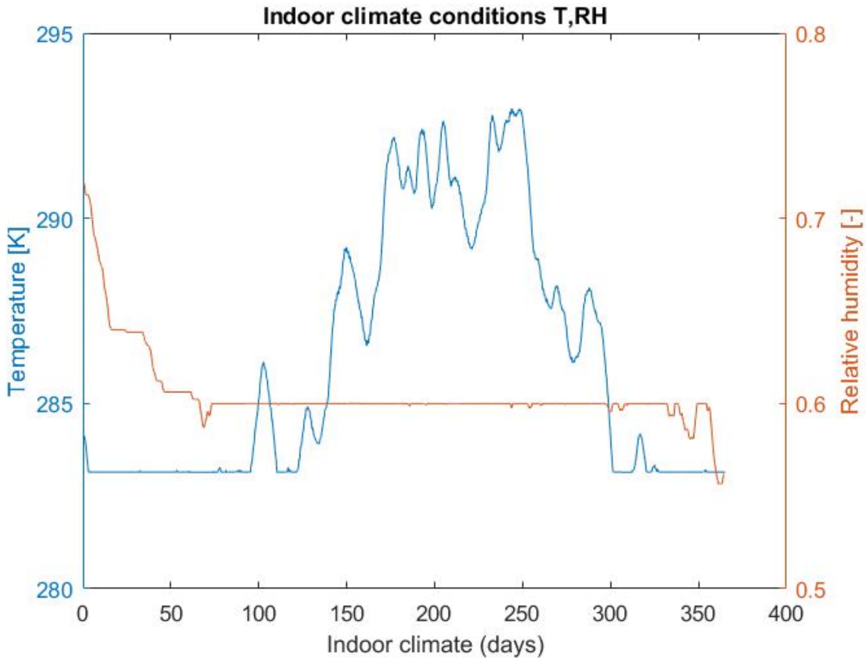

Figure 8.12: Indoor climate for standard configuration

Table 8.10: Temperature and relative humidity behaviour with climate controle

	T [°C]	RH [%]
Yearly average	12.96	60.52
Yearly minimum	10.00	53.99
Yearly maximum	19.81	72.00
Maximal yearly variation	9.81	18.01
97.5 percentile year	19.48	67.87
2.5 percentile year	10	58.14
Mean day variation	0.173	0.25
maximal day variation	0.17	1.73

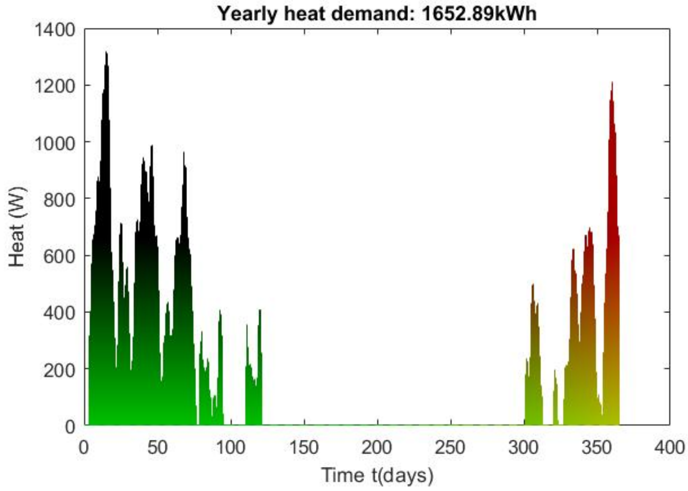

FIGURE 8.13: Heat requirement for standard configuration

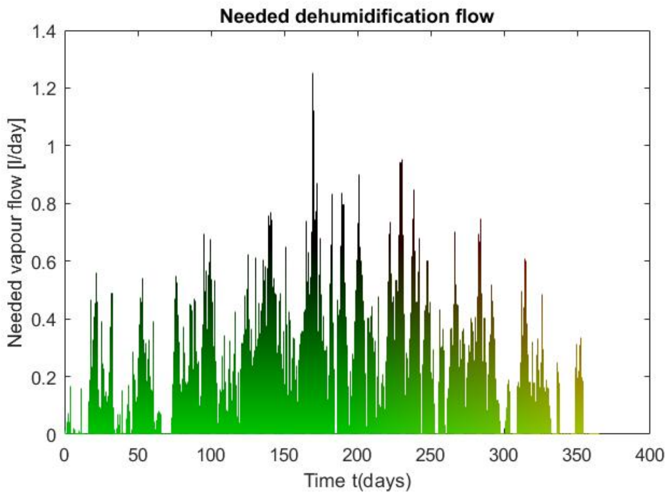

FIGURE 8.14: Dehumidification requirement for standard configuration

TABLE 8.11: Energy requirements standard configuration

	$Q_{heat}[W]$	$Q_{cool}[W]$	$G_{v,dry}[kg/s]$	$G_{v,evap}[kg/s]$
maximal	1319.6	0	$1.45 \cdot 10^{-5}$	0
97,5 percentile	286.82	0	$2.71 \cdot 10^{-6}$	0
Yearly requirement	1659.89 kWh	0	70.43 l	0

Chapter 9

Dynamical behaviour

9.1 Interaction between heat and mass flows

The goal of this section is to investigate the influence of the dynamic interaction between heat and mass flow on the indoor environment. To do this, sudden and real time environmental changes are analysed by comparing the heat and moisture flow determined with and without including the effect of latent heat. To excluded the effect of latent heat, A factor is included within in formula B.1 and B.2, which drops the effect of latent when set as zero and includes the effect when set as one.
The simulations are done with the standard configuration model under consideration that there are no internal heat or moisture gains, there are no objects stored so the effective capacitance factors are set as one.

9.1.1 Sudden environmental changes

To analyse the effect of including latent heat under sudden environmental changes several assumptions are done. The indoor temperature is set as 20 ℃ and the relative humidity is set to 50 %RH. The initial and final conditions in case of sudden cooling and sudden heating are given in table 9.1. This boundary conditions are selected so such the vapour pressure remains constant and only the temperature will vary, such that the enthalpy will only vary due to a changing temperature. The vapour pressure is equal to 820 Pa in case of sudden cooling and equal to 1845 Pa in case of sudden heating.

Table 9.1: Boundary conditions exterior climate in case of sudden cooling and heating

	$T_{initial}$[Ľ]	T_{final}[Ľ]	$RH_{initial}$[%]	RH_{final}[%]
Sudden cooling	20	5	35	95
sudden heating	20	40	80	20

Cooling

The heat fluxes through the wall are visualised in figure 9.1. Because the effect on the inside climate is the point of interest, the flux from out to inside is taken positive.

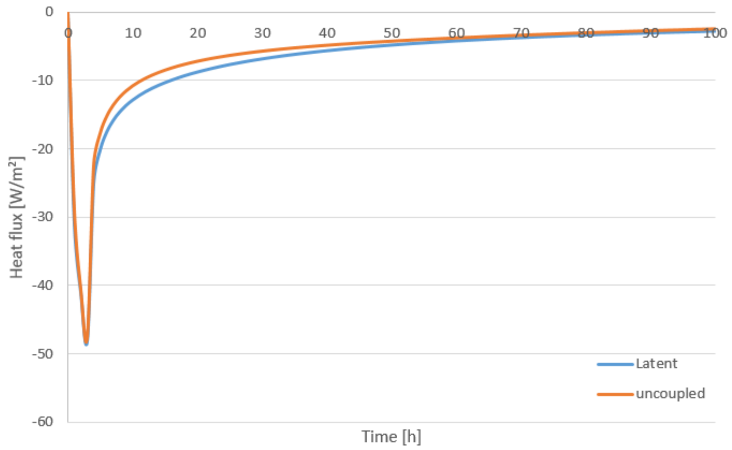

Figure 9.1: Comparison of the heatfluxes due to sudden cooling in case of in- and excluding latent heat

Including latent heat results in a total loss of outward energy equal to 2547.94 kJ, and equal to 2240 kJ. Which means that latent has a negative influence in case of sudden cooling.

Heating

The heat fluxes are visualised in figure 9.2

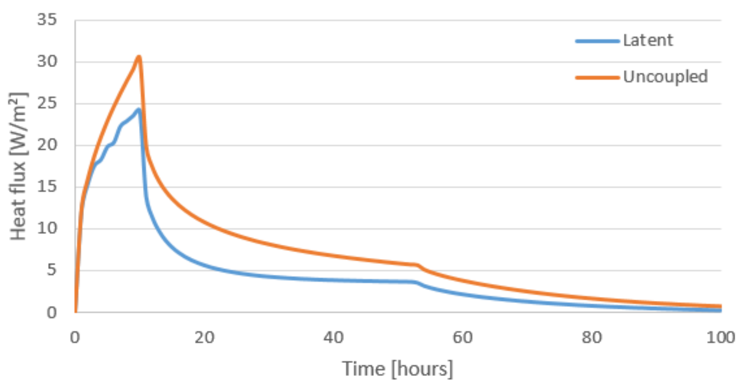

Figure 9.2: Comparison of the heatfluxes due to sudden heating in case of in- and excluding latent heat

In this case the latent heat has a positive effect on the indoor climate. In case including latent heat, the total energy that flows through the wall is equal to 2776 kJ, whereas when excluding latent heat 4241 kJ of energy flow in. This is a rise by 53 %. Evrard and De Herde (REF) measured a difference of 9.6 %.

9.1.2 Real time environmental changes

To see if the latent heat has an effect on the indoor climate, the results of the yearly temperature, relative humidity and energy demand of the standard hempcrete configuration will be compared with a the results from a simulation which excludes latent energy. The needed energy is dependent of the moisture and heat fluxes passing through the wall. The results are given in table 9.3

Table 9.2: Temperature and relative humidity behaviour excluding latent heat

	T [°C]	RH [%]
Yearly average	13.01	58.23
Yearly minimum	9.99	49.72
Yearly maximum	19.87	60.00
Maximal yearly variation	9.88	10.28
97.5 percentile year	19.45	60.00
2.5 percentile year	10.00	51.14
Mean day variation	0.159	0.21
maximal day variation	0.80	1.79

Table 9.3: Temperature and relative humidity behaviour excluding latent heat

Table 9.4: Energy requirements standard configuration excluding latent heat

	$Q_{heat}[W]$	$Q_{cool}[W]$	$G_{v,dry}[kg/s]$	$G_{v,evap}[kg/s]$
maximal	1174.31	0	$1.34 \cdot 10^{-5}$	0
97,5 percentile	911.86	0	$6.52 \cdot 10^{-6}$	0
Yearly requirement	1485.71 kWh	0	42.89 l	0

To compare these values with the one found when including latent heat, the heat flows are compared in table 9.5.

Table 9.5: Energy requirements standard configuration excluding latent heat

	latent heat	Uncoupled	Δ[%]
Inflowing heat [MJ]	99.90	86.96	114.88
Outflowing heat [MJ]	83.83	84.93	88.30

9.1.3 Drying

Hempcrete is able to store a high content of moisture. To investigate the drying kinetics, the moisture content will be set to 100 kg/m^3. Which is equivalent to a relative humidity of 100 %RH n case of the investigated hempcrete, based on the estimated desorption isotherm. The drying conditions are set as 22 ℃ and 50 %RH. It is assumed that both sides of the wall can that part in the drying process. This is why the ventilation rate is set as 1 ACH. The relative humidity profile including resp. excluding latent heat are given in figure 9.3 resp. 9.4.

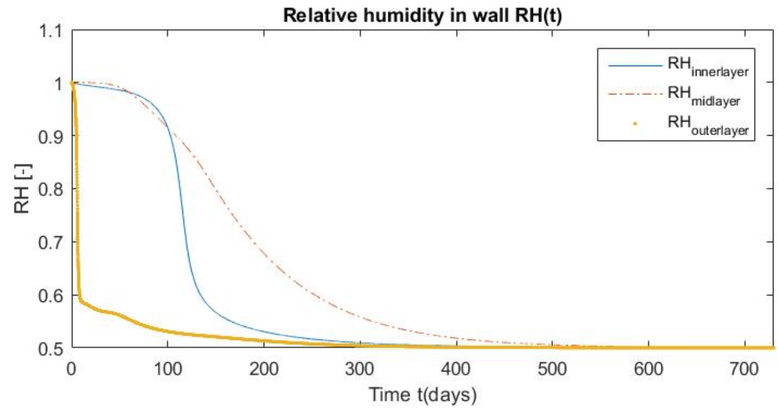

Figure 9.3: Relative humidity profile including latent heat

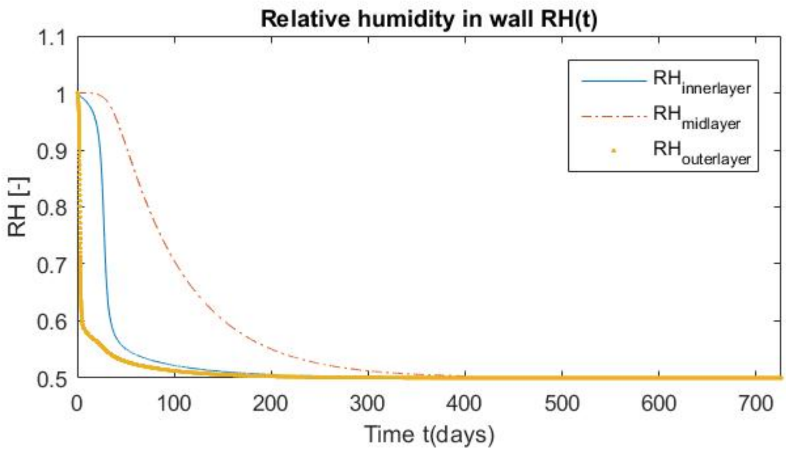

Figure 9.4: Relative humidity profile excluding latent heat

The change is moisture content along the time can be described by Fick′s second law. It states that the change of moisture content by time is related to the gradient of the moisture content by the effective diffusion coefficient of the whole wall. Translated to the results shown in previous graphs, it means that the moisture content of the wall decrease by the square root of the time.

Taking into account latent heat implements a that the time dry is higher compared when excluding latent heat. This means that without taking into account latent heat, hempcrete would dry faster, so that the moisture flux G $[g/(m^2h)]$ would be higher compared with the real model, which is given in 9.5 and 9.6, including the temperature difference of the surface layer compared with the ambient air.

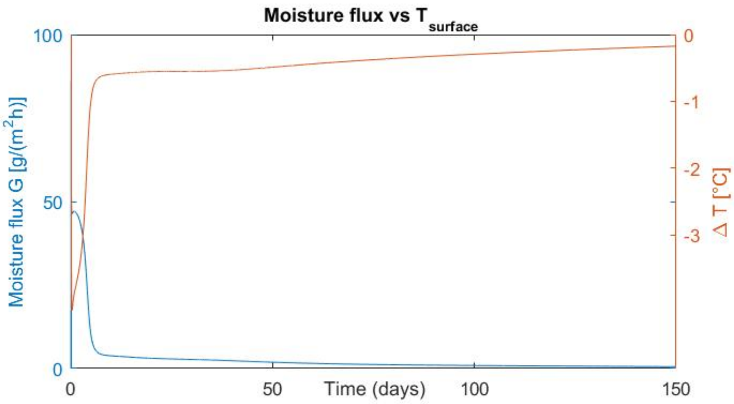

FIGURE 9.5: Moisture flux vs. temperature difference of the surface based on latent heat

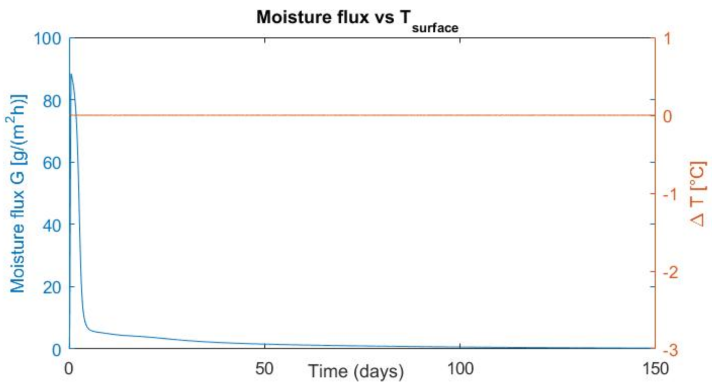

FIGURE 9.6: Moisture flux vs. temperature difference of the surface excluding latent heat

The sudden temperature decrease of the surface layer can be explained by the latent heat effect. Due to lowering of the relative humidity, and so the capillary vapour pressure, moisture with the pores can evaporate, which demand a certain amount of heat.

9.2 Moisture buffer value

As mentioned, hempcrete is classified as excellent moisture buffering material, which means that the moisture buffer value must be higher then 2.00 $g/(m^2\%RH)$. This classification is based on the Nordtest Protocol. It describes the ability of material to buffer an amount of moisture during a 8 hours of high relative humidity, 75 %RH, followed by 16 hours of low relative humidity, 33 %RH when the temperature is kept constant, 23 ℃. A simulation is done to check if the used hempcrete fulfills this classification. The exterior climate is set such that they describes the periodic moisture load according the Nordtest Protocol. Which is shown in figure 9.7.

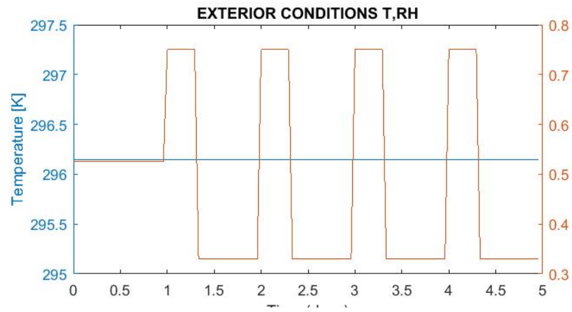

Figure 9.7: Climate conditions according the Nordtest Protocol

The interior temperature is set to 23 ℃and the relative humidity to 52.5 %RH, there is no human activity inside and the air change rate is set to zero. The behaviour of the vapour pressure at a depth of 5 mm is given in figure 9.8, whereas the temperature behaviour is given in figure 9.9.

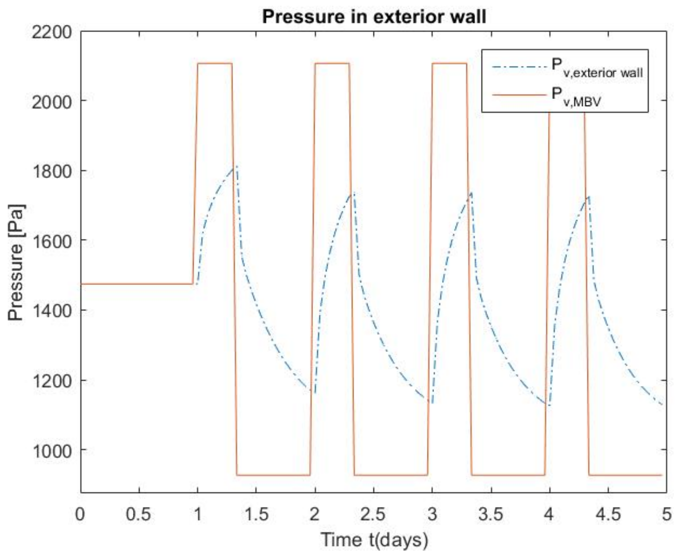

Figure 9.8: Vapour pressure profile at a depth of 5 mm during a MBV-simulation

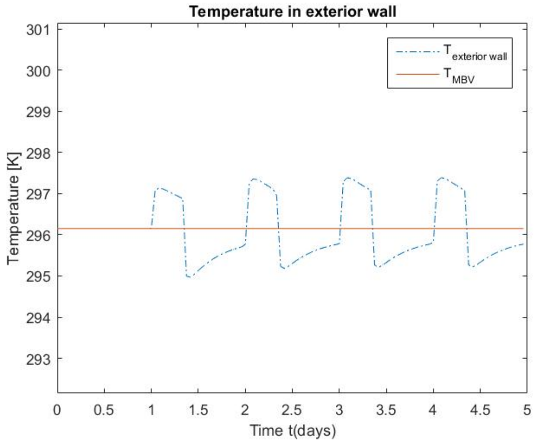

FIGURE 9.9: Temperature profile at a depth of 5 mm during a MBV-simulation

The moisture buffer value itself can be determined according equation 6.22. Δm, the amount of moisture that is buffered within the material, is the integral of the moisture flow which happens during the period of high moisture load. This results in a moisture buffer value 2.30 $g/(m^2\%RH)$ in case of hempcrete. The results from simulations with other materials are given in table

TABLE 9.6: Moisture buffer value of several materials

	Wooden fiber board	cellular concrete	lime silica stone
MBV [g/(m^2%RH)]	1.64	0.70	0.27

Note that for the calculations for lime silica stone and cellular concrete, the wall was divided in fourteen equal parts. The reason why this was done is the fact the simulation tool could not handle a smaller mesh. A smaller mesh results in an imaginary solution, which could be due reaching saturation pressure. For the materials given in previous table, are done with the uncoupled heat and moisture transfer model (latent heat factors set to zero). Table 9.7 gives the moisture buffer values of hempcrete wall constructions with a 20 mm thick finishing layer indicated in the table.

TABLE 9.7: Moisture buffer value of several finishing layers

	Lime plaster	gypsum plaster
MBV [g/(m^2%RH)]	2.14	1.29

9.3 Thermal inertia

Another point of interest is its damping effect. Daily temperature variations are often proposed as thermal cycles. When hempcrete is exposed to a thermal cycle, it has the ability to dampen the incoming heat flow. To show this effect, a cyclic thermal load is applied to the external wall surface of the standard hempcrete configuration. In this setup, the human activity within the building is neglected and the air change rate is set to zero in order to concentrate on the properties of hempcrete. The initial temperature on both sides of the wall is set to 20 °C. The exterior temperature is set such that the period of one cycle is 24 hours. The amplitude of the wave is set to 5 °C. The relative humidity on both sides is set to 50 %RH. The temperature behaviour within the wall is shown in figure 9.10.

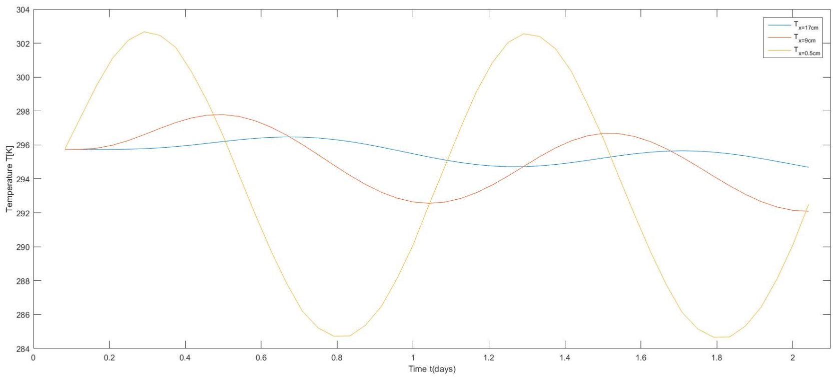

Figure 9.10: Thermal behaviour within a wall under a cyclic load

The thermal wave is dampened in depth. Also a certain thermal discrepancy can be mentioned between the difference curves. This is the increase in time difference between the maximum values of thermal cycles within the depth. This phenomena can be explained by thermal diffusivity a $[m^2/s]$ of hempcrete. Thermal diffusivity is the ease by which a material is able to spread out a sudden increase of heat. The higher the value, the more easily will an increase in surface temperature be spread out, the lower the value the longer it takes. So a good insulation material is one with a thermal diffusivity. It is a material property which is dependent of its density, thermal conductivity and heat capacity. Which can be expressed as

$$a = \lambda/(\rho c) \tag{9.1}$$

In this case, the thermal diffusivity is equal to $1.48 \cdot 10^{-7}$ m^2/s. Comparing this value with lime silica stone (a= 5.68 $\cdot 10^{-7}$ m^2/s) and aerated concrete (a= 4.08 $\cdot 10^{-7}$ m^2/s) hempcrete performs better.
In case of thermal heat flow, this can be translated to thermal effusivity b $J/(m^2 K \sqrt{s})$. It describes the uptake or release of heat at the surface of a material. Materials with a high thermal effusivity are more active as thermal buffering material. Such is

insulation a good insulation material due to its low thermal effusivity. The thermal effusivity is expressed as:

$$b = \sqrt{\rho c \lambda} \tag{9.2}$$

This effect is exemplified in figure 9.11, by comparing the hempcrete with cellular concrete. Initially, the temperature at both sides of the wall is set to 20 ℃, whereas the inside resp. outside relative humidity is set to 50 %RH, resp. 85 %RH. At a certain moment, the external wall surface is exposed to a thermal shock. The outside temperature is set to 40 ℃ and the relative humidity to 25 %RH such that the outside vapour pressure is kept constant.

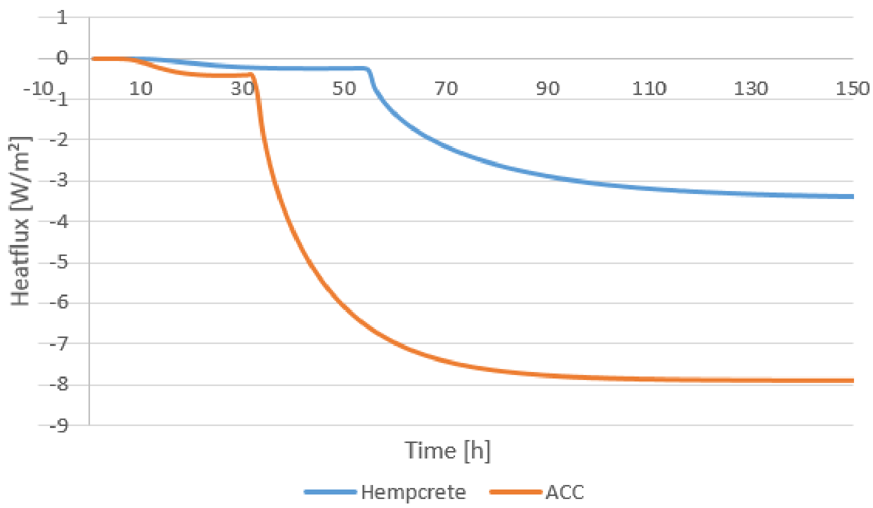

FIGURE 9.11: The effect of thermal effusivity within a slap of ACC and hemcrete

Previous graph shows the heat flux through the inside surface. In case of cellular concrete, it takes 100 days to reach a constant value, whereas it takes 150 days in the case of hempcrete. In terms of thermal effusivity, this means that cellular concrete has higher value compared with hempcrete. This is true, because the thermal effusivity of hempcrete (b = 212.88 $J/(m^2K\sqrt{s})$, is lower then the one of cellular concrete (b = 383.41 $J/(m^2K\sqrt{s})$. Compared with mineral wool (b = 32 $J/(m^2K\sqrt{s})$ this is a rather high value, but low compared with Lime silica stone(b = 1140.32 $J/(m^2K\sqrt{s})$.

Chapter 10

Sensitivity analysis

The object of this chapter is to analyse several deviations of the standard hempcrete configuration. The analysis are done based on the indoor climate conditions and the energy requirements.

10.1 box-in-box principle

Firsty, the effect of the box-in-box principle is investigated. The temperature and relative humidity within the shed of Depot Rato are set to the one of the external climate. This safety factor is then compared with the results of a simulation using climate data measured within the shed of the Hempcrete Museum Store. The results of a simulation of the indoor climate of the standard configuration are given in figure 10.1, which was done for a period of one year, starting in January. The effective capacitance multipliers for heat and moisture are set both as 1, according an empty hempcrete store. The averages and variations of the indoor climate are given in table C.1. It can be concluded that it is not possible to fulfill the requirements for heritage storage without climate control.

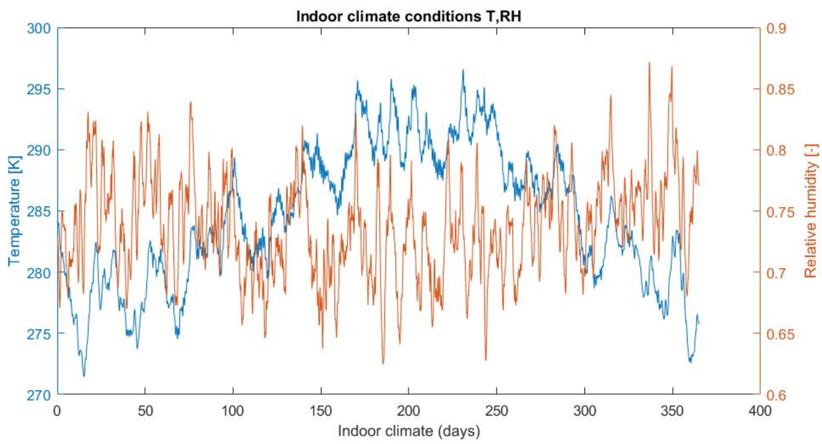

FIGURE 10.1: Indoor conditions without climate control

Table 10.1: Temperature and relative humidity behaviour without climate controle

	T [°C]	φ[%]
Annual average	11.33	73.38
Annual minimum	-0.67	71.50
Annual maximum	21.31	76.15
Maximal Annual variation	21.98	4.65
97.5 percentile year	21.24	75.15
2.5 percentile year	0.76	72.06
Mean day variation	0.57	0.73
maximal day variation	1.69	1.88

In figure 10.2, the indoor conditions are represented for the standard hempcrete store using the climate data measured in the shed of the Hempcrete Musuem Store as exterior conditions. The simulations have started on 22 May and ends on 19 April, due to start data and time span of the received data. The effective capacitance multipliers for heat and moisture are again set both as 1, according an empty hempcrete store. The averages and variations of the indoor climate are given in table **??**. It can be concluded that it is not possible to fulfill the requirements for heritage storage without climate control.

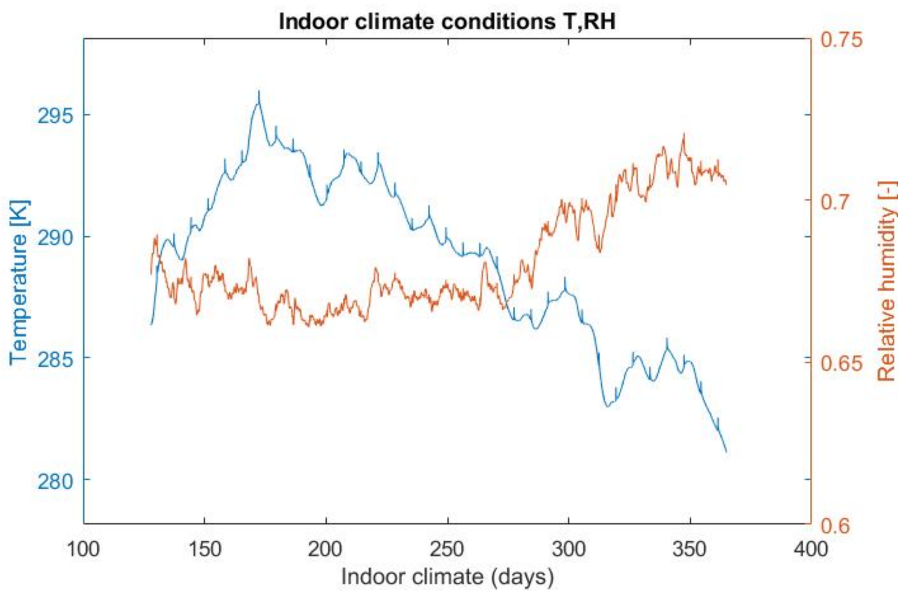

Figure 10.2: Indoor conditions without climate control using climate of HMS shed

Table 10.2: Temperature and relative humidity behaviour without climate control using climate of HMS shed

	T [°C]	φ[%]
Annual average	13.89	74.22
Annual minimum	6.34	71.92
Annual maximum	21.69	74.22
Maximal annual variation	15.35	2.30
97.5 percentile year	20.35	77.66
2.5 percentile year	7.44	72.21
Mean day variation	0.24	0.19
maximal day variation	0.77	0.54

It can be concluded, based on table C.1 and C.1, that the influence of the box-in-box principle is positive on the indoor climate. It must be mentioned that this conclusion is based on the results with a different exterior climate. But it is worth to mention that the annual and daily fluctuations within the hempcrete storage box is dampened when comparing the data from HMS with the one of Uccle.
The data of the climate conditions within the shed of HMS was delivered together with data for the external climate. Unfortunately, there are doubts about the reliability the measurement equipment. An average annual relative humidity of 90.60 %RH was measured with a 50 percentile of 99.90 %RH. This is why no reliable correlation could been made between the indoor climate between the shed of HMS and the one of Depot Rato. The further simulations will therefor be done with the climate data of Uccle. This can be seen as a safety factor.

10.2 Comparison with deviations on the standard configuration

10.2.1 Objective

In this section, the standard store configuration will be compared with several deviating configurations. The comparison is based on the energy requirements and the in- and outgoing moisture and heat fluxes.
The first and second deviation will handle the degree of heritage occupation within the store, a situation with no heritage (EC=5) and a one with a full occupation (EC=25). The third and forth deviation is higher building usage. In the third case, 2 persons will be working 8 hours a day, from 9 till 12 o′ clock and from 13 till 18 o′ clock. In the forth case, a simulation will be done on the effect of a daily occupation during the workweek over a period of 4 weeks, from 9 o′ clock till 13 o′ clock. The fifth and sixth deviation will investigate the influence of a more resp. less airtight building shell. Case 7 will investigate the tightening of the climate requirements. Case 8 resp. 9 compares hempcrete with cellular concrete resp. lime silica brick. The properties of the used materials can be found in the appendix. All the cases are investigated with a same thickness: 340 mm, as prescribed in the program of requirements. The effect of a lime plaster finishing is neglected, based on the comparison between the moisture buffer values of table 9.6 and **??**.

Table 10.3: Deviations

Case	description	Standard	deviation
1	occupation	Normal (EC = 15)	Empty (EC = 5)
2	occupation	Normal (EC =15)	Full (EC=25)
3	Occupation	1h per week, 2 persons	8h per week, 2 persons
4	Occupation	1h per week, 2 persons	4h per workday during 4 weeks, 2 persons
5	Airtightness	0.04 ACH	0.01 ACH
6	Airtightness	0.04 ACH	0.1 ACH
7	Climate conditions	zone C	zone A
8	Building material	Hempcrete	cellular concrete
9	Building material	Hempcrete	Lime silica brick

10.2.2 Needed heat and moisture supply

Heat

The results of this sensitivity analysis are given in the following figures. Case zero represents the standard hempcrete configuration. The results are given in appendix ??.

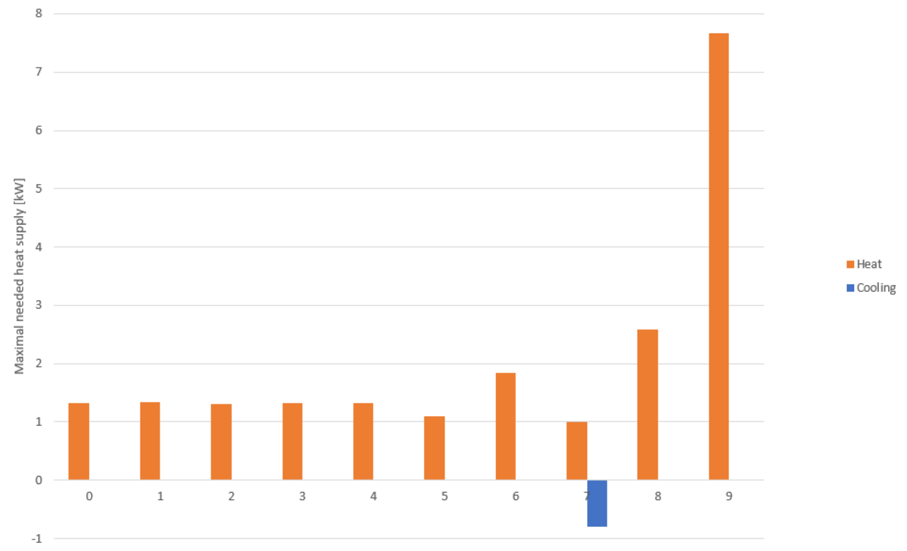

FIGURE 10.3: Maximal needed heat and cooling supply for the investigated cases

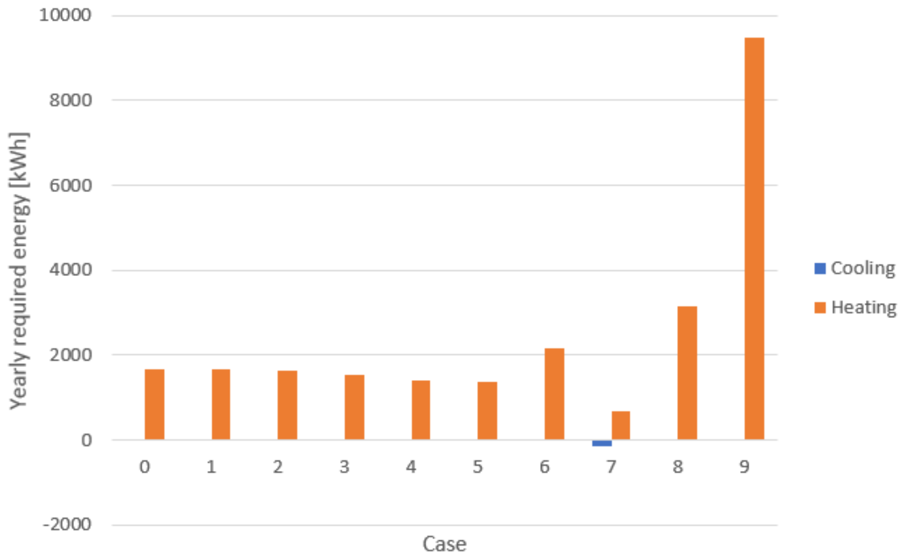

FIGURE 10.4: Yaerly heat demand for the investigated cases

Dehumidification

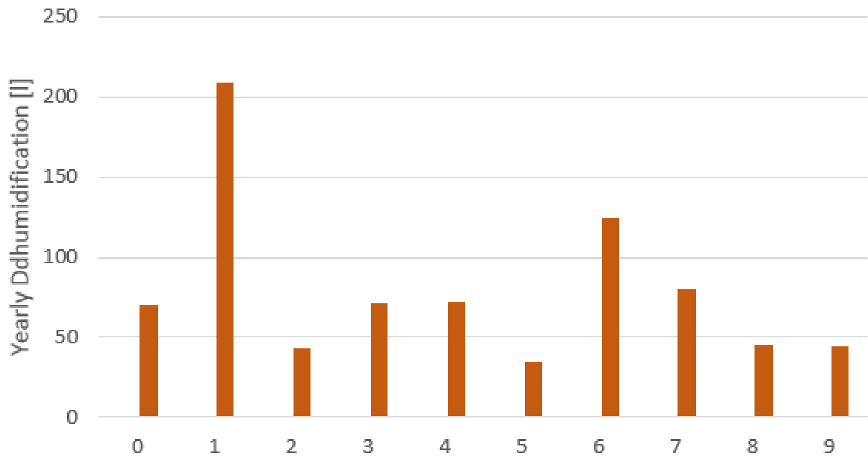

Figure 10.5: Yearly dehumidification demand for the investigated cases

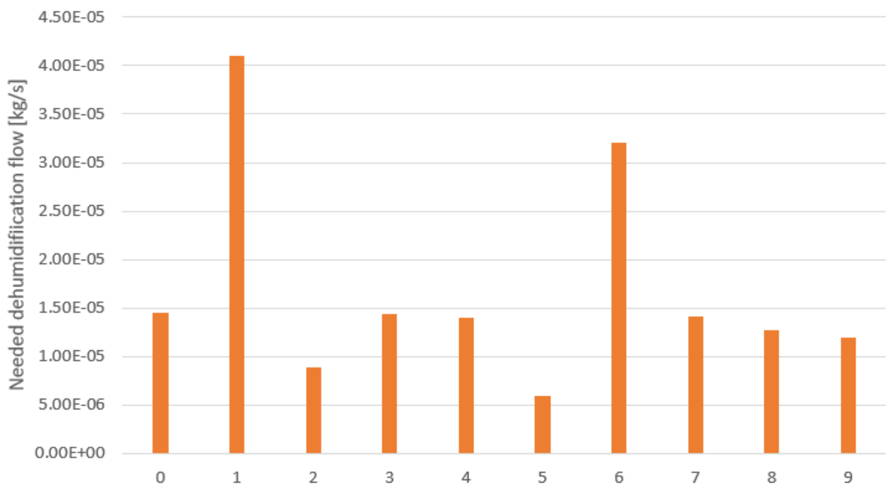

Figure 10.6: Maximal needed dehumidification flow for the investaged cases

Discussion

Comparing previous graphs and regarding the related values in Appendix **??**, the following conclusions can be made.
The configuration with lime silica brick asks a lot more of energy for heating compared with the other configurations. This can be explained by its high thermal conductivity ($\lambda = 0.85$ W/mK). But in turn, it has a lower demand of dehumidification compared with the standard configuration. A more air tight building shell performs better.
Setting a stringent indoor climate range, case 7, implements the need of a cooling

equipment. A possible solution for this problem is a dehumidifier based on condensation. Which is based on the cooling of air such that the saturation range is reach and a certain amount of vapour is extracted from the external air by further cooling. This cool air could then be used to lower the internal temperature. The profit of this combined proposal is the fact that cooling as well dehumidification is needed in summer. This equipment could be expand for usage in winter by heating the out flowing air in winter.
The degree of occupation has a small influence on the heating requirement. The spread of occupation is profitable for the amount of needed heat supply. Whereas it has it consequences on the needed drying.
The air tightness has a bigger influence on the vapour treatment compared with the demands relating to heat. The occupations seems to have less In case of heating, hempcrete performs better compared with cellular concrete lime silica brick.
It is worth to mention that implementing the effective capacitance of the stored heritage has a high impact on the needed dehumidification. Setting a low effective capacitance implements a higher demand of dehumidification flow. As mention before, this is due to effect that a high effect capacitance is more able to temper short term fluctuations.

10.2.3 Effect of different wall set up on indoor climate

The second point of interest is the effect of each case on the stability of the indoor climate. The comparison is done based on the assumption that there are no internal restrictions on the interior climate. The results of the simulations are given in table 10.4 and table 10.5.

Table 10.4: Temperature variations for of the deviating cases

T [°C]	0	8	9
Annual mean	11.31	11.20	11.10
Annual maximum	20.07	20.93	22.31
Annual minimum	0.46	-1.17	-2.66
Yearly deviation	19.61	22.10	24.98
97.5 percentile	19.67	20.04	20.65
2.5 percentile	2.14	1.03	0.08
mean daily variation	0.34	0.48	0.75
maximal daily variation	1.1	1.51	2.36

Table 10.5: Relative humidity variations for of the deviating cases

RH [%]	0	8	9
Annual mean	72.78	74.60	75.19
Annual maximum	75.74	82.03	83.93
Annual minimum	69.62	69.14	70.19
Yearly deviation	6.12	12.89	13.74
97.5 percentile	75.18	79.70	81.10
0.025 percentile	70.42	70.07	70.82
mean daily variation	0.04	0.59	0.62
maximal day variation	1.59	2.2	2.44

The fluctuations of relative humidity and temperature in case of hempcrete are lower compared with cellular concrete and lime silica stone. This proofs the statement that hempcrete performs as a good damping and buffering material.

10.3 Final proposal

The fact that hempcrete is a moisture buffer value is presented as an advantage for the material. Nevertheless, it could also been seen as a negative property. When a large vapour pressure difference is set over the wall, so when the relative humidity is high at one side compared with the other, a permanent moisture flow could occur. This phenomena needs to be prevented. Equalise the vapour pressure at both sides is hardly impossible without an excessive energy demand. A possible proposal is treating one surface of the wall with a coating which functions as a vapour barrier. A vapour barrier increases the diffusion resistance significantly. Vapour barriers and vapour retarders can be implemented in simulation tools by their equivalent vapour diffusion thickness s_d [m], which can be described as

$$s_d = \mu \cdot d$$

(10.1)

Since vapour barriers and retarders are often coatings, it is hard to estimate the the layer thickness. An alternative is the usage of surface coefficients. The surface transfer coefficient for vapour, β, will be set to a low value.
To treat the hempcrete surface, which is highly porous, it is recommended to first apply a prime surface layer. This could be done for example by a lime-plaster.
To investigate the influence of an vapour barrier coating as exterior finishing layer, a comparison is made between cellular concrete and hempcrete. It is a the vapour barrier with a s_d-value of 1000 m with a thickness of 0.2 mm is . This implies a vapour diffusion resistance of $5 \cdot 10^6$. Therefor, the vapour surface transfer coefficient is set to $1.9 \cdot 10^{-13}$ $kg/(m^2 sPa)$. The initial temperature is set to the start conditions of the climate data, which is 11 °C. The relative humidity within the wall is set to 50 %RH, which is often preferred. The results of the simulation of period of four years is shown in figure 10.3. The results of the needed energy requirements are given in table 10.6. The climate statistics are given in table C.4. Again, hempcrete performs better then cellular concrete. Remark that energy demand in case of cellular concrete is twice as high compared with hempcrete.

TABLE 10.6: Heat and moisture requirements for optimal proposal for hempcrete and ACC

	Dehumidification [kg/s]		Heat demand [W]	
	Hempcrete	ACC	Hempcrete	ACC
Yearly requirement	1.09 kg	6.12 kg	1241.43 kWh	2670.82 kWh
Yearly maximum	$3.99 \cdot 10^{-6}$	$4.07 \cdot 10^{-6}$	1093.19	2373.97
97.5 percentile	$5.89 \cdot 10^{-7}$	$1.50 \cdot 10^{-6}$	831.48	1766.61

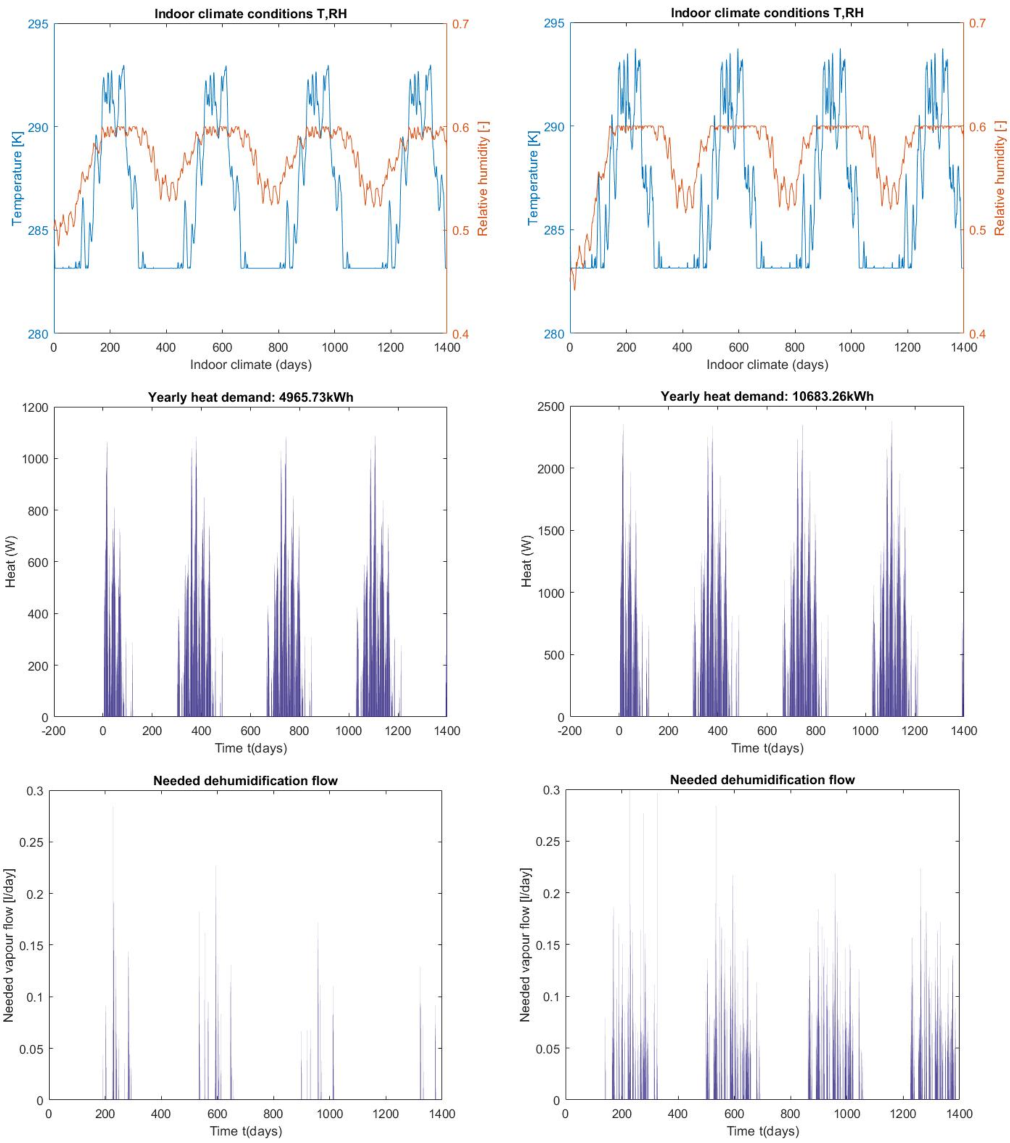

Figure 10.7: Comparison of hempcrete (left) and cellular concrete (right) in case of vapour barrier

In case no restrictions are set to the interior climate, relative humidity remains very stable as shown in figure 10.8.

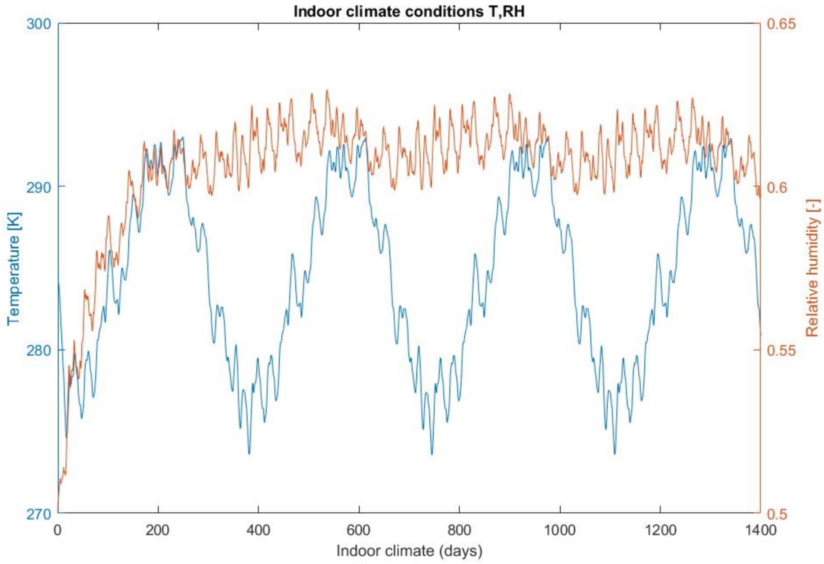

FIGURE 10.8: Temperature and relative humidity behaviour in case of optimal proposal without climate control

Chapter 11

Conclusion

In a society, where the need for a transition to sustainable materials is higher then ever, hempcrete could be the solution. Hempcrete has good thermal performances and it is classified as a excellent moisture buffering material. Another advantage is the carbon dioxide buffering capacity of hempcrete. In the path of manufacturing, from hemp seed till end product, it absorbs more energy then was needed to produce the end product.

Nevertheless, hempcrete is at this moment in its development phase of transition, which means that their is barely movement in the building material market. To accelerate the transition and the move hempcrete to the take-off phase, several hazards need to be overcome. Those hazards are mainly based on conservative thoughts, Why choose for a new material while the conventional building material are still performing well? An effective way to change these thoughts is the presentation of an clear answer by providing facts and data.

An example of a sector which demands a design stringent climate conditions is the heritage storage sector. It demands a very stable indoor climate. To obtain such indoor conditions, it a good design of the building shell is essential. During the design, a certain wall set up and ventilation strategy has to be pointed out. A material that fulfills the requirements for heritage storage, a stable indoor climate, is hempcrete, based on its hygrothermal performances.

An attempt was made to determine the material characteristics of hempcrete. The specimens used for the diffusion and sorption isotherm test were extracted out of a large sample. Due to the fragility of the specimens, the results of the experimental determined vapour diffusivity resistance factor did not match the results found in literature. Due to a lack of time, it was not possible to restart the test. The results of the scanning test were not reliable. An investigation pointed out that one salt was saturated.

The effect of latent heat on the heat and moisture transport through within hempcrete was analysed. It can be concluded, based on the simulations, that latent heat has a high impact on the heat and moisture transport. It must be mentioned that their is a deviation between the results found in literature, which could be explained by several assumption that were maid in the composition of the simulation tool.

The simulations showed that hempcrete can be classified is an excellent moisture buffer value, based on the Nordtest Protocol classification. The influence of a lime-plaster as finishing layers on the Moisture Buffer Value was small, in the order 1%. It appears, based on simulations, that hempcrete performs well compared with conventional building materials used for heritage storage, like cellular concrete and lime silica stone. These results prove the hygrothermal privileges of hempcrete.
An attempt is made to serve an optimal proposal. The optimal proposal is a hempcrete wall with an exterior finishing layer and a building shell which is more air tight. The finishing layer which consists of vapour barrier. When the used vapour barrier is a coating, a surface treatment with lime is suggested, due to porosity of hempcrete. Based on the simulations with this wall setup, hempcrete performs better then cellular concrete. The yearly energy demand for heating can be lowered with a factor two when using hempcrete compared with cellular concrete. The yearly requirements for dehumidification was nearly six times higher compared with a cellular concrete construction. The fluctuations of the indoor climate were lower for a hempcrete wall.
In the future it may be worth to analyse the effect of scanning and to implement it in the roommodel. To complete the model, the interaction between the earth and the roof could be implemented. To compare theory and the real behaviour of hempcrete, a monitoring of the indoor climate and the conditions within the wall would be useful.

Appendices

Appendix A

Characterisation of specimens

A.1 Sorption behaviour

A.1.1 Dimensions of specimens

TABLE A.1: Dimensions of specimens

Specimen	Dimensions [cm^3]	Volume [cm^3]
1	6.06 x 4.92 x 4.967	148.09
2	6.057 x 4.956 x 4.848	145.53
3	6.002 x 4.891 x 5.278	154.94
4	5.88 x 4.99 x 4.68	137.32
5	5.96 x 4.96 x 4.89	148.65
6	5.97 x 4.98 x 5.00	148.65
7	4.97 x 5.04 x 6.00	150.29
8	4.85 x 4.94 x 4.93	118.12
9	4.93 x 4.8 x 5.00	118.32
10	4.82 x 4.89 x 4.84	114.08
11	4.83 x 5.15 x 4.78	118.90
12	4.86 x 4.86 x 4.93	116.44
13	5.11 x 4.89 x 6.83	170.67
14	5.1 x 4.99 x 5.15	131.06
15	5.08 x 4.82 x 5.07	124.14
16	5.97 x 5.2 x 4.92	152.73
17	4.9 x 4.98 x 4.87	118.84
18	4.85 x 5.1 x 5.15	127.39

A.1.2 Drying

In table the mass of the samples before and after drying in a furnace, by 50 ℃ and 5 %RH, are given in table A.2, including the calculated initial gravimetric moisture content. The main value of the initial gravimetric moisture content is equal to 0.0460 kg/kg, with a maximal variation of 9.90 $\cdot 10^{-3}$ kg/kg.

Table A.2: Mass of specimens before and after drying and there initial gravimetric water content

Specimen	$m_i[g]$	$m_f[g]$	$\Delta m[g]$	$u_i[kg/kg]$	$\rho[kg/m^3]$
1	55.569	52.788	2.771	0.0525	356.45
2	56.910	54.585	2.325	0.0426	375.08
3	59.271	56.671	2.600	0.0459	365.74
4	62.686	59.727	2.959	0.0495	434.96
5	68.446	65.464	2.982	0.0455	452.86
6	69.025	66.131	2.894	0.0438	444.87
7	62.709	60.043	2.666	0.0444	399.51
8	53.474	51.220	2.254	0.0440	433.63
9	49.840	47.573	2.267	0.0477	402.07
10	51.549	49.242	2.307	0.0468	431.65
11	48.021	54.860	2.161	0.0471	385.71
12	48.954	46.818	2.136	0.0456	402.06
13	62.095	59.248	2.847	0.0481	347.15
14	54.151	51.910	2.241	0.0432	396.07
15	56.136	53.815	2.321	0.0431	433.50
16	66.502	63.640	2.862	0.0450	416.66
17	46.568	44.472	2.096	0.0471	374.22
18	42.482	40.601	1.881	0.0463	318.73

A.1.3 Scanning

The results of the scanning curves are given in table A.3

TABLE A.3: Measurement data scanning curves

set	Specimen	density	Step 1		Step 2		Step 3	
			kg/kg	RH	kg/kg	RH	kg/kg	RH
1	1	356.45	0.024692	0.33	0.05107	0.43	0.049238	0.54
1	2	375.08	0.024547	0.33	0.050676	0.43	0.049077	0.54
1	3	365.76	0.053975	0.33	0.080192	0.43	0.078307	0.54
2	4	434.96	0.05336	0.43	0.033338	0.33	0.043267	0.43
2	5	452.86	0.053359	0.43	0.033368	0.33	0.043657	0.43
2	6	444.87	0.055245	0.43	0.030561	0.33	0.042022	0.43
3	7	399.51	0.042393	0.43	0.040934	0.54	0.040772	0.65
3	8	433.63	0.042307	0.43	0.04078	0.54	0.04078	0.65
3	9	402.07	0.040687	0.43	0.0391	0.54	0.0391	0.65
4	10	431.65	0.023336	0.54	0.021677	0.65	0.021775	0.54
4	11	385.70	0.044358	0.54	0.041412	0.65	0.041833	0.54
4	12	402.06	0.022621	0.54	0.021006	0.65	0.021107	0.54
5	13	347.15	0.040751	0.54	0.041731	0.43	0.032741	0.33
5	14	396.07	0.010499	0.54	0.010688	0.43	0.008282	0.33
5	15	433.50	0.020704	0.54	0.021071	0.43	0.016761	0.33
6	16	416.67	0.022926	0.65	0.025841	0.54	0.027899	0.43
6	17	374.22	0.018945	0.65	0.022009	0.54	0.023745	0.43
6	18	318.73	0.018414	0.65	0.020892	0.54	0.0224	0.43

A.1.4 Isotherm

TABLE A.4: Measurement data sorption isotherm

Specimen	RH	m [g]	u [kg/kg]
1	86	57.41	0.051619
2	86	59.42	0.056187
3	86	63.38	0.086018
4	94	66.38	0.080544
5	94	73.57	0.081435
6	94	73.65	0.082133
7	65	64.2	0.040772
8	65	54.53	0.040589
9	65	52.37	0.038902
10	75	104.88	0.023629
11	75	49.66	0.04499
12	75	101.32	0.022722
13	33	62.93	0.028655
14	33	213.41	0.007055
15	33	110.66	0.014652
16	43	119.22	0.022154
17	43	99.85	0.019762
18	43	94.49	0.018091

A.2 diffusion resistance

Table A.5: Weight of specimens during diffusion resistance test

	1	2	3	4	5	6
8/3/2016 16:00	1.147297	1.116121	1.085465	1.024368	0.944805	0.990173
14/03/2016 16:00	1.147303	1.117232	1.08544	1.024317	0.944566	0.982407
21/03/2016 16:00	1.14726	1.118708	1.085315	1.024172	0.944443	0.981009
25/03/2016 17:00	1.147254	1.11926	1.085184	1.024054	0.944214	0.977659
30/03/2016 17:00	1.147199	1.120415	1.085105	1.023967	0.944141	0.976586
4/4/2016 17:00	1.147136	1.121024	1.084929	1.023907	0.94391	0.974628
12/4/2016 9:00	1.146981	1.122478	1.08487	1.023738	0.94354	0.973979
18/04/2016 17:00	1.146889	1.123187	1.084768	1.023695	0.943358	0.973201

Appendix B

Manual of simulation tool

B.1 Composition of the differential equations

Initially, an room model based on uncoupled heat transfer was preformed. During the investigation of the transition of hempcrete the question emerged if latent heat has a high contribution within the heat and vapour transfer. This is way the choice was made to switch to a coupled heat and moisture transfer model.
The differential equations are included within the Matlab-file *divfunc.m*. This matlab is written as a function such that the file can be called by ODE45, the differential equation solution tool of matlab. A set of differential equations is composed to determine the behaviour of the temperature and the relative humidity of the internal air and within the wall of the hempcrete standard configuration. This means that if the wall is divided in n parts, $n+1$ differential equations will be composed to include the interior air. For each zone there are two unknown parameters: temperature and vapour pressure. This is why the set of differential equations consists out of $2 \cdot (n_{dev1} + n_{dev2} + 1)$ equations, which are represented as $dx(1), dx(2), ..., dx(2 * (n_{dev1} + n_{dev2} + 2)$.
The choice is made to work with temperature T and relative humidity ratio φ due to available information about the material. The odd parameters $(x(1), x(3), ...)$ represent the temperature, the even represent the relative humidity $(x(2), x(4), ...)$. This is done such that two consecutive parameters, an odd and an even, belongs to a specific point. So $x(1)$ and $x(2)$ belong to the interior, $x(3)$ and $x(4)$ belong to the first inner layer of the wall, $x(2 * n_{dev1} + 1$ and $x(n_{dev2} + 2)$ is the contact layer of wall part 1 and wall part 2. The outer layer of wall part 2, so the surface layer in contact with the shed, is describe by $x(2 * (n_{dev1} + n_{dev2} + 1)$ and $x(2 * (n_{dev1} + n_{dev2}) + 2)$. This is indicated in figure B.1.

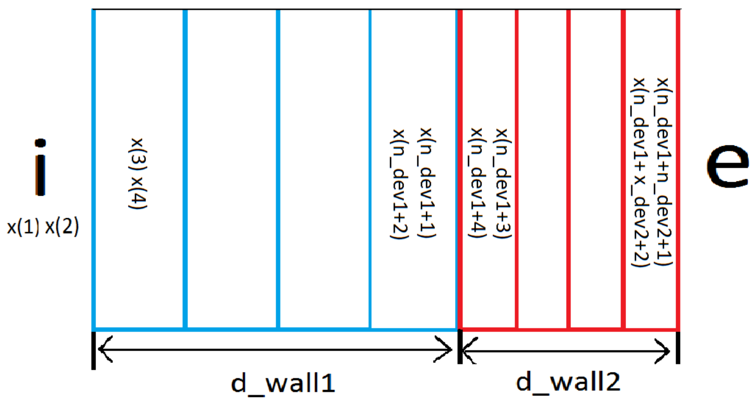

Figure B.1: Indication of the parameters

B.2 Manual of the simulation tool

B.2.1 Input files

There is one input file which consists of several sheets. Notice that the climate file of bath has a period of 333 days. 1 month of data was missing.
The sheets corresponding the exterior moisture and vapour load are given in table B.1.

Table B.1: location Climate data

Sheet	Climate data
2	UCCLE
3	Bath (within shed)
4	MBV PROTOCOL
5	SUDDEN HEATING
6	SUDDEN COOLING
7	THERMAL CYCLES (Damping)
8	DRYING

Material and storage input file

The first sheet asks the material and storage parameters. The sheet is represented in table B.2 and B.3. n_{dev1} and n_{dev2} needs to be set higher then 2 because the set of differential equations is composed with minimal three (when n_dev is equal to one) differential equations belonging to a wall part.

TABLE B.2: Fist part of input file

TIME		
Time t [days]	365	
Climate	2	
MATERIAL PROPERTIES		
	Layer 1	Layer 2
Thickness		
d [m]	0.32	0.2
mesh size		
n_dev [-]	32	4
heat		
$\lambda[W/mK]$	0.072	0.25
c [J/kgK]	1300	925
mass		
$\rho[kg/m^3$	460	1200
permeability		
a	-31.5	-110
b	26.5	112
c	6	2
Sorption isotherm		
a	2.7E-11	2.7E-11
b	2.24E-10	2.24E-10
c	4.94	4.94
Liquid transfer properties		
p1	-13.5	-10.461
p2	0.12	0.159

B.3 How to run a simulation

A simulation can be done by opening the matlab file Roommodel.m and to run the file.
To choose another temperature file, change the sheet number at line 4. Beware to pick the the wright sheet within the INPUT file. The start conditions within the

Table B.3: Second part of input file

ROOM PROPERTIES	
V [m^3]	1026.66667
A_wall [m^2]	263.67
n [1/h]	0.04
RH_min [-]	0.40
RH_max [-]	0.60
T_min [K]	283.15
T_max [K]	298.15
T_initial [K]	
M_heat [-]	15
M_moist [-]	15
AIR PROPERTIES	
$R_v [J/kgK]$	462
$c_{air} [J/kgK]$	1000
$\rho_a ir [kg/m^3]$	1.25
h_i [W/($m^2 K$)]	10
h_e [W/($m^2 K$)]	10
$\beta_i [kg/(m^2 Pa)]$	$2 \cdot 10^{-8}$
$\beta_e [kg/(m^2 Pa)]$	$2 \cdot 10^{-8}$
d_air	1.9 ·10−10
C_liq [J/(kgK)]	4186
C_vap [J/(kgK)]	1864
Lv [J/kg]	$2.5 \cdot 10^6$
T_ref [K]	273.15
Latent heat factor [-]	1

wall can be set at line 124 and 125 within the file Roommodel. When it is preferred to have a linear changing humidity, choose the code on line 127.

B.4 How to run a video

As mentioned, it is possible to show the behaviour of the vapour pressure within the wall during a certain period. To obtain such a video. The lines 357 til 392 needs to be unlocked. Beware, it asks memory and time to run long periods.

B.5 Differential equations

Addition of Latent heat factors.

$$\rho_s(c_{p,s} + L_{lat} w c_{p,l})\frac{\partial T}{\partial t} = -\nabla \bullet (-\lambda \nabla T) + \nabla \bullet (D_v^{\varphi} \nabla \varphi + D_v^T \nabla T) \times L_{lat}(L_v + (c_{p,v} - c_{p,l})(T - T_{ref}) \quad \text{(B.1)}$$

$$\rho_s \theta \frac{\partial \varphi}{\partial t} = -\nabla \bullet (-(D_l^{\varphi} + D_v^{\varphi})\nabla \varphi - L_{lat} D_v^T \nabla T) \quad \text{(B.2)}$$

B.6 Output

In the folder where the Roommodel-matlab is stored, several graphs will be generated. The heat and moisture fluxes are given matrices. The right column represents the net flux through the material. Positive values correspond to a net flux from in- to outside. Negative values corresond a net flux from outside to inside. The statics are constructed as follows:

Table B.4: Indication of output statistical data

T [°C]	RH [%]
Annual mean	Annual mean
Annual maximum	Annual maximum
Annual minimum	Annual minimum
Mean daily variation	Mean daily variation
Max daily variation	max daily variation

Appendix C

Sensitivity analysis

C.1 Material properties

TABLE C.1: Temperature and relative humidity behaviour without climate controle

	Lime plaster	Lime silica stone	WFB	ACC
reference	[86]	[20]	[52]	[72]
sorption isotherm				
a	-70	-400	-58	-350
b	61	440	62	352
c	10	10	1	0.5
vapour diffusion coefficient				
a $[10^{-11}]$	3.2	0.65	1.8	1.9
b $[\cdot 10^{-10}]$	5.0	0.084	0.7	0.05
c	8.38	2	4.4	5
Liquid diffusion				
p1	-10.461	/	/	/
p2	-0.159	/	/	/
thermal properties				
$\lambda[W/mK]$	0.3	0.86	0.3	0.2
C [J/(kgK)]	925	840	1700	1050
Mass properties				
$\rho[kg/m^3]$	1200	1800	750	700

C.2 Outputdata of cases

C.2.1 Heat

Table C.2: Results from simulations of the specific cases (0-4)

Case	0	1	2	3	4
Energy					
heating					
sum [kWh]	1659.89	1680.08	1625.38	1545.01	1394.54
max [W]	1319.6	1337.07	1303.58	1318.31	1316.07
0.975 [W]	286.82	1025.50	991.01	990.24	958.58
cooling					
sum [kWh]	0	0	0	0	0
max [W]	0	0	0	0	0
0.975 [W]	0	0	0	0	0
Gevap					
sum [kg]	0	0	0	0	0
max [kg/s]	0	0	0	0	0
0.975[kg/s]	0	0	0	0	0
Gdry					
sum [kg]	70.43	208.7874	42.77	71.12	72.41
max [$\cdot 10^{-6} kg/s$]	14.5	41.00	8.94	14.35	13.9
0.975[$\cdot 10^{-6} kg/s$]	2.71	20.70	4.52	7.38	7.53
Temperature [°C]					
mean	12.99	12.94	13.13	13.36	12.95
max	20.45	19.65	20.33	20.69	19.73
min	10.00	10.00	10.00	10.00	10.00
Annual variation	10.47	9.66	10.34	10.6	9.74
meandayvar	0.23	0.13	0.21	0.23	0.14
maxdayvar	1.24	0.71	0.93	0.97	0.83
$\varphi[-]$					
mean	0.60	0.60	0.60	0.60	0.64
max	0.60	0.60	0.60	0.60	0.64
min	0.55	0.56	0.56	0.58	
	0.05	0.04	0.04	0.04	0.06
meandayvar	0.0011	0.0006	0.00083	0.0008	0.0003
maxdayvar	0.0152	0.0083	0.0115	0.0091	0.0049

Table C.3: Results from simulations of the specific cases (5-9)

Case	5	6	7	8	9
Case	5	6	7	8	9
Energy					
heating					
sum [kWh]	1366.97	2180.65	692.41	3162.01	9482.38
max [W]	1090.77	1842.27	1002.84	2580.31	7673.39
0.975 [W]	830.86	1357.02	682.98	1955.07	5728.45
cooling					
sum [kWh]	0.00	0.00	-137.64	0.00	0.00
max [W]	0.00	0.00	-796.74	0.00	0.00
0.975 [W]	0.00	0.00	-241.59	0.00	0.00
Gevap					
sum [kg]	0.00	0.00	0.00	0.00	0.00
max [kg/s]	0.00	0.00	0.00	0.00	0.00
0.975 [kg/s]	0.00	0.00	0.00	0.00	0.00
Gdry					
sum [kg]	34.70	123.72	79.60	44.70	44.01
max [kg/s]	0.00	0.00	0.00	0.00	0.00
0.975[kg/s]	0.00	0.00	0.00	0.00	0.00
Temperature [°C]					
mean	13.01	11.69	12.95	13.07	13.07
max	20.11	18.01	19.80	22.28	22.28
min	10.00	6.99	10.00	9.99	9.99
	10.12	11.02	9.81	12.29	12.29
meandayvar	0.22	0.20	0.17	0.41	0.41
maxdayvar	1.06	0.91	0.95	2.02	2.02
$\varphi[-]$					
mean	0.60	0.63	0.60	0.60	0.60
max	0.60	0.63	0.72	0.73	0.73
min	0.52	0.58	0.55	0.52	0.52
	0.08	0.05	0.17	0.21	0.21
meandayvar	0.0004	0.0008	0.0023	0.0023	0.0008
maxdayvar	0.0233	0.0117	0.0252	0.0252	0.0116

C.3 Optimal proposal

Table C.4: Climate statistic for optimal proposal with hempcrete and AAC

T [°C]		RH [%]		
	Hemcrete	ACC	Hempcrete	ACC
Annual mean	13.16	13.16	57.14	57.49
Annual maximum	19.84	20.59	60.00	60.00
Annual minimum	9.99	10.00	48.44	44.14
Annual variation	9.85	10.60	11.56	15.86
97.5 percentile	19.44	19.92	60.00	60.00
2.5 percentile	10.00	10.00	50.48	46.86
Daily variation	0.16	0.25	0.16	0.14
Daily variation	0.81	1.47	0.65	0.76

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Fiche masterproef

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Titel: Hempcrete as a sustainable material for heritage storage; applicability and transition

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Korte inhoud:
Deze thesis beschrijft het gebruik en de transitie van kalkhennep als duurzaam materiaal voor erfgoed opslag. Het nieuwe erfgoed depot *Depot Rato* is de rode draad in van dit onderzoek. Om de transitie beschrijven zijn er verscheidende interviews met professionelen, aannemers, conservators en producenten vooraf gegaan. Hieruit is getracht een objectief beeld te scheppen over de transitie van kalkhennep. Om de hygrothermische eigenschappen van het materiaal na te zijn de thermische geleidbaarheid, warmte capaciteit, dampdiffusieweerstand en absorptie isotherm bepaald. Deze parameters zijn vervolgens gebruikt als gegevens voor verscheidene simulaties. Om de hygrothermische eigenschappen van het materiaal te simuleren is er een model samengesteld. In dit model worden de temperatuur en de relatieve vochtigheid gekoppeld om zo het effect van de latente warmte in rekening te kunnen brengen. Hierna is er onderzoek verricht naar de invloed van de latente warmte, de bepaling van de Moisture Buffer Value (MBV) en het drogingsproces. Uiteindelijk is er aan de hand va het simulatie model een gevoeligheidsanalyse uitgevoerd om zo afwijkingen met van het ontwerp te anlyseren. Na deze analyse is er een finaal voorstel gedaan van een optimale wandopbouw, dit gerelateerd aan het ontwerp van het depot.

Thesis voorgedragen tot het behalen van de graad van Master of Science in de ingenieurswetenschappen: bouwkunde, optie Gebouwentechniek

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