Carey J. Simonson, Mikael Salonvaara&
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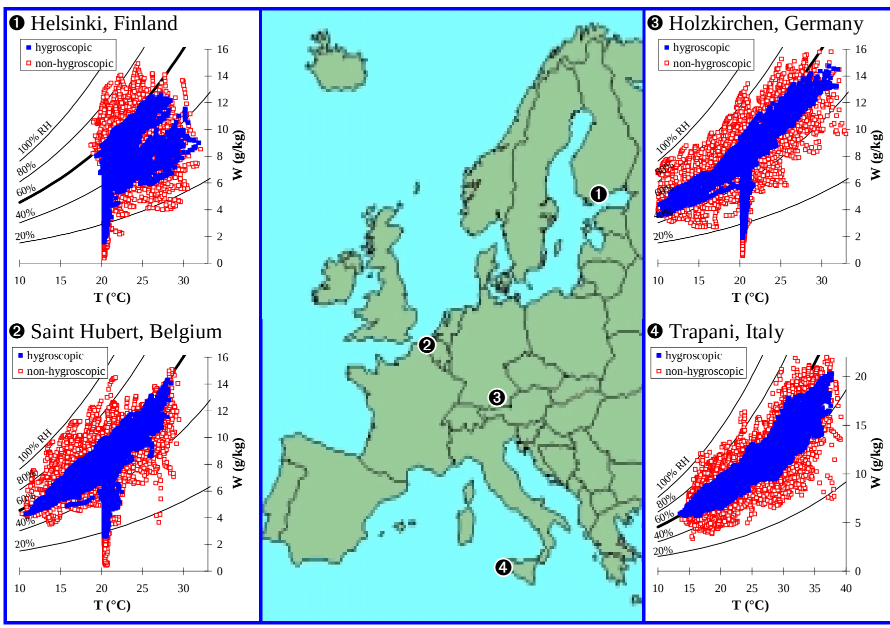
Improving Indoor Climate and Comfort with Wooden Structures



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Keywords indoor air quality, indoor climate, wooden structures, construction, moisture, mass transfer, heat transfer, building envelope, thermal comfort, fungi, apartment buildings, ventilation

Abstract

In this report, the moisture performance of a bedroom in a wooden apartment building is studied numerically using hourly weather data from 4 different cities (Helsinki, Finland, Saint Hubert, Belgium, Holzkirchen, Germany and Trapani, Italy). The bedroom is occupied for 9 hours by two adults during the night (22:00 to 7:00), the volume is 32.4 m^3 and the wall surface area is 60 m^2. With the basic input parameters (moisture production of 60g/h, ventilation rate of 0.5 ach and a permeable internal coating on the ceiling and walls) the moisture transfer between indoor air and the building structure is very active. With these parameters, the moisture transfer between indoor air and structures can significantly improve the indoor climate and air quality compared to the case where the internal coating is vapour tight. Moisture storage in wood based materials can reduce the peak humidity during the night and this moisture can then be removed by ventilation air during the following day. In general (at a ventilation rate of 0.5 ach), the indoor humidity is close to the outdoor humidity when the occupants enter the room (22:00) for all structures and materials. The increase in absolute humidity during the night is quite independent of the climate, but the amount of time when the indoor climate and air quality are unsatisfactory is very dependent on the climate. Passive methods of controlling the indoor climate are naturally more successful in moderate climates than in hot and humid climates, even though they provide benefits in all climates.

With the basic input parameters, there are many materials that can realise an enhanced moisture performance. For example, either a hygroscopic wallboard or hygroscopic insulation can provide good performance. However, when there is a hygroscopic wallboard, the insulation behind the wallboard has little effect on the performance. Therefore, the indoor moisture level of a room with a hygroscopic wallboard is quite insensitive to the hygroscopicity of the insulation and the vapour resistance of the elements behind the wallboard. When there is hygroscopic insulation behind a non-hygroscopic and permeable wallboard (most wallboard materials have some hygroscopicity), the performance is only slightly worse than when there is a hygroscopic wallboard. These results are for the basic input parameters and the difference between different materials and solutions becomes more important when: the moisture production increases, the ventilation rate decreases, the active area decreases, the vapour resistance of the paint increases or during long term weather changes. With the basic parameters, the risk of mould growth is low, but the risk increases as the moisture production rate increases.

The simulation results in this report demonstrate that thermal mass and solar shading are important for moderating indoor temperatures in northern and central European climates, but even a structure with a high thermal mass performs poorly in southern Europe when there is no heating or cooling. A room with a massive wooden floor and ceiling (200 mm) has a similar thermal performance as a room with a concrete floor and ceiling (200 mm). Also, moisture transfer can help cool the room when the outdoor temperature increases.

The sensitivity of the ventilation rate is analysed and the results show that ventilation is very important for removing moisture, especially when an impermeable coating is applied. The increase in humidity during the night becomes greater as the ventilation rate decreases for all cases. With a permeable paint and a ventilation rate of 0.1 ach, the indoor air humidity increases on average by 7.4 g/h during the night, which is equivalent to the humidity increase when the ventilation rate is 0.9 ach and the paint is impermeable. Nevertheless, the amount of time that the indoor humidity exceed 60% RH during occupation, decreases as the ventilation rate decreases because the indoor temperature increases as the ventilation rate decreases. The thermal comfort and perceived indoor air quality at the end of occupation can be similar with 0.1 ach and a permeable paint as with 0.25 ach and an impermeable paint.

As the moisture production increases, the fraction of the produced moisture that is stored in the wall increases very slightly. The moisture removed by the ventilation air, the moisture removed by the hygroscopic structure and moisture that remains in the indoor air are nearly linearly dependent on the rate of moisture production.

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Tiivistelmä

Tässä raportissa tarkastellaan sisäilman kosteustasoja ja kosteusteknistä toimintaa. Tarkastelu tehtiin numeerisesti puurakenteisen kerrostalon makuuhuoneelle käyttäen reunaehtoina neljän eri paikkakunnan tunneittain ilmoitettuja ulkoilman olosuhteita. Tarkastellut paikkakunnat olivat Helsinki, Saint Hubert Belgiassa, Holzkirchen Saksassa ja Trapani Italiassa. Tarkastellun makuuhuoneen koko on 32.4 m^3 ja sen seinäpinta-ala on 60 m^2. Sisäilman kosteuskuormitus (60 g/h) aiheutuu kahden hengen 9 tuntia kestävästä oleskelusta huonetilassa (klo 22:00 - 07:00). Huoneen ilmanvaihtokerroin on 0.5 1/h. Kun seinä- ja kattorakenteiden sisäpinnat ovat hyvin vesihöyryä läpäiseviä, on kosteusvirtaus sisäilman ja rakenteiden välillä hyvin aktiivista. Näissä olosuhteissa kosteusvirtaus sisäilman ja rakenteiden välillä voi olennaisesti parantaa sisäilman laatua verrattuna tapaukseen, jossa rakenteiden sisäpinta on höyrytiivis. Kosteuden varastoituminen puupohjaisiin materiaaleihin voi alentaa sisäilman suhteellisen kosteuden yöllisen kuormitustilanteen aikaisia huippuarvoja ja varastoitunut kosteus voidaan poistaa rakennuksesta ilmanvaihdon avulla seuraavan päivän aikana. Yleensä, rakenteista ja materiaaleista riippumatta, ilmanvaihdon ollessa 0.5 1/h sisäilman kosteustaso on lähellä ulkoilman vastaavaa tasoa kun huonetilan kuormitus alkaa (klo 22:00). Sisäilman absoluuttisen kosteustason nousu kuormituksen aikana ei juurikaan riipu ilmastosta, mutta se aika, jonka sisäilman laatu on epätyydyttävä, on voimakkaasti ilmastosta riippuva. Passiiviset menetelmät sisäilman olosuhteiden säätelemiseksi ovat luonnollisesti toimivampia leudoissa ilmastoissa kuin kuumissa ja

kosteissa oloissa, vaikkakin ne kaikissa ilmastoissa parantavat sisäilman tilaa.

Oletuksen mukaisessa tilanteessa useilla materiaaleilla voidaan aikaansaada sisäilman kosteuden kannalta hyvä vuorovaikutus. Tällaisia materiaaleja ovat esimerkiksi hygroskooppinen (kosteutta materiaaliin sitova) sisäverhouslevy tai hygroskooppinen lämmöneristys. Kuitenkin lämmöneristeellä, joka on hygroskooppisen sisäverhouslevyn takana, on vain pieni vaikutus sisäilman kosteuteen. Sen vuoksi sisäilman kosteustaso ei juurikaan riipu hygroskooppisen sisäverhouslevyn takana olevan lämmöneristeen hygroskooppisuudesta tai levyn takana olevan kerroksen vesihöyrynvastuksesta. Kun ei-hygroskooppisen (kosteutta heikosti sitovan) ja kosteutta hyvin läpäisevän sisäverhouslevyn (useimmat seinälevymateriaalit kuitenkin ovat hygroskooppisia) takana on hygroskooppinen lämmöneristys, kosteusvaikutus sisäilmaan on vain hiukan heikompi kuin tapauksessa, jossa on pelkästään hygroskooppisen sisäverhouslevy. Nämä tulokset pätevät edellä esitetyillä perusoletuksilla ja erot eri materiaalien ja sovellutusratkaisujen välillä tulevat edellistä merkittävämmiksi silloin kun: kosteustuotto kasvaa, ilmanvaihto pienenee, aktiivinen pinta-ala pienenee tai sisäverhouksen maalin vesihöyrynvastus kasvaa sekä pitkäaikaisten, useita päiviä tai viikkoja kestävien säämuutosten aikana. Perusoletuksen mukaisissa tapauksissa riski homeen kasvusta rakenteissa on pieni, mutta riski lisääntyy kun sisäilman kosteuskuormitus kasvaa.

Tässä raportissa esitetyt numeeriset simulointitulokset osoittavat, että terminen massa ja auringon varjostus ovat tärkeitä tekijöitä sisäilman lämpötilahuippujen tasoittamisessa Pohjois- ja Keski-Euroopan ilmastoissa. Sen sijaan Etelä-Euroopassa rakenteiden suurikaan terminen massa ei yksinään riitä varmistamaan sisäilman viihtyisyyttä, jollei rakennuksessa ole lämmitystä ja jäähdytystä. Jos huoneessa on massiivinen puulattia ja katto (200 mm), sen lämpötekninen toimivuus on samanlainen kuin vastaavan paksuisten betoniseinämien kanssa. Myös kosteuden siirtyminen voi auttaa huoneen jäähdytyksessä silloin kun ulkoilman lämpötila nousee.

Ilmanvaihtomäärän vaikutukset on analysoitu ja tulokset osoittavat, että ilmanvaihto on hyvin tärkeä tekijä kosteuden poistamisessa sisäilmasta erityisesti silloin, kun huoneen seinämät on käsitelty vesihöyryä läpäisemättömiksi. Kuormituksen aikainen huoneilman kosteustason muutos (kasvu) suurenee kaikissa tapauksissa silloin kun ilmanvaihtomäärä laskee. Kun seinämissä on vesihöyryä läpäisevä maalipinta ja ilmanvaihtokerroin on 0.1 1/h, kasvaa sisäilman kosteustaso yön aikana keskimäärin 7.4 g/h. Tämä vastaa kosteustason muutosta tilanteessa, jossa seinämien sisäpinta on käsitelty vesihöyryä läpäisemättömäksi ja ilmanvaihtokerroin on 0.9 1/h. Tästä huolimatta, se aika, jona sisäilman suhteellinen kosteus ylittää yöaikana tason 60 % RH (viihtyisyysraja) on ilmanvaihdon laskiessa lyhyempi kuin normaali-ilmanvaihdolla. Tämä johtuu sisäilman lämpötilan kohoamisesta pienellä ilmanvaihdolla. Sisäilman terminen viihtyisyys ja aistittavissa oleva ilman laatu voivat olla samat kuormitustilanteen lopussa ilmanvaihdolla 0.1 1/h ja läpäisevällä maalipinnalla tai kun ilmanvaihto on 0.25 1/h ja seinämien maalipinta on vesihöyryä läpäisemätön.

Kun kosteudentuotto sisäilmassa kasvaa, rakenteisiin varastoituneen kosteuden osuus koko kosteustuotosta kasvaa vain hyvin vähän. Ilmanvaihdon poistaman, rakenteisiin varastoituneen ja sisäilmaan jäävän kosteuden määrät riippuvat jokseenkin lineaarisesti kosteuden tuotosta sisäilmaan.

Preface

This report presents the results from the research project "Lämpö- ja kosteusoloiltaan miellyttävä puutalo" (A Wooden Building with Comfortable Temperature and Humidity Conditions), which has been funded by WoodFocus Oy (Finnish Wood Research Ltd.), Termex-Eriste Oy, Teknos Winter Oy, Ekovilla Oy, Puhos Board Oy, Aislo Oy and Tekes, the National Technology Agency. The manager of the entire project was Pekka Nurro of WoodFocus Oy and the managers of the research were Carey Simonson and Erkki Kokko of VTT Building and Transport. Keijo Kolu of Schauman Wood Oy was the steering group chairman and Mikael Salonvaara of VTT Building and Transport was the secretary. The contributions of these and all members of the steering group and working group (names are listed in Acknowledgements) are appreciated. This report has been reviewed and the results evaluated by Hartwig Künzel of Fraunhofer Institut Bauphysik, Holzkirchen, Germany and the Helsinki University of Technology (Laboratory of HVAC Technology and Laboratory of Structural Engineering and Building Physics).

Espoo, January 2001

Carey J. Simonson, Mikael Salonvaara and Tuomo Ojanen

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APPENDICES

List of symbols

A	surface area (m^2)
a	constant
A*	ratio of active area of a test case relative to test case 1
Acc	acceptability of clean indoor air
b	constant
C	constant
C	thermal capacity (J/K)
Cm	moisture capacity (g/%RH)
Cp	specific heat capacity (J/(kg·K))
D_w	liquid moisture diffusivity (m^2/s)
ES	Helsinki, Finland
F	function
f	function
g	acceleration of gravity (m/s^2)
H	enthalpy (J/kg or kJ/kg)
h	convective heat transfer coefficient ($W/(m^2 \cdot K)$)
h_p	permeance of the interior surface including the convective mass transfer coefficient ($kg/(s \cdot m^2 \cdot Pa)$)
HVAC	heating, ventilating and air-conditioning

IAQ	indoor air quality
K	moisture permeability (s)
k	thermal conductivity (W/(m·K))
k*	ratio of the vapour permeance of the interior coating in a given test case to the vapour permeance in test case 1 (k*=1/R*)
kd	water vapour permeability (kg/(s·m·Pa)) or water vapour permeance (kg/(s·m^2·Pa))
MKE	Saint Hubert, Belgium
$\dot{m}_{j,i}$	mass flow rate of dry air from zone j into zone i including infiltration, exfiltration and ventilation (positive for flow entering zone i) (kg/s)
$\dot{m}_{prod}$	average moisture production rate during occupation (g/h)
$\dot{m}_{storage,air}$	average moisture that remains in the air during occupation (g/h)
$\dot{m}_{storage,structure}$	average moisture transfer rate from the indoor air to the building structure during occupation (g/h)
$\dot{m}_{vent}$	average moisture removal rate by the outdoor ventilation air during occupation (g/h)
P	pressure (Pa)
P_a	partial pressure of air (Pa)
PAQ	perceived air quality
PD	percent dissatisfied with comfort conditions

P_v	partial pressure of water vapour (Pa)
$P_{v,sat}$	partial pressure of water vapour at saturation
Q	outdoor ventilation rate (ach)
q	heat flux (W/m^2)
q_M	mass flux ($kg/(m^2 \cdot s)$)
R*	ratio of the vapour resistance of the interior coating in a given test case to the vapour resistance in test case 1 (R*=1/k*)
R_{air}	vapour resistance of air per unit thickness (inverse of vapour permeability)
RH	relative humidity
RH*	non-dimensional change in relative humidity
RH_{30}	indoor relative humidity before the first step change in outdoor weather (i.e., on day 30)
Rt	thermal resistance ($m^2 \cdot K/W$)
S	heat sources or sinks per unit volume (W/m^3)
S_M	moisture or contaminant sources or sinks per unit volume ($kg/(m^3 \cdot s)$)
SH	Holzkirchen, Germany
T	temperature (C or K)
t	thickness (mm) or time (s)

t_{active}	active thickness for moisture (or heat) transfer or the depth into a material at which the RH in the material is about one third of the variation in the room
T_p	period of the moisture production cycle (s)
u	moisture content (kg/kg)
V	volume of the room (32.4 m^3) or a general zone or volume of a material (m^3)
v_a	velocity of air (m/s)
VMR	Trapani, Italy
VOC	volatile organic compound
W	absolute humidity (g/kg or kg/kg)
W*	non-dimensional change in absolute humidity
W_{30}	indoor absolute humidity before the first step change in outdoor weather (i.e., on day 30) (g/kg)
X	general variable

Greek letters

α_m	moisture diffusivity (m^2/s)
α_t	thermal diffusivity (m^2/s)
ΔRH_{out}	the value of the step change in outdoor relative humidity (30%)
Δt	occupation time (9 hours)

ΔW_{out}	the value of the step change in outdoor absolute humidity (3.9 g/kg)
ΔX_{night}	maximum increase in a variable during occupation (night)
$\Delta X_{night,ave}$	yearly average of the maximum increase in a variable during occupation
Λ	latent heat of vaporisation (J/kg)
ρ	density (kg/m^3)

Subscripts

a	dry air
ave	average
g	gas phase (including dry air and water vapour)
i	zone index or test case number
in	indoor variable
j	zone index
m	dry property of the porous medium
max	maximum value during occupation or during a given month
min	minimum value during occupation or during a given month
n	surface index
o	initial value when the occupants enter the room (i.e., 22:00)

out	outdoor variable
s	interior surface of a zone
s,in	the internal surface
v	water vapour
w	liquid water

1. Introduction

Well designed heating, ventilating and air-conditioning (HVAC) systems add or remove heat and moisture from the occupied spaces of buildings and provide an acceptable indoor climate in many climates. However, in many hot and humid climates, conventional air conditioning units are unable to meet the latent load and the indoor relative humidity exceeds the often recommended value of 60% to 70% RH (ASTM, 1994, ANSI/ASHRAE Standard 55-1992 and ANSI/ASHRAE Standard 62-1989). This has led to the growing application of heat and moisture transfer devices which can reduce the latent load on air conditioning units (Besant and Simonson, 2000, Harriman et al., 1999, Rengarajan et al., 1996 and Nimmo et al., 1993). With these devices, it is possible to provide an acceptable indoor climate in even hot and humid climates. Nevertheless, there is a desire to develop more passive and less energy intensive methods of moderating the indoor environment. The passive method investigated in this research uses the moisture (and thermal) storage capacity of wood based materials to damp occupant-induced moisture (and heat). The main focus will be on moisture transfer between indoor air and wood based building materials and the resulting effect on indoor climate, air quality (IAQ) and building durability.

Passive methods of moderating the indoor environment are gaining popularity because they are energy conscious and environmentally friendly. In moderate climates, where air conditioning is seldom or never used, passive methods may make it possible to provide an acceptable indoor climate during hot periods without the need of air conditioning. In cold climates, such as Finland, passive methods could help control the occupant induced diurnal variations in indoor humidities, which are often moderated by providing outdoor ventilation air. By appropriately utilising moisture transfer between indoor air and building structures, the needed ventilation rate could possibly be reduced because the perception of IAQ is closely linked to the humidity of indoor air (Fang et al., 1998a and b and 1999a). Furthermore, the ability of buildings to damp changes in temperature is much greater than their ability to damp changes in humidity (Padfield, 1998) even though humidity control can be extremely important. These factors indicate that there is a great need for research and development before buildings with greater hygroscopic mass will be realised.

1.1 Relationship between Temperature and Relative Humidity

The basic equations relating temperature and relative humidity have been known for many decades and can be found from many references. Relative humidity (RH) is defined as the ratio of the mole fraction of water vapour in air to the mole fraction of water vapour in saturated air at the same temperature (T) and pressure (P). Since the mole fraction of water vapour is equal to the partial pressure of water vapour, relative humidity can be defined as the ratio of the partial pressure of water vapour in air (P_v) to partial pressure of water vapour in saturated air ($P_{v,sat}$). Therefore, relative humidity (RH) can be expressed as,

$$RH = \left.\frac{P_v}{P_{v,sat}}\right|_{T,P} . \tag{1}$$

The partial pressure of water vapour at saturation is a function of temperature (T) as follows:

$$P_{v,sat} = f(T) = e^F \tag{2}$$

where F can be calculated from (ASHRAE, 1997):

$$F = \begin{cases} \frac{C_1}{T} + C_2 + C_3 T + C_4 T^2 + C_5 T^3 + C_6 T^4 + C_7 \ln T; 173 < T < 27. \\ \\ \frac{C_8}{T} + C_9 + C_{10} T + C_{11} T^2 + C_{12} T^3 + C_{13} \ln T; 273 < T < 473\text{K} \end{cases} \tag{3}$$

with the constants having the following values: $C_1 = -5674.5359$, $C_2 = 6.3925247$, $C_3 = -9.677843 \times 10^{-3}$, $C_4 = 6.22115701 \times 10^{-7}$, $C_5 = 2.0747825 \times 10^{-9}$, $C_6 = -9.484024 \times 10^{-13}$, $C_7 = 4.1635019$, $C_8 = -5800.2206$, $C_9 = 1.3914993$, $C_{10} = -4.8640239 \times 10^{-2}$, $C_{11} = 4.1764768 \times 10^{-5}$, $C_{12} = -1.4452093 \times 10^{-8}$, and $C_{13} = 6.5459673$. As the temperature decreases, the saturation vapour pressure decreases (Figure 1).

Another useful variable is the absolute humidity (W), which is defined as the mass of water vapour per mass of dry air. The absolute humidity is calculated from the ratio of the partial pressure of water vapour to the partial pressure of air (P_a) as follows,

$$W = 0.62198 \frac{P_v}{P_a} \ . \tag{4}$$

Equations (1) to (4) describe the relationship between temperature, absolute humidity and relative humidity and are presented graphically in Figure 1, which is known as the psychrometric chart. Examining Figure 1 reveals that if air is cooled with no change in absolute humidity (i.e., no moisture removal), the RH will increase because the saturation pressure decreases with temperature. For example, the sensible cooling of air (i.e., cooling without moisture removal) from 24°C and 60% RH (W=11.2 g/kg), will result in a relative humidity of 80% RH at about 19°C. Further cooling will result in saturated air (100% RH) at a temperature of 15.8°C. The temperature at which the RH is 100% is called the dew point and cooling below the dew point will cause water to condense from the air. When cooling below the dew point, the absolute humidity will decrease, while the relative humidity will remain at 100% RH.

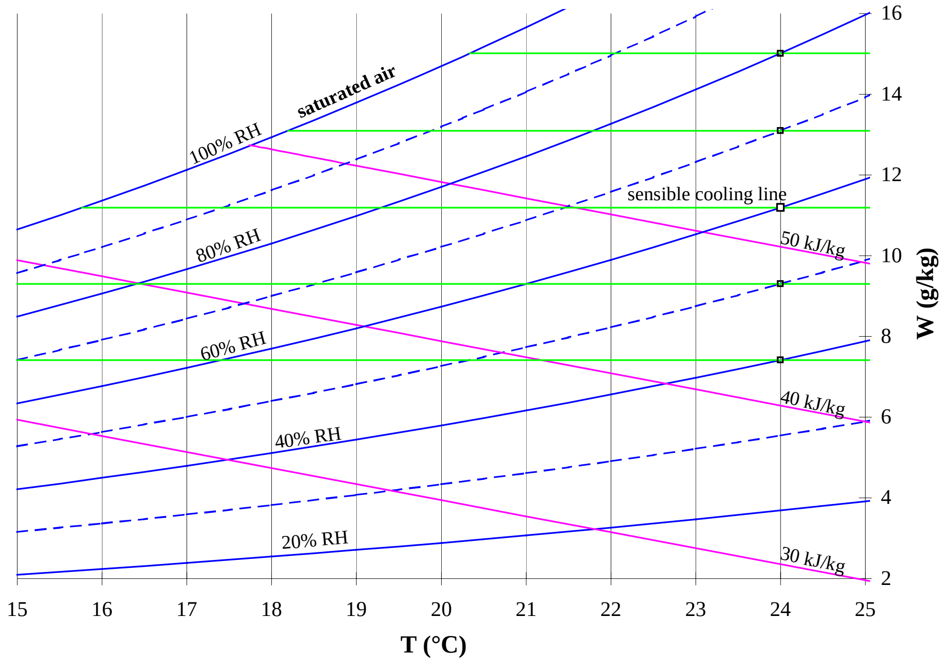

Figure 1. Psychrometric chart showing the relationship between temperature, relative humidity, absolute humidity and enthalpy of moist air.

Figure 1 also contains the enthalpy (H) of moist air, which represents the energy content and is the sum of the partial enthalpies of the components (i.e., dry air and water vapour). As temperature and humidity increase, the enthalpy of the air increases according to the following relation:

$$H = T + W(2500.8 + 1.805\,T). \tag{5}$$

1.2 Importance of Humidity on Occupants and Buildings

Conditioning indoor air is very important because research has shown that both the indoor climate and IAQ can influence comfort, health and productivity (Wargocki et al., 1999, Seppänen et al., 1999, Seppänen, 1999 and Wyon, 1996). Therefore buildings with a good indoor environment are necessary for a healthy, productive and prosperous society because people spend 90% of their time indoors. An important, but often neglected, indoor environmental parameter is humidity and often indoor humidity is considered to be of small importance for a successful design because temperature is easier to sense and quantify. Nevertheless, research has shown that the indoor relative humidity can significantly affect:

- thermal comfort (Toftum et al., 1998a and b, Berglund, 1998, ANSI/ASHRAE Standard 55-1992 and Fanger, 1970),
- the perception of IAQ (Fang et al., 1998a and b and 1999a),
- occupant health (Clausen et al., 1999, Cooper-Arnold et al., 1997, Dales et al., 1991, and Green, 1985),
- the durability of building materials (Viitanen, 1996, Ojanen and Kumaran, 1996 and ASTM, 1994), and
- energy consumption (Besant and Simonson, 2000, and Harriman et al., 1999 and 1997).

1.2.1 Thermal Comfort

The mechanism by which humidity affects human comfort is not fully understood and there are no known human sensors that record humidity, but the literature shows that humidity does influences thermal comfort (Toftum and Fanger, 1999, Fountain et al., 1999, Berglund, 1998 and Fanger, 1970). Humidity has a small effect on general thermal comfort (i.e., thermal comfort for the body as a whole), but a greater effect on local thermal comfort (e.g., respiratory comfort).

1.2.1.1 General Thermal Comfort

Several thermal comfort standard exist (e.g., ISO 7730-1994, ANSI/ASHRAE 55-1992 with Addendum 55a-1995 and DIN 1946, 1994), which include relative humidity as a parameter affecting general thermal comfort as shown in Figure 2. Some criteria recommend an indoor relative humidity below 60% RH, while other criteria allow the relative humidity to be as high as 80% RH, but the general trend is that the comfort conditions are poorer at very high or very low humidities. The ranges specified in the ANSI/ASHRAE standard are based on a 10% dissatisfaction criterion.

In order to calculate the predicted mean vote and the percent dissatisfied (PD) with given indoor conditions, Tuomaala and Piira (2000) have developed a new application based on ISO 7730-1994. With the application of Tuomaala and Piira (2000), the effect of temperature and humidity on the percent dissatisfied with general thermal discomfort can be demonstrated as shown in Figure 3. Figure 3 presents PD as a function of temperature and relative humidity assuming: a metabolic rate of 1.2 met (filing, seated in office), a clothing factor of 1 clo (long sleeve shirt, fitted trousers, suit jacket), an air speed is 0.1 m/s and a mean radiant temperature equal to the air temperature. Figure 3 confirms that humidity is relatively unimportant for general thermal comfort, especially at an indoor temperature of 22°C. When the temperature is 22°C, PD with general thermal comfort is nearly independent of the relative humidity. When the air temperature is cool (20°C), PD decreases with increasing humidity, but when the air temperature is warm (24°C), PD increases with increasing humidity. Above 24°C and 40% RH and below 20°C and 20% RH, PD exceeds the 10% dissatisfaction criteria for general thermal discomfort specified in ISO 7730-1994 and ANSI/ASHRAE 55-1992.

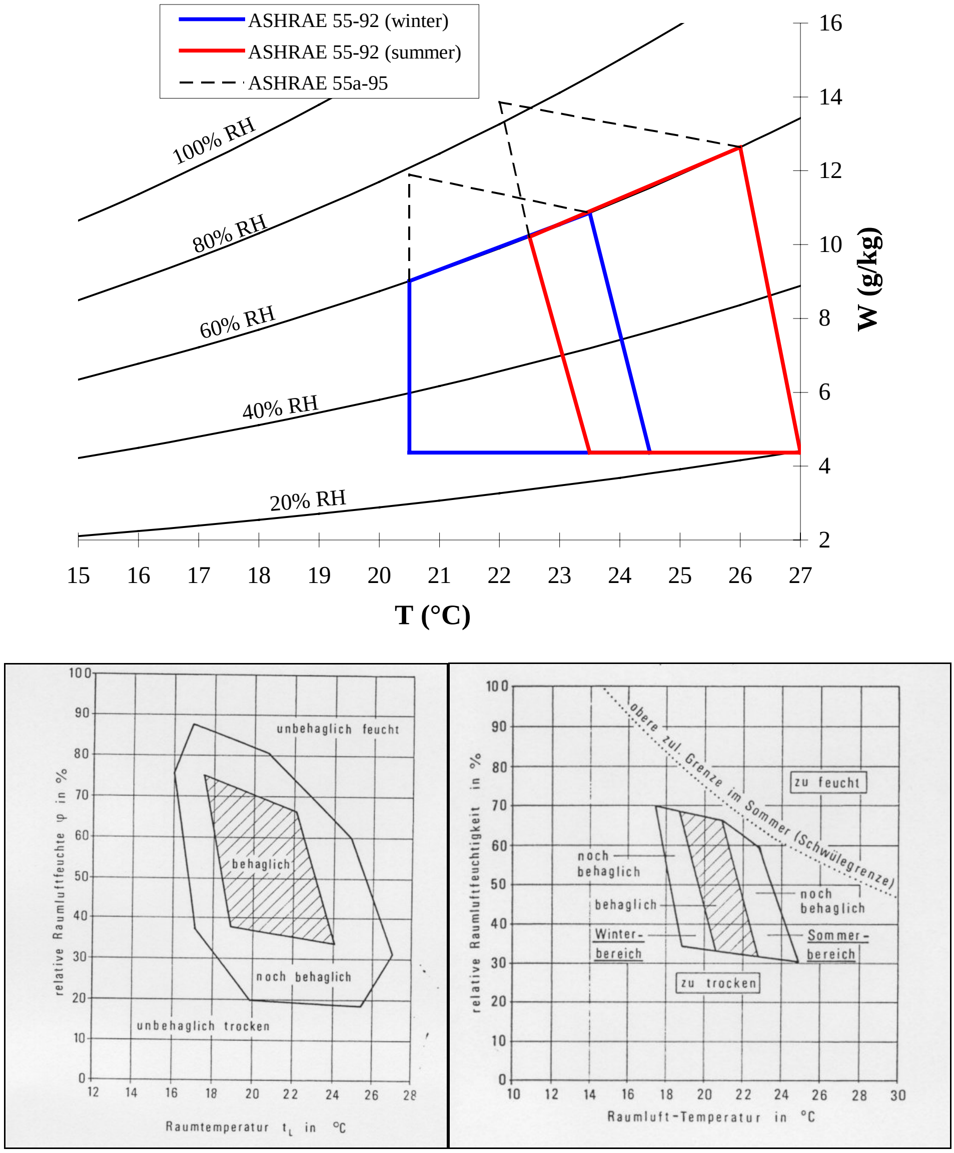

Figure 2. Summer and winter comfort conditions specified in ANSI/ASHRAE 55-1992 and Addendum 55a-1995 and Buss (1994).

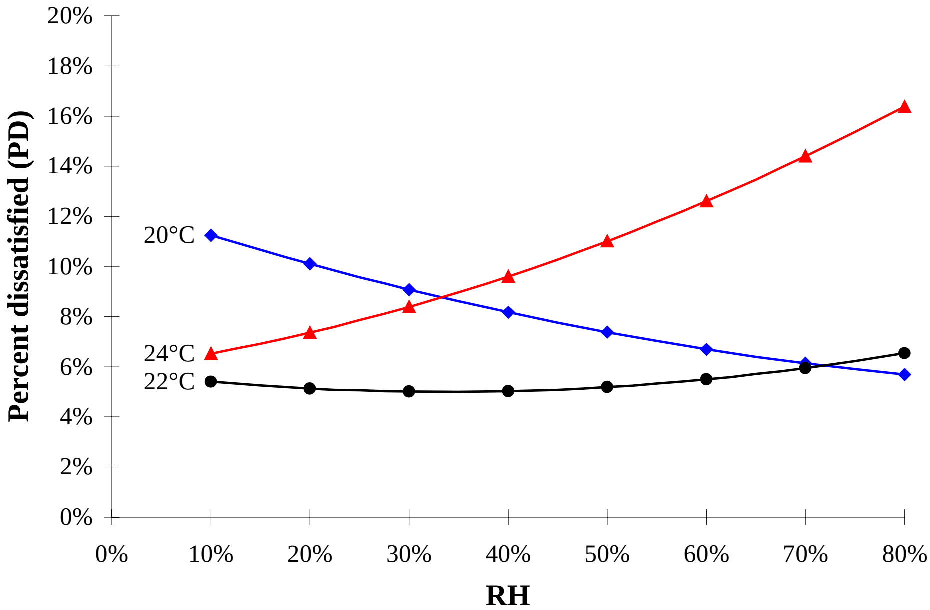

Figure 3. Percent dissatisfied with general thermal comfort at various temperatures and relative humidities.

1.2.1.2 Local Thermal Comfort

Local thermal discomfort is generally due to temperature gradients or drafts in a space causing one part of the body to by warmer or colder than another. However, recent work by Toftum et al. (1998a and b) has shown that local thermal discomfort can also be due to high skin humidity or insufficient cooling of the mucous membranes in the upper respiratory tract cooling. The humidity limits for humid skin are usually more restrictive than the limits for respiratory discomfort and therefore the latter results will be examined here.

Toftum et al. (1998b) studied the response of 38 subjects exposed to 14 combinations of temperature (20°C to 29°C) and humidity (6 to 19 g/kg) ranging from 20°C and 45% RH to 29°C and 70% RH. Unpolluted air from a climate chamber was led to a sampling box where the subjects evaluated the air three or four inhalations after positioning their head inside the box. Based on the response of the subjects, Toftum et al. (1998b) developed the following correlation, which quantifies PD with warm respiratory comfort,

$$PD = \frac{100}{1 + \exp[-3.58 + 0.18(30 - T) + 0.14(42.5 - 0.01P_v)]} \quad (6)$$

where T is the air temperature (C) and P_v is the water vapour pressure (Pa). Equation (6) is valid for clean indoor air and will be used in this report to estimate the percent dissatisfied with warm respiratory comfort. Figure 4 presents the percent dissatisfied with respiratory cooling at various temperatures and relative humidities and shows that PD is very sensitive to humidity, especially at higher temperatures. As the relative humidity increases, the percent dissatisfied with warm respiratory comfort always increases. For example at 24°C, increasing the humidity from 40% RH to 60% RH, doubles the percent dissatisfied with warm respiratory comfort (PD=14% at 24°C and 40% RH and PD=28% at 24°C and 60% RH).

The values of PD in Figure 4 and Figure 3 reflect the dissatisfaction with local and general thermal comfort respectively and are not directly comparable because it is often recommended to keep PD with local and general thermal comfort below 15% and 10% respectively (ISO 7730-1994 and ANSI/ASHRAE 55-1992). The results in Figure 4 show that when the temperature is 22°C, a humidity above 55% RH will cause PD to exceed 15%, while at 24°C, a humidity above 40% RH will give PD>15%.

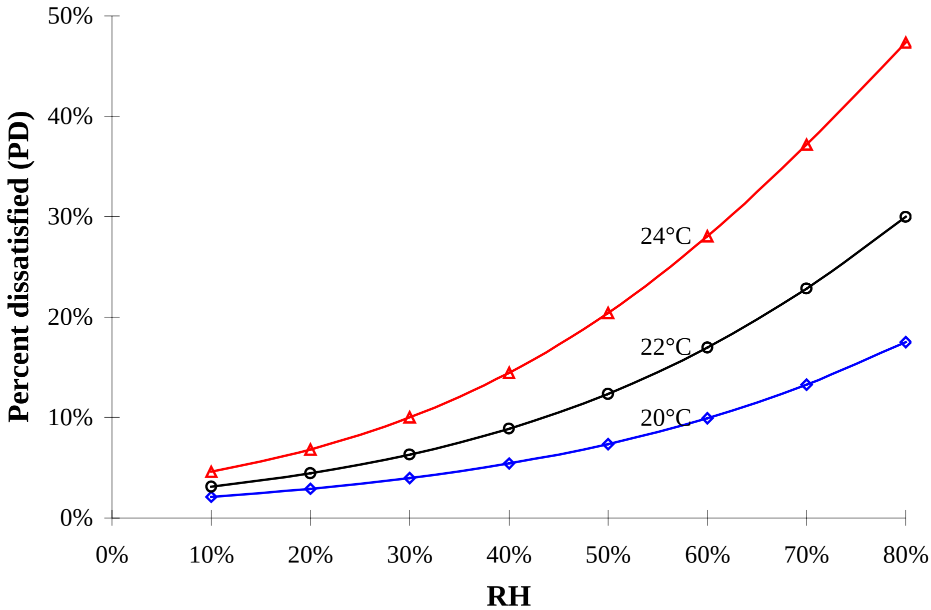

Figure 4. Percent dissatisfied with warm respiratory comfort at various temperatures and relative humidities.

1.2.2 Perceived Indoor Air Quality

Local thermal comfort due to inadequate respiratory cooling and perceived indoor air quality (PAQ) are closely related because inadequate cooling makes the air feel stuffy and unacceptable. Research has shown that the odour intensity of air is not strongly influenced by temperature and humidity, but PAQ is strongly affected (Toftum et al., 1998b and Fang et al., 1998a and b). In fact, PAQ and acceptability are linear related to enthalpy. Air is more acceptable (has a higher perceived quality) at low enthalpies and as the enthalpy increases, the acceptability decreases. Fang et al. (1998a) conducted laboratory tests where 40 subjects were facially exposed to air supplied through a diffuser and asked the following question: "Imagine that during your daily work you would be exposed to the air from the diffusers. How acceptable is the air quality?" The subjects assessed the acceptability of polluted and unpolluted air at different temperatures and humidities and Fang et al. (1998a) developed the following equation to calculate the acceptability of air:

$$\text{Acceptability} = aH + b \tag{7}$$

where H is the enthalpy of the air (kJ/kg) and a and b are empirical coefficients. The constants a and b have been calculated for clean air and air polluted with five building materials at two different loading levels. For clean air, a=-0.033 and b=1.662 giving,

$$\text{Acceptability} = -0.033\,H + 1.662 \tag{8}$$

which will be used in this report to estimate the acceptability of indoor air. Figure 5 presents the acceptability of clean air and air polluted with carpet (a=-0.023 and b=0.966) and sealant (a=-0.013 and b=0.263) under loading 2 conditions described by Fang et al. (1998a). Figure 5 shows that as the temperature and humidity increase (enthalpy increases), the acceptability decreases for all pollution sources and the importance of the pollution source decreases. Above an enthalpy of 50 kJ/kg (24°C and 55% RH), the air is unacceptable regardless of the pollution source. This shows that PAQ is better at lower humidities (in fact enthalpies), which means that ventilation rates could be decreased notably by maintaining a moderate enthalpy in spaces.

The relative importance of temperature and humidity on PAQ can be directly compared using Figure 5. For example, clean air at 20°C and 60% RH is slightly more acceptable than clean air at 24°C and 40% RH. This means that if the air temperature in a room increases from 20°C to 24°C (ΔT=4°C), the acceptability of the air will remain nearly constant provided the relative humidity decreases from 60% RH to 40% RH (ΔRH=20%). Therefore, a temperature change of 1°C is approximately equivalent to a humidity change of 5% RH. This means that if the temperature increases by 1°C, the humidity must be decreased by 5% RH to keep the same acceptability. On the other hand, if the temperature decreases by 1°C, the humidity of the air is allowed to increase by 5% RH and the acceptability will still be similar.

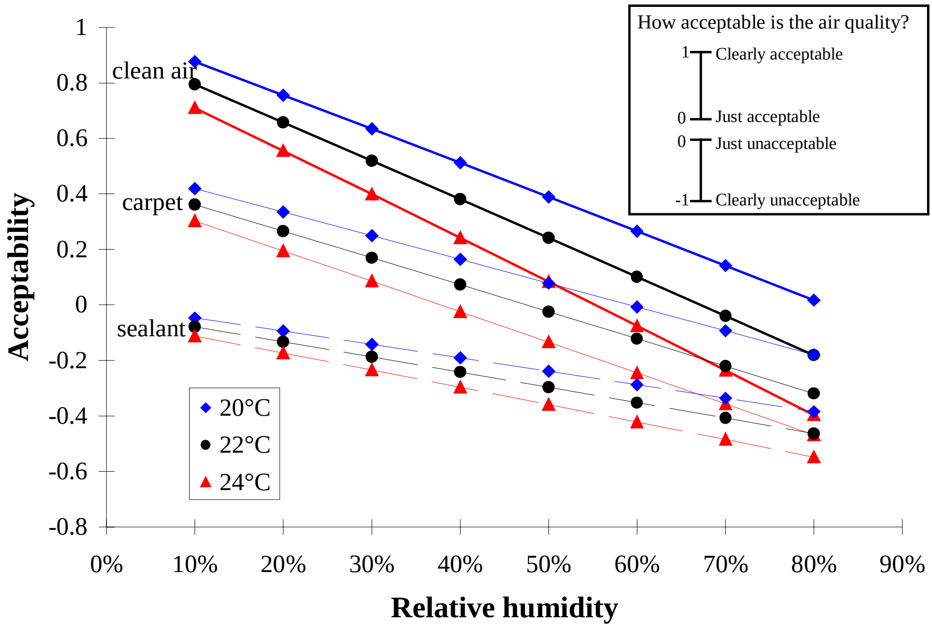

Figure 5. The acceptability of indoor air as a function of relative humidity for different temperatures and pollution sources.

The effect of humidity on PAQ is typically greater than the effect of humidity on thermal sensation. For example, Toftum et al. (1998b) state that changing the air temperature by 1°C has the same effect on acceptability, freshness and thermal comfort as changing the vapour pressure by 121, 130 and 231 Pa respectively. This means that at 22°C, changing the relative humidity by 10% RH has a similar effect on PAQ and thermal sensation as changing the temperature by 2.2°C and 1.1°C respectively. Therefore, according to these results, humidity is about twice as important for PAQ as it is for thermal comfort.

If we consider a cooling system that removes heat from a space, but does not remove moisture unless condensation occurs, such as radiant cooling without dehumidification (Olesen, 2000, Simmonds, et al., 2000 and

Olesen, 1997), the importance of humidity is very clear. Figure 6 shows the sensible cooling of air in a room (i.e., no change in absolute humidity) from 29°C and 50% RH to 23°C (process $\overline{AB}$) and from 25°C and 60% RH to 20°C (process $\overline{ab}$). These processes are expected to significantly increase thermal comfort and productivity (Seppänen and Vuolle, 2000 and Wyon, 2000). Nevertheless, Figure 6 shows that the same change in enthalpy of air can be achieved by simply reducing the humidity by 10% RH and keeping the temperature constant (processes $\overline{AC}$ and $\overline{ac}$). Since PAQ is a function of enthalpy, the acceptability of the air after either process (cooling or dehumidifying) is expected to be the same. Here a change in humidity of 10% RH at constant temperature is equivalent to a change in temperature of 5 or 6°C at constant absolute humidity. Since temperature strongly affects comfort and productivity, these results also indicate that indoor humidity affects ventilation requirements, symptoms of sick building syndrome and human productivity, but additional research is needed to quantify these effects.

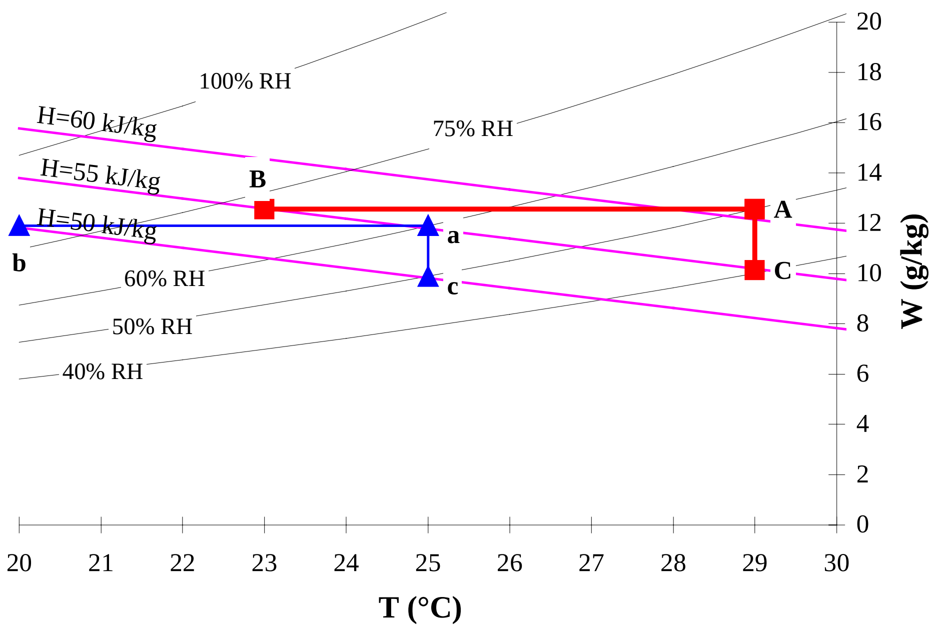

Figure 6. Sensible cooling and dehumidification process lines on the psychrometric chart showing the importance of humidity on enthalpy.

1.2.3 Other Factors

As well as affecting comfort and perceived air quality, indoor humidity affects many other parameters as shown in Figure 7. A low humidity is needed to reduce the effect of some parameters, while a high humidity is needed to reduce the effect of others. The indoor humidity should be kept below 60% to 70% RH to curb the growth of fungi and mites (ASTM, 1994 and Viitanen, 1996) and above 30% RH to reduce respiratory infections (ASHRAE, 1997). For example, research by Green (1985) has shown that increasing the relative humidity from 20% RH to 40% RH in schools, located in cold dry regions, can reduce absenteeism and upper respiratory infections by 50%.

Moisture transfer is an important part of energy consumption in warm moist regions where mechanical cooling is often applied to control humidity in buildings. The energy required to remove moisture is a scientific fact that is often under appreciated and not well known. For example, the ideal cooling of air from 30°C and 60% RH to 25°C and 50% RH requires over 4 times as much energy as cooling air from 30°C to 25°C with no change in absolute humidity. Moisture also affects energy consumption because it can decrease the thermal resistance of building envelopes by 5 to 10%, which is important during heating, but less important during cooling.

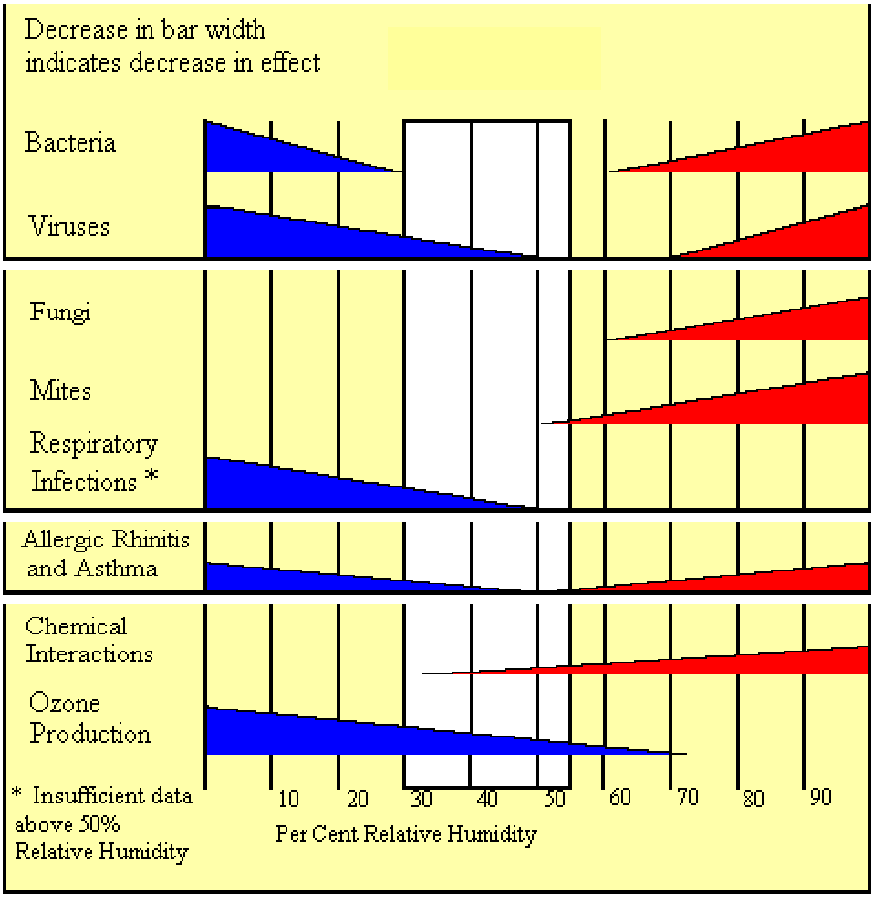

Figure 7. The effect of humidity on several health and IAQ parameters showing that a favourable range of indoor humidity is between 30% RH and 55% RH (ITS, 1999).

1.3 Objectives

Previous research has shown that indoor humidity has a significant effect on thermal comfort, perceived air quality and other factors and that building materials have the potential to moderate indoor humidity. As a result, the main purpose of this report is to investigate the possibility of using wood based materials to damp diurnal changes in indoor humidity. This has been done through the following activities, which are addressed in the following chapters:

1. Chapter 2: Workshop 10 at Healthy Buildings 2000 conference;

2. Chapters 3 and 4: Simulation of heat and moisture transfer within a wooden building; and

3. Chapter 5: Summary of results and consideration of a possible phase II of this project.

2. Healthy Buildings 2000, Workshop 10: The effect of wood based materials on indoor air quality and climate

Workshop 10 “The effect of wood based materials on indoor air quality and climate” was held on August 8, 2000 at the Healthy Buildings 2000 Conference in Espoo, Finland. The workshop included 16 brief presentations together with discussion on moisture storage in building materials (mainly wood based) and emissions from wood based materials. The workshop participants presented the state-of-the-art and future research plans related to moisture transfer between indoor air and wood based materials and emissions from wood based materials as shown in the agenda (Table 1). The presentations have been posted on the workshop homepage (http://www.hb2000.org/workshop10.html).

The workshop was attended by 37 people from 13 countries and the names and contact information are given in Table 2. The summary of the workshop, which is in section 2.1, was published as: Virtanen M.J., Künzel, H.M. and Simonson, C.J., 2000, WS10 The effect of wood based materials on indoor air quality and climate, *Healthy Buildings 2000 Workshop Summaries*, Espoo, Finland, (edited by O. Seppänen, M. Tuomainen and J. Säteri), SIY Indoor Air Information OY, 55 - 60. The workshop created a network of researchers from several countries and this network will be exploited in phase II of the current project or in future research and development activities.

Table 1. Agenda for Workshop 10 at the Healthy Buildings 2000 conference.

WORKSHOP 10: THE EFFECT OF WOOD BASED MATERIALS ON INDOOR AIR QUALITY AND CLIMATE

Tuesday, August 8th at 2 – 5.30 pm, Room 406

Sponsor: Schauman Wood OY

Chairs: Markku J. Virtanen, VTT Building Technology, Finland, markku.virtanen@vtt.fi
Hartwig M. Künzel, Fraunhofer Institut Bauphysik, Germany, kuenzel@hoki.ibp.fhg.de
Secretary: Carey J. Simonson, VTT Building Technology, Finland, carey.simonson@vtt.fi

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WORKSHOP AGENDA

14:00-14:05	Introduction (*Markku Virtanen*)
14:05-14:10	Wood based materials in Finland (*Keijo Kolu*)
14:10-15:10	State-of-the-art presentations and discussion (*Markku Virtanen*) Moisture transfer between wood based materials and indoor air • experiments (*Tim Padfield, Kaisa Svennberg, Philipp Plathner, Takao Tsuchiya*) • modelling (*Carsten Rode, Mikael Salonvaara, Monika Woloszyn*) • applications (*Pauli Lindström, Peter Matiasovsky*) Emissions from wood based materials (*Annelise Larsen*)
15:10-15:30	General discussion on state-of-the-art presentations
15:30-16:00	Coffee
16:00-16:30	Future Research Plans (*Hartwig Künzel*) Presenters (*Carsten Rode, Carey Simonson, Thomas Frank, Kaisa Svennberg, Hartwig Künzel*)
16:30-17:15	Final discussions and conclusions (drafting list of future R&D needs)

EVENING PROGRAM
Hosted by Schauman Wood OY

17:15-18:45	Travel to Lahti, light snack served on bus
18:45-21:00	Tours: Schauman Wood OY, wood decorated apartments and Sibelius Hall
21:00-22:00	Dinner
22:00-23:00	Return to Helsinki University of Technology

Table 2. Participant list for Workshop 10 (37 people from 13 countries).

Country	Participant	E-mail	Affiliation
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Denmark	Tim Padfield	tim@padfield.dk	National Museum of Denmark
	Lis Winther Funch	lis.winther.funch@teknologisk.dk	Danish Technological Institute
	Annelise Larsen	Annelise.Larsen@teknologisk.dk	Danish Technological Institute
	Carsten Rode	car@ibe.dtu.dk	Technical University Denmark
	Teruaki Mitamura	temi@ibe.dtu.dk mitamura@sabine.pln.archi.tohoku.ac.jp	Technical University Denmark Tohoku University in Japan
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Germany	Hartwig Künzel	kuenzel@hoki.ibp.fhg.de	Fraunhofer-Institut Bauphysik
	Olof Wilke	olaf.wilke@bam.de	BAM
	Olf Herbarth	herbarth@expo.ufz.de	UFC-Centre for Envir. Research
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South Africa	Michael Sekhotha	983206275@enu.ac.za	University of Natal
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	Finn Englund	finn.englund@tratek.se	Traetek
	Anders Karlsson	anders.karlsson@raa.se	National Heritage Board
Switzerland	Thomas Frank	Thomas.Frank@empa.ch	EMPA
UK	Philipp Plathner	PlathnerP@bre.co.uk	BRE
	Lorraine Gibson	lorraine.gibson@strath.ac.uk	University of Strathclyde

Unknown affiliation:
Risto Salmi
Mukesy Kmattar

2.1 Workshop Summary (Virtanen et al., 2000)

WS10 THE EFFECT OF WOOD BASED MATERIALS ON INDOOR AIR QUALITY AND CLIMATE

Markku J. Virtanen[1], Hartwig M. Künzel[2], Chairmen
Carey J. Simonson[1], Secretary

[1]VTT Building Technology, Espoo, Finland
[2]Fraunhofer Institut Bauphysik, Holzkirchen, Germany

BACKGROUND

Moderate indoor relative humidity is a prerequisite for a healthy building because humidity affects both occupants and buildings. Humidity affects the perception of indoor air quality (IAQ), thermal comfort, occupant health (asthma, respiratory illnesses, mites and fungi), building durability, material emissions and energy consumption. Since wood based materials have the ability to moderate indoor humidity, they are the focus of this workshop.

AIM AND SCOPE

The aim of this workshop is to obtain a consensus of the future research and development needs relating to mass transfer between indoor air and wood based materials. The two main topics of the workshop are *moisture storage* and *emissions* and are listed below.

- Moisture storage: The ability of wood based materials to adsorb/desorb moisture from indoor air and thus moderate diurnal changes in the indoor humidity.

- Emissions: The emissions of volatile organic compounds (VOC's) from wood based materials and, in particular, the sensitivity of emissions to indoor humidity and wood moisture content.

HUMIDITY AND HEALTHY BUILDINGS

Regulating the indoor temperature and humidity in buildings (usually between 19°C and 26°C and 30% RH and 60% RH) is important, but energy intensive, and accounts for about 25% of primary energy use and over 50% of the energy used in buildings. Even though conditioning indoor air is energy intensive, it is very important because research has shown that both the indoor climate and IAQ can influence comfort, health and productivity (Wargocki et al., 1999, Seppänen et al., 1999 and Wyon, 1996).

Indoor humidity depends on many factors including: outdoor humidity, HVAC system, ventilation rate, occupant behavior and building materials (ASTM, 1994). Measurements have shown that the indoor humidity is usually from 2 to 4 g/m^3 greater indoors than outdoors due to indoor moisture sources (Tolstoy, 1993 and Rodriguez et al., 2000). As a result, indoor humidities are too high in many climates and too low in others. Currently, building designers and occupants consider indoor humidity to be of small importance for a successful design because temperature is easier to sense, quantify and comprehend. Nevertheless, research has shown that the indoor relative humidity (RH) is extremely important and significantly affects: thermal comfort (ANSI/ASHRAE Standard 55-1992, Berglund, 1998 and Toftum et al., 1998b), the perception of IAQ (Fang et al., 1998a), occupant health (Green, 1985, Dales et al,. 1991, Cooper-Arnold et al., 1997 and Clausen et al., 1999), the durability of building materials (ASTM, 1994) and energy consumption (Harriman et al., 1997 and 1999 and Besant and Simonson, 2000). Therefore, the main focus of this workshop is on moisture transfer and indoor humidity levels.

Moisture transfer between wood based materials and indoor air

The current methods of predicting indoor humidity are lacking because they neglect moisture adsorption and desorption by building materials and furnishings, even though several researchers have shown sorption effects to be significant. Numerical and experimental results have demonstrated that the peak indoor humidity can be reduced by 20% to 30% RH, while the lowest humidity can be increased by 10% to 15% RH (Teischinger, 1990, Tsuchiya and Sakano, 1993, Plathner et al., 1998 and Simonson and Salonvaara, 2000). These works have also shown that wood based materials are well suited for moisture storage applications because moisture transfer occurs rapidly. The following wood based materials have shown particular suitability for moisture storage applications: medium density fibre board, parquet tile, chip board, organic insulation, and perforated and non-perforated wood.

Models

There are two basic approaches to modelling the moisture transfer between materials and indoor: simplified models assuming a uniform moisture content in a thin material layer (Kerestecioglu et al., 1990, Cunningham, 1992, Ten Wolde, 1992, Tsuchiya and Sakano, 1993 and Jones, 1993) and detailed models including a distribution of moisture within materials (Salonvaara, 1998 and Harderup, 1998). Currently, there is a need for building simulation models that accurately account for moisture storage in building materials and model the interaction between materials, indoor air, and HVAC systems (Harderup, 1999, Grau and Wittchen, 1999 and Crawley et al., 2000).

Experiments

Many measurements have been carried out on the properties of building materials, such as vapour permeability and sorption isotherm (IEA, 1991), but there is a general lack of data that quantifies the rate of moisture transfer, especially for surface coatings and furnishings. Typically, environmental chamber tests have been used to measure the rate of moisture storage of various components when exposed to step changes in humidity (Rudd, 1994, Padfield, 1998 and Plathner et al., 1999). Some field measurements have been reported by Teischinger (1990), Tsuchiya and Sakano (1993), Plathner et al. (1998) and Simonson and Salonvaara (2000). These tests have shown the potential of building envelopes and components to store moisture, but more measurements are needed and several organisations have plans to continue field and laboratory measurements (Technical University of Denmark, Lund University, Finnish Wood Research Ltd. and VTT Building Technology) to confirm the effect of materials on indoor climate and to verify numerical models.

Emissions from wood based materials and indoor air

Emissions of VOC's from wood and wood based materials has been extensively investigated by Larsen et al. (1999), and an increase in emissions from building materials with an increase in indoor humidity has been shown recently by Fang et al. (1999b) and Wolkoff (1998). Nevertheless, there is a need for additional work in this field and a recently started research project at Lund University intends to investigate these effects (Harderup, 1999).

FUTURE WORK

Several organisations from many countries contributed ideas for this workshop and identified needs for future work. The identified needs for future work are listed below.

Properties

1. The surveyed literature clearly indicates that there is a lack of data concerning material properties such as vapour permeability and moisture capacity. Future measurements should concentrate on the

sorption behaviour of building and furnishing materials to obtain more data on sorption rates. Also, further determination of material properties describing the transient moisture transport and accumulation capability of wood based materials in comparison with other hygroscopic materials is needed.

2. Investigation of territorial variability in transport and accumulation properties for particular wood species (different bioclimatic conditions of growth).

Models

1. There is a need to improve existing moisture transport models between materials and indoor air, considering the specific transport and accumulation properties of wood (anisotropy, hysteresis, time dependent material properties, etc.). Also, the influence of the room microclimate on the exchange of moisture between materials and indoor air needs to be included.

2. The simulation of single room humidity levels should be extended to simulations of multi-room humidity levels. Variations in temperature and relative humidity in rooms and the effect of the HVAC system and solar radiation on the temperature and RH on interior surfaces and furnishings should be considered.

3. The effect of moisture storage in building materials and furnishings needs to be included in whole building simulation models that calculate the energy consumption of buildings.

4. Models that allow a statistical variation of material properties and outdoor weather conditions to assess the importance of uncertainties in input data. These models will permit an assessment of the importance of material properties and identify target properties for manufactures to strive for.

Experiments

1. There is a great need for experiments of hygrothermal conditions for whole buildings that will demonstrate, in full scale, the interaction between indoor spaces, building envelope components, and furnishing.

2. Development of standard test methods to evaluate the hygrothermal performance of building systems using full-scale experiments and to allow systematic validation of numerical models.

3. The issue of the durability of wood based materials and the problems of mould growth on wood based materials and its resulting smell, even after elimination of the moisture source and emissions, which are difficult to detect by modern analysers apart from the human nose, need further work.

4. Emissions from coatings used to protect wood and provide interior finishing require further measurements. Increased emissions, as a function of moisture content and possible secondary emissions due to reactions with other gases such as ozone should be addressed.

Applications

1. There is a need for design methods that allow designers and architects to specify appropriate moisture storage solutions for buildings. One question is how do we estimate the area and the influence of the exposed surfaces in a room? For example, does the white wood backside of the bookshelf effect the relative humidity of the indoor air as much as the coated tabletop?

2. Simplified methods of including moistures storage when determining the energy consumption of buildings.

3. New solutions for the application of wood based materials to simultaneously decorate and improve the indoor air quality and climate in new and refurbished buildings.

4. Measurements quantifying the effect of surface coating and furnishings. Development of wood surface protection measures which enable satisfactory moisture storage.

5. Ageing of wood materials and the resulting change of material properties during its service life.

6. Optimisation of the relationship between required wood moisture storage capacity and the possible volume and shape changes caused by moisture changes.

7. Over the last decades we have changed the materials we use for interior surfaces in the building, furniture and furnishing. What influence does this have on the indoor air in general and the relative humidity indoors in particular?

RECOMMENDATIONS

Most of the participants at the workshop felt that communication should be continued on the topics discussed and listed as future research needs during the workshop. Several possible forums for this communication were mentioned as follows:

- Publication of the presentation material from the workshop on the Healthy Building 2000 conference web site.

- E-mail discussion group on whole building hygrothermal conditions which has been set up at the Technical University of Denmark by Carsten Rode. The e-mail address is bldghum@ibe.dtu.dk.

- Additional workshops at future Healthy Building conferences and Nordic Building Physics symposia.

- There was a strong interest in international research projects under the IEA, EU or ASHRAE frameworks.

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3. Input Data and Numerical Model

In this chapter, the input data for the simulations (i.e., geometry, material property data and climates) and the numerical model are briefly described. The analysis will focus on a west-facing bedroom that is surrounded by similar bedrooms on all sides, thus the interior walls, floor and ceiling are assumed to have impermeable and adiabatic boundary conditions at the mid-plane. Since the main objective of the simulations is to assess the importance of hygroscopic mass on the indoor climate, the construction, ventilation and occupation will be the same in each climate. This means that the standards and practice in different countries has not been accounted for in these simulations. The following geometry, materials and climates have been selected:

- Bedroom:
    - 12 m^2 floor area, 2 occupants for 9 hours each night
    - outdoor ventilation rate (0.5 ach)

- Materials:
    - interior board (wooden panel, porous wood fibre board, log, or gypsum board)
    - insulation (hygroscopic or non-hygroscopic)
    - vapour barrier (vapour tight paint, paper or plastic behind interior board)

- Climates:
    - North (Helsinki, Finland)
    - Maritime (Saint Hubert, Belgium)
    - Central (Holzkirchen, Germany)
    - South (Trapani, Italy)

3.1 Description of Bedroom and Indoor Conditions

The main features of the bedroom as well as the heating, cooling and ventilation of the bedroom are listed below.

- The bedroom is assumed to be in an apartment building where the surrounding rooms have the same temperature and vapour pressure as the investigated room.
- The room is 4 m x 3 m x 2.7 m and the west-facing external wall is 3 m long.
- The external and internal walls have the same construction.
- In most cases, the ceiling is active in moisture transfer with the indoor air, but the floor is not active because it is coated with a non-permeable coating.
- The external wall has a 1.2 m x 1.5 m triple-pane window with a closed venetian blind, which transmits 25% of the solar radiation striking the window. For simplicity, it is assumed that the solar radiation is evenly distributed over all the internal surfaces.
- The building is located in an open terrain and the absorption coefficient for the external wall is 0.8.
- The ventilation rate is normally 0.5 ach, which corresponds to 4.5 L/s, but will be varied in a few cases to determine the sensitivity of the results to the ventilation rate.
- There is no mechanical cooling in the room.
- The indoor temperature is at least 20°C during the heating season, where the heating season is chosen to be from 1.9 to 31.5 in Finland, from 1.10 to 30.4 in Central Europe. No heating is used in the Mediterranean climate.

- The indoor loads are 2 adults for 9 h per day and lighting of 100 W for 1 the first hour of occupation.

Here it is important to note that the bedroom structures and indoor climate tend to represent well-designed and well-constructed building in Finland. For example, triple-pane windows and dark exterior colours (absorption coefficient of 0.8) are not common in Italy. On the other hand, the solar shading of windows is often greater than 25% in Italy, but less than 25% in Finland. Ventilation and indoor temperature standards and practice also vary significantly in different countries. In southern and central Europe, natural ventilation through operable windows is common and the indoor temperature is often lower than 20°C (Sanders, 1996). For example, Künzel (1979) measured the mean bedroom temperature in 2000 German dwellings to be 15.5°C ± 3°C.

Despite the different standards and practice in different countries (and quality differences within individual countries as well), the structures and indoor conditions are set the same in each country to enable a direct comparison of the effect of climate on the hygrothermal performance of a bedroom. It is also worthy to note that a west facing room is a worst case situation in the summer, but is partially compensated by the lack of other heat sources in the room (e.g., radio, TV and computer). The moisture production in the room is limited to people and the moisture storage capacity is limited to the structures. However in real bedrooms, there exists other moisture sources (e.g., plants, pets and cleaning) and other materials with moisture capacity (e.g., furniture and fabrics). These should be considered in future work.

The heat and moisture production used to represent occupation during the night are given in Figure 8. These values are two thirds of the values given in ASHRAE (1997) for adults seated at a theatre because no values are given for sleeping adults. However, the heat and moisture production selected to represent sleeping people may be slightly lower than in reality because the metabolic rate for sleeping people (0.8 met) is 80% of the metabolic rate for seated and quiet people (1.0 met) (ASHRAE/ANSI Standard 55-1992).

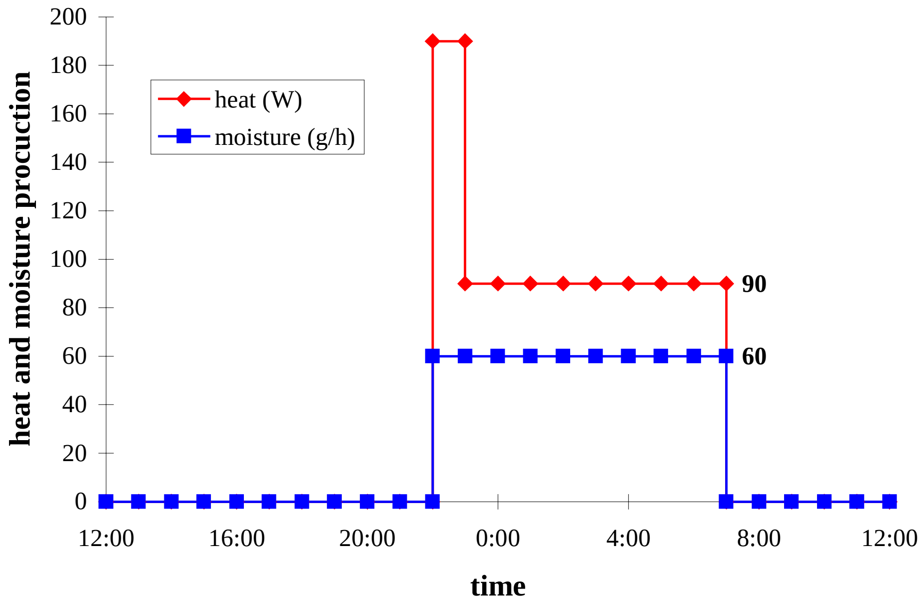

Figure 8. Heat and moisture production in the bedroom.

3.1.1 Test Cases

The basic structure in all the cases is wooden frame walls insulated with fibrous insulation. In most of the cases, the floor and ceiling of the room are the of the same construction, but some of the cases include a log or concrete floor and ceiling to demonstrate the effect of thermal mass. Different construction cases are selected to demonstrate the relative importance of the water vapour diffusion and hygroscopicity of different material layers. The construction cases and the materials chosen to represent the materials with high and low permeability and high and low hygroscopicity are summarised in Table 3. The material properties and dimensions for each case are in Appendix A.

Table 3. Simulation test cases.

Case	Internal coating	Interior wallboard (11 mm)		Air/vapour barrier (0.3 mm)	Insulation (150 mm)
	permeance	hygroscopicity	permeability	permeability	hygroscopicity
1	high (v. perm. paint)	high (porous wood	high fibre board)	high (paper)	high (cellulose)
2	low (v. tight paint)	high (porous wood	high fibre board)	high (paper)	high (cellulose)
3	high (v. perm. paint)	high (porous wood	high fibre board)	high (paper)	low (mineral fibre)
4	high (v. perm. paint)	high (porous wood	high fibre board)	low (plastic)	high (cellulose)
5	high (v. perm. paint)	low (wood fibre board with	high mineral fibre sorption)	high (paper)	high (cellulose)
6	high (v. perm. paint)	high (wooden	low panel)	high (paper)	high (cellulose)

In cases 1 to 6, all the walls plus the ceiling and floor are of the same light-weight construction (except the floor covering is 28 mm of wood). The permeance of the vapour permeable paint is 5 x 10^{-9} kg/(s·m^2·Pa), which is 6 times more resistant than normal convection mass transfer in a well-mixed room. The permeance of the vapour tight paint is 5 x 10^{-12} kg/(s·m^2·Pa).

7	Same as case1, except the exterior wall and ceiling have a vapour tight paint
8	Same as case1, except only the ceiling has a vapour permeable paint
9	Same as case1, except a lower permeable paint (kd = 1 x 10^{-9} kg/(s·m^2·Pa))
9mp	Same as case1, except a more permeable paint (kd = 5 x 10^{-8} kg/(s·m^2·Pa))
9lp	Same as case1, except a lower permeable paint than in case9 (kd = 5 x 10^{-10} kg/(s·m^2·Pa))
10	Same as case1, except the floor and ceiling are massive (i.e., 200 mm of concrete) with impermeable coatings
11	Same as case10, except the interior wallboard is massive wood (125 mm log)
12	Same as case10, except the interior wallboard is less massive wood (50 mm log)
13	Same as case1, except the interior wallboard is gypsum
14	Same as case11, except the massive ceiling and floor are wood (200 mm)

In all cases, the floor is impermeable and the wind barrier in the exterior wall is 11 mm of porous wood fibre board.

3.2 Outdoor Climates

The geographical locations of the chosen climates are shown in Figure 9.

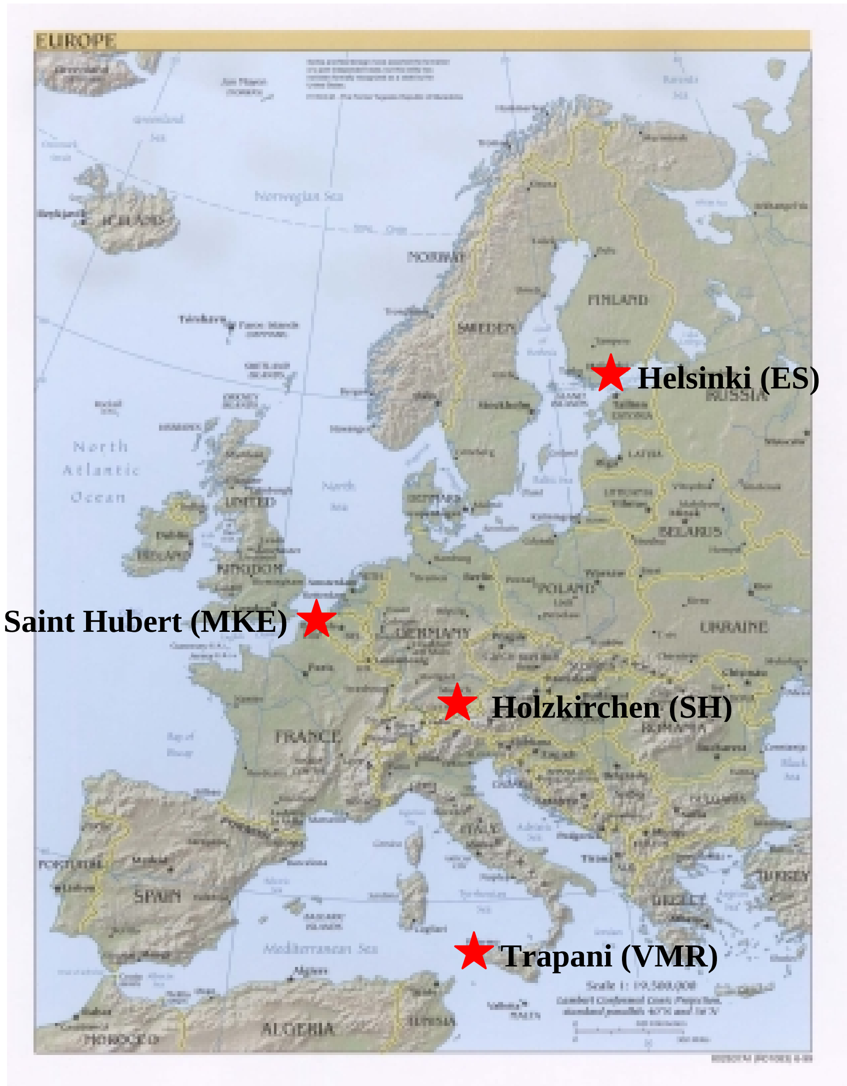

Figure 9. Map of Europe showing the location of the cities chosen to represent the following European climates: North (Helsinki, Finland), Maritime (Saint Hubert, Belgium), Central (Holzkirchen, Germany) and South (Trapani, Italy).

The monthly average outdoor temperature, absolute humidity and the total solar radiation are given in Figure 10, Figure 11 and Figure 12 show that the southern climate is significantly warmer and more humid than the other climates. Trapani, Italy is likely one of the most hot and humid climates in Europe.

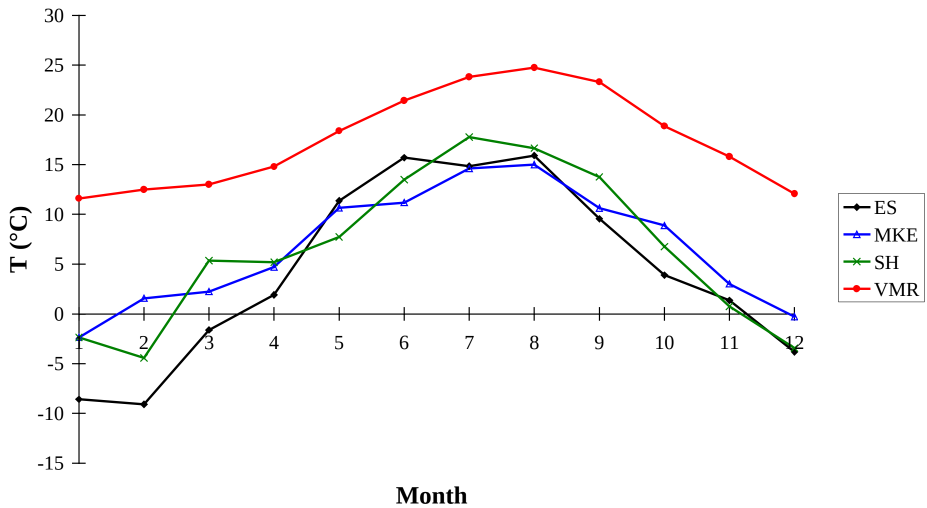

Figure 10. Monthly average outdoor temperature in the four climates.

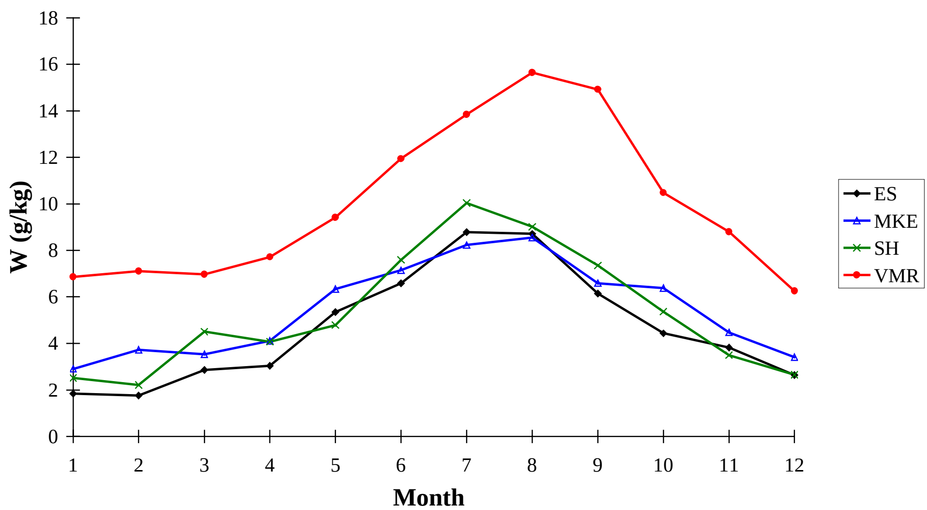

Figure 11. Monthly average outdoor absolute humidity in each climate.

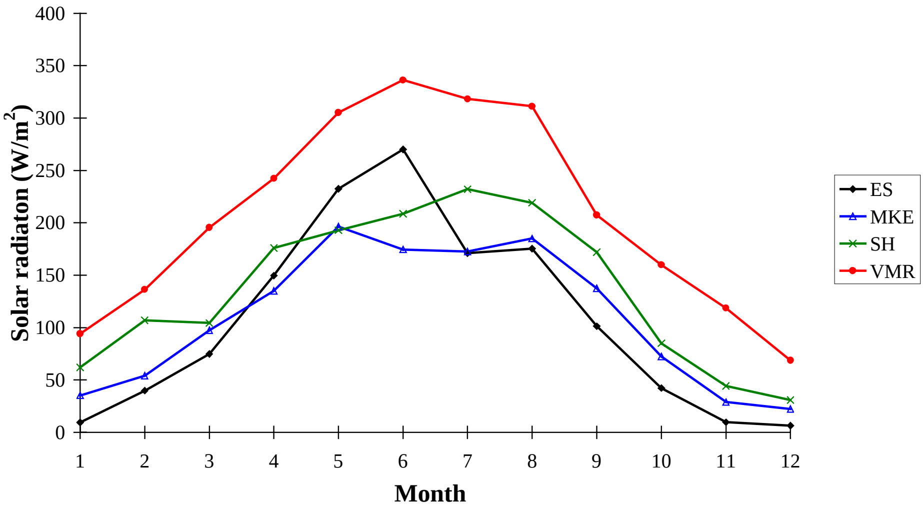

Figure 12. Monthly average solar radiation in the four climates.

The hourly variations of outdoor temperature, absolute humidity and solar radiation are presented for a few days in January, July and September in Figure 13, Figure 14 and Figure 15 respectively.

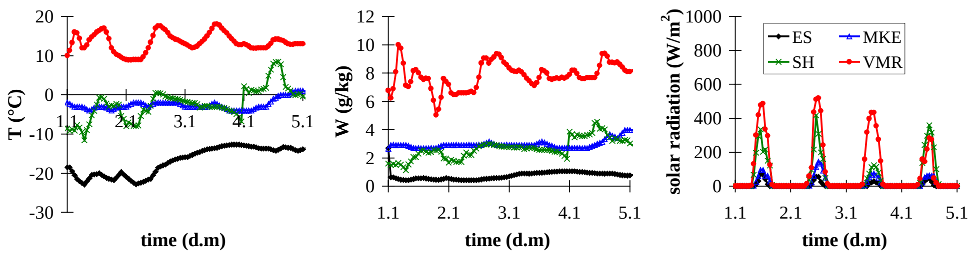

Figure 13. Hourly outdoor temperature, absolute humidity and solar radiation during a few days in January in each climates.

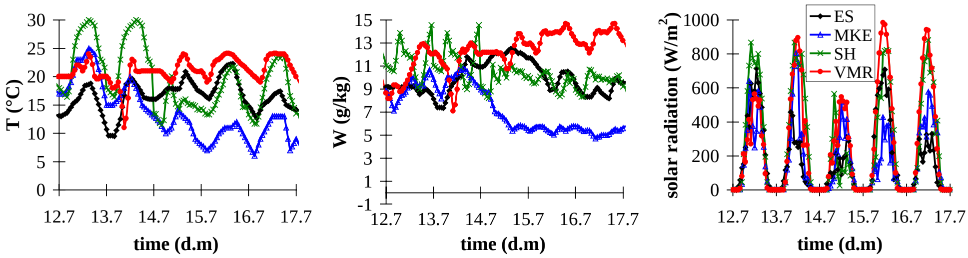

Figure 14. Hourly outdoor temperature, absolute humidity and solar radiation during a few days in July in each climates.

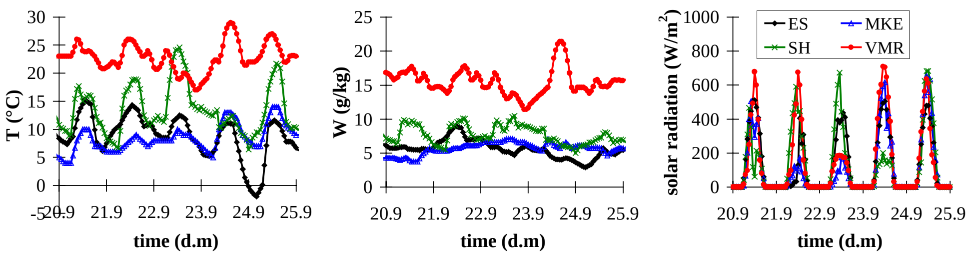

Figure 15. Hourly outdoor temperature, absolute humidity and solar radiation during a few days in September in each climates.

3.3 Numerical Model

The model used for the simulations has been developed starting from an existing model that is primarily used for the hygrothermal simulation of building envelope parts (LATENITE). The model combines the heat, air, moisture and contaminant balance of indoor air with the hygrothermal performance of the building envelope. The model has been used and presented previously by Salonvaara (1998), Salonvaara and Kokko (1999), Kokko et al. (1999) and Simonson et al. (2001). The model has been validated with field and laboratory experiments (Simonson, 2000, Simonson and Salonvaara, 2000, Salonvaara and Simonson, 2000, Salonvaara and Kokko, 1999 and Salonvaara, 1998).

An overview of the LATENITE version 1.0 hygrothermal model is given by Hens and Janssens (1993) and a more detailed description is given by

Salonvaara and Karagiozis (1994). The moisture transport potentials used in the model are moisture content and vapour pressure. The porous media transport of moisture (vapour and liquid) through each material layer is considered strongly coupled to the material properties (i.e., the sorption-suction curves). The corresponding moisture fluxes are decomposed for each phase and are treated separately. The heat and moisture transfer equations, including liquid and vapour transfer, are:

$$q_M = -kd(u,T)\,\nabla P_v - \rho_m D_w(u,T)\,\nabla u + v_a \rho_v + K\rho_w \vec{g} \text{ and} \tag{9}$$

$$q = -k(u,T)\,\nabla T + v_a \rho_a H_g + q_{M,v} Cp_v T + q_{M,w} Cp_w T \tag{10}$$

where the symbols are defined in Table 4 and the list of symbols. The most important term in the moisture transfer equation, for the conditions in this report, is the first term. Here the moisture transfer is assumed to follow Fick's law, which states that moisture transfer is proportional to the vapour pressure gradient, even though it is not strictly correct for some wood based materials. Nevertheless, the results should be quite accurate and give a reasonable estimation of the moisture transfer in real materials. The energy transfer equation uses temperature as the transport potential and includes the energy transfer resulting from air and moisture flow. The energy and moisture conservation equations are coupled via the latent heat of phase change as follows:

$$\rho_m \frac{\partial u}{\partial t} = -\nabla \cdot q_M + S_M \text{ and} \tag{11}$$

$$\rho_m Cp_m \frac{\partial T}{\partial t} = -\nabla \cdot q + S - \nabla \cdot q_{M,v} \Lambda \tag{12}$$

The energy released/absorbed during adsorption/desorption, condensation/evaporation and thawing/freezing is included and the latent heat of sorption is assumed equal to the latent heat of vaporisation.

Table 4. Nomenclature for the governing equations.

A	surface area (m^2)
Cp	specific heat capacity (J/(kg·K))
D_w	liquid moisture diffusivity (m^2/s)
g	acceleration of gravity (m/s^2)
H	enthalpy (J/kg)
h	convective heat transfer coefficient (W/(m^2·K))
h_p	permeance of the interior surface including the convective mass transfer coefficient (kg/(s·m^2·Pa))
K	moisture permeability (s)
k	thermal conductivity (W/(m·K))
kd	vapour permeability (kg/(s·m·Pa))
$\dot{m}_{j,i}$	mass flow rate of dry air from zone j into zone i including infiltration, exfiltration and ventilation (positive for flow entering zone i) (kg/s)
P	partial pressure (Pa)
q	heat flux (W/m^2)
q_M	mass flux (kg/(m^2·s))
S	heat sources or sinks per unit volume (W/m^3)
S_M	moisture or contaminant sources or sinks per unit volume (kg/(m^3·s))
T	temperature (°C)
t	time (s)
u	moisture content (kg/kg)
V	volume of the zone (m^3)
v_a	velocity of air (m/s)
W	absolute humidity (kg/kg)
Greek Symbols	
Λ	latent heat of vaporisation (J/kg)
ρ	density (kg/m^3)
Subscripts	
a	dry air
g	gas phase (including dry air and water vapour)
i	zone index
j	zone index
m	dry property of the porous medium
n	surface index
s	interior surface of a zone
v	water vapour
w	liquid water

The indoor air model, which has been added to the LATENITE model, is fully coupled with the building envelope solution. The coupling is made possible by using the delta-form equations and by deriving the equations in such a way that changes in the building envelope affect the solution already during the solution of the discretised equations. The building envelope components are modelled one-dimensionally when coupled to the indoor air model. The indoor air model is a multi-zone model with the limitation that the air flow rates between zones are known a priori (i.e., the air flow rates due to forced or natural ventilation are not calculated but instead given as input). The airflow may come from different zones, directly from outdoors or through a heat exchanger with a known thermal efficiency. Walls may exist between the zones and interior hygroscopic mass within a zone may be included in the form of walls with an adiabatic and impermeable exterior surface.

Indoor air is handled by assuming perfect mixing within each zone and the conservation of moisture and energy in zone i are:

$$\rho_{a,i} V_i \frac{\partial W_i}{\partial t} = \sum_{j=1}^{zones} \dot{m}_{j,i}(W_j - W_i) + \sum_{n=1}^{surfaces} h_{p,n} A_n \left(P_{v,s,n} - P_{v,i}\right) + S_{M,i} V_i \text{ and} \tag{13}$$

$$\rho_{a,i} V_i \frac{\partial H_{g,i}}{\partial t} = \sum_{j=1}^{zones} \dot{m}_{j,i}(H_{g,j} - H_{g,i}) + \sum_{n=1}^{surfaces} h_n A_n \left(T_{s,n} - T_i\right) + S_i V_i \,. \tag{14}$$

The model allows time dependent heat and moisture (and contaminant - not discussed in this report) sources to be given as input. The moisture source term (S_M) is positive for moisture sources (most common) and is negative if there are known moisture sinks in the room such as a dehumidifier that is known to remove a certain amount of moisture per unit time. The moisture sources are currently defined and scheduled through user input and the moisture source term (S_M) can represent all types of moisture sources (and sinks). The currently used moisture sources include: constant moisture sources from occupants (according to occupancy schedule as used in this report), heated or unheated water surface, or known release of vapour from a humidifier.

The heating and cooling systems are modelled with the source term (S) and the heating system can be controlled based on the indoor or outdoor temperature and humidity (e.g., known heat source as a function of outdoor temperature). In this report, the heating system is controlled with a proportional controller when the indoor temperature is between 20°C and 21°C. The system provides no heat when T≥21°C and provides 100% heat output at T≤20°C. The maximum heat output from the heating system (i.e., for T≤20°C) varies linearly according to the outdoor temperature, such that the maximum heat output increases with decreasing outdoor temperature. The heating is assumed to affect only the indoor air enthalpy (no radiative heating). Solar gains through windows can be taken into account by evenly distributing the heat gain on an interior surface of the zone.

3.3.1 Material Property Data

The property data of the building materials given in Table 3 are taken mainly from the database of property data included in the LATENITE simulation program (Karagiozis et al., 1994) and are presented in Appendix A. Appendix A also includes the geometry and grid selection for each material in each simulation case. Table 5 presents a summary of the property data for the thickness of the interior board (11 mm), insulation (100 mm) and air/vapour barrier (0.3 mm). In Table 4 the moisture capacity is calculated using the sorption curve between 40% and 60% RH as follows:

$$Cm = (u_{60\%RH} - u_{40\%RH})\rho V 1000/20 \,, \qquad (15)$$

where Cm is the moisture capacity (g/%RH), u is the moisture content (kg/kg), ρ is the density of the material (kg/m^3) and V is the volume of the material (m^3). The moisture diffusivity is calculated analogous to thermal diffusivity (e.g., Incropera and Dewitt, 1996) as,

$$\alpha_m = \frac{kd}{Cm/(1000\,V)\,\frac{100}{P_{v,sat}}} \quad , \qquad (16)$$

using the saturation pressure for water vapour at 22°C ($P_{v,sat}$ = 2645 Pa).

Table 5. Summary of property data for different materials.

	por wfb	por wfb (non-hyg)	gypsum	wood	concrete	mf	cellulose	paper	plastic
t (mm)	11.0	11.0	11.0	11.0	11.0	100.0	100.0	0.3	0.3
A (m^2)	1	1	1	1	1	1	1	1	1
vapor perm (g/(d·Pa))	0.17	0.17	0.17	0.03	0.01	0.11	0.07	0.21	4.3E-05
ratio of vapor resistance to air	8.9	8.9	8.6	52.5	114.8	1.5	2.4	256.8	1.3E+06
moisture capacity (g/(%RH))	2.6	0.5	1.6	7.4	4.2	0.4	5.7	0.1	0.1
Rt ((m^2·K)/W)	0.200	0.200	0.042	0.122	0.004	2.439	2.439	0.002	0.002
C (J/K)	7161	7161	5729	11173	20328	2520	4200	317	317
αt (m^2/s)	8.4E-08	8.4E-08	5.0E-07	8.9E-08	1.5E-06	1.6E-06	9.8E-07	1.5E-07	1.5E-07
αm (m^2/s)	2.4E-09	1.3E-08	3.9E-09	1.4E-10	1.1E-10	8.0E-07	3.7E-08	5.5E-11	1.1E-14

Table 6 and Table 7 compare the permeance and moisture capacity of the different materials when the thickness is such that the moisture capacity and permeance are the same for each material. Using Table 6 and Table 7 it is easy to compare the rate at which moisture diffuses through different materials (permeability) and the amount of moisture different materials can hold (capacity) under steady state conditions.

Table 6. Permeance and thickness of different materials that have the same moisture capacity as 11 mm of porous wood fibre board.

	por wfb	por wfb (eihy)	gypsum	wood	concrete	mf	cellulose	paper	plastic
t (mm)	11.0	57.8	17.6	3.9	6.8	597.7	45.4	7.4	7.4
A (m^2)	1	1	1	1	1	1	1	1	1
vapor perm (g/(d·Pa))	0.17	0.03	0.11	0.08	0.02	0.02	0.15	0.01	1.8E-06
ratio of permeance	1.0	0.19	0.64	0.48	0.13	0.11	0.90	0.05	0.00
ratio of vapor resistance to air	8.9	8.9	8.6	52.5	114.8	1.5	2.4	256.8	1.3E+06
moisture capacity (g/(%RH))	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Rt ((m^2·K)/W)	0.200	1.052	0.068	0.043	0.003	14.579	1.108	0.046	0.046
C (J/K)	7161	37657	9158	3941	12516	15063	1908	7757	7757

Table 7. Moisture capacity and thickness of different materials that have the same permeance as 11 mm of porous wood fibre board.

	por wfb	por wfb (eihy)	gypsum	wood	concrete	mf	cellulose	paper	plastic
t (mm)	11.0	11.0	11.3	1.9	0.8	67.1	40.9	0.4	0.0
A (m^2)	1	1	1	1	1	1	1	1	1
vapor perm (g/(d·Pa))	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
ratio of vapor resistance to air	8.9	8.9	8.6	52.5	114.8	1.5	2.4	256.8	1.3E+06
moisture capacity (g/(%RH))	2.6	0.5	1.7	1.2	0.3	0.3	2.3	0.1	0.0
ratio of moisture capacity	1.0	0.19	0.64	0.48	0.13	0.11	0.90	0.05	0.00
Rt ((m^2·K)/W)	0.200	0.200	0.043	0.021	0.000	1.638	0.998	0.002	0.000
C (J/K)	7161	7161	5876	1885	1568	1692	1719	400	0

Under transient moisture conditions, the moisture diffusivity is best able to quantify the potential for materials to damp changes in indoor humidity. The active thickness of a material for moisture exchange can be estimated using (Padfield, 1999):

$$t_{active} = \sqrt{\alpha_m T_p / \pi} \tag{17}$$

where t_{active} is the distance at which the variation of RH in the material is about one third of the variation in the room and T_p is the period of the moisture production cycle. Using equations (17) and (15) for a daily moisture cycle (24 hours), the active thickness and capacity of the materials used in this report are presented in Figure 16 and Figure 17. The active thickness is a useful concept because the total change in moisture content of a thick material can be approximated by a uniform change in moisture content (equal to the moisture content change at the active thickness) throughout a material thickness equal to the active thickness. The active thickness, however, does not represent the depth at which the humidity in the pores of the material is unaffected by the changes in the indoor humidity.

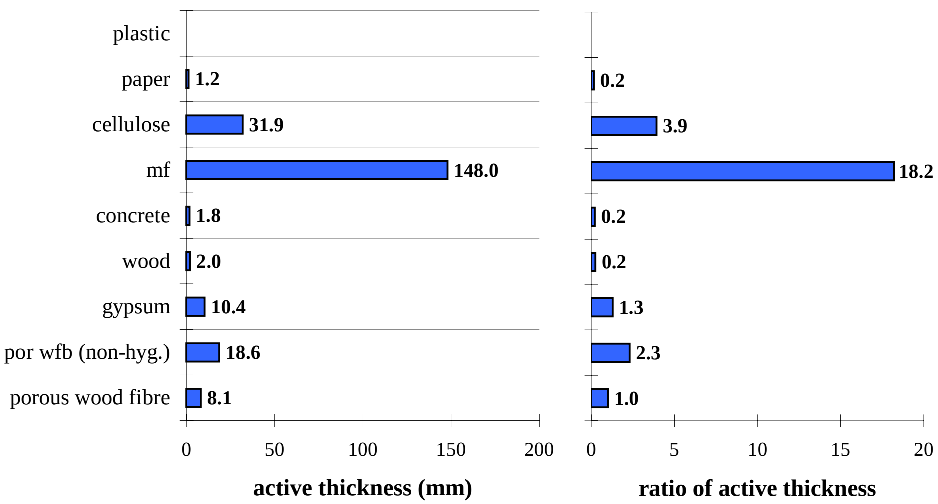

Figure 16. Estimated active thickness for the materials used in this report and the ratio of the active thickness to the active thickness of porous wood fibre board. The active thickness represents the distance at which the variation of RH in the material is about one third of the variation in the room during a 24 hour cycle. The active thickness will approximately double if a criterion of 10% is used.

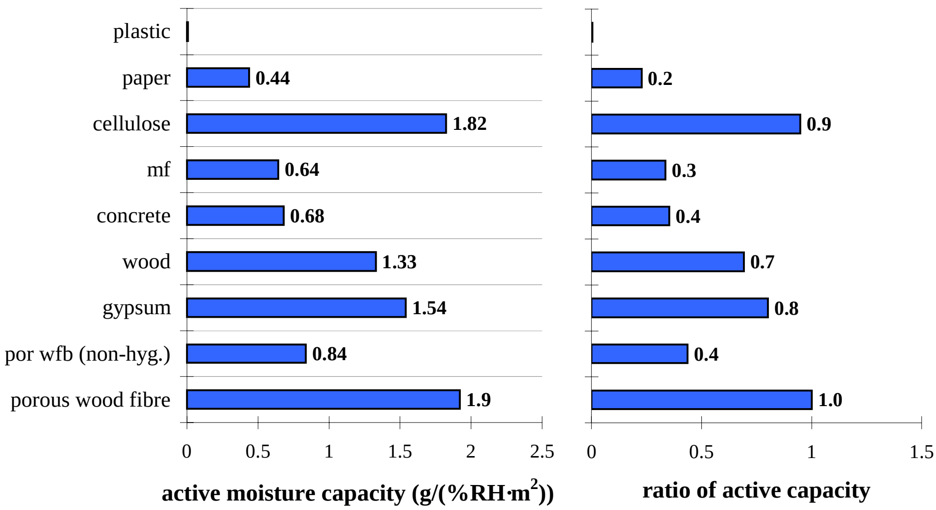

Figure 17. Estimated active moisture capacity for the materials used in this report and the ratio of the moisture capacity to the moisture capacity of porous wood fibre board.

Figure 17 shows that porous wood fibre board has the highest active moisture capacity and cellulose insulation has the second highest. Plain pine wood has a very small active thickness (2 mm), but the active moisture capacity is only 30% lower than the active moisture capacity of porous wood fibre board. As noted above, the active thickness and capacitance determined using equations (17) and (15) are useful because they allows the comparison of different materials, but they do not represent the total penetration depth for moisture during diurnal changes. The active thickness will approximately double if a criterion of 10% is used. This means that the material must be 2 to 3 times thicker than the active thickness determined using equation (17) in order to achieve the moisture capacities. For example, simulation results show that cellulose fibre insulation plays a role behind 11 mm of gypsum board, even though the active thickness of gypsum board in Figure 16 is less than 11 mm.

The active thickness for heat conduction can be determined by applying equation (17) for conduction heat transfer. The results are in Figure 18 and show that the penetration depth for the temperature wave is significantly greater than the penetration depth for the humidity wave.

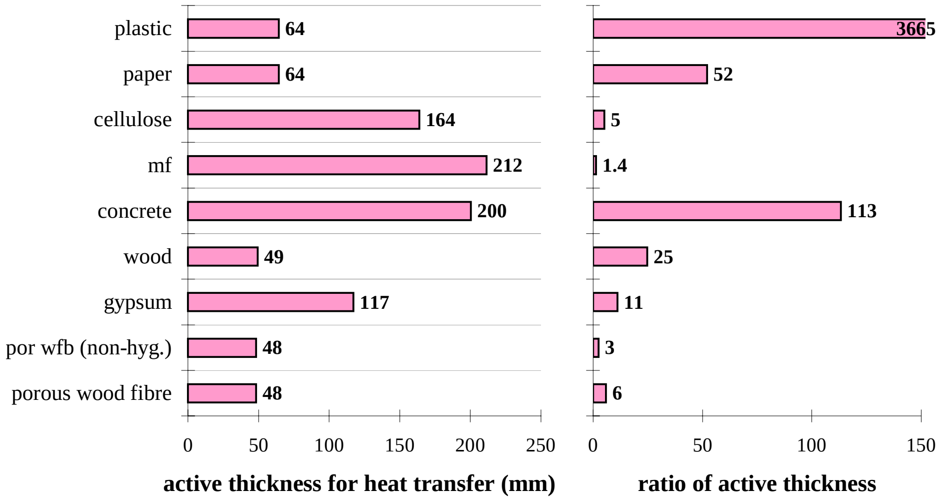

Figure 18. Estimated active thickness for conduction heat transfer and the ratio of the active thicknesses for heat transfer and moisture transfer.

4. Numerical Results

The variables that will be used to compare the performance of different cases (structures), climates, ventilation rates and moisture productions are the indoor: temperature (T), relative humidity (RH), absolute humidity (W), enthalpy (H), percent dissatisfied with warm respiratory comfort from equation (6) (PD) and the acceptability of clean indoor air (Acc) from equation (8). The indoor humidity parameters (RH and W) are the most important when comparing the moisture performance, while T and H tend to reflect the thermal and energy performance respectively. The variables PD and Acc are also important because they combine the effect of temperature and humidity to predict human response.

Sections 1.2.1 and 1.2.2 show that indoor humidity has a strong effect on warm respiratory discomfort and the acceptability and freshness of indoor air. Equations were presented from the literature, which are based on the initial response of subjects facially exposed to clean air in laboratory settings and quantify the effect of humidity on warm respiratory comfort (equation (6)) and the acceptability of indoor air (equation (8)). In this report, equations (6) and (8) will be used to estimate the effect of humidity on PD and acceptability. The equations are based on clean air which will underestimate PD and overestimate acceptability compared to the normal situation in buildings. On the other hand, they are based on facial exposures, which show a greater effect of temperature and relative humidity than whole-body exposures (Fang et al., 1998b). Furthermore, these equations are based on the first impression of thermal comfort and air quality, but Fang et al. (1998b) have shown that the initial acceptability of air is nearly the same as the acceptability after 20 minutes of exposure. Therefore, the equations used to estimate PD and acceptability are not exact, but give some indication of expected human response to temperature and humidity conditions.

4.1 Comparison of Permeable and Impermeable Structures

Case1 (permeable) and case2 (impermeable) allow a direct comparison of the case where moisture transfer between indoor air and structures is uninhibited by the surface coating and strongly inhibited (practically eliminated) by the surface coating. In case1, the permeance of the indoor surface is 5×10^{-9} kg/(s·m^2·Pa), which is 6 times more resistant to moisture transfer than normal convection moisture transfer in a well-mixed room. The permeance of the indoor air boundary layer, assuming a Lewis number of unity and a convective heat transfer coefficient of 5 W/(m^2·K) is 3×10^{-8} kg/(s·m^2·Pa). The indoor surface in case1 is also more permeable than many paints, where the permeability of paints varies from 1×10^{-9} to 2×10^{-11} kg/(s·m^2·Pa) (ASHRAE, 1997). Therefore, the coating in case1 is about 5 times more permeable than very permeable paints and represents a bedroom with essentially no interior surface coating. Case2, on the other hand, is chosen to have a vapour resistance slightly greater (5 times) than the vapour retarder paint listed in ASHRAE (1997), for example, and the vapour permeance is 5×10^{-12} kg/(s·m^2·Pa). Case2 is where the bedroom is painted with a very vapour resistant paint.

The hourly indoor conditions for cases 1 and 2 are plotted on the psychrometric chart in Figure 19 for all climates. These results clearly show that the permeable case1 has lower maximum indoor humidities than the impermeable case2. In case1, the humidity seldom exceeds 60% RH, while case2 has significant time with RH>60%, especially when the indoor temperature is below 20°C. This means that, in the impermeable case2, the indoor RH will be excessively high in many bedrooms in central Europe because the average indoor temperature during the night is often about 15°C (Sanders, 1996 and Künzel, 1979). As well as reducing the peak humidity, the permeable structure in case1 increases the minimum humidity and there are fewer hours below 20% RH in case1 than in case2. The difference between the difference climates is also evident with the southern climate showing the greatest range of indoor temperature and absolute humidity.

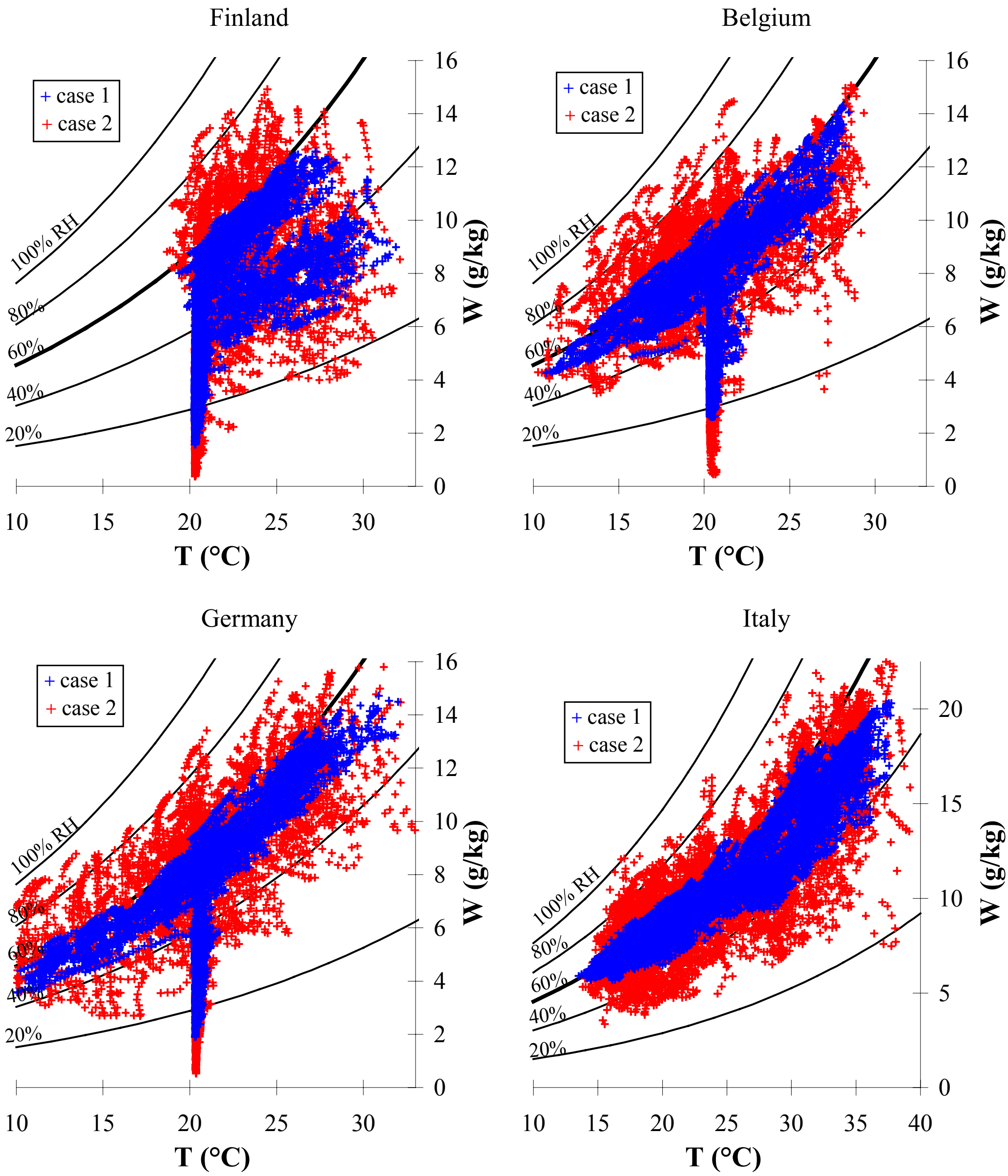

Figure 19. Hourly values of indoor temperature and humidity during the entire year in the permeable case1 and impermeable case2 in all climates.

4.1.1 Performance during Different Weather Conditions

A comparison between the performance of the room in case1 and case2 are presented in the Appendix B for several weather conditions in all climates. In this section, the performance of the room will be presented for mild (May), humid (July) and dry (February) periods in Belgium. The performance during a period of increasing outdoor temperature in July in Belgium will also be presented.

4.1.1.1 Mild Period in Belgium (May)

Just after the heating season in Belgium, the temperature is quite moderate (10°C to 15°C) and the outdoor humidity is quite moderate (6 g/kg) as shown in Figure 20. As a result, the indoor temperature is quite low and the indoor relative humidity is quite high (Figure 21). The difference in performance between the permeable case1 and the impermeable case2 is very evident in Figure 21, with case1 showing better performance. The indoor temperature is about 1°C higher in case1 than in case2 (due to phase change energy released during sorption), while the maximum relative humidity is 35% RH higher in case2 than in case1. The indoor humidity is above 60% RH for only a few hours in case1, but is almost always above 60% RH during occupation in case2. The indoor absolute humidity and enthalpy are also higher during occupation in case2 than in case1. Figure 21 also shows that PD is quite low and the acceptability is quite high in both cases. Nevertheless, PD is as much as 3% higher in case2 than in case1. During these conditions, respiratory cooling will be adequate, but the high relative humidity in case2 may lead to other humidity related problems (e.g., asthma, mould, mites) as discussed in section 1.2.3.

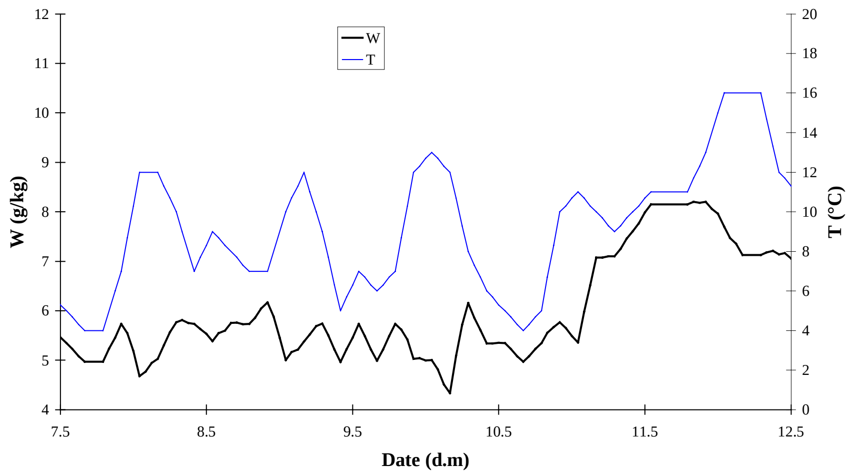

Figure 20. Outdoor humidity and temperature during mild weather in Belgium.

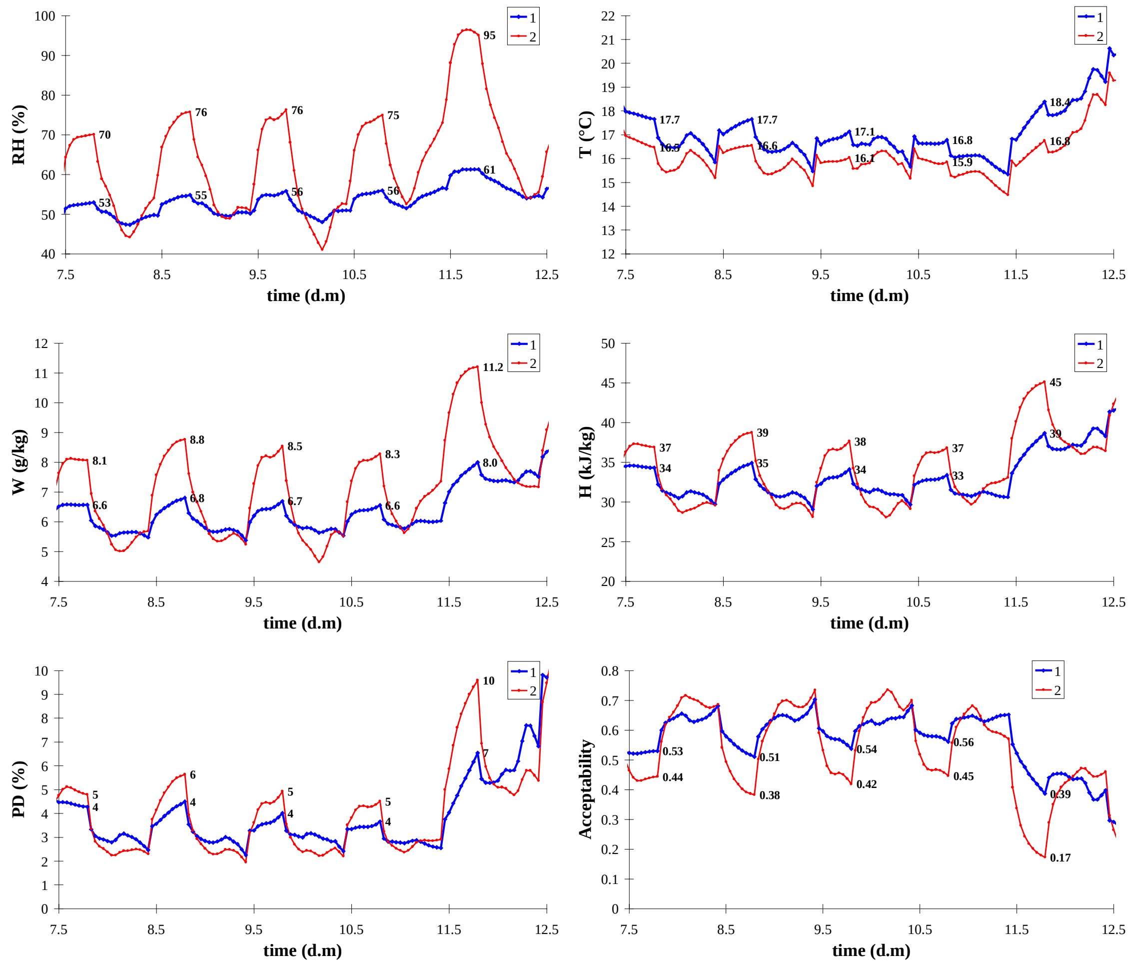

Figure 21. Temporal variation of the important indoor air variables during mild weather in Belgium. Case1 has an interior coating that is permeable and case2 has a impermeable coating. (The values at the end of occupation (7:00) are in each graph.)

4.1.1.2 Humid Period in Belgium (July)

To compare the performance of the permeable and impermeable cases during more humid weather (as in Figure 22), the same 6 indoor air variables are presented in Figure 23 for a 5 day period in July when the outdoor humidity approaches 12 g/kg. Once again there is a clear difference between permeable case1 and impermeable case2, with case2 having a higher indoor humidity and enthalpy and case1 having a higher indoor temperature. Since the moisture transfer between indoor air and the structure is greater during humid weather, the temperature difference between case1 and 2 is greater than in Figure 21. During the 5 day period, the maximum temperature is 23.6°C in case1 and 21.7°C in case2. Based on temperature alone, it is expected that case2 would have a better thermal comfort and PAQ, but Figure 23 shows that the opposite is true because the indoor humidity is significantly lower in case1. The net result is that, during occupation, PD is as much as 6% higher in case2 and the acceptability is as much as 0.2 lower in case2.

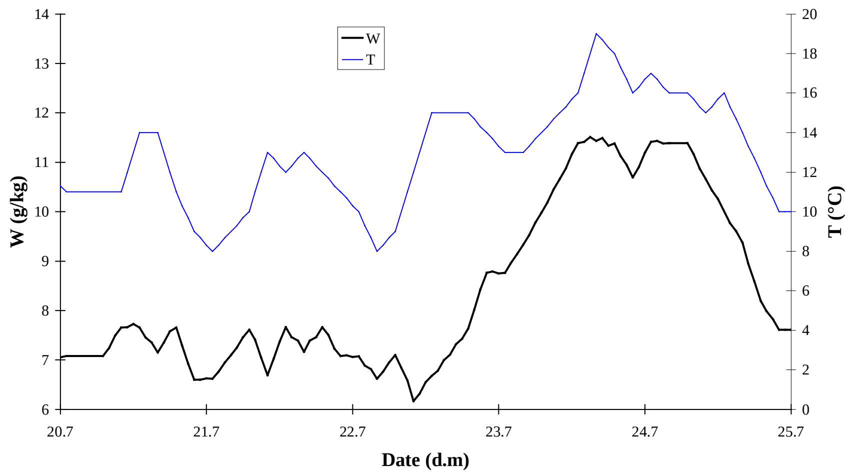

Figure 22. Outdoor humidity and temperature during a humid period in Belgium.

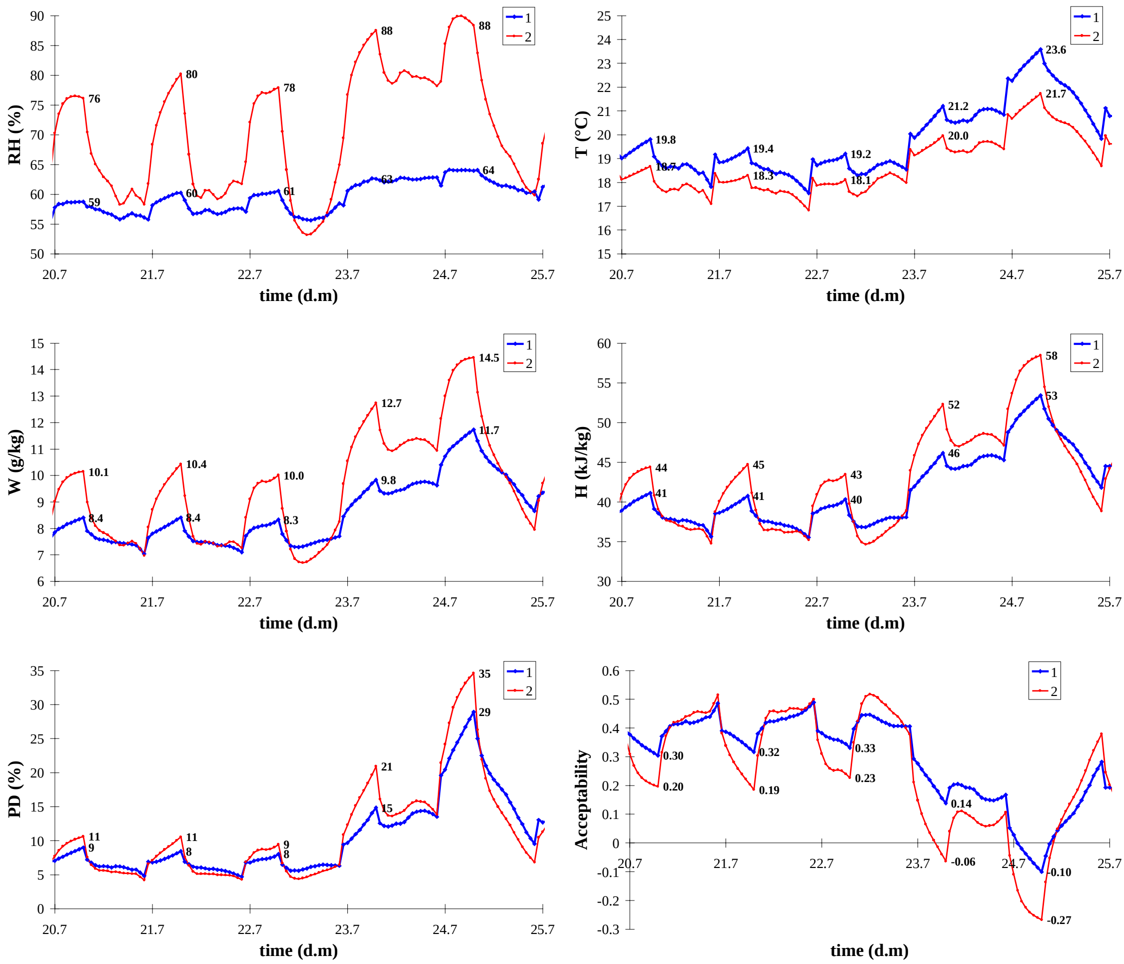

Figure 23. Temporal variation of the important indoor air variables during humid weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

4.1.1.3 Dry Period in Belgium (February)

Figure 24 presents the outdoor temperature and humidity during a dry period in Belgium when the outdoor temperature is near 0°C and the outdoor humidity is about 4 g/kg. The calculated indoor air variables for this time are in Figure 25 and show generally a better performance for the permeable case1. The indoor temperatures are nearly equal because of heating, but the indoor humidity is as much as 17% RH higher in case2 even though the humidity does not exceed 60% RH in either case. The indoor humidity in case1 varies between 30% and 40% RH, while the humidity in case2 varies between 20 and 55% RH. When the occupants enter the room at 22:00 on 3.2, the indoor humidity in case2 will be nearly 10% RH lower than in case1. This shows that moisture storage can reduce the maximum and increase the minimum indoor humidity. The PD and Acc results show that the occupant satisfaction will be greater for the permeable case1 than for the impermeable case2, however, during the day (unoccupied time) PD and Acc are often better in case2 that in case1. The improvement in PD and Acc during occupation is similar to that during mild and humid weather.

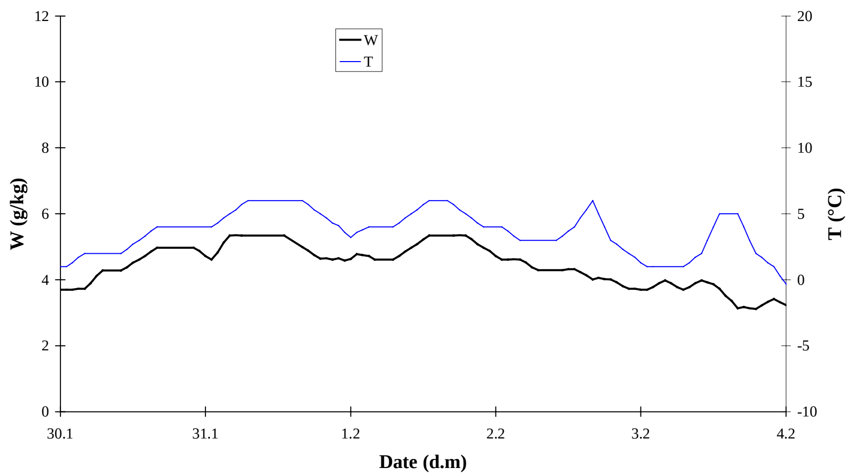

Figure 24. Outdoor humidity and temperature during a dry period in Belgium.

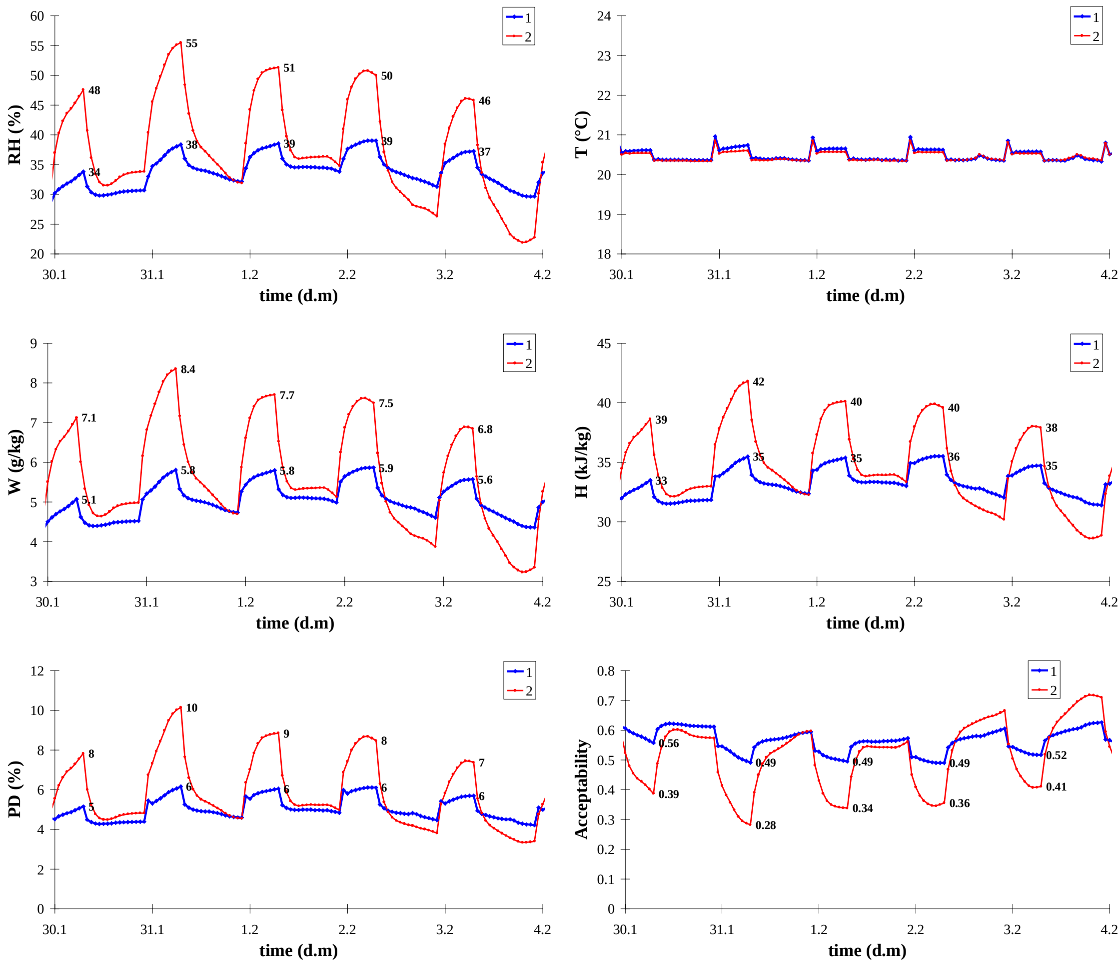

Figure 25. Temporal variation of the important indoor air variables during dry weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

4.1.1.4 Period of Increasing Temperature in Belgium (July)

Figure 26 presents the outdoor temperature and humidity during a time when the outdoor temperature increases by 15°C (10°C to 25°C) quite rapidly and then slowly decreases by about 5°C. During this time, the outdoor humidity increases from 5 g/kg to nearly 12 g/kg after which it fluctuates between 7 and 10 g/kg for the rest of the 9-day period.

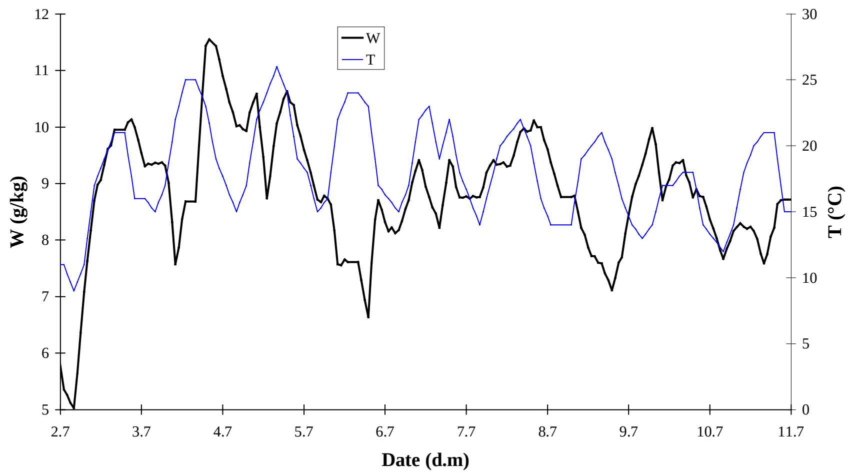

Figure 26. Outdoor humidity and temperature during a period of increasing outdoor temperature in Belgium.

The calculated indoor air variables (T, RH, W, H, PD and Acc) are very similar in cases 1 and 2 on 2.7 when the outdoor temperature and humidity begin to increase as can be seen in Figure 27. As the outdoor temperature increases, the indoor temperature increases and the indoor RH decreases. During this time, the indoor RH is greater for the permeable case1 than for the impermeable case2 because moisture is desorbed from the permeable structure. Since the removal of moisture from the permeable structure requires the addition of phase change energy, the indoor temperature is 1 to 2°C lower in the permeable case1 than in the impermeable case2. Even though case1 has a slightly higher indoor humidity, the lower indoor temperature causes the indoor enthalpy to be typically lower during occupation. As a result, the acceptability is typically higher in case1. Only on the night of 5.7 does case1 have a consistently lower acceptability than case2. The percent dissatisfied with warm respiratory comfort, on the other hand, is consistently higher in case2 than in case1 during occupation. On average, PD during occupation is 4% higher in case2 than in case1. The maximum difference occurs on 9.7 at 7:00 where PD is 11% higher in case2 than in case1. These results clearly show that moisture transfer between indoor air and building wood based building structure is able to significantly improve the indoor climate conditions.

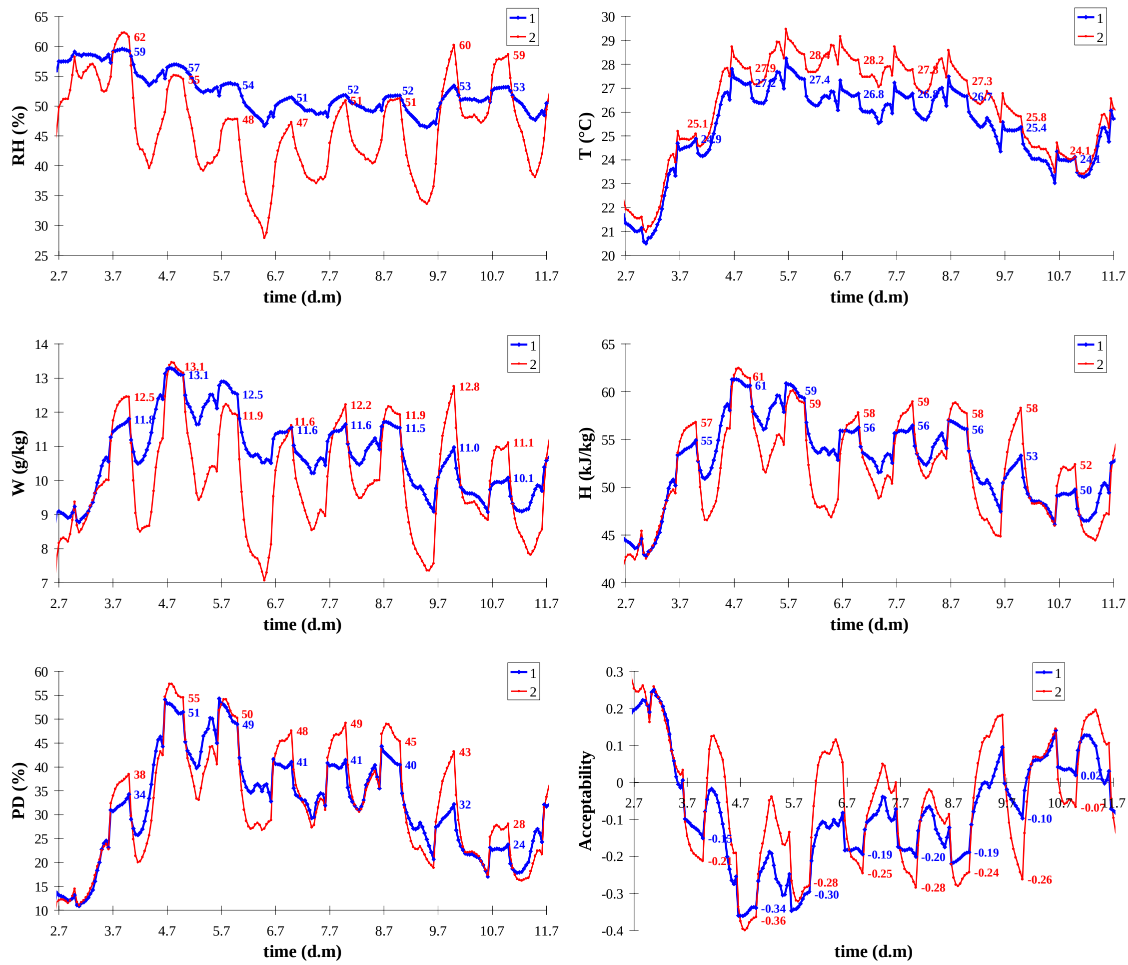

Figure 27. Temporal variation of the important indoor air variables during period of increasing outdoor temperature in Belgium. (The values at the end of occupation (7:00) are in each graph.)

4.1.2 Performance during Occupation

The results in section 4.1.1 and Appendix B show that the performance of the room depends on whether the room is occupied or unoccupied. Often the permeable case has a better performance during occupation, while the impermeable case sometimes has a better performance when the room is unoccupied. Naturally, the most important time is when the room is occupied and therefore this section will focus on the performance during occupation. One way to assess the performance during occupation is to determine the most unfavourable indoor conditions during this time. To facilitate this, the daily maximum and minimum values of a variable (X) during occupation are defined as:

$$X\max = \max\left[X(22:00):X(7:00)\right] \text{, and} \tag{18}$$

$$X\min = \min\left[X(22:00):X(7:00)\right] . \tag{19}$$

Therefore Xmax is the maximum value of variable X during the night and X min is the minimum. The most unfavourable condition is assumed to be the maximum value for all variables except for acceptability and the results are given in Figure 28 for Belgium.

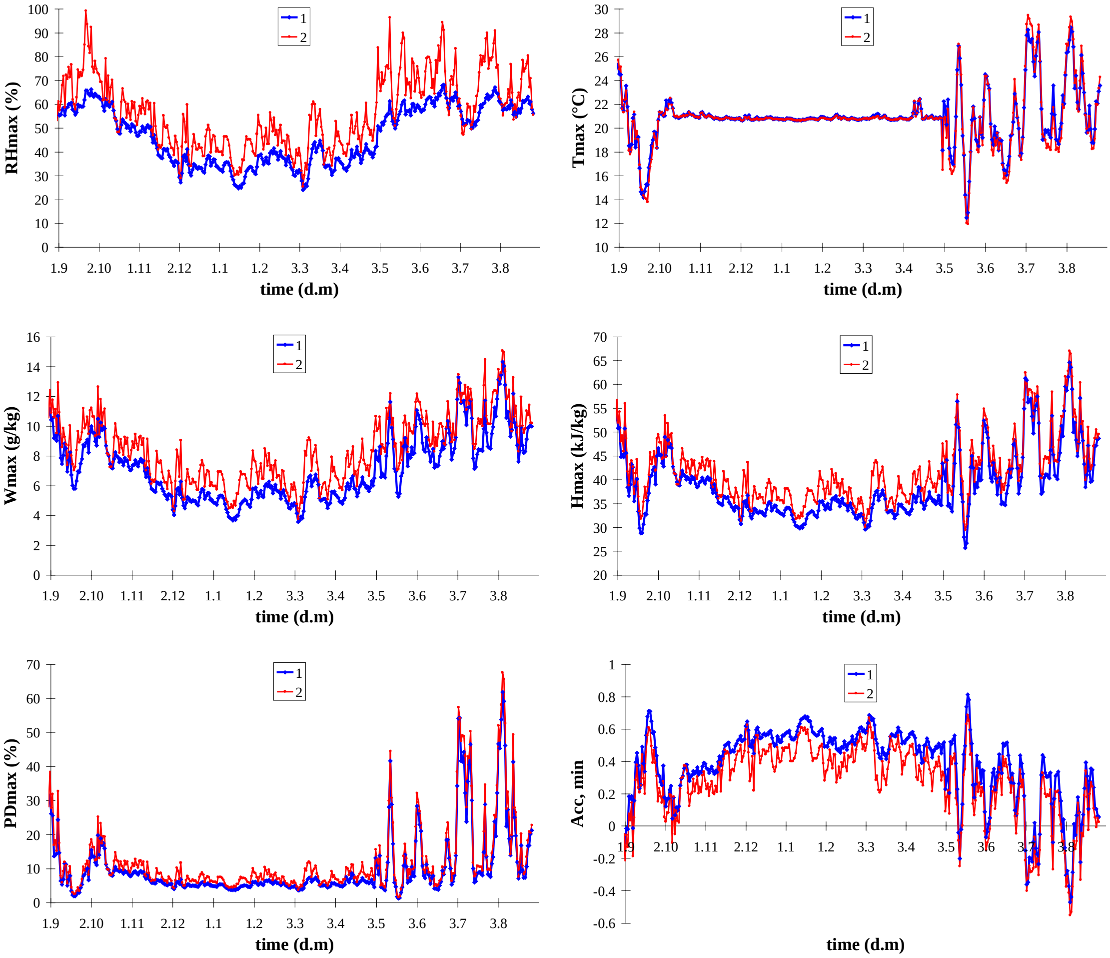

Figure 28. Maximum (or minimum) daily value of each variable during occupation in cases 1 and 2 in Belgium.

As expected, the results in Figure 28 show that the daily maximum and minimum values during the night vary throughout the year, with temperatures and humidities being higher in the summer. The relative humidity results show the greatest difference between case1 and 2, while the temperature results shows the least difference. Permeable case1 has peak humidity values of about 65% RH and impermeable case2 has peak values near 100% RH. The absolute humidity and enthalpy are typically higher in case2 than in case1 and PD and Acc are slightly better in case1 than in case2.

Even though the level of temperature and humidity varies throughout the year, the increase in humidity during the occupied period (i.e., night) is quite consistent throughout the year. This can be seen in Figure 29 where the increase in humidity during the night is presented throughout the year in case1 and case2, where:

$$\Delta Xnight = X\max - Xo \ . \qquad (20)$$

ΔXnight represents the maximum increase in a variable during occupation and Xo is the initial value when the occupants enter the room, i.e.:

$$Xo = X(22:00) \ . \qquad (21)$$

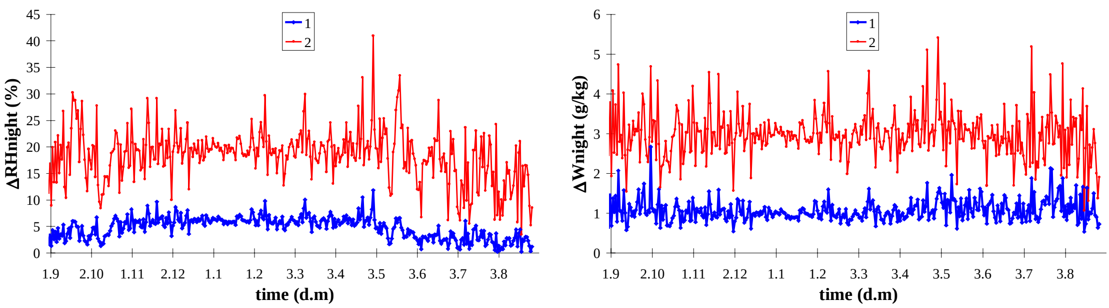

Figure 29. Increase in relative and absolute humidity during the night for permeable case1 and impermeable case2 in Belgium.

To further assess the variation of the increase in humidity during occupation, Figure 30 and Figure 31 contain the average, maximum, minimum and standard deviation of ΔRHnight and ΔWnight for each month and the entire year. These results show some difference between winter and summer for RH because the temperature is higher in the summer, however, ΔWnight is nearly constant each month. In all cases, the standard deviation is low. Figure 29, Figure 30, Figure 31 and Figure 32 show important differences between the permeable and impermeable cases. The increase in RH is about 4 times greater for impermeable case2 than for permeable case1 and the increase in W is about 3 times greater in case2 than in case1. Figure 32 also shows that the increase in absolute humidity during the night is nearly constant in all climates. The increase in relative humidity is lower in the southern climate because the indoor temperature is typically higher.

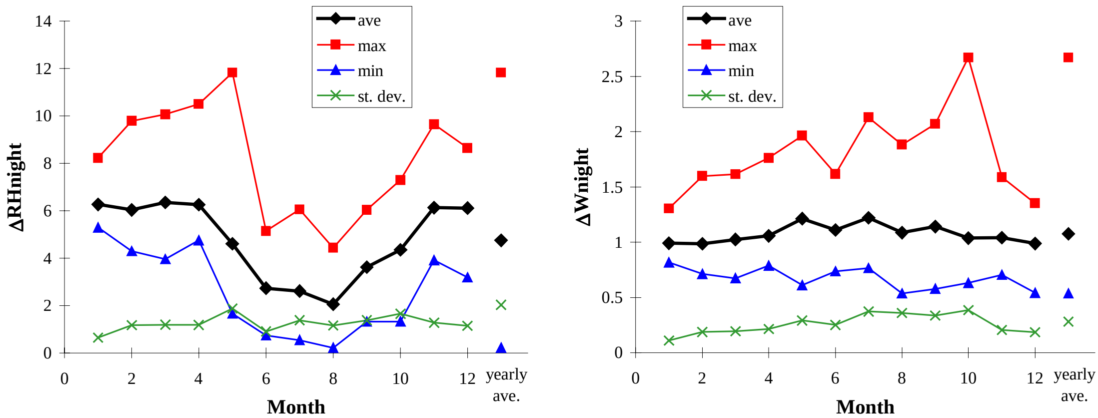

Figure 30. Maximum, minimum, average and standard deviation of the increase in humidity during the night in case1 in Belgium.

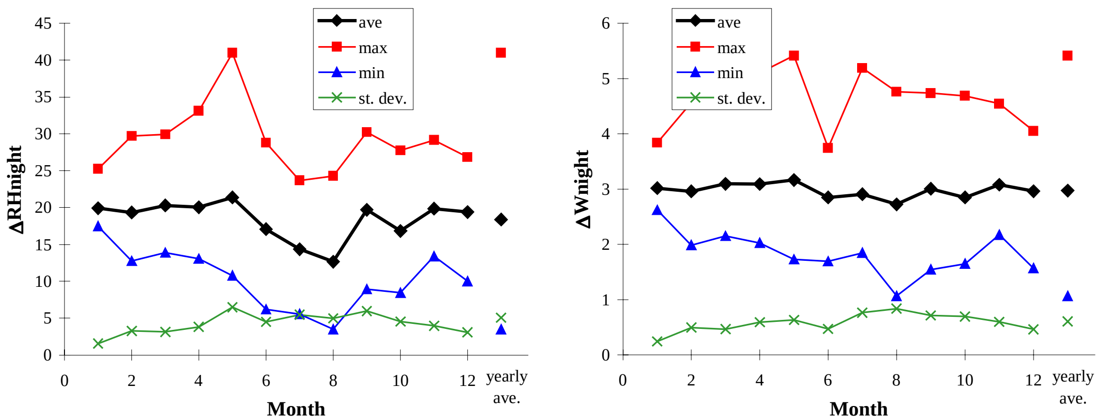

Figure 31. Maximum, minimum, average and standard deviation of the increase in humidity during the night in case2 in Belgium.

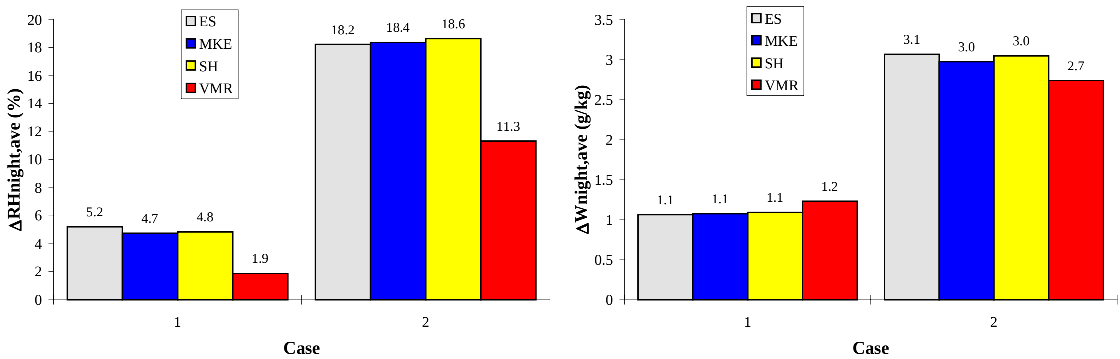

Figure 32. Yearly average increase in relative and absolute humidity during the night in all climates.

Values of RHo and Wo are given in Figure 33 and Figure 34 and show that the initial humidity is similar in both case1 and case2, but case2 typically has slightly lower values that are closer to the absolute humidity of the outdoor air. This means that at the design ventilation rate (0.5 ach) the humidity level at the beginning of the night is similar to the outdoor air.

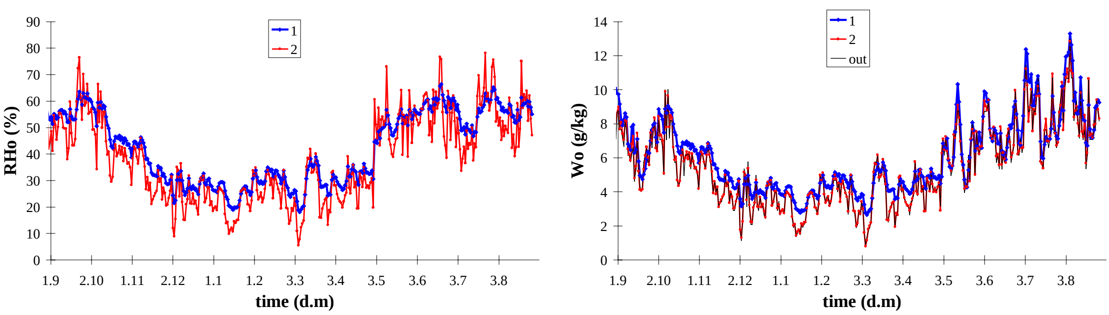

Figure 33. Values of relative and absolute humidity when the occupants enter the room for permeable case1 and impermeable case2 in Belgium.

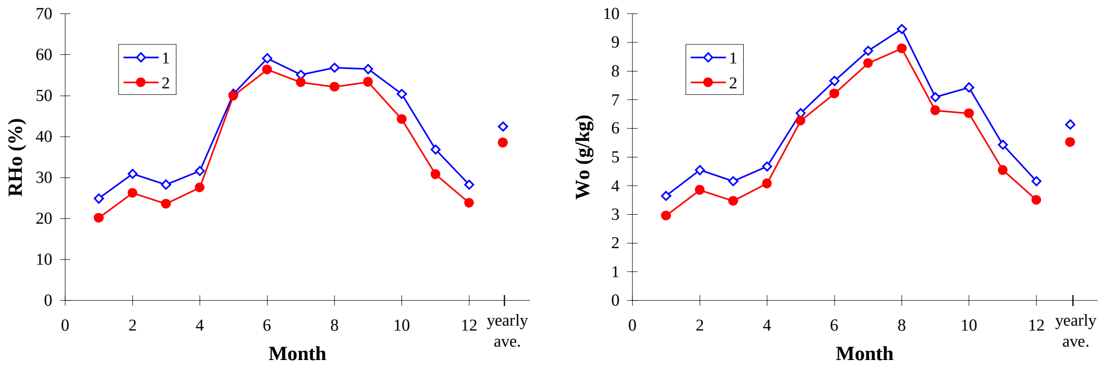

Figure 34. Monthly and yearly average values of relative and absolute humidity when the occupants enter the room in case1 and case2 in Belgium.

Since ΔRHnight and ΔWnight are quite constant throughout the year, it may be possible to represent the performance of the room with the initial value (Xo), which varies throughout the year, and the change (ΔXnight) that is quite constant throughout the year. For this purpose, a monthly average will be adequate because the outdoor and indoor humidity change slowly from winter to summer. The month with the lowest average indoor relative humidity during occupation is January and the month with the highest average indoor relative humidity during occupation is June. The average, maximum and minimum relative humidity at each hour during occupation for these months is presented in Figure 35.

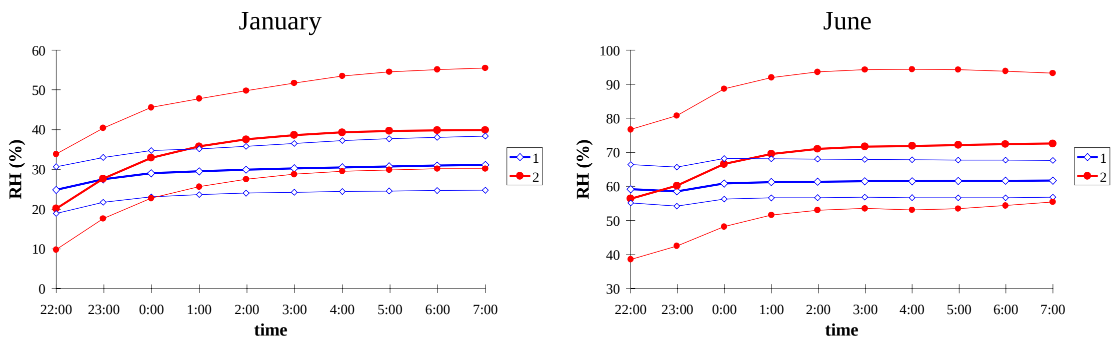

Figure 35. Average (thick line), maximum and minimum (thin lines) relative humidity for each occupied hour during January and June in case1 and 2 in Belgium.

Figure 35 shows that at 22:00 case2 typically has a lower RH than case1, but the humidity in case2 exceeds case1 after a few hours. The average humidity at 7:00 is always higher in case2 than in case1, in fact the maximum humidity in case1 is lower than the average humidity in case2. The average value in case2 at 7:00 is 9% RH and 11% RH greater than case1 during January and June respectively (see Table 8). The differences between the maximum values at 7:00 are even larger (17% RH in January and 26% RH in June at 7:00). Clearly the permeable case has a better average and extreme performance than the impermeable case. As a result, the percentage of occupants dissatisfied with warm respiratory comfort is slightly lower in case1 than in case2 (Figure 36).

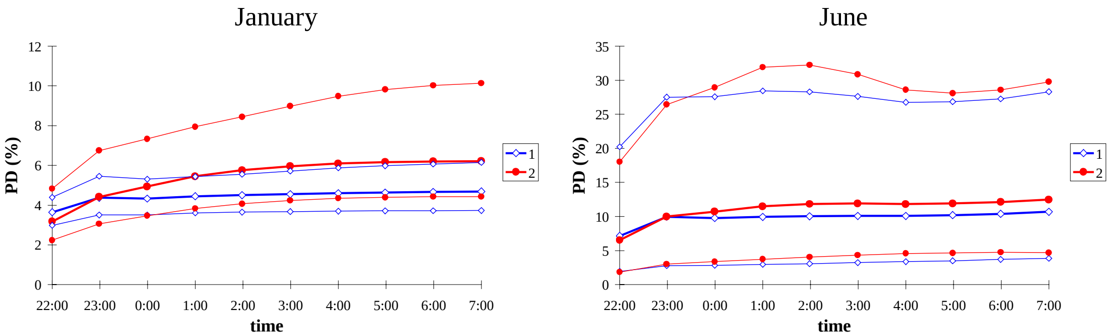

Figure 36. Average (thick line), maximum and minimum (thin lines) percent dissatisfied for each occupied hour during January and June in case1 and 2 in Belgium.

The average, maximum and minimum humidity during the months with the lowest (winter) and highest (summer) average indoor relative humidity are presented in Figure 37, Figure 38 and Figure 39 for the northern, central and southern climates respectively and the differences between case1 and case2 are summarised Table 8.

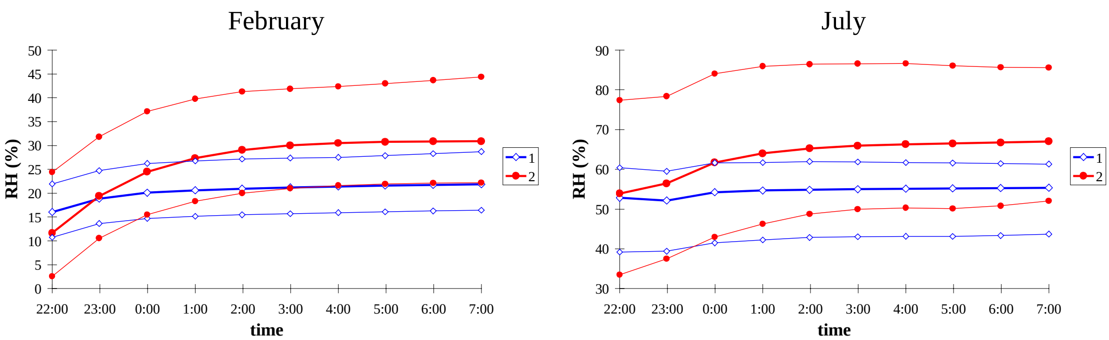

Figure 37. Average (thick line), maximum and minimum (thin lines) relative humidity for each occupied hour during February and July in case1 and 2 in Finland.

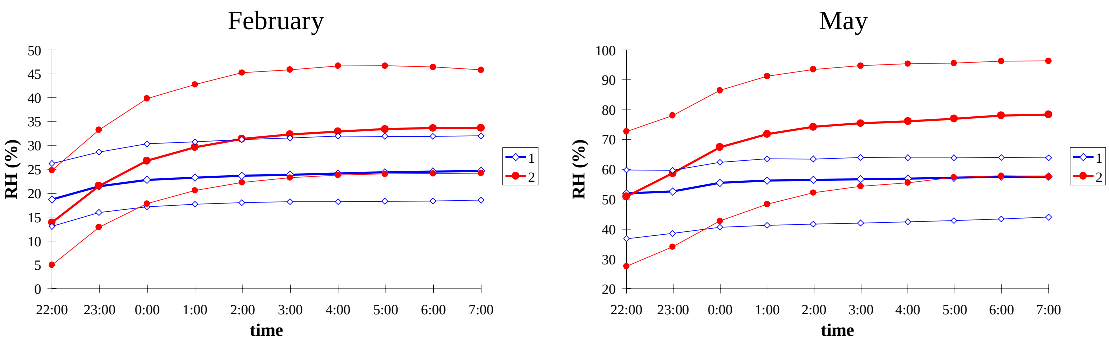

Figure 38. Average (thick line), maximum and minimum (thin lines) relative humidity for each occupied hour during February and May in case1 and 2 in Germany.

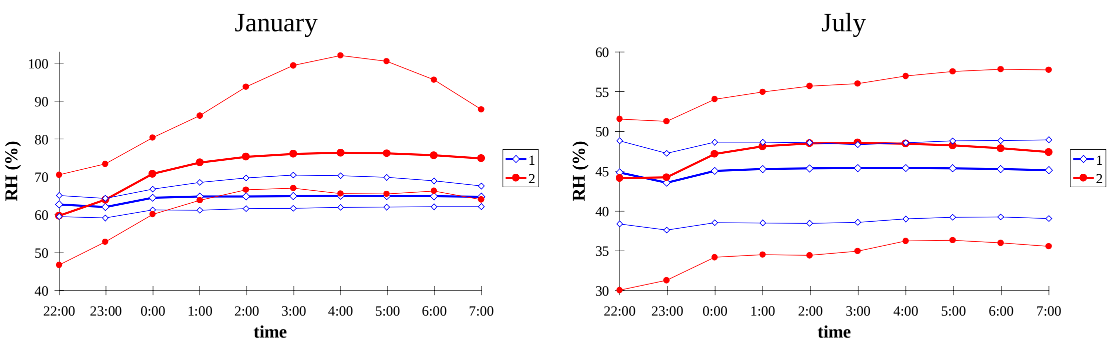

Figure 39. Average (thick line), maximum and minimum (thin lines) relative humidity for each occupied hour during January and July in case1 and 2 in Italy.

Table 8. Difference between the average, maximum and minimum relative humidities in the impermeable case2 and permeable case1 at 7:00 (and 22:00 where noted) during the months with the lowest and highest RH in each climate. A positive value means that case2 has a higher RH and a negative number means case1 has a higher RH.

	Summer				Winter			
	max	ave	ave (22:00)	min	max	ave	ave (22:00)	min
Finland	24.2	11.7	1.1	8.3	15.7	9.0	-4.4	5.8
Belgium	25.6	10.9	-2.8	-1.4	17.1	8.8	-4.7	5.4
Germany	32.4	20.8	-1.0	13.5	13.8	9.0	-4.8	5.7
Italy	8.8	2.3	-0.7	-3.5	20.2	10.1	-3.0	1.9

At the end of occupation (7:00), the average and maximum indoor relative humidity is on 21% RH and 32% RH lower in the permeable case (Germany in May). In the winter, the average RH at the beginning of occupation (22:00) is about 5% lower in case2, which shows the ability of a permeable structure to reduce the humidity at the end of occupation and increase the humidity at the beginning of occupation during dry weather.

4.1.2.1 Moisture Flows during Occupation

In this section, the yearly average moisture flow during occupation is presented to show what fraction of the occupant-induced moisture is removed from the room (by ventilation or moisture transfer to the structure) and what fraction remains in the room air. The amount that remains in the room air is calculated using the yearly average of ΔWnight as follows,

$$\dot{m}_{storage,air} = \frac{\rho V \ \Delta W night, ave}{\Delta t} \tag{22}$$

where ρ is the density of air (1.2 kg/m^3), V is the volume of the room (32.4 m^3) and Δt is the occupation time (9 hours). The moisture that does not remain in the air is removed from the room by the ventilation air or diffusion to the building structure. The average moisture removed by the ventilation air is calculated as:

$$\dot{m}_{vent} = \rho V Q \left(W_{in,ave} - W_{out,ave} \right) , \tag{23}$$

where Q is the ventilation rate (ach), while the moisture transfer to the structure is,

$$\dot{m}_{storage,structure} = \dot{m}_{prod} - \dot{m}_{storage,air} - \dot{m}_{vent} \tag{24}$$

where $\dot{m}_{prod}$ is the moisture production in the room (60 g/h).

Figure 40 compares the average moisture flows during the night in Belgium for the permeable case1 and impermeable case2. In case1, 4.6 g/h or 8% of the moisture production remains in the air, while in case2, 12.8 g/h or 21% of the moisture production remains in the air. Ventilation is clearly more important in the impermeable case where on average 76% of the moisture is removed by ventilation. In the permeable case1, moisture removal by storage in the structures is of similar importance as moisture removal by ventilation. Comparing case1 and case2 shows that decreasing the moisture storage by 1 g/h does not increase the indoor humidity by 1 g/h because the ventilation will remove part of the moisture that is not stored in the building structure. In fact reducing the moisture storage in the structure from 25 g/h (case1) to 1 g/h (case2), increases the indoor humidity by 8 g/h and increases the moisture removed by ventilation by 16 g/h. This means that two thirds of the moisture that was not stored in the structure in case2 is removed by ventilation, while one third remains in the air. Figure 41, Figure 42 and

Figure 43 contain the moisture flow diagrams for the other climates, which are similar to those in Belgium. The moisture flows in Italy are the most different from the other climates and 10% more moisture is removed by the ventilation in case1 in Italy than in case1 in Belgium. These results indicate that the occupants are the main source of moisture, but the outdoor weather has an influence as well.

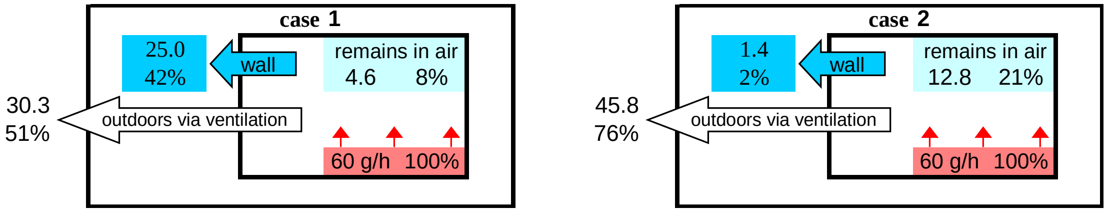

Figure 40. Yearly average moisture flows during the night in Belgium.

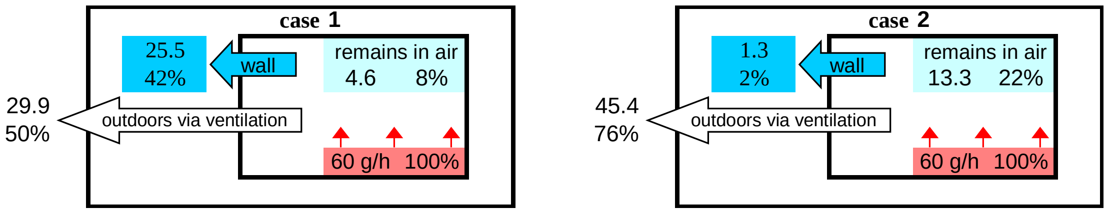

Figure 41. Yearly average moisture flows during the night in Finland.

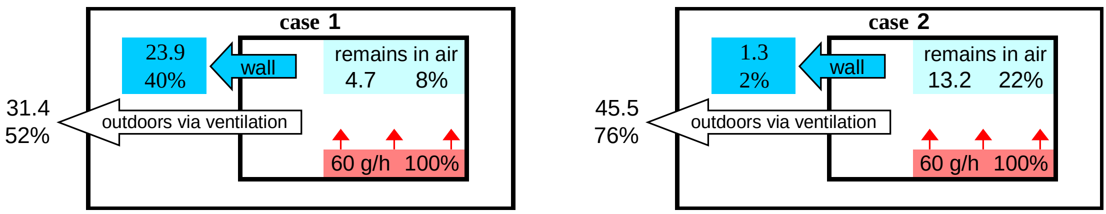

Figure 42. Yearly average moisture flows during the night in Germany.

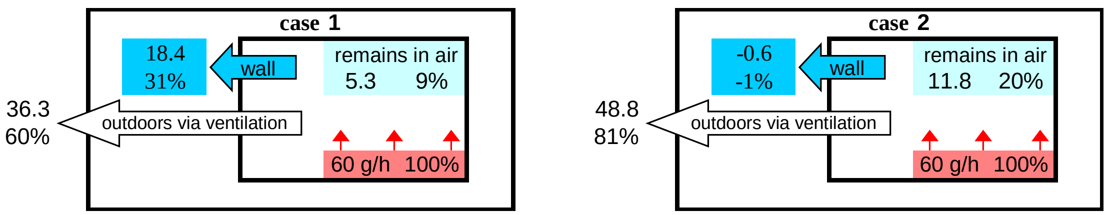

Figure 43. Yearly average moisture flows during the night in Italy.

4.1.2.2 Time of Poor Performance

In order to assess the overall performance of the impermeable and permeable cases in different climates, the amount of time during the year that the indoor variables are outside certain limits will be presented in this section. The difference between cases 1 and 2 is in Figure 44 and the absolute values are in Figure 45. Once again, only the performance during occupation is considered (22:00 to 7:00) and the times are presented in equivalent nights where 1 equivalent night means that the variable is outside the limit for 1 entire night (i.e. from 22:00 to 7:00 or 10 hours). The limits have been chosen as follows: 25% > RH > 60%, 18°C > T > 26°C, PD > 15% and Acc < 0.

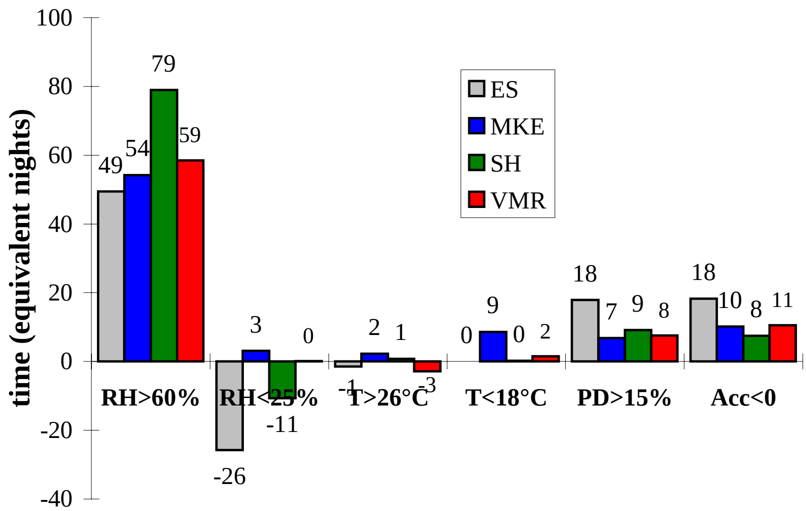

Figure 44. Difference in time that the indoor conditions are outside certain limits during occupation between cases 1 and 2 (22:00 to 7:00) in all climates. A positive value means that case2 has more time outside the limits.

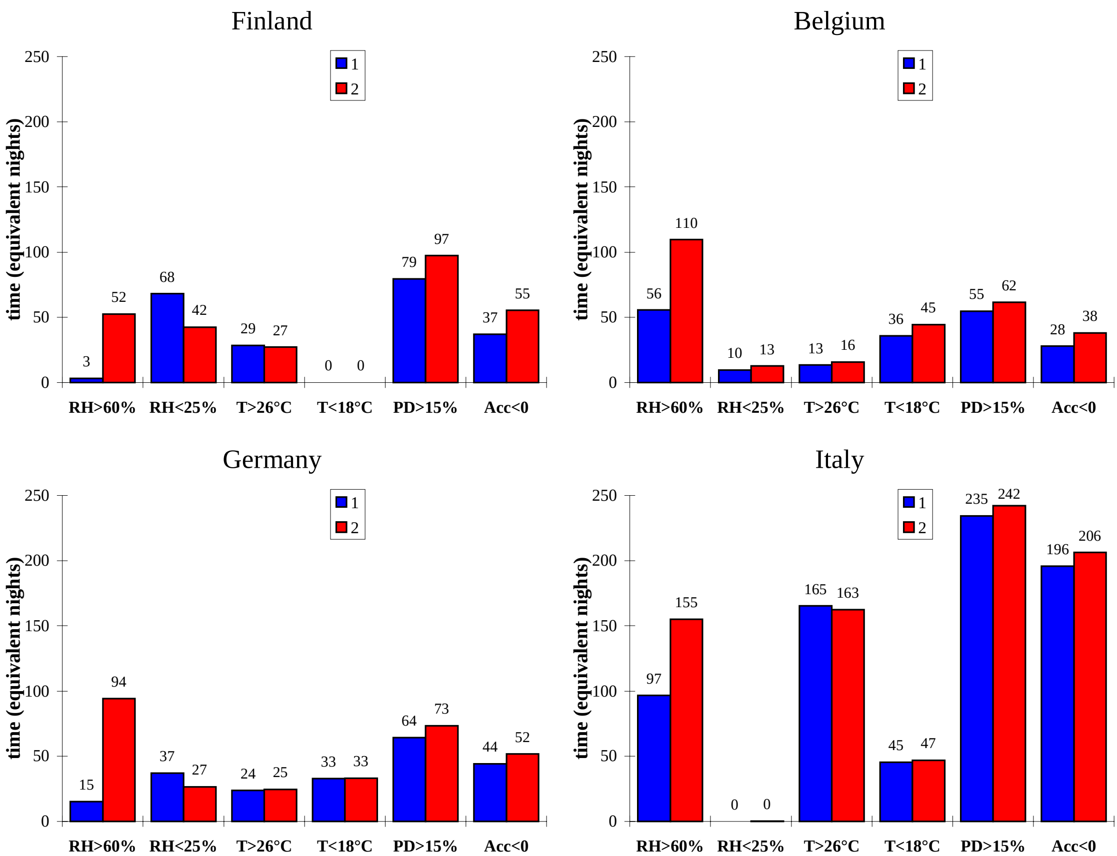

Figure 45. Time that the indoor conditions are outside certain limits during occupation (22:00 to 7:00) in all climates.

The most significant difference between case1 and case2 in Figure 44 and Figure 45 is the time when the indoor humidity is high (i.e., RH > 60%). In all climates the permeable case1 has significantly less time with RH > 60%, even thought the time when RH > 60% is strongly dependent on the climate (49 nights less in Finland and 79 nights less in Germany). The time when the indoor air is dry (RH < 25%) is greater for the permeable case1 than the impermeable case2, especially in Finland where the difference is 26 nights.

The time when the temperature is outside the limits is quite insensitive to the permeance of the structure, but strongly sensitive to the climate. Italy has the most time when T > 26°C. The greatest thermal difference between case1 and case2 is for T < 18°C in Belgium where the impermeable case2 has 9 more equivalent nights (86 hours) with T < 18°C. Since moisture is often stored in the structure during the night, which releases energy, the higher temperatures in case1 are expected.

The time when PD > 15% is quite high in all cases and climates, particularly in Italy where 65% of the time PD is greater than 15%. In all climates the permeable case has less time with PD > 15%. The time difference between case1 and case2 is 18, 7, 9 and 9 equivalent nights in Finland, Belgium, Germany and Italy respectively. Figure 45 shows that the indoor air is unacceptable (i.e., Acc < 0) for 1 to 2 months in Finland, Belgium and Germany, but for nearly 7 months in Italy. In all climates, the permeable case1 has less time with Acc < 0 than the impermeable case2. The greatest difference occurs in Finland where the indoor air is unacceptable for 18 more nights with case2. The difference in other climates varies between 8 and 11 equivalent nights.

4.1.3 Moisture Performance of Structures

Moisture accumulation in building envelopes due to the convection and diffusion of water vapour from indoor air is an important issue, especially in cold climates (ASTM, 1994). Moisture accumulation can degrade building materials through mould growth, rotting, corrosion and other physical or aesthetic damage. To minimise convection moisture transfer, the building envelope should be made airtight and any exfiltration airflow should be very small (Ojanen and Kumaran, 1996). An airtight layer (often called air barrier) reduces air leakage through the building envelope, thereby improving the moisture performance, energy consumption and thermal comfort. Even with a tight building envelope, the diffusion of water vapour may be significant and therefore it is important to have a layer that is resistant to vapour diffusion on the warm side of an insulated envelope in cool climates. The purpose of this layer (often called vapour barrier or vapour retarder) is to reduce the diffusion of moisture from indoor air into the building envelope to such a level that is does not cause problems. Naturally, in cold climates, a very high vapour resistance is safer than a very low resistance and often polyethylene vapour retarders are recommended and applied in practice. Polyethylene also has a very low air permeance and therefore functions as both an air and vapour barrier. Because of its dual function, polyethylene is often specified and the safety of envelopes with air and vapour barriers other than polyethylene is often questioned. However, experimental and numerical results have shown that properly designed envelopes without plastic vapour barriers are safe in Finland (Simonson and Ojanen, 2000). The purpose of this section is to present numerical results that illustrate the moisture performance of the exterior wall in the permeable (case1) and impermeable (case2) structures studied in this report.

In this section, mould growth will be considered to be the most critical moisture concern for wood based materials, where the risk of mould growth depends on the temperature, humidity and time of exposure. Mould growth can occur at temperatures as low as 0°C (requires 100% RH) and humidities as low as 80% RH (requires temperatures greater than 15°C), but requires at least six weeks exposure to these conditions (Viitanen, 1996). Hukka and Viitanen (1999) have developed a numerical algorithm that predicts the risk of mould growth using a mould growth index. The mould growth index varies between 0 and 6, with an index value of 1 and 3 representing the first microscopic and visible signs of mould growth respectively. This mould growth model has been incorporated into the LATENITE simulation tool (Ojanen and Salonvaara, 2000), which is used in this report, thus the mould growth index as a function of time can be plotted.

For the conditions in this report (perfectly airtight structure with only moisture diffusion), the permeable case1 will have the highest risk for mould growth and the impermeable case2 will have the lowest risk. The material with the highest mould risk is expected to be the porous wood fibre wind barrier. Figure 46 presents the mould growth index for the wind barrier in cases 1 and 2 as a function of time in all climates when the moisture production is 60 g/h. The mould growth index is very low in all cases - even microscopic mould growth (mould index = 1) is not expected.

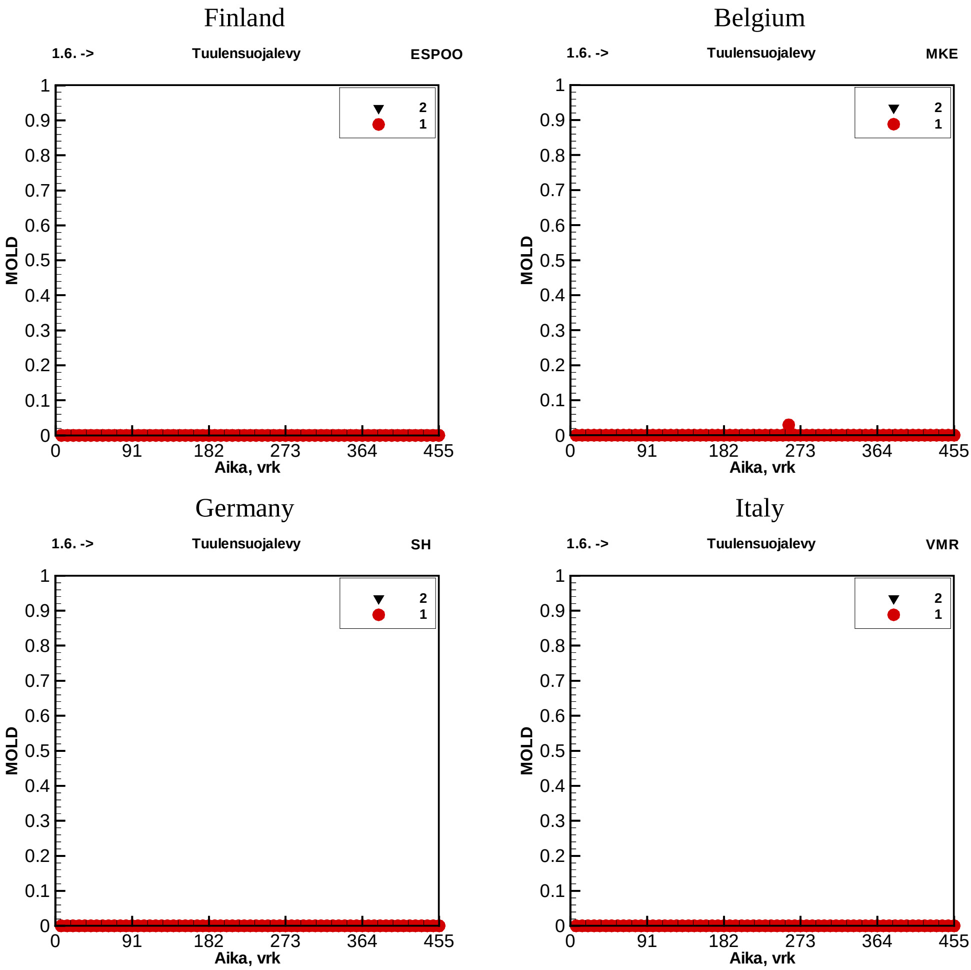

Figure 46. Mould growth index at the interior surface of the porous wood fibre wind barrier as a function of time in all climates. The time starts at the beginning of June and is given in units of days.

The results in Figure 46 are in agreement with the measurements of Simonson (2000) and Simonson and Ojanen (2000), which show good moisture performance for a house with no plastic vapour retarder and an internal to external vapour resistance ratio of about 3:1 or 4:1 (case1 has a ratio of about 2:1 to 4:1 depending on the humidity). It is important to note that the results in Figure 46 are based on a perfectly airtight envelope with no convection mass transfer. If there is a leak in the building envelope, the risk for mould growth will increase and the risk may be greater in case2 than in case1 because the peak indoor humidities are lower in case1 than in case2.

At higher moisture production rates, the risk of mould growth in the wind barrier increases for the permeable case1 as shown in Figure 47. For moisture production rates less than or equal to 120 g/h, no microscopic mould is expect, but for a moisture production rate of 180 g/h the first signs of visible mould are expected. It should be noted that a moisture production rate of 180 g/h is quite high. On average, the indoor humidity is 4.2 g/m^3 higher than the outdoor humidity and, in the morning, the indoor humidity is 7 g/m^3 (case1) to 11 g/m^3 (case2) higher than the outdoor humidity. The risk of mould growth in case1 could be reduced, without destroying the moisture storage benefits of the structure, by moderately increasing the vapour resistance of the structure.

There is also a risk for mould growth at the internal surface of the room when the humidity exceeds the mould growth threshold humidity (i.e., 80% RH because the indoor temperature is almost always above 15°C). The relative humidity will be the highest at thermal bridges and thus these locations have the highest risk of condensation and mould growth at the interior surface (Hens, 2000). Figure 47 presents the number of hours that the humidity at the internal surface of the thermal bridge exceeds 80% RH for various temperature ratios in Belgium. The temperature ratio indicates the severity of the thermal bridge and is defined as,

$$\text{temperature ratio} = \frac{T_{s,in} - T_{out}}{T_{in} - T_{out}} \qquad (25)$$

where $T_{s,in}$ is the internal surface temperature at the thermal bridge, T_{in} is the indoor temperature and T_{out} is the outdoor temperature. Since many buildings have temperature ratios between 0.6 and 0.8, Figure 47 shows that there is a significant risk for mould growth at the internal surface of the room when the moisture production rate is high, especially as the temperature ratio decreases (the thermal bridge increases). With a temperature ratio of 0.75 and a moisture production rate of 60, 120 and 180 g/h, the time that the humidity at the internal surface exceeds 80% RH is 0, 4 and 14 weeks respectively in case1 and 4, 16 and 21 weeks respectively in case2. The permeable case1 is clearly less susceptible to mould growth and condensation at the interior surface than the impermeable case2 for common thermal bridges.

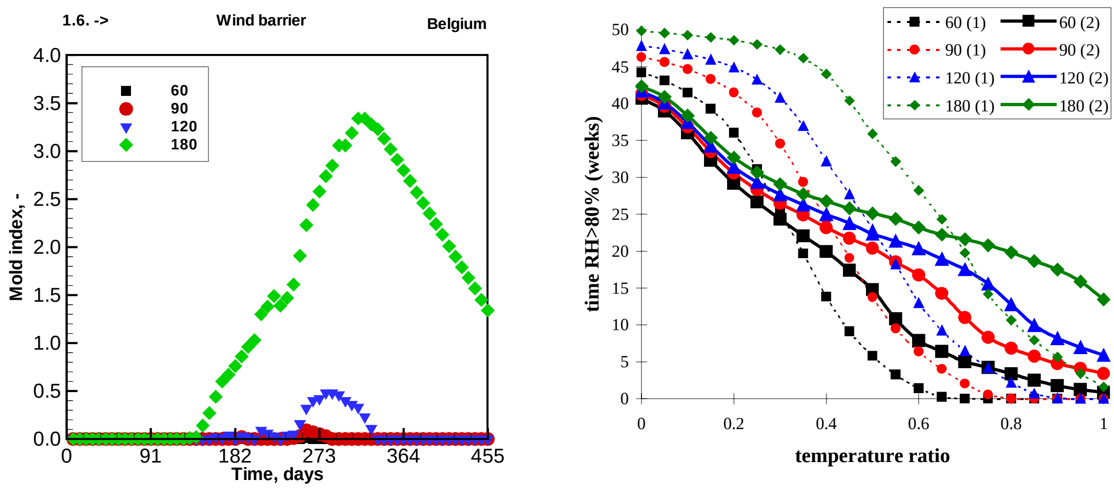

Figure 47. Mould growth index at the interior surface of the porous wood fibre wind barrier in case 1 and the time that the humidity at the interior surface of the room exceeds 80% RH for different temperature ratios and indoor moisture production rates in Belgium.

A detailed risk analysis is not presented in this section, but the results show that the permeable structure is safe when the moisture production rate is 60 g/h. As the moisture production increases, the risk of mould growth increases in both the permeable case (wind barrier) and impermeable case (interior wallboard). The risk of mould growth in the wind barrier can be reduced by increasing the vapour resistance of the structure and the risk of mould growth at the interior surface of the room can be reduced by reducing the thermal bridges.

4.2 Effect of Insulation

Comparing cases 1, 3, 4 and 5 reveals the influence of insulation on the indoor temperature and humidity (Table 9). For comparison, case2 will be included in this comparison as well. Cases 1 and 3 are identical except for the insulation. Case1 has hygroscopic insulation (cellulose fibre) and case3 has non-hygroscopic insulation (mineral fibre). Case4 has hygroscopic insulation, but a plastic vapour retarder behind the interior board. Therefore, the insulation cannot play a role in moisture transfer and moisture cannot diffuse through the envelope to the outdoor air. It is important to remember that all walls (including interior walls) in case4 have a plastic vapour retarder. The purpose of case5 is to see how the insulation performs without a hygroscopic wallboard. The wallboard in case5 is a fictitious material with the sorption characteristics of mineral fibre and all other properties as porous wood fibre board. Therefore in case5, the cellulose insulation will represent the main storage capacity of the structure.

Table 9. Simulation cases which show the effect of insulation.

Case	Internal coating	Interior wallboard (11 mm)		Air/vapour barrier (0.3 mm)	Insulation (150 mm)
	permeance	hygroscopicity	permeability	permeability	hygroscopicity
1	high (v. perm. paint)	high (porous wood	high fibre board)	high (paper)	high (cellulose)
2	low (v. tight paint)	high (porous wood	high fibre board)	high (paper)	high (cellulose)
3	high (v. perm. paint)	high (porous wood	high fibre board)	high (paper)	low (mineral fibre)
4	high (v. perm. paint)	high (porous wood	high fibre board)	low (plastic)	high (cellulose)
5	high (v. perm. paint)	low (wood fibre board with	high mineral fibre sorption)	high (paper)	high (cellulose)

4.2.1 Performance during Different Weather Conditions

Using the humid, mild and dry weather in Belgium, as in section 4.1.1, the effect of insulation on the indoor air variables will be presented to show the performance of the room. Since the results are very similar for each weather condition, only the results during the humid weather will be presented and the results during the mild and cold weather periods are in Appendix C.

4.2.1.1 Humid Period in Belgium (July)

Figure 48 and Figure 49 present the outdoor and indoor conditions during a relative humid period during July in Belgium.

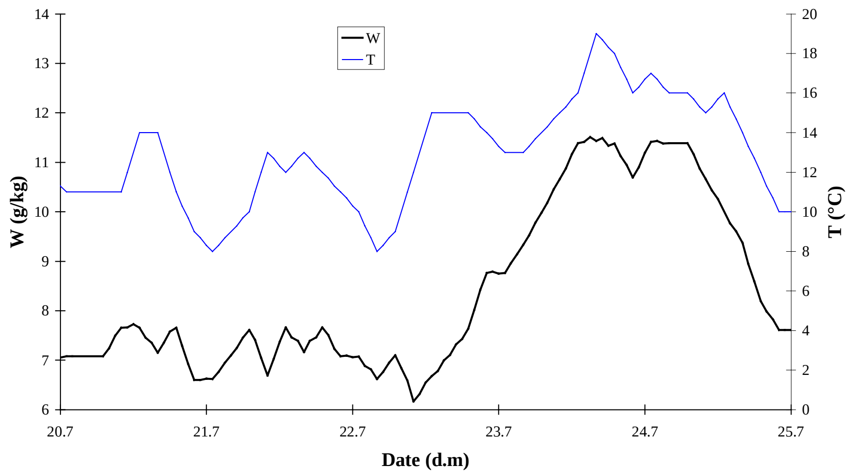

Figure 48. Outdoor humidity and temperature during a humid period in Belgium.

Comparing cases 3, 4 and 5 with cases 1 and 2, the results in Figure 49 clearly show that cases 3, 4 and 5 are quite similar and much closer to the permeable case1 than the impermeable case2. In particular, PD and Acc are nearly equal in all cases except in case2. The difference between case1 and case3 directly shows the influence of insulation that is placed behind a hygroscopic wallboard. Since the maximum difference between case1 and case3 is quite low (less than 5% RH), the results demonstrate that the insulation behind a hygroscopic building boards is not very important.

The performance of cases 3 and 4 are nearly identical in Figure 49, which shows that diffusion through the envelope is not very important. Even during cold weather, the humidity of the indoor air is only about 1% RH higher with plastic behind the wallboard than without plastic (see Appendix C).

The performance of case5 is very similar to cases 3 and 4. This means that when the interior board is non-hygroscopic, as in case5, the insulation is able to play a large role in moderating the indoor humidity. It is important to note, however, that most interior wallboards are somewhat hygroscopic and have higher moisture capacities than that used in case5 (i.e., mineral fibre insulation). Therefore in practice, the effect of hygroscopic insulation will be lower than that shown in case5. The main difference between cases 5 and 3 is that case5 responds to moisture changes more rapidly. When the occupants enter or leave the room, the humidity of the indoor air in case5 changes more than in case3 because in case5 the moisture is stored further in the structure. When the occupants enter the room in case5, the humidity in the room must increase before moisture can be transferred through the non-hygroscopic internal board and building paper and into the insulation. On the other hand, when the occupants leave in case5, the indoor humidity decreases quite rapidly because the moisture is stored deeper in the structure and not returned as quickly to the indoor air.

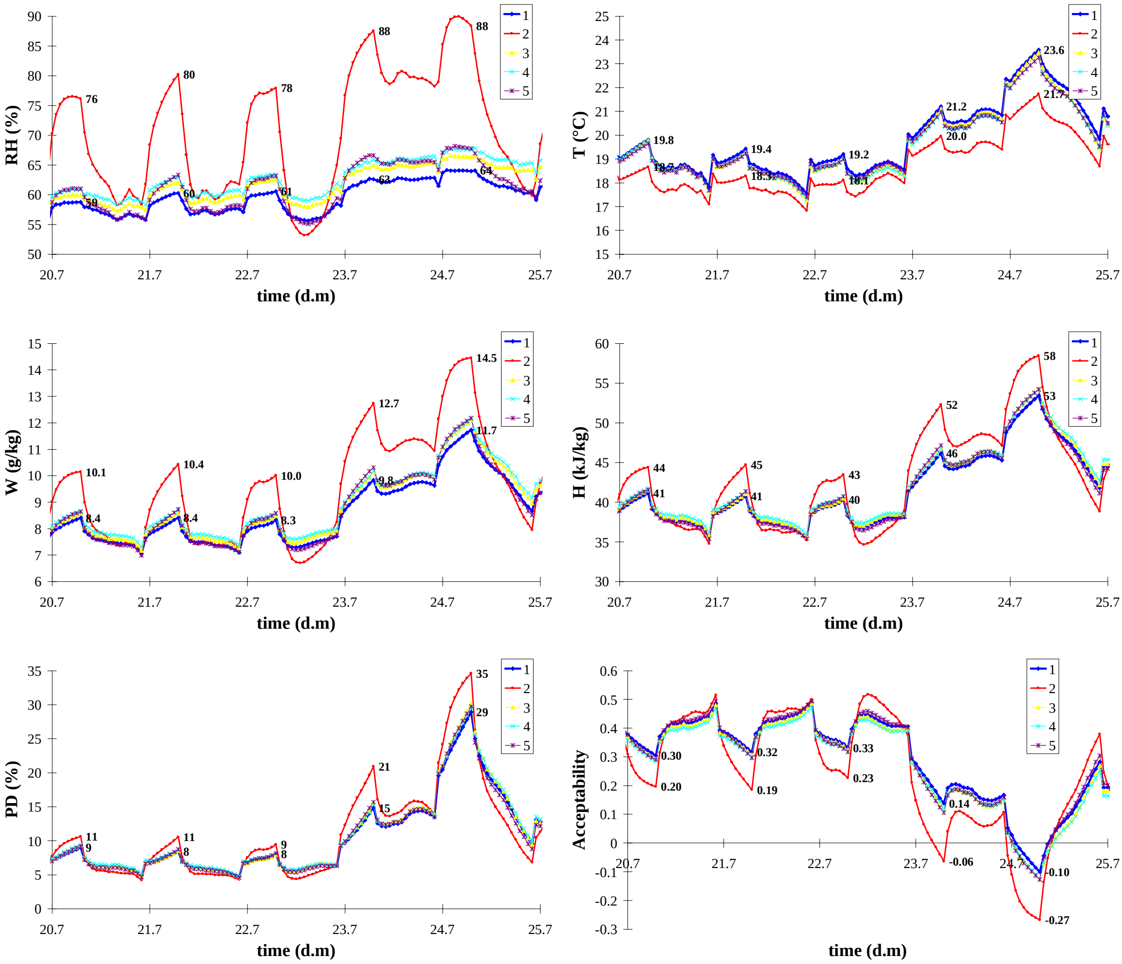

Figure 49. Temporal variation of the important indoor air variables during humid weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

4.2.2 Performance during Occupation

The average, maximum and minimum relative humidity for each occupied hour during the humid and dry months is presented for Belgium in Figure 50 and for the other climates in Appendix C. These results are similar to those in Figure 49 and show only small differences (a few % RH) between cases 1, 3, 4 and 5. This means that when insulation is situated behind a hygroscopic wallboard, the insulation does not have a significant effect on the moisture performance of the room, but when the insulation is behind a non-hygroscopic wallboard, the insulation has a large effect. In general, cases 1 and 5 have the lowest indoor RH at 22:00, followed by cases 3 and 4. At 7:00, case1 has the lowest RH, followed by cases 3 and 4 and subsequently by case5. Nevertheless, the difference is small in all cases.

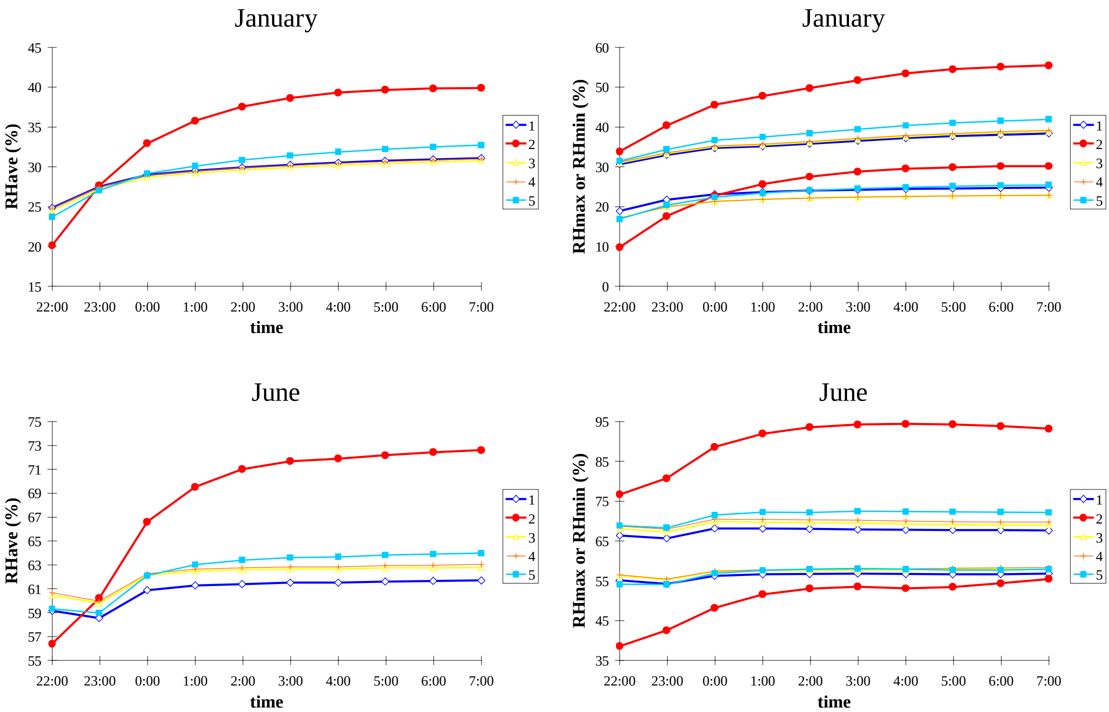

Figure 50. Average, maximum and minimum relative humidity for each occupied hour during January and June in Belgium.

Figure 51 contains similar results showing that the yearly average value of the maximum increase in humidity during the night is very similar in cases 1, 3 and 4, but slightly higher in case5. These results are for the Belgium climate and Appendix C contains results for the other climates. These results show, again, that the insulation is not very important behind a hygroscopic internal board, but is very important behind a non-hygroscopic interior board. The increase in RH during the night is only

2.5% RH greater when the moisture storage capacity of the wall is behind the interior wallboard. This comparison, however, does not reveal the fact that the humidity is usually lower when the occupants enter the room in case5.

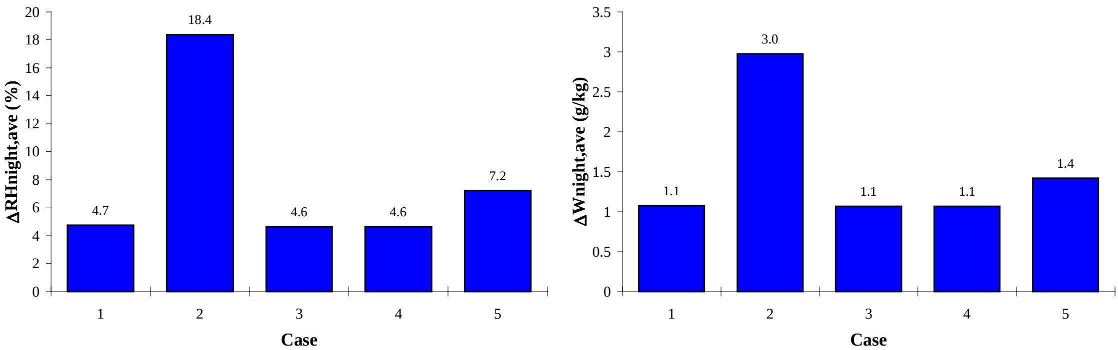

Figure 51. Average increase in relative and absolute humidity during the night in cases 1 to 5 in Belgium.

4.2.2.1 Moisture Flows during Occupation

Using the values of ΔWnight,ave from Figure 51, Figure 52 presents the average moisture flows during the night in Belgium for cases 1 to 5. The moisture stored in the structure is equal in cases 1, 3 and 4, while the storage in the structure is 6% less in case5. As a result, the humidity of the indoor air and the moisture removed by the ventilation increases in case5 compared to cases 1, 3 and 4. The moisture removed by ventilation increases by 4% of the produced moisture and the moisture stored in the air increases by 2%. This means that the ventilation removes two thirds of the moisture that is not stored in the structures in case5 compared to case1.

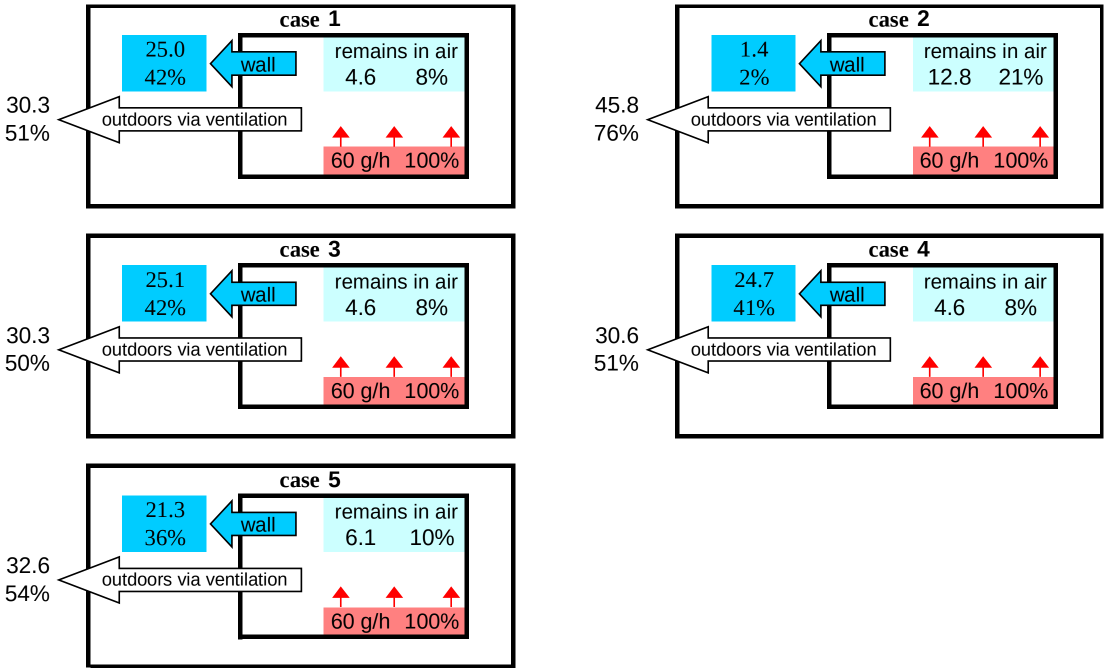

Figure 52. Yearly average moisture flows during the night in Belgium.

4.2.2.2 Time of Poor Performance

As a final comparison of the effect of insulation, the time when the indoor variables are outside certain limits are given in Figure 53. Similarly as in section 4.1.2.2, the results in Germany show the greatest difference between the different cases for RH > 60%. The time when RH > 60% is over twice a great in cases 3, 4 and 5 compared to case1. The difference between cases 2, 4 and 5 is typically 2 to 10 nights with case5 having more time with RH > 60%. The time when RH < 25% varies by about 5 nights between cases 1, 3, 4 and 5. It is interesting to note that case5 (non-hygroscopic wallboard) has less time with RH < 25% than cases 3 and 4. The results of PD > 15% and Acc < 0 give a similar ranking to the various cases as the RH results, but the time difference between the hygroscopic and non-hygroscopic insulation is very small (within a few days).

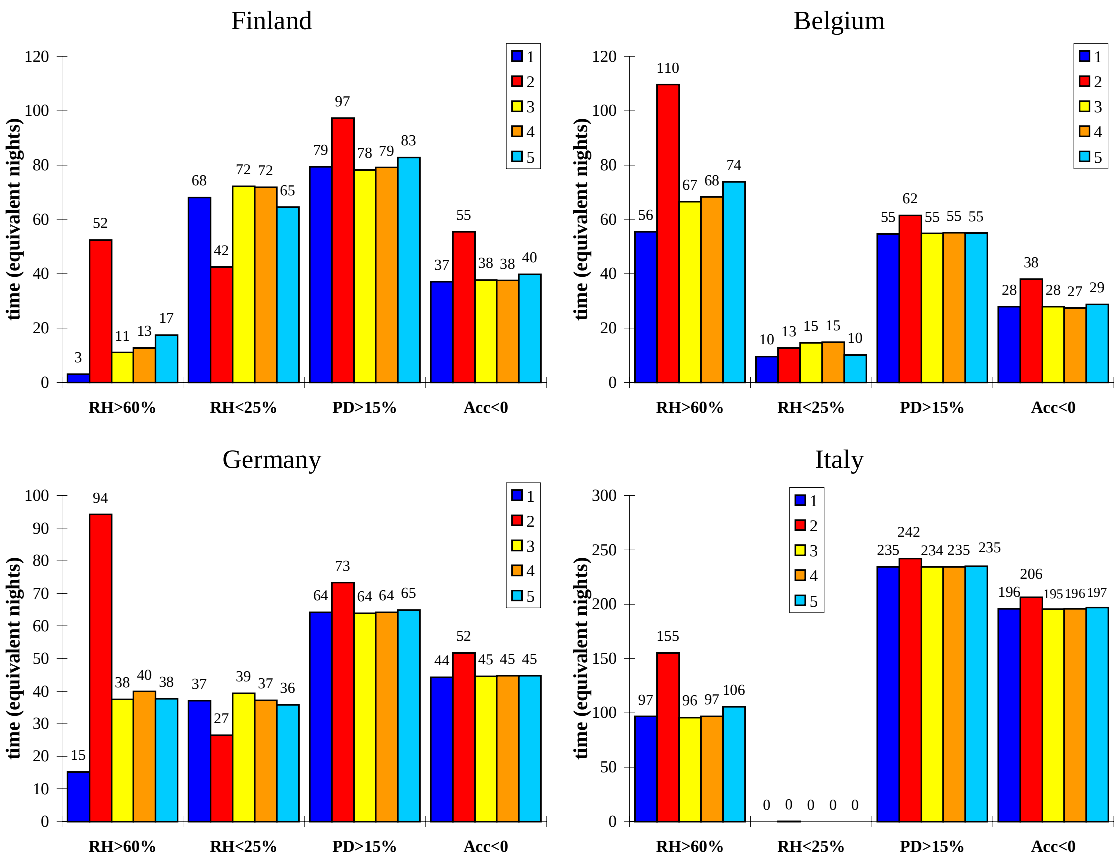

Figure 53. Time that the indoor conditions are outside certain limits during occupation (22:00 to 7:00) in all climates.

4.3 Effect of Interior Wallboard

Section 5.1.2 showed that, for a ventilation rate of 0.5 ach and a moisture production rate of 60 g/h, the interior board is able to store a large portion of the moisture produced in the bedroom. The purpose of this section is to investigate other internal boards (wooden panel – case6 and gypsum – case13 as listed in Table 10). In the case of 11 mm of wooden panel, the insulation behind the board is expected to be even less important than the insulation behind porous wood fibre board because wood is less permeable and has a higher moisture capacity per unit thickness than porous wood fibre board.

Table 10. Simulation cases which show the effect of the interior wallboard.

Case	Internal coating	Interior wallboard (11 mm)		Air/vapour barrier (0.3 mm)	Insulation (150 mm)
	permeance	hygroscopicity	permeability	permeability	hygroscopicity
1	high (v. perm. paint)	high (porous wood fibre board)	high	high (paper)	high (cellulose)
2	low (v. tight paint)	high (porous wood fibre board)	high	high (paper)	high (cellulose)
6	high (v. perm. paint)	high (wooden panel)	low	high (paper)	high (cellulose)
13	high (v. perm. paint)	moderate (gypsum board)	high	high (paper)	high (cellulose)

4.3.1 Performance during Different Weather Conditions

The transient performance of the room is presented again for the humid period in Belgium (Figure 54) and the results for other periods are in Appendix C. The results for the humid period are in Figure 55 and show no significant difference between cases 1, 6 and 13. This means that it is not critical whether the internal board is 11 mm of porous wood fibre board, 11 mm of wood or 11 mm of gypsum board. This is not surprising, however, because even a non-hygroscopic board (i.e., a board with sorption properties of mineral fibre insulation) provides results quite similar to case1 when the insulation is hygroscopic (i.e., case5 in the previous section). If a plastic vapour barrier was added behind the interior boards, it is expected that the RH in case6 (wooden panel) would change very little, but the RH in case13 (gypsum) would increase somewhat. Simulations show that if a plastic vapour barrier is used in case13, the indoor RH will increase by about 7% RH.

4.3.1.1 Humid Period in Belgium (July)

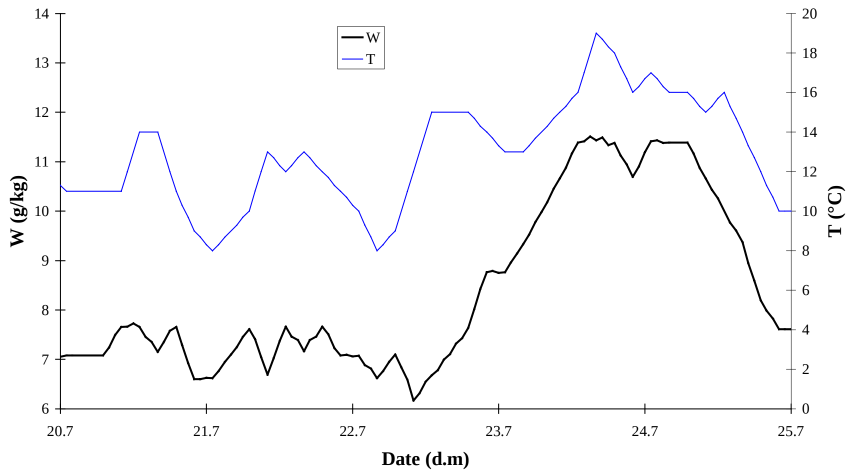

Figure 54. Outdoor humidity and temperature during a humid period in Belgium.

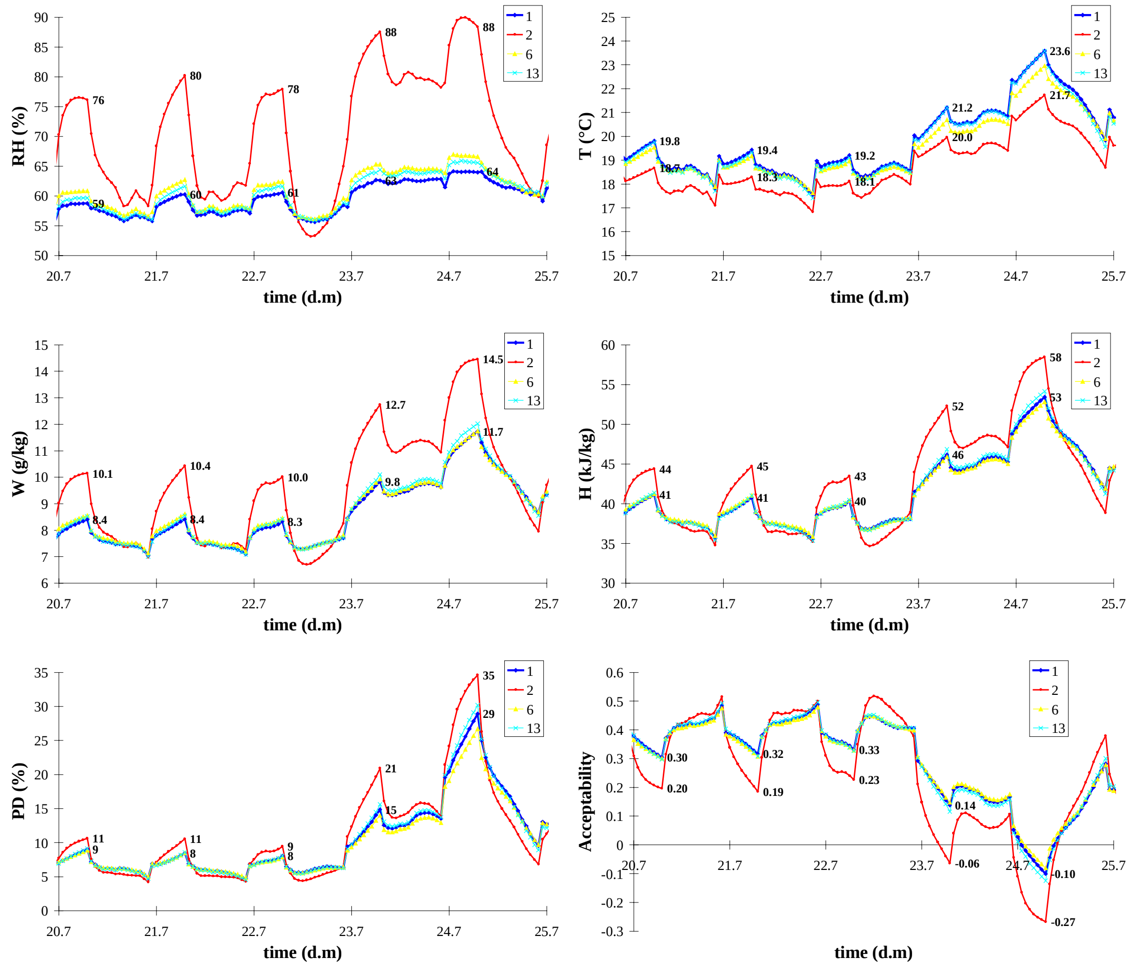

Figure 55. Temporal variation of the important indoor air variables during humid weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

4.3.2 Performance during Occupation

The monthly average indoor humidities during occupation are not presented for the different wallboards because the results of each case are so similar. The similar performance during occupation is evident in Figure 56, which presents the average increase in humidity during the night in case1 (porous wood fibre board), case6 (wooden panel) and case13 (gypsum board).

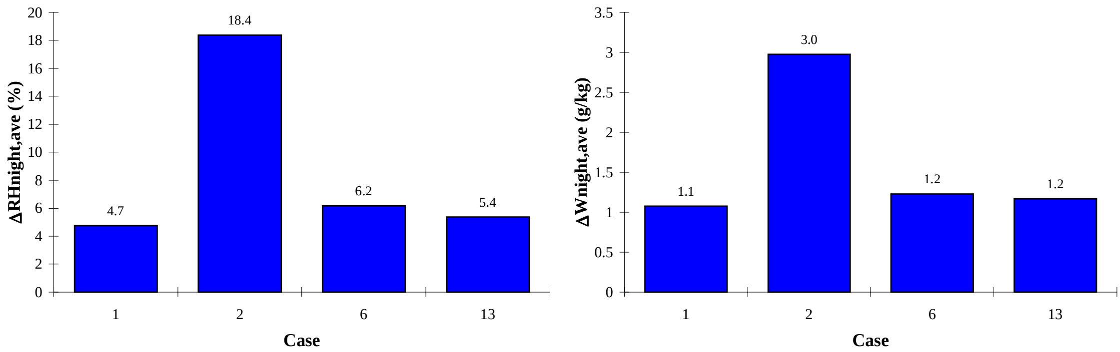

Figure 56. Average increase in relative and absolute humidity during the night in cases 1, 2, 6 and 13 in Belgium.

4.3.2.1 Moisture Flows during Occupation

The average moisture flows during the night are in Figure 57. These results also show that all the studied interior covering boards are able to effect the indoor moisture levels.

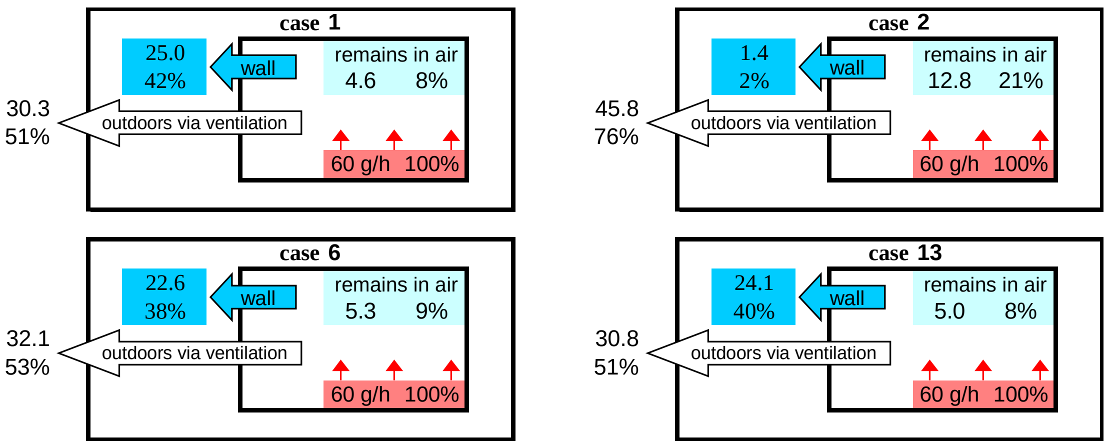

Figure 57. Yearly average moisture flows during the night in Belgium.

4.3.2.2 Time of Poor Performance

The time when the indoor conditions are outside the chosen limits are presented Figure 58 and show a slightly larger effect of the interior board. For example in Germany, the case with wooden panel has 3 more nights with RH>60% and the case with gypsum board has 10 more nights with RH>60% compared to case1 (see Figure 53). If a non-hygroscopic insulation or plastic vapour retarder was used behind the gypsum board in case13, the time with RH>60% would be about 2 weeks greater than in case13. Therefore, gypsum board with a plastic vapour retarder would have a similar amount of time with RH>60% as a non-hygroscopic wallboard with hygroscopic insulation (case5). The wooden panel reduces the time of dry indoor conditions (RH<25%) compared to the porous wood fibre board and gypsum. The interior board has a minor effect on the time PD>15% and Acc<0.

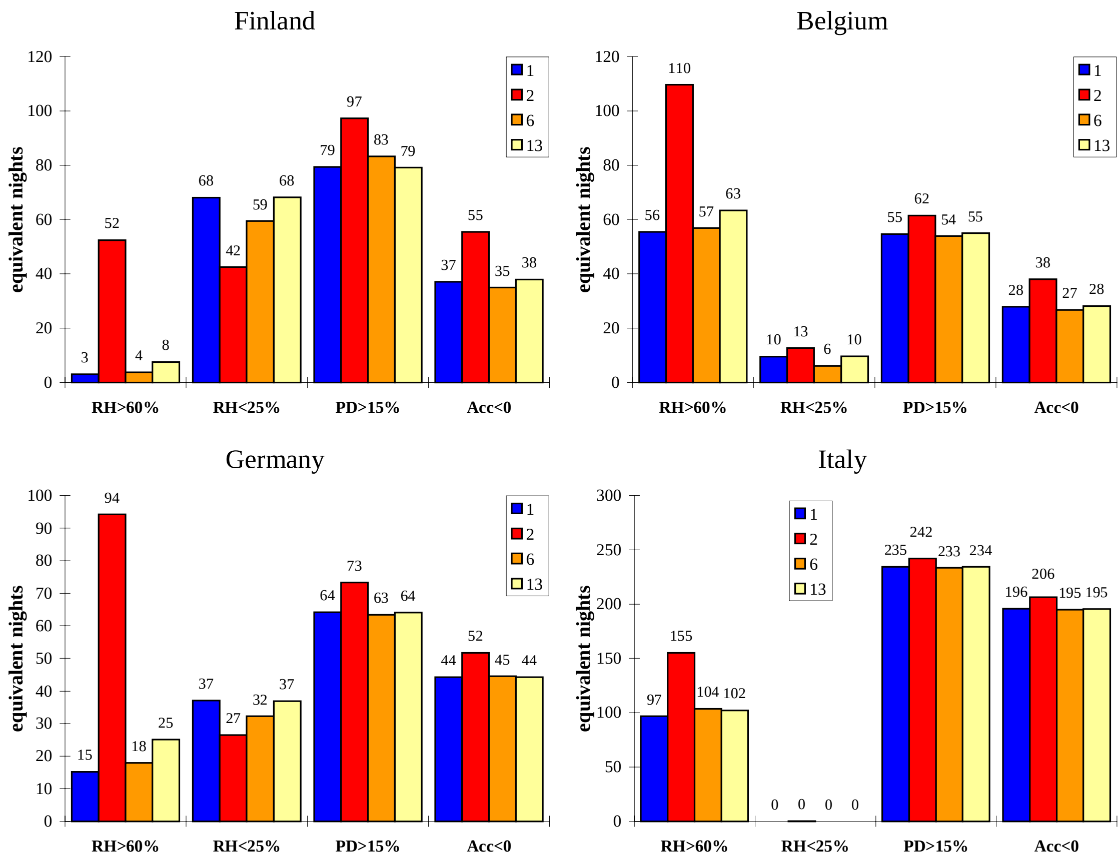

Figure 58. Time that the indoor conditions are outside certain limits during occupation (22:00 to 7:00) in all climates.

4.4 Effect of Active Area

The previous results have had similar structures and interior coatings for all the walls in the room and the purpose of this section is to examine the sensitivity of the active area. To facilitate this, the external wall and ceiling have a vapour tight paint in case7 (active area 62% of case1) and all walls have a vapour tight paint while the ceiling is permeable in case8 (active area 25% of case1). The ratio of active area of each case relative to case1 (A*) is defined as,

$$A^* = \frac{A_i}{A_1} \quad . \tag{26}$$

4.4.1 Performance during Different Weather Conditions

The temporal results are presented during a humid period in Belgium (Figure 59 and Figure 60) and the mild and dry results are in Appendix C. The results show that the active area has a larger impact than the insulation and covering board. As the active area increases, the RH, W, H and PD decrease, while T and Acc increase. Case8 (A*=0.25) seems to be about half way between cases 1 and 2, while case7 (A*=0.62) is about half way between case8 and case1.

4.4.1.1 Humid Period in Belgium (July)

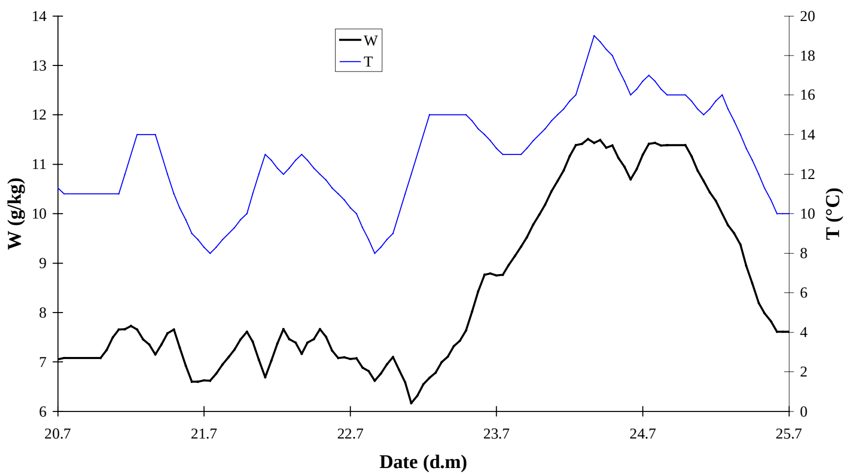

Figure 59. Outdoor humidity and temperature during a humid period in Belgium.

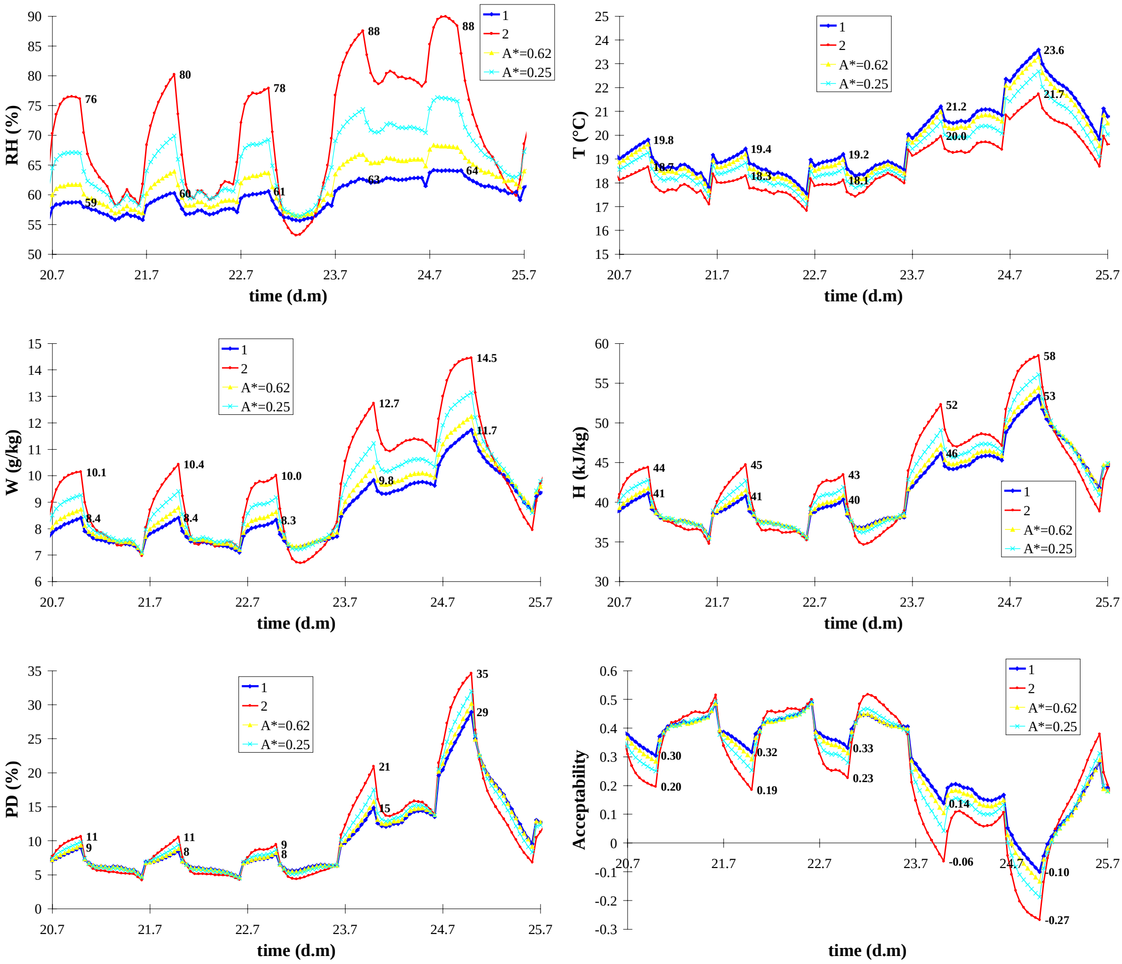

Figure 60. Temporal variation of the important indoor air variables during humid weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

4.4.2 Performance during Occupation

4.4.2.1 Moisture Flows during Occupation

The average of the maximum increase in humidity during the night is presented in Figure 61 as a function of the active area ratio (A* and

$\sqrt{A^*}$). Increasing A*, decreases the increase in humidity during the night. The effect of A* on the absolute humidity seems to be proportional to $\sqrt{A^*}$. Similarly the moisture flows during the night are linearly proportional to $\sqrt{A^*}$ in the range of 0 to 1 as shown in Figure 62. However, increasing A* beyond 1 is expected to have only a small effect on the performance for this moisture production rate (60 g/h) and ventilation rate (0.5 ach) because all the moisture flows are levelling out as A* approaches 1 in Figure 62.

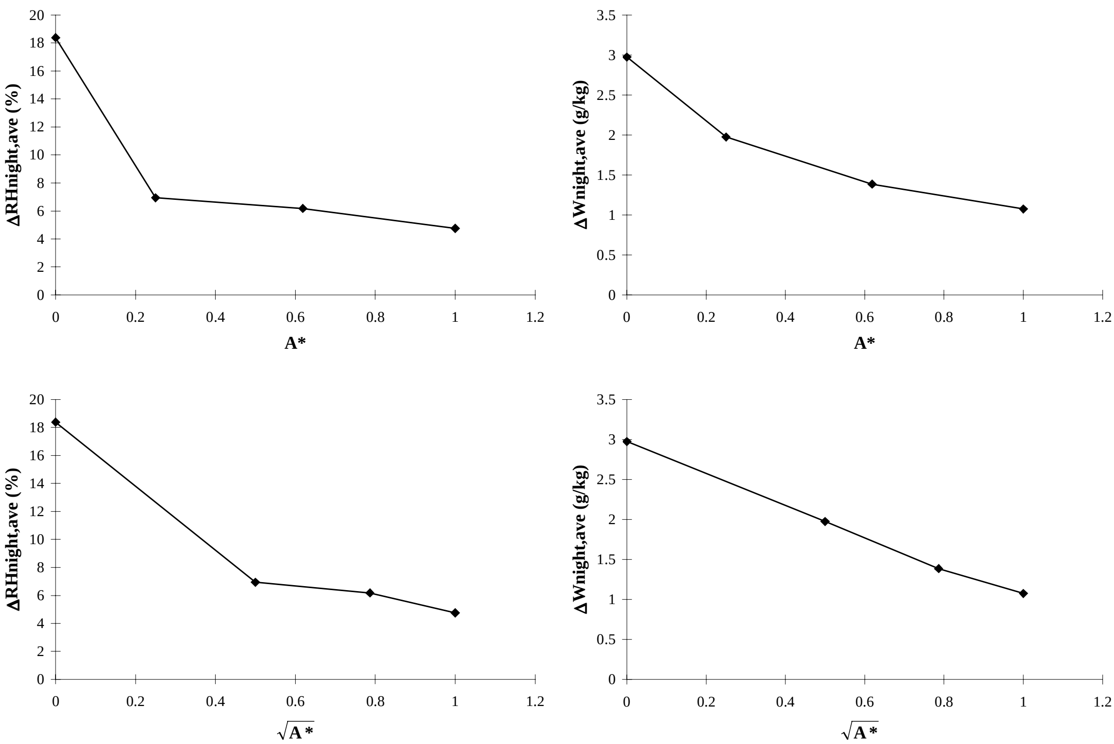

Figure 61. Average increase in relative and absolute humidity during the night as a function of A and* $\sqrt{A^*}$ *in Belgium.*

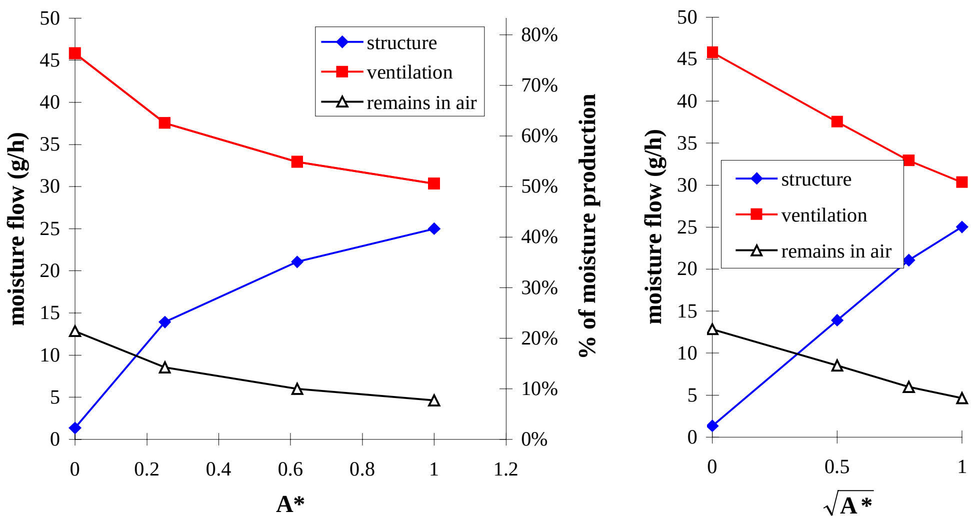

Figure 62. Yearly average moisture flows during the night in Belgium.

4.4.2.2 Time of Poor Performance

The active area has a significant effect on the time when the humidity is high (RH>60%) or low (RH<25%), but a smaller effect on the time when PD>15% and Acc<0 as shown in Figure 63. Increasing A*, decreases the time when RH>60% during occupation, but increases the time when RH<25% during occupation.

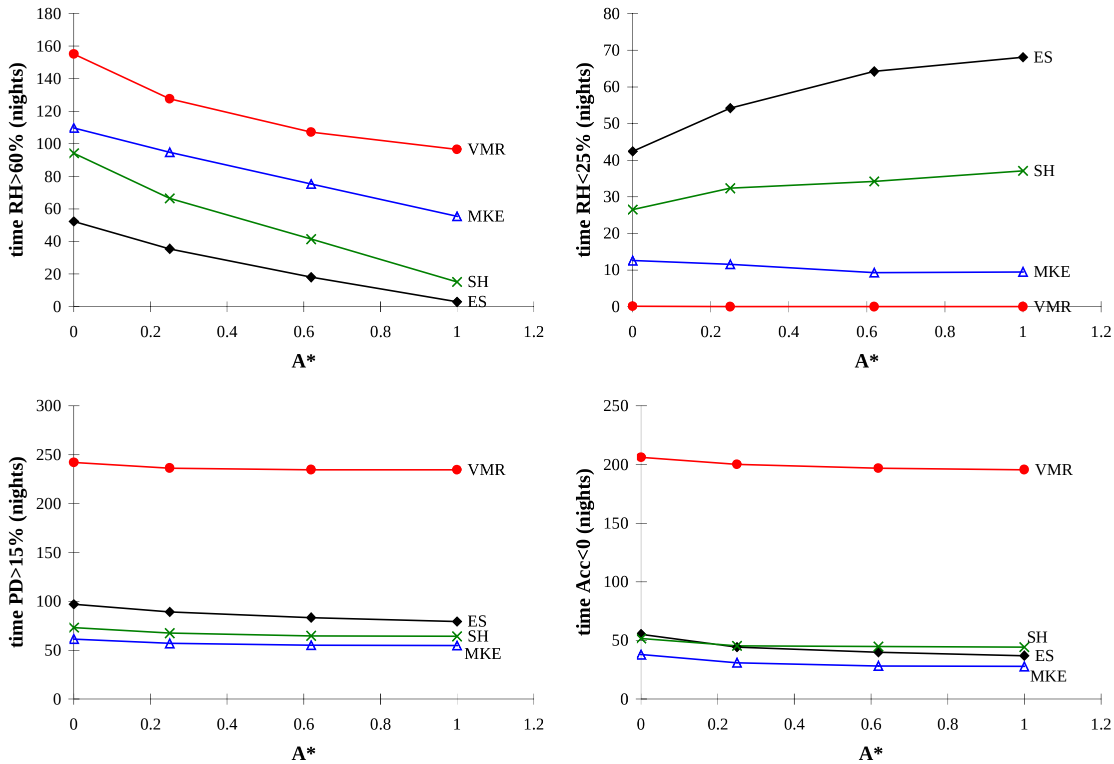

Figure 63. Time that the indoor conditions are outside certain limits during occupation (22:00 to 7:00) in all climates.

Since the performance of the room is quite sensitive to the active area, the difference between different insulations and interior boards may be more pronounced at lower active areas. This means that if the entire room cannot be made permeable and hygroscopic, the choice of wallboard and insulation may be more critical.

4.5 Effect of Vapour Resistance of Interior Coating

Since all rooms have some coating on the interior surface, this section will study the sensitivity of the permeance of the coating. Previous results are based on an extremely permeable coating (case1: 5 x 10^{-9} kg/(s·m^2·Pa)) and an extremely non-permeable coating (case2: 5 x 10^{-12}

kg/(s·m^2·Pa)). The ratio of the coating vapour resistance chosen for the sensitivity study to the ratio of the coating in case1 (R*), will be used to distinguish between different cases, where

$$R^* = \frac{R_i}{R_1} = \frac{1}{k^*} = \frac{kd_1}{kd_i} \quad . \tag{27}$$

The permeability in the various cases and the values of R* and k* are as follows:

case9mp:	kd = 5 x 10^{-8} kg/(s·m^2·Pa)	R* = 0.1	k* =10
case1:	kd = 5 x 10^{-9} kg/(s·m^2·Pa)	R* = 1	k* = 1
case9:	kd = 1 x 10^{-9} kg/(s·m^2·Pa)	R* = 5	k* =0.2
case9lp:	kd = 5 x 10^{-10} kg/(s·m^2·Pa)	R* = 10	k* = 0.1
case2:	kd = 5 x 10^{-12} kg/(s·m^2·Pa)	R* = 1000	k* = 0.001

It should be noted that for convection mass transfer in a well-mixed room, the permeance of the surface is expected to be 3 x 10^{-8} kg/(s·m^2·Pa) (R*=0.16). The permeability of paint varies from 1 x 10^{-9} to 2 x 10^{-11} kg/(s·m^2·Pa) (ASHRAE, 1997) (R*=5 to 250), which means that the most permeable paints are expected to have an R* value of about 5.

4.5.1 Performance during Different Weather Conditions

Once again the results presented here will be for the humid weather in July in Belgium (Figure 64 and Figure 65) and the results from a mild period in May and a dry period in February are presented in Appendix C.

4.5.1.1 Humid Period in Belgium (July)

The results show that the permeability of the interior coating is very important. Decreasing the resistance of the coating by a factor of 10 (R*=0.1) does not have a large effect, but increasing the resistance by a factor of 5 (R*=5) does. This shows that it is quite critical to have a coating with a high permeance to utilise the moisture capacity of the building structure. Since the most permeable paints available have R*~5, it appears that moisture transfer between indoor air and structures could be enhanced with the development of paints and coatings that are more permeable.

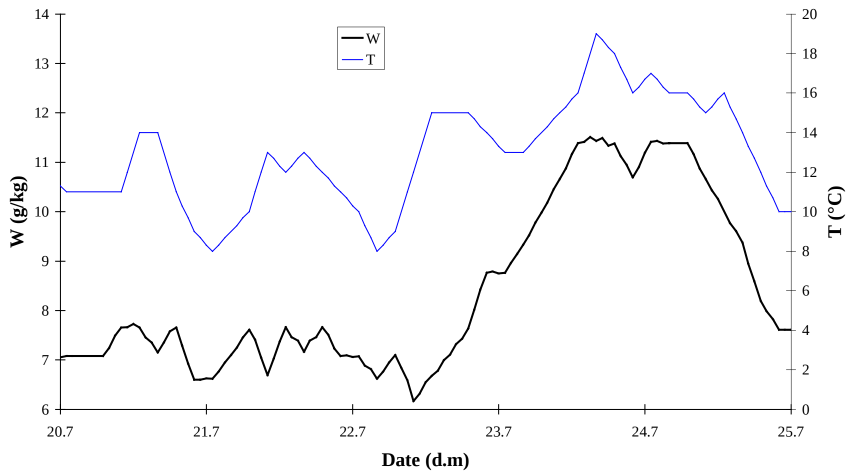

Figure 64. Outdoor humidity and temperature during a humid period in Belgium.

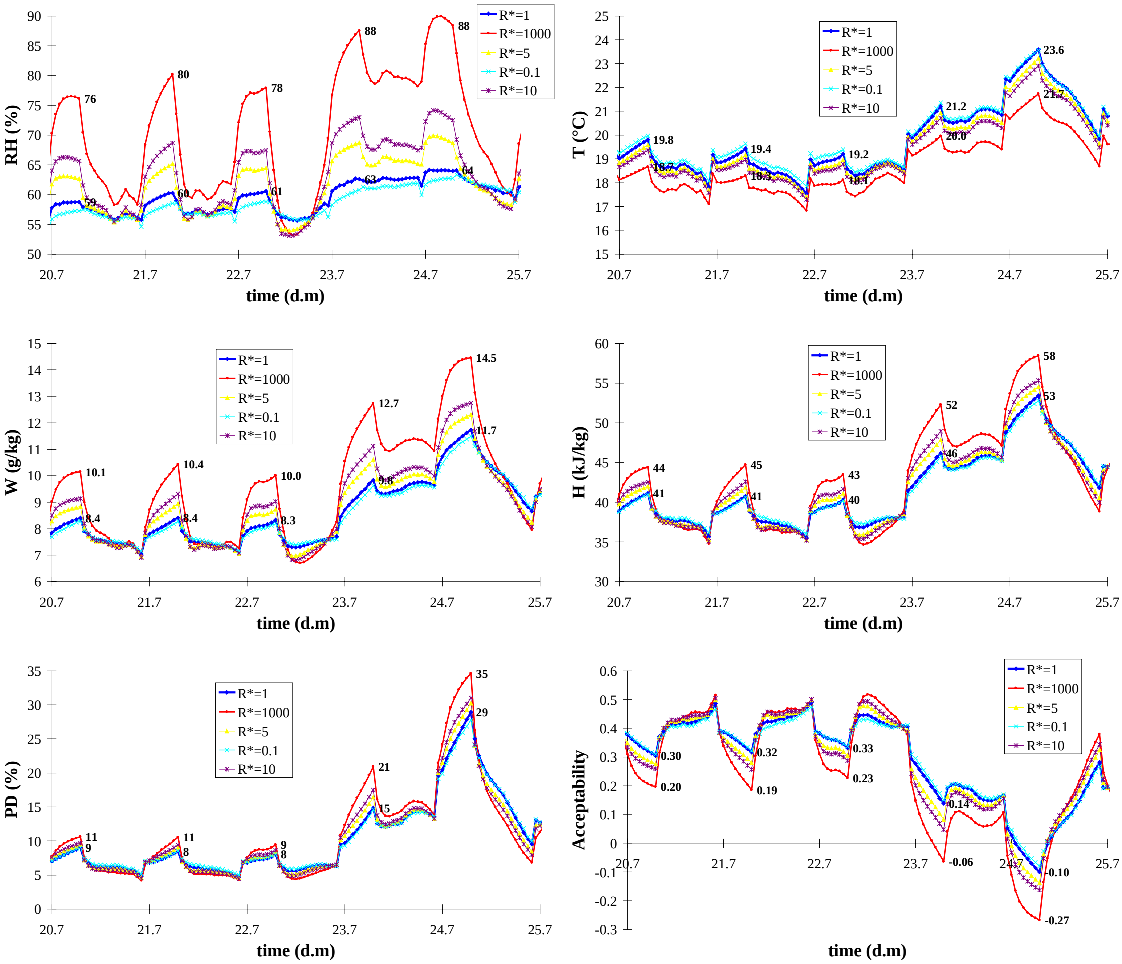

Figure 65. Temporal variation of the important indoor air variables during humid weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

4.5.2 Performance during Occupation

4.5.2.1 Moisture Flows during Occupation

The effect of the vapour resistance of the interior coating can also be seen when examining the maximum increase in humidity during occupation

(Figure 66) and the moisture flows during occupation (Figure 67). The results clearly show that decreasing R* below 1 (i.e., increasing the permeability above 5 x 10^{-9} kg/(s·m^2·Pa)) has a very small effect, but increasing R* above 1 has a significant effect.

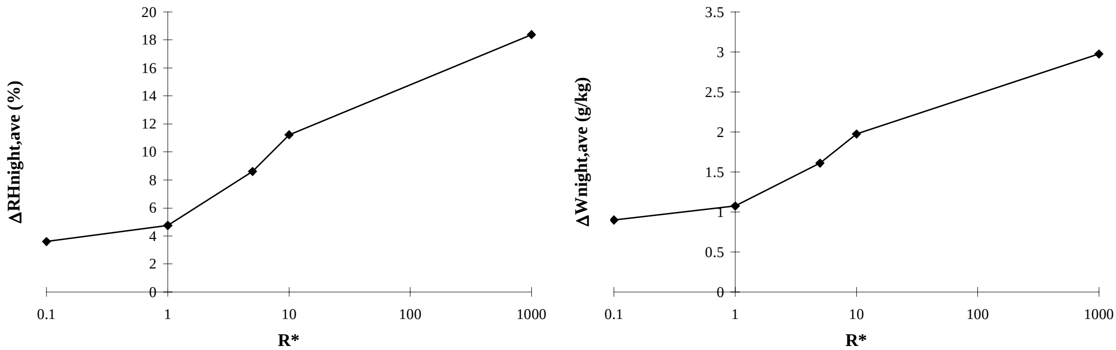

Figure 66. Average increase in relative and absolute humidity during the night as a function of the vapour resistance ratio.

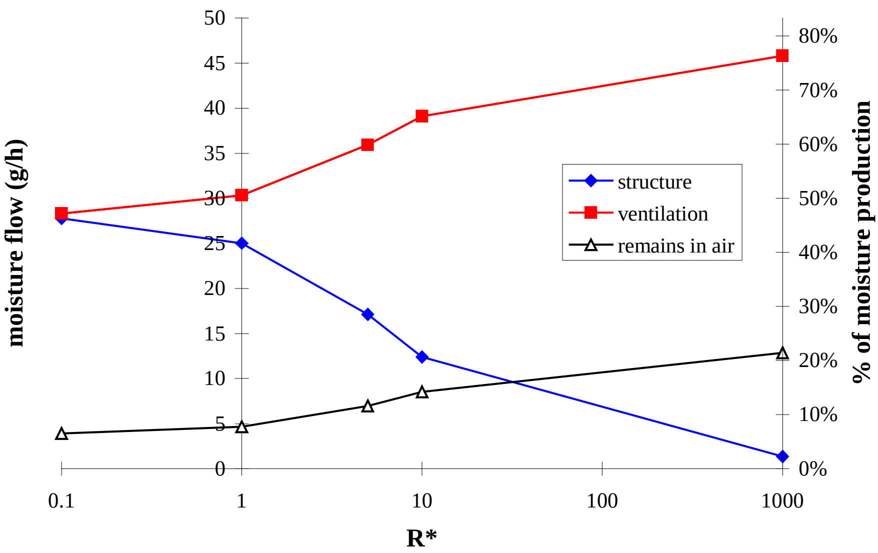

Figure 67. Yearly average moisture flows during the night in Belgium.

Often the designer will have limited control over R* and A* and therefore it is interesting to compare the effect of R* and A* on the moisture performance of the room (Figure 68 and Figure 69). It is interesting to note that the performance with R*=10 is quite comparable to the performance when A*=0.25. Therefore, it is possible to use the vapour resistance of the interior coating to compensate for a low active area and vice versa.

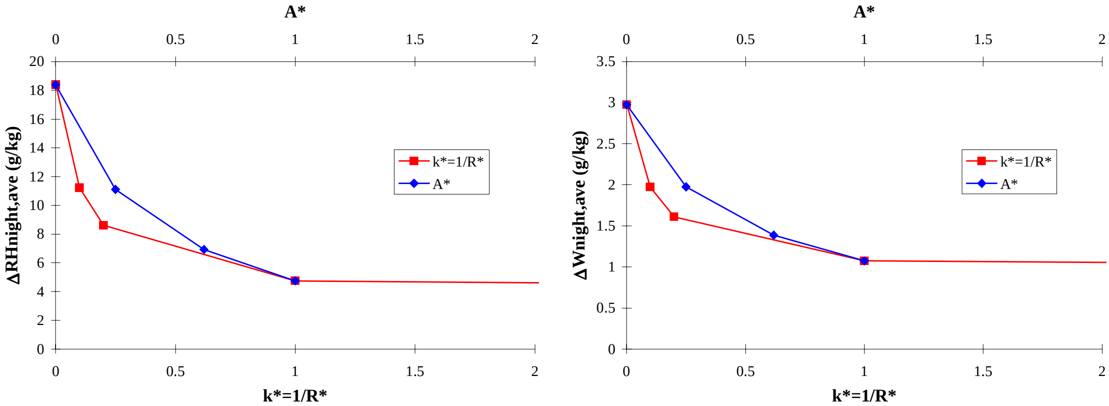

Figure 68. Average increase in relative and absolute humidity during the night in Belgium comparing the effect of the effect of active area and vapour resistance of the interior coating.

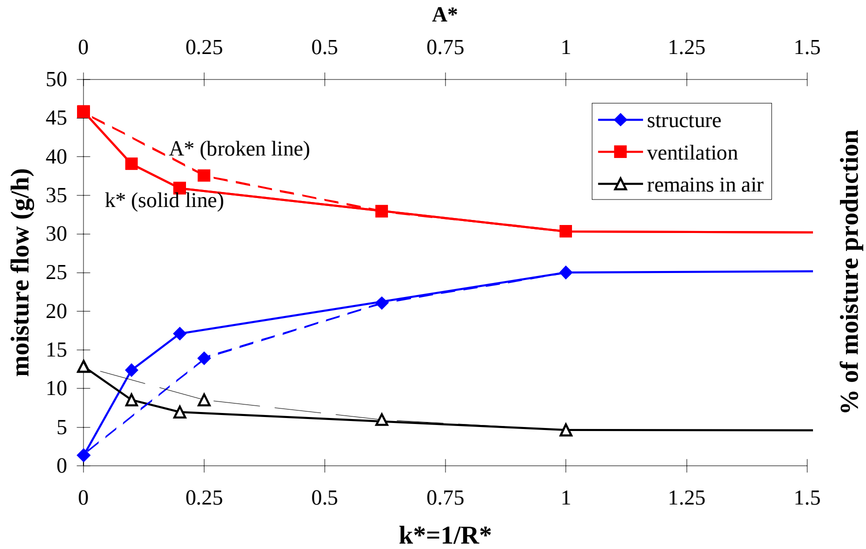

Figure 69. Yearly average moisture flows during the night in Belgium comparing the effect of active area and vapour resistance of the interior coating.

4.5.2.2 Time of Poor Performance

As with the active area, the vapour resistance of the interior coating has a significant effect on the time when the humidity is high (RH>60%) or low (RH<25%), but a smaller effect on the time when PD>15% and Acc<0 as shown in Figure 70. Increasing R*, increases the time when the indoor humidity is high (i.e., RH>60%) during occupation, but decreases the time when the indoor humidity is dry (i.e., RH<25%) during occupation. It is interesting to note that decreasing R* from 1 to 0.1, has a large effect on the time when RH>60% in Italy and Belgium, but a limited effect in Germany and Finland. Since the results are quite sensitive to the vapour resistance of the interior coating, it is expected that the effect of insulation and interior board will be more important when the interior coating has a higher vapour resistance.

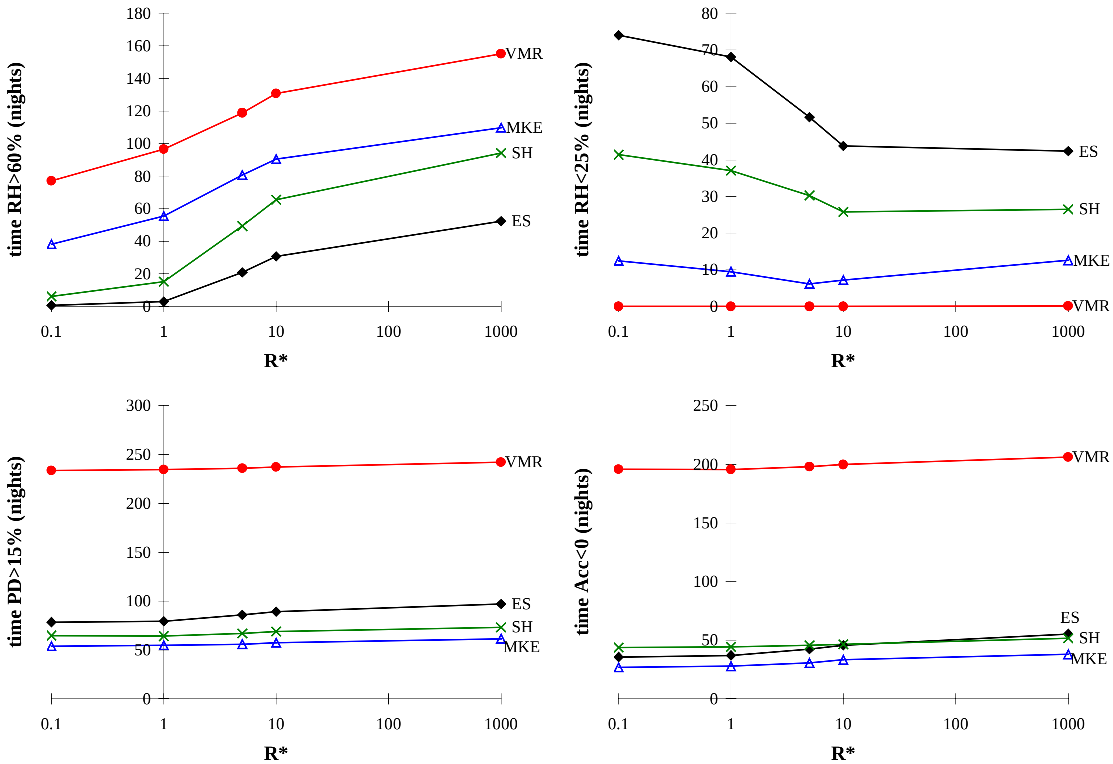

Figure 70. Time that the indoor conditions are outside certain limits during occupation (22:00 to 7:00) in all climates.

4.6 Effect of Thermal Mass

Cases 10, 11, 12 and 14 have been selected with a higher thermal mass to show the importance of thermal mass on the indoor climate in buildings without cooling. Case10 is like case1 except the floor and ceiling of the bedroom are made of concrete (200 mm). Cases 11 and 12 also have a concrete floor and ceiling, but have thick wooden panel (125 mm in case11 and 50 mm in case12). Case14 is an entirely wooden construction with a 200 mm thick floor and ceiling and 125 mm log wall with 150 mm of cellulose insulation. The floor and ceiling are both impermeable in the massive cases, whereas the ceiling is permeable in the lightweight cases 1 and 2.

4.6.1 Performance during Different Weather Conditions

The effect of thermal mass is most important during the summer and the performance during the summer is presented in this section. The performance during mild and dry weather is in Appendix C.

4.6.1.1 Humid Period in Belgium (July)

The 6 indoor parameters for the humid outdoor conditions in Figure 71 are presented in Figure 72. It is clearly difficult to compare the RH values because the thermal performance is so different between the massive and lightweight cases. The absolute humidity is slightly lower in case1 than in the massive cases, but this is likely a result of the impermeable ceiling in the massive cases. The temperature is higher in the massive cases (cases 10 to 12 and 14) than in the lightweight cases (cases 1 and 2) because the outdoor temperature was previously warmer as is evident in Figure 73. The performance is very similar in all the massive cases.

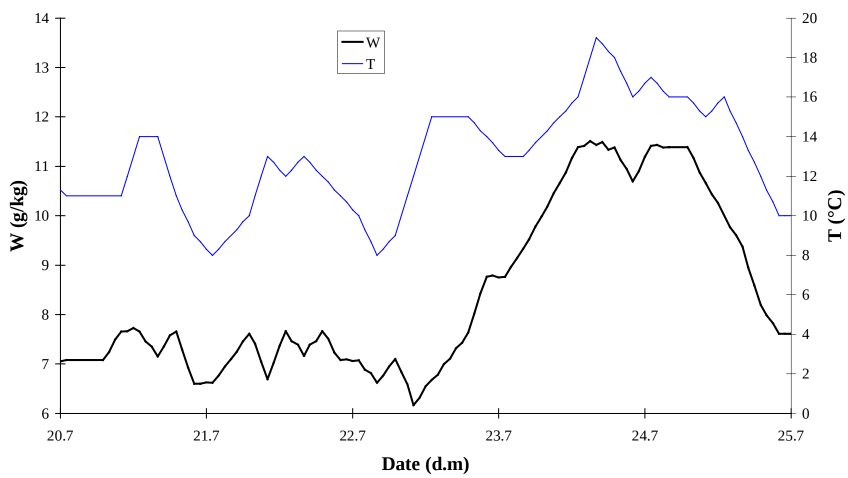

Figure 71. Outdoor humidity and temperature during a humid period in Belgium.

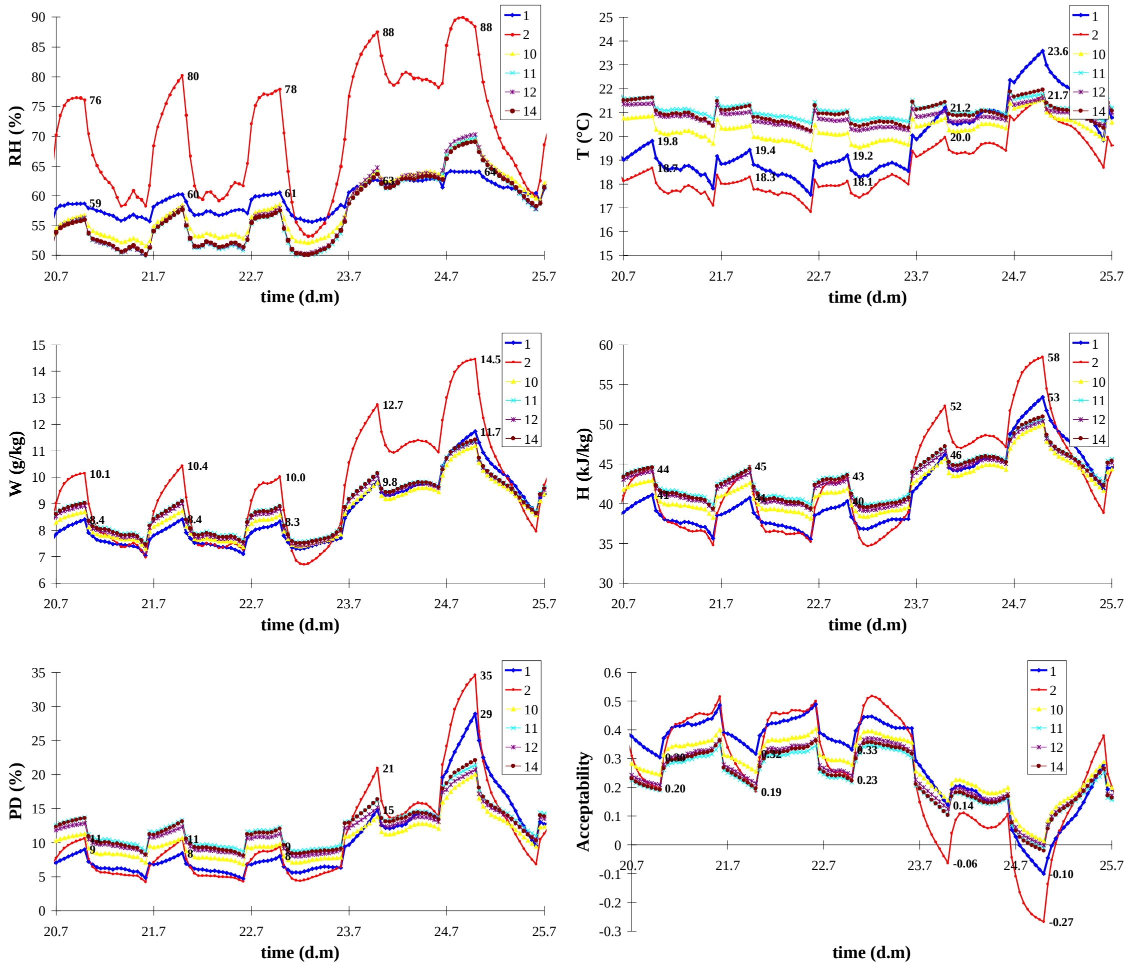

Figure 72. Temporal variation of the important indoor air variables during humid weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

The indoor temperature in the various cases along with the outdoor temperature are given for a longer period in Figure 73. Here the effect of thermal mass is evident. The results show that a room with a massive wooden floor and ceiling (200 mm) has a similar thermal performance as a room with a concrete floor and ceiling (200 mm). The cooling effect of the moisture transfer is evident during the first 10 days of July when comparing cases 1 and 2. Since the outdoor temperature and consequently the indoor temperature increase at the beginning of July, the indoor relative humidity decreases and moisture begins to desorb from the porous envelope. This moisture removal requires energy and as a result the room with permeable structures is 1 to 2°C cooler than the room with impermeable structures during the first 10 days of July. The reversal is true during a period of increasing indoor humidity (e.g., 17.7 to 25.7).

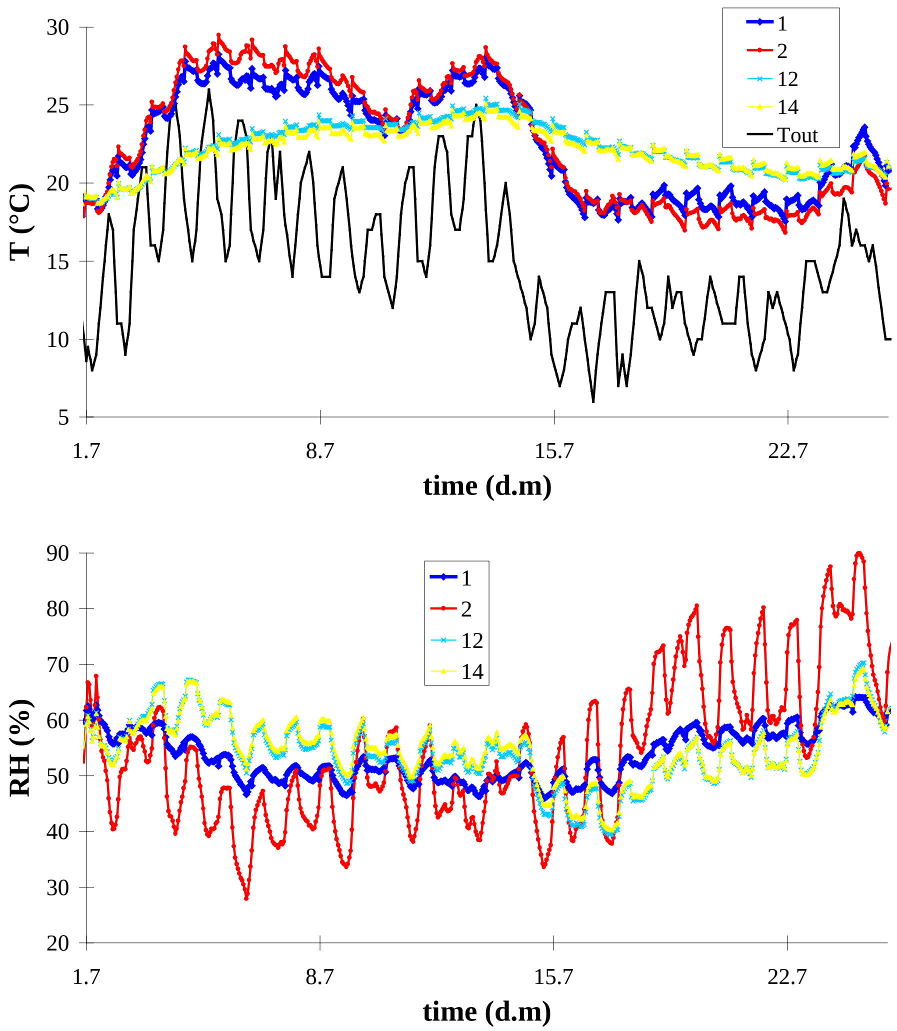

Figure 73. Temperature and relative humidity in Belgium showing the effect of thermal mass on indoor temperature and relative humidity.

To demonstrate the importance of solar shading, Figure 74 compares cases with and without venetian blinds. In the case with blinds, the transmission of solar radiation through the window is 25% and, in the case without blinds, the transmission is 60%. These results show that solar shading is very important for moderating indoor temperatures because it reduces the indoor temperature by about 10°C.

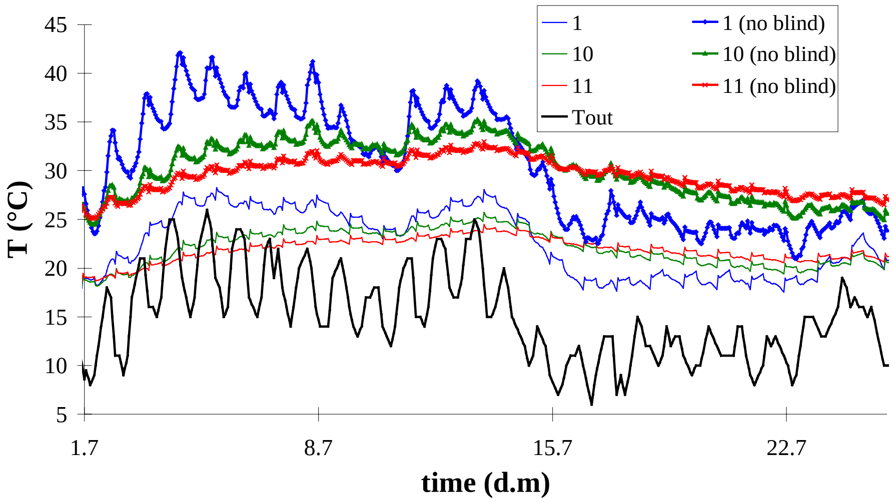

Figure 74. Temperature and relative humidity in Belgium showing the importance of thermal mass and sun shading in Belgium.

4.6.2 Performance during Occupation

4.6.2.1 Time of Poor Performance

The time that the indoor conditions are outside the selected limits is presented in Figure 75. Compared to the lightweight case1, the massive cases have, in general: slightly more time with RH>60%, slightly less time with RH<25%, slightly more time with PD>15% and slightly less time with Acc>0. These trends are, however, climate dependent and the trends vary between climates.

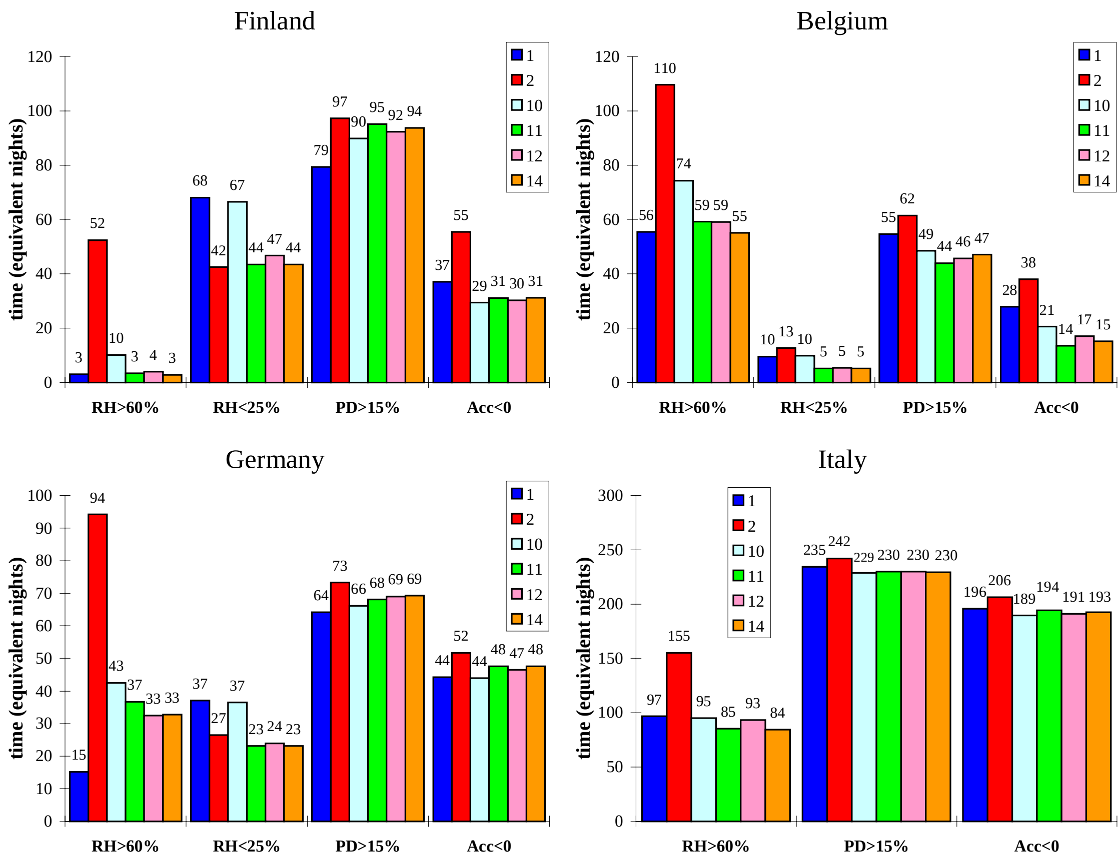

Figure 75. Time that the indoor conditions are outside certain limits during occupation (22:00 to 7:00) in all climates.

The most important difference between the massive and lightweight cases is the temperature (Figure 76). In Finland and Belgium, the massive cases have significantly less time with T>26°C and T<18°C. In Italy the mass has a small effect on the time T>26°C, but a noticeable effect on the time T<18°C.

Comparing between the different massive cases shows that the amount of thermal mass impacts the time 18°C>T>26°C in many climates and that the greater the mass the better the performance, which is expected. Nevertheless, the results show that in Italy the temperature exceeds 26°C for all levels of thermal mass and some cooling is clearly needed. It is important to note that in all climates, except Italy, the massive wood construction with a log wall (case14) performs well.

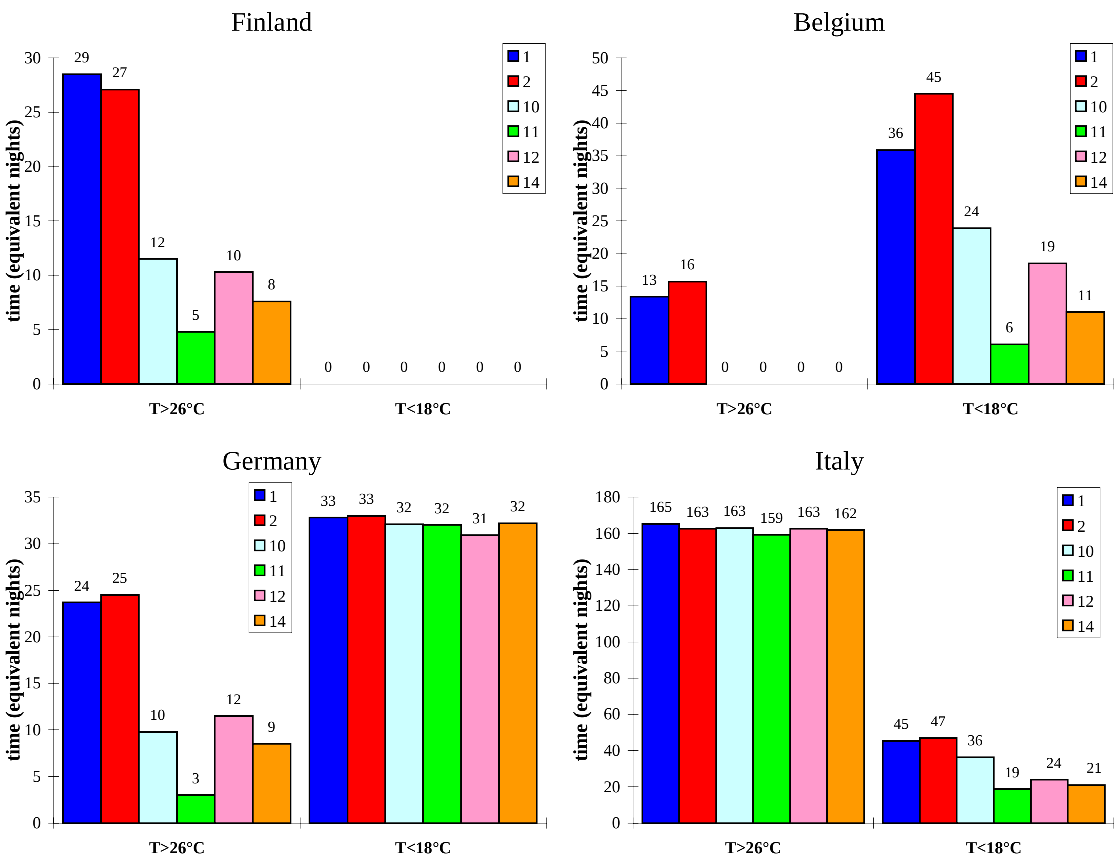

Figure 76. Time that the indoor temperature is above 26°C and below 18°C during occupation (22:00 to 7:00) in all climates.

4.7 Effect of Ventilation Rate

Since the outdoor ventilation air is an important moisture sink (i.e., it removes moisture from the indoor air), the purpose of this section is to study the effect of varying the ventilation rate. This is important because many dwellings and especially individual rooms have outdoor ventilation rates much lower than 0.5 ach.

4.7.1 Performance during Different Weather Conditions

4.7.1.1 Humid Period in Belgium (July)

Using the humid period in July (Figure 77), the indoor variables are presented for different ventilation rates in Figure 78. The RH results are somewhat unexpected because they show that the RH decreases as the ventilation rate decreases because the indoor temperature increases as the ventilation rate decreases. Nevertheless, the absolute humidity, enthalpy and percent dissatisfied with warm respiratory comfort all increase as the ventilation rate decreases. The acceptability decreases as the ventilation rate decreases. Here it is important to remember that the acceptability of indoor air is calculated assuming that the indoor air is clean. Clearly the indoor air will be more polluted as the ventilation rate decreases.

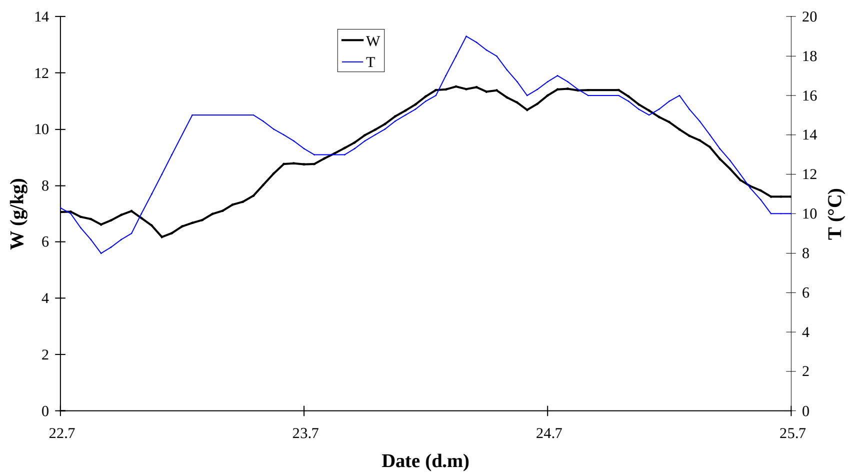

Figure 77. Outdoor humidity and temperature during a humid period in Belgium.

Comparing the permeable case1 and impermeable case2, it is evident that W, H, PD and Acc have more favourable values in case1 than in case2 for all ventilation rates. In fact, the results in case1 with a ventilation rate of

0.25 ach are comparable to the results in case2 with a ventilation rate of 0.5 ach.

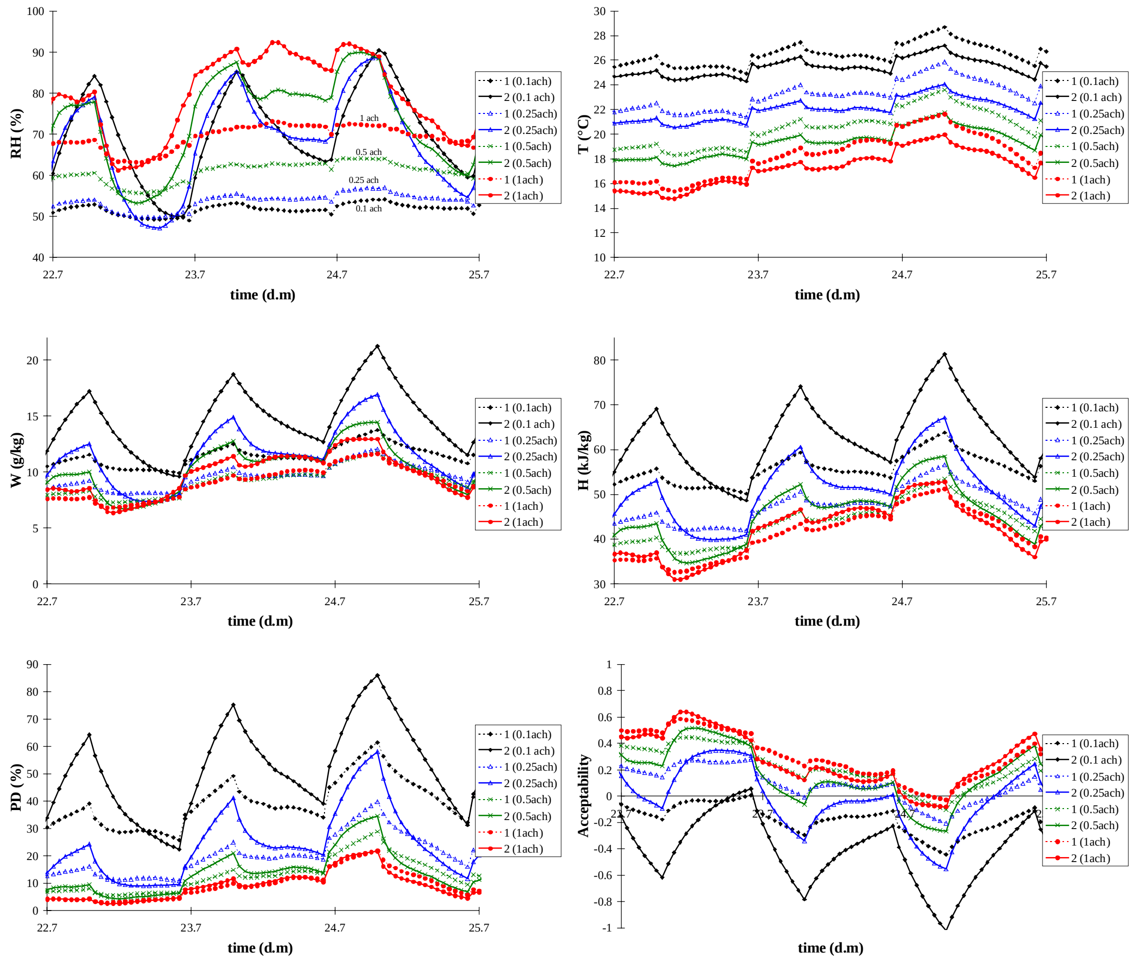

Figure 78. Temporal variation of the important indoor air variables during humid weather in Belgium showing the effect of ventilation.

4.7.1.2 Cooler Period in Belgium (March)

To reduce the thermal effects of ventilation, the effect of ventilation is presented for a cooler period (Figure 79) in Figure 80. In this case, both the indoor relative humidity and temperature increase as the ventilation rate decreases, and, as a result, W, H and PD increase and Acc decreases with decreasing ventilation rate. The difference between the permeable and impermeable case is even more pronounced than in July. Here the PD and Acc results are much better in the permeable case1 with a ventilation rate of 0.25 ach than in the impermeable case2 with a ventilation rate of 0.5 ach. The acceptability is nearly the same in the permeable and impermeable cases when the permeable case has a ventilation rate of 0.5 ach and the impermeable case has a ventilation rate of 1 ach. The peak RH during the night is higher in case2 with 0.5 ach than in case1 with 0.1 ach.

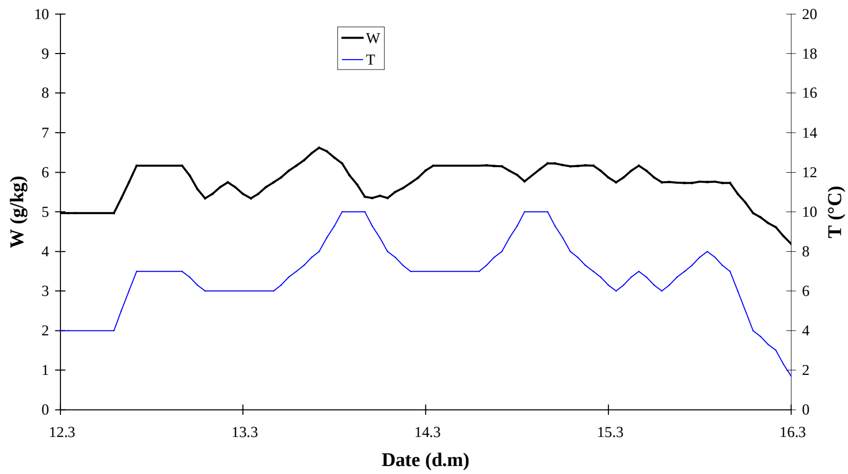

Figure 79. Outdoor humidity and temperature during a cooler period in Belgium.

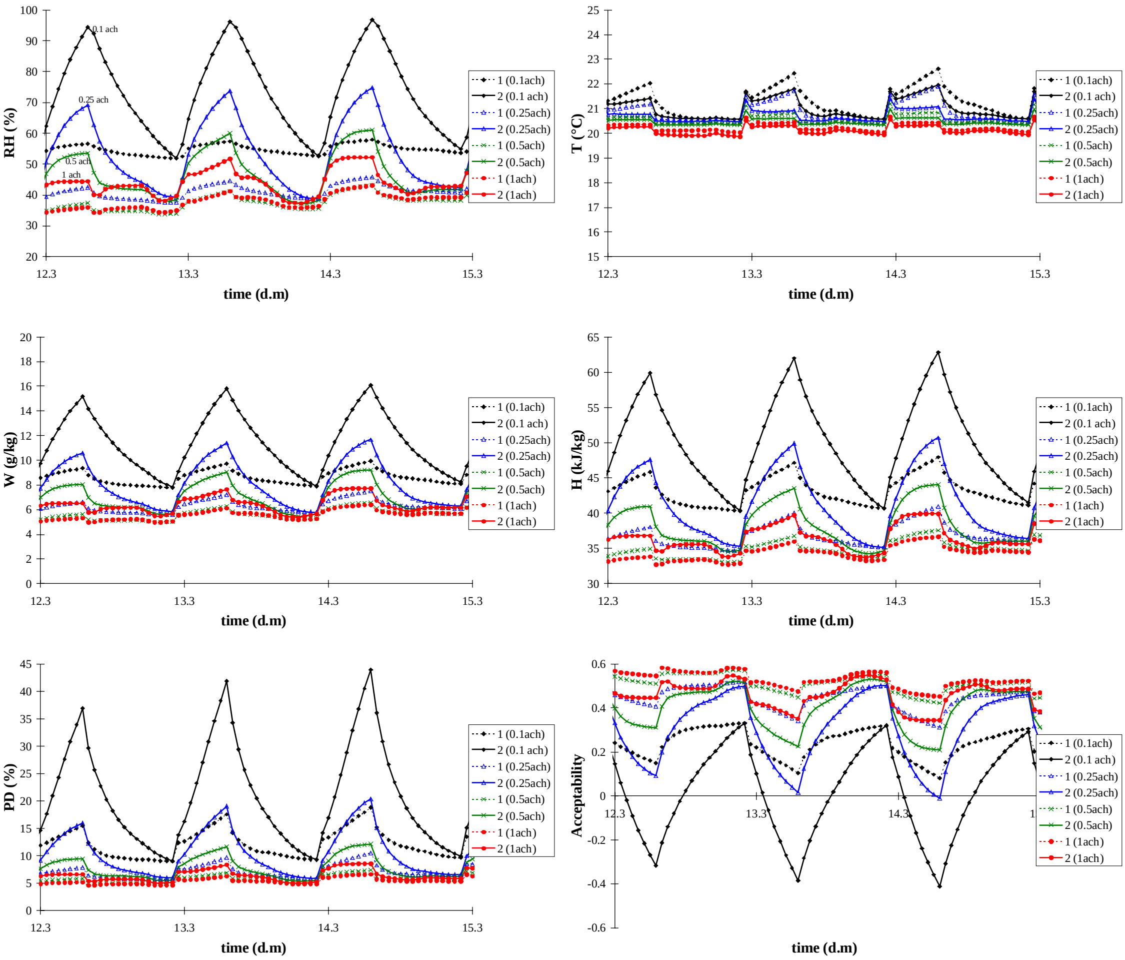

Figure 80. Temporal variation of the important indoor air variables during cooler weather in Belgium showing the effect of ventilation.

4.7.2 Performance during Occupation

4.7.2.1 Moisture Flows during Occupation

The average of the maximum increase in humidity during the night as a function of the ventilation rate showing the effect of insulation, interior board, active area and resistance of interior coating is presented in Figure 81.

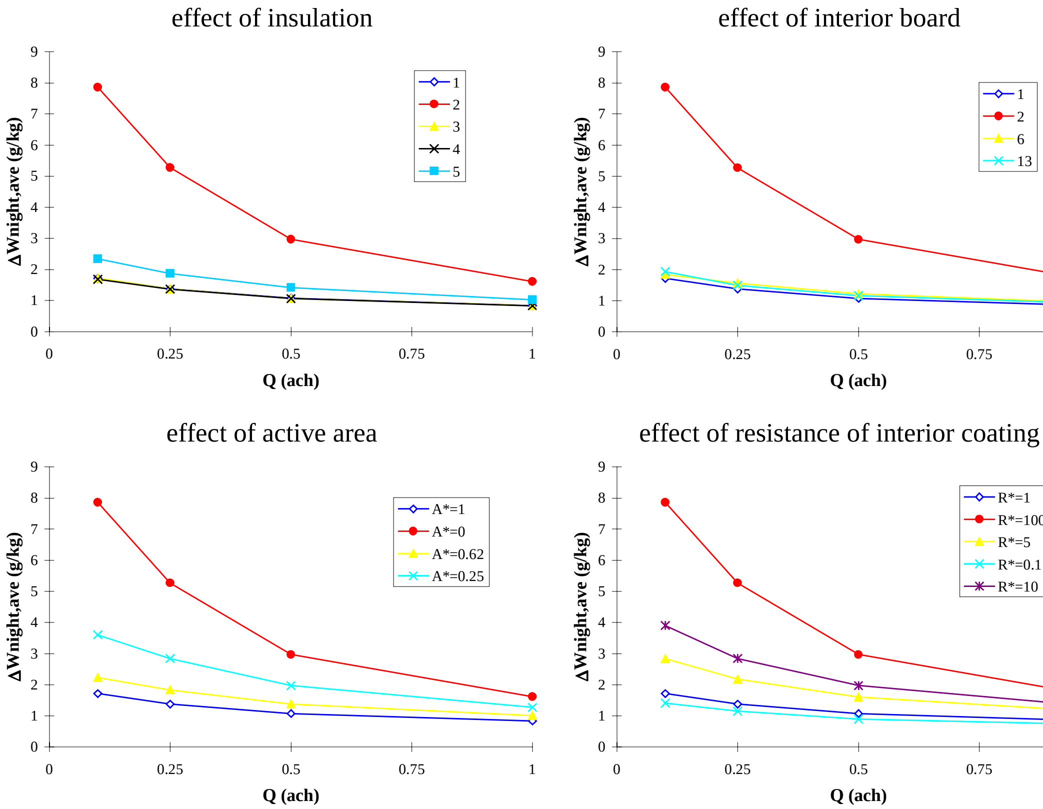

Figure 81. Average increase in absolute humidity during the night for various ventilation rates and different cases.

The results in Figure 81 show that the increase in humidity during the night is very sensitive to the ventilation rate and that the difference between different cases increases as the ventilation rate decreases. At 0.5 ach, ΔWnight is 2.8 times greater for the impermeable case2 than for the impermeable case1, while at 0.1 ach ΔWnight is nearly 4.6 times greater in case2 than in case1. With a permeable internal coating and a ventilation rate of 0.1 ach, the yearly average increase in humidity during the night is 1.7 g/kg, which is equivalent to the humidity increase when the ventilation rate is 0.9 ach and the coating is impermeable. This means that if the conditions at the beginning of occupation are the same regardless of the night-time ventilation rate (due to airing or air exchange with the rest of the house during the day), the permeable case will have a similar moisture performance at a significantly lower ventilation rate than the impermeable case.

Figure 82 presents the yearly average moisture flows in cases 1 and 2 and shows that as the ventilation rate decreases, the moisture removed by the ventilation air decreases. However, even at a ventilation rate of 0.1 ach, the ventilation removes 35% of the produced moisture in case1 and 44% of the produced moisture in case2. As the ventilation rate decreases, Figure 82 shows that the moisture transfer to the structure increases. On average, the moisture transfer to the structure removes more moisture than the ventilation air in case1 when the ventilation is below 0.15 ach. As a result the moisture remaining in the air is significantly lower in case1 than in case2 at the low ventilation rates.

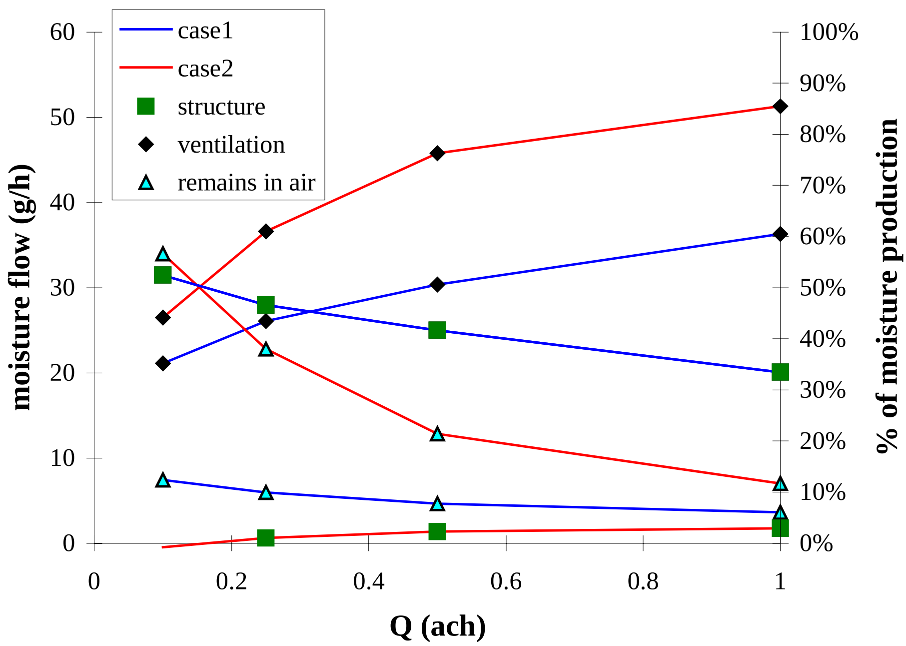

Figure 82. Yearly average moisture flows during the night in Belgium.

4.7.2.2 Time of Poor Performance

The above results clearly show that moisture transfer to the structure can perform as a significant moisture sink, which can moderate the increase in humidity during the night. The increase in humidity during the night is several times greater for the impermeable case than for the permeable case and this ratio increases as the ventilation rate decreases. The time of poor performance for different ventilation rates and cases is given in Figure 83 to Figure 87.

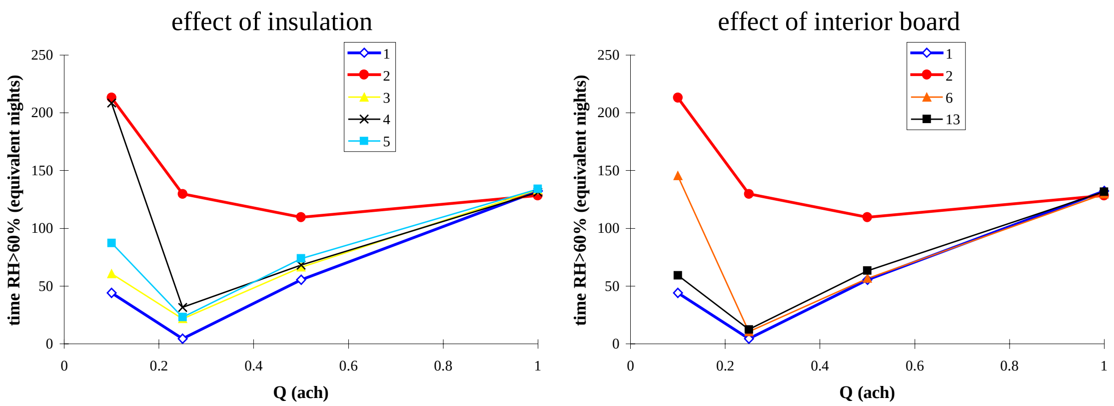

Figure 83. Time that the indoor humidity is greater than 60% RH during occupation as a function of the outdoor ventilation rate (Belgium).

The results in Figure 83 show that, for case1, the time when RH>60% decreases as Q decreases from 1.0 to 0.25 ach. The reason for this is that the ventilation rate affects the indoor temperature as was seen in Figure 78. As the ventilation rate decreases, the indoor temperature increases and the relative humidity can decrease, especially in the summer. Decreasing the ventilation beyond 0.25 ach, increases the time when RH>60% for all cases. For Q<0.5 ach, the impermeable case2 has much more time with RH>60%, while at Q=1 ach, cases 1 and 2 have similar times with RH>60%.

The effect of the insulation and interior board is more significant at low ventilation rates. The diffusion resistance of the wall is particularly important at low ventilation rates and case4 (plastic vapour retarder behind interior wallboard) and case6 (wooden panel with 6 times higher vapour resistance than porous wood fibre board) have significantly more time with RH>60% when the ventilation rate is 0.1 ach.

The time when RH<25% decreases as Q decreases (Figure 84) because, during cold dry weather, the outdoor ventilation removes moisture and reduces the indoor RH. Decreasing Q reduces the moisture sink and thus increases the indoor humidity. The time PD>15% increases as Q decreases and the difference between the time PD>15% in cases 1 and 2 increases as Q decreases (Figure 85). The acceptability results in Figure 86 are similar to the PD results.

The time when T>26°C increases as Q decreases and the time when T<18°C decreases as Q decreases as shown in Figure 87. This is logical because ventilation cools the room during most weather conditions.

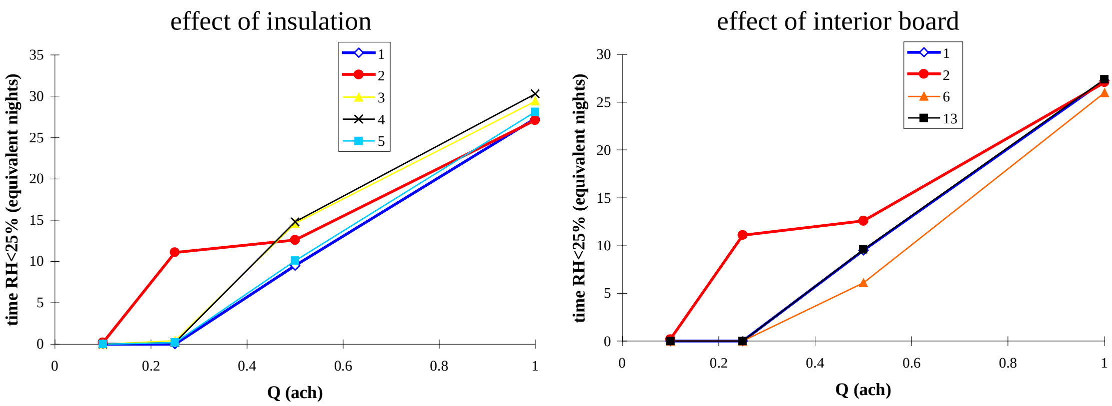

Figure 84. Time that the indoor humidity is less than 25% RH during occupation as a function of the outdoor ventilation rate (Belgium).

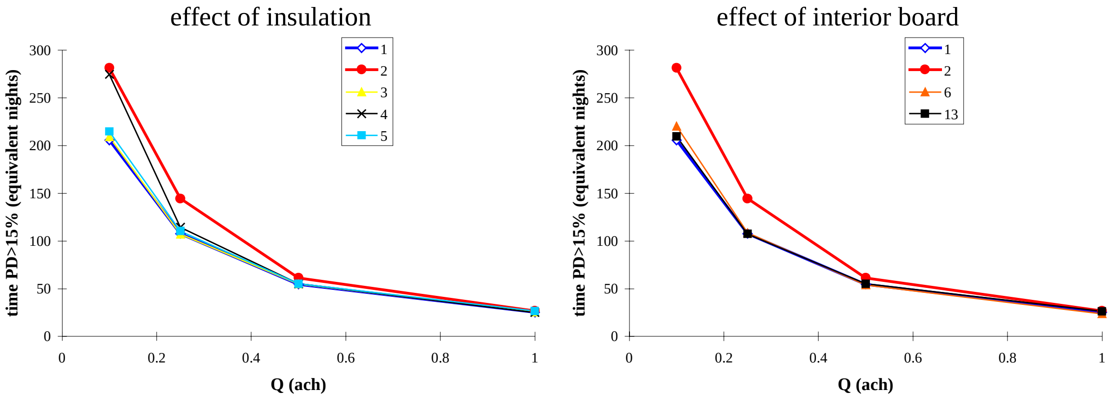

Figure 85. Time that the percent dissatisfied with warm respiratory comfort is greater than 15% during occupation as a function of the outdoor ventilation rate (Belgium).

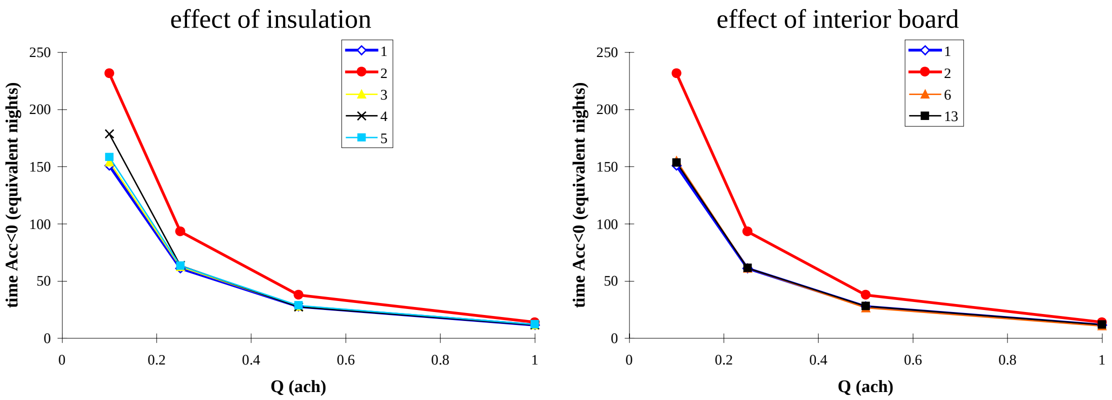

Figure 86. Time that the indoor air quality is unacceptable during occupation as a function of the outdoor ventilation rate (Belgium).

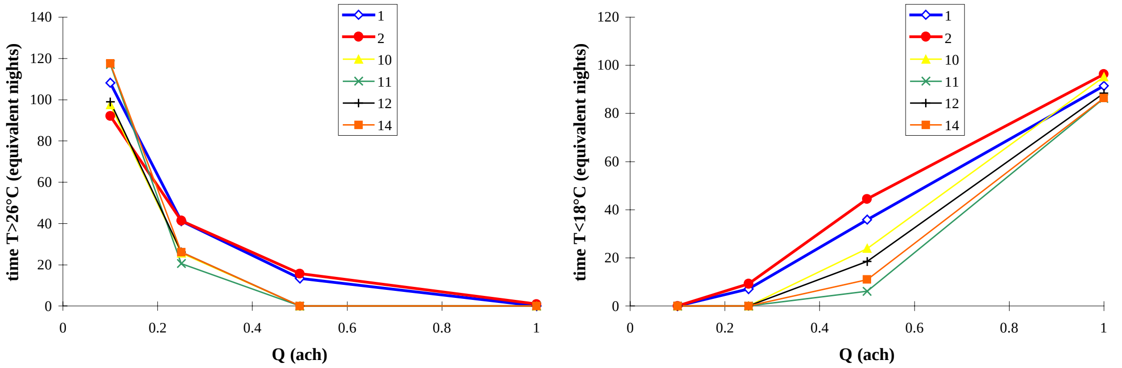

Figure 87. Time that the indoor temperature is greater than 26℃ or less than 18℃ as a function of the outdoor ventilation rate (Belgium).

4.7.2.3 Monthly Average Performance

Moisture transfer to a permeable structure can be as important a moisture sink as ventilation during the night. Therefore, the increase in humidity during the night can be significantly affected by increasing the ventilation rate or moisture transfer to the structure. The ventilation rate and moisture transfer to the structure not only affect the increase in humidity during the night, but also affect the humidity level during occupation. This can be seen in Figure 88 where the monthly average values of the indoor air variables during occupation are presented for different ventilation rates. The difference between the permeable case1 and the impermeable case2 is still significant on a monthly average level, but changing the ventilation rate between the 4 tested ventilation rates (i.e., 0.1-0.25 ach, 0.25-0.5 ach and 0.5-1 ach) usually has a greater affect on the results than changing between cases 1 and 2. This is different from the short term results in section 4.7.1 and the nightly moisture increase results 4.7.2.1 where it was possible to have a similar performance with a lower ventilation rate when applying the permeable case1. When comparing the effect of ventilation rate and the effect of moisture storage monthly average effects should be considered as well. However, in many practical situations the short-term effects are important because the ventilation rate or air change rate of a room may be significantly different during occupation, which is not considered in the simulation. For example, many people keep their bedroom door closed during the night and open during the day. As a result, the ventilation rate may be below the design value during the night, while the ventilation rate will approach the design value during the day. Furthermore, the air exchange with the rest of the house during the day, which typically has lower humidity levels than the bedroom, will increase the moisture removal from the bedroom. This means that the conditions at the beginning of occupation will often be similar regardless of the night-time ventilation rate, but the increase in humidity during the night will depend on the ventilation rate and building construction. In this situation, the moisture removal of ventilation and the building envelope can be directly compared to the ventilation rate.

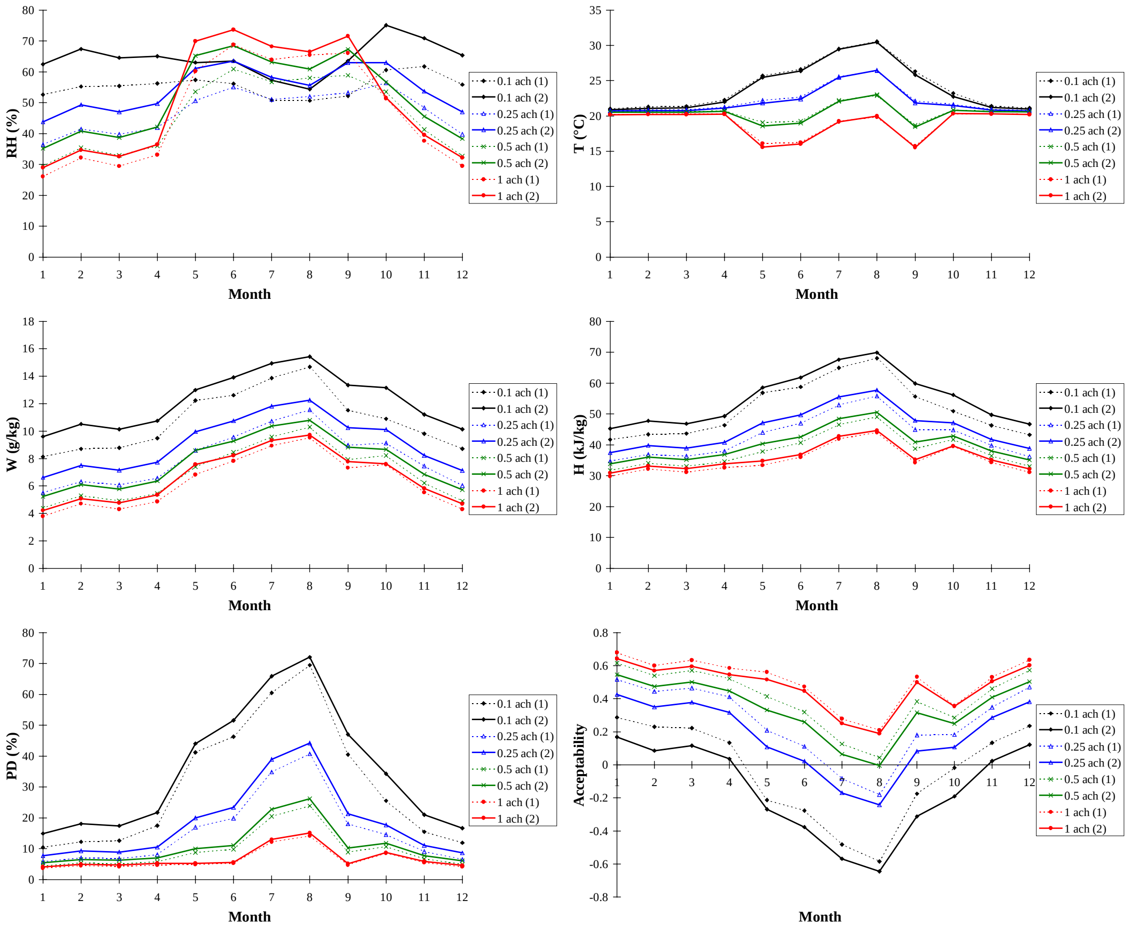

Figure 88. Monthly average of the indoor parameters during occupation for different outdoor ventilation rates (Belgium).

4.8 Effect of Moisture Production

To study the effect of moisture production, the moisture production rate is set higher than the 60 g/h used in all the previous results, but the sensible heat production remains as before (i.e., 190 W for 1 hour and 90 W for 8 hours). The chosen moisture production rates are: 90, 120 and 180 g/h. The higher moisture production rates could represent more people in the room or a larger moisture production rate per person.

4.8.1 Performance during Different Weather Conditions

In this section, the short-term performance will be presented for humid weather in July and more cool conditions in March in the same way as the effect of ventilation was presented in section 4.7.1.

4.8.1.1 Humid Period in Belgium (July)

When the moisture production rate is very high (180 g/h) and the interior surface is impermeable during the humid weather in July (Figure 89), the humidity in the room becomes very high (greater than 100% RH) as shown in Figure 90. This is a numerical value that would not occur in practice because condensation would occur on the interior surfaces of the room. This anomaly occurs because the simulation model includes the vapour resistance of the interior surface in the convective mass transfer coefficient. Therefore in the impermeable case, the convective mass transfer coefficient is very low and the moisture transfer to the surface of the room is very slow and humidities above 100% are possible. This phenomenon could be more correctly accounted for in the model by separating the convective mass transfer coefficient and the surface resistance. To accomplish this, the interior surface of the wall would be treated as a separate node that is connected to the indoor air through the convective mass transfer coefficient and then this surface node would be connected to the rest of the wall through the resistance of the interior coating. This would allow surface condensation to occur even when the indoor coating has a high vapour resistance and would help keep the indoor humidity below 100% RH. However, during normal conditions when the indoor humidity is below 100% RH, this improved model would have essentially no effect on the results.

The difference between the permeable case1 and impermeable case2 is very evident in Figure 90. By comparing peak indoor humidity values (RH and W), it is apparent that the permeable case1 can withstand 3 times the moisture production rate as the impermeable case2. Comparing the peak values of other parameters (H, PD and Acc) shows that case1 can withstand twice as much moisture production as case2.

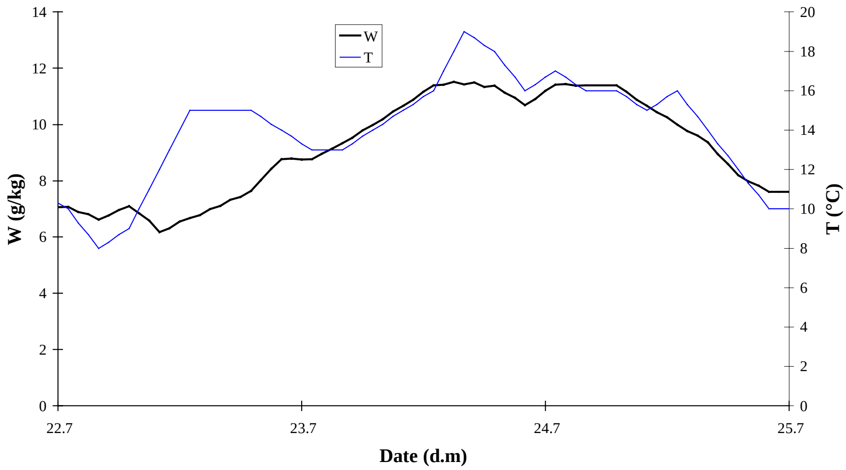

Figure 89. Outdoor humidity and temperature during a humid period in Belgium.

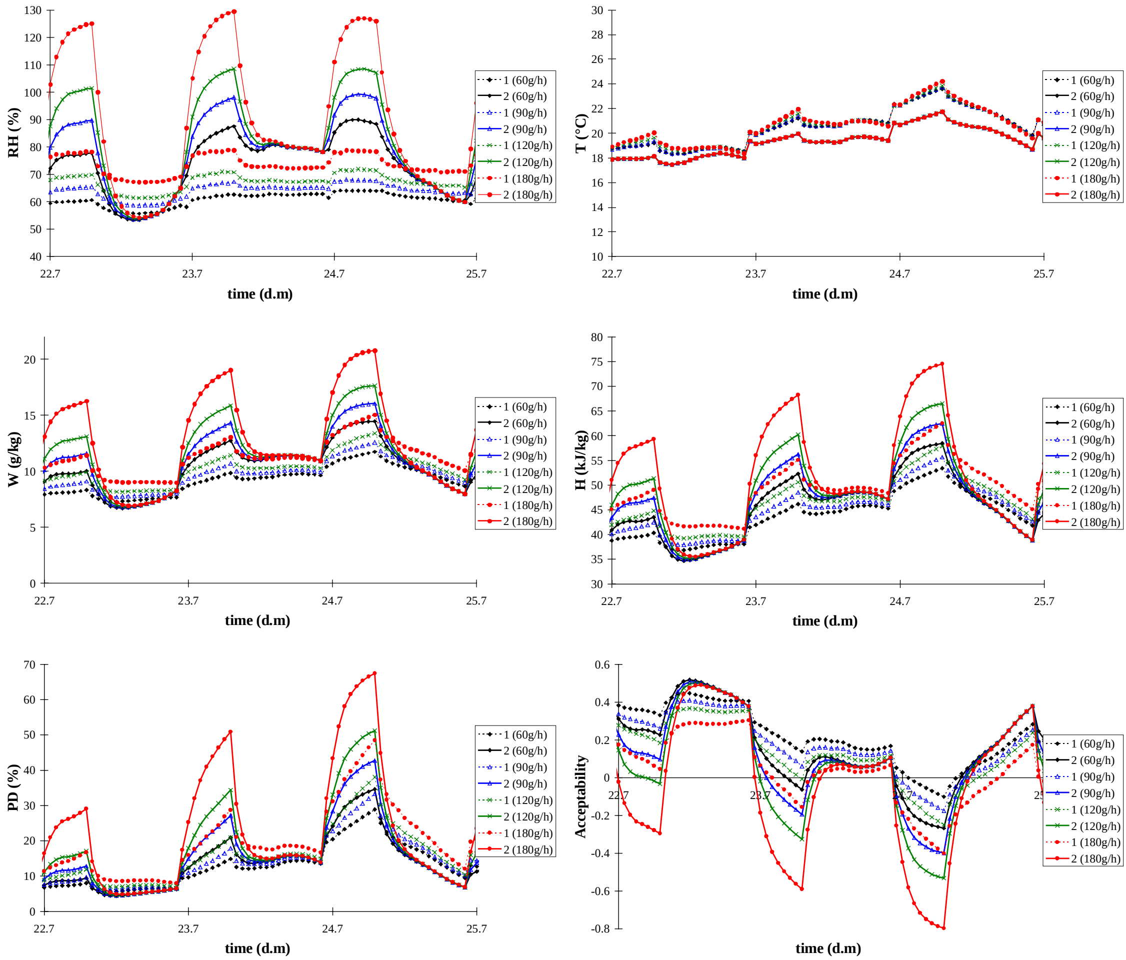

Figure 90. Temporal variation of the important indoor air variables during humid weather in Belgium showing the effect of moisture production.

4.8.1.2 Cooler Period in Belgium (March)

The effect of moisture production is presented in this section for a cooler period in March shown in Figure 91. The results in March (Figure 92) are similar to those in July except that the indoor humidity levels are more moderate in March. Again, the permeable case has similar peak humidity values as the impermeable case even when the moisture production rate is

3 times higher in the permeable case. The peak enthalpy, comfort and IAQ parameters are similar in the permeable and impermeable cases, when the moisture production rate is twice as high in the permeable case.

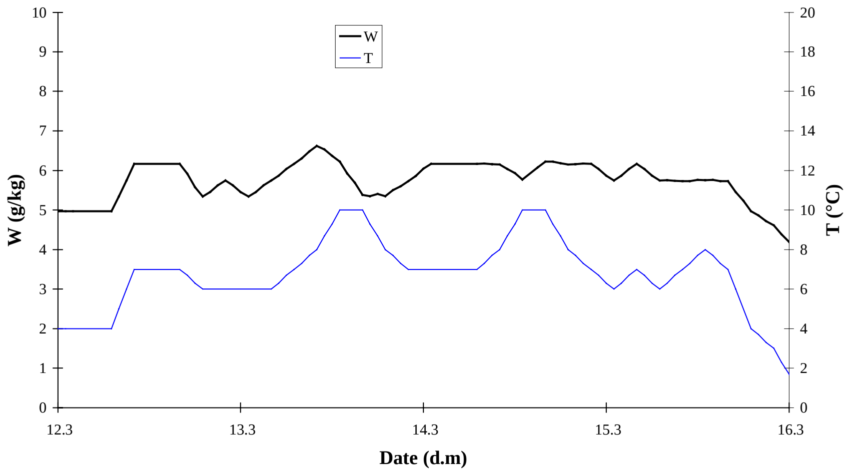

Figure 91. Outdoor humidity and temperature during a cooler period in Belgium.

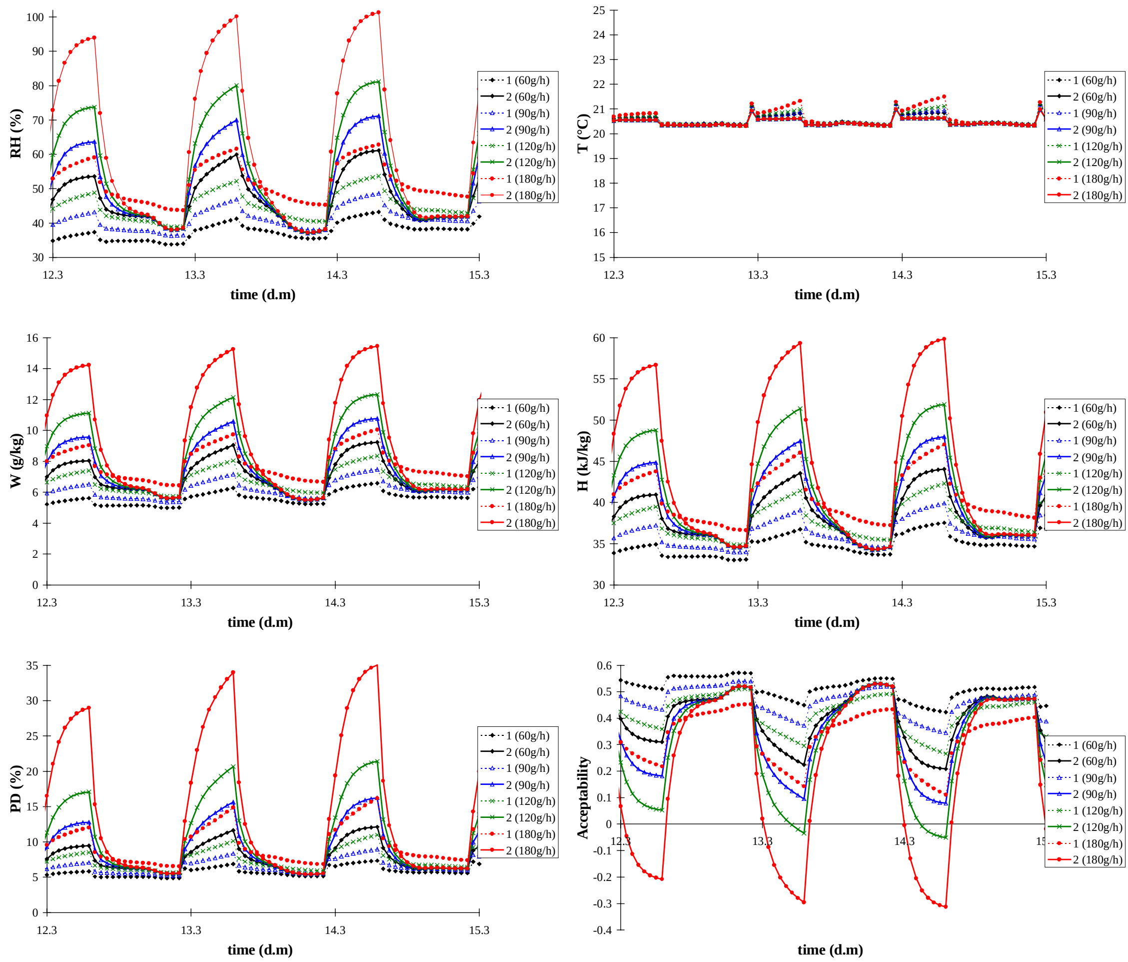

Figure 92. Temporal variation of the important indoor air variables during cooler weather in Belgium showing the effect of moisture production.

4.8.2 Performance during Occupation

4.8.2.1 Moisture Flows during Occupation

The yearly average of the maximum increase in humidity during the night as a function of the moisture production rate showing the effect of insulation, interior board, active area and resistance of interior coating is presented in Figure 93. The results show that the increase in humidity during the night is proportional to the moisture production rate. This means that the fraction of moisture removed by ventilation and moisture transfer to the structure remains nearly constant as the moisture production increases, which can be seen in Figure 94.

Figure 93 also shows that the difference between the various cases increases as the moisture production rate increases. The increase in humidity during the night with permeable case1 and a moisture production rate of 180 g/h is equivalent to that with impermeable case2 and a moisture production rate of 60 g/h. This means that the permeable case can endure three times the moisture production, if the moisture conditions at the beginning of occupation are the same.

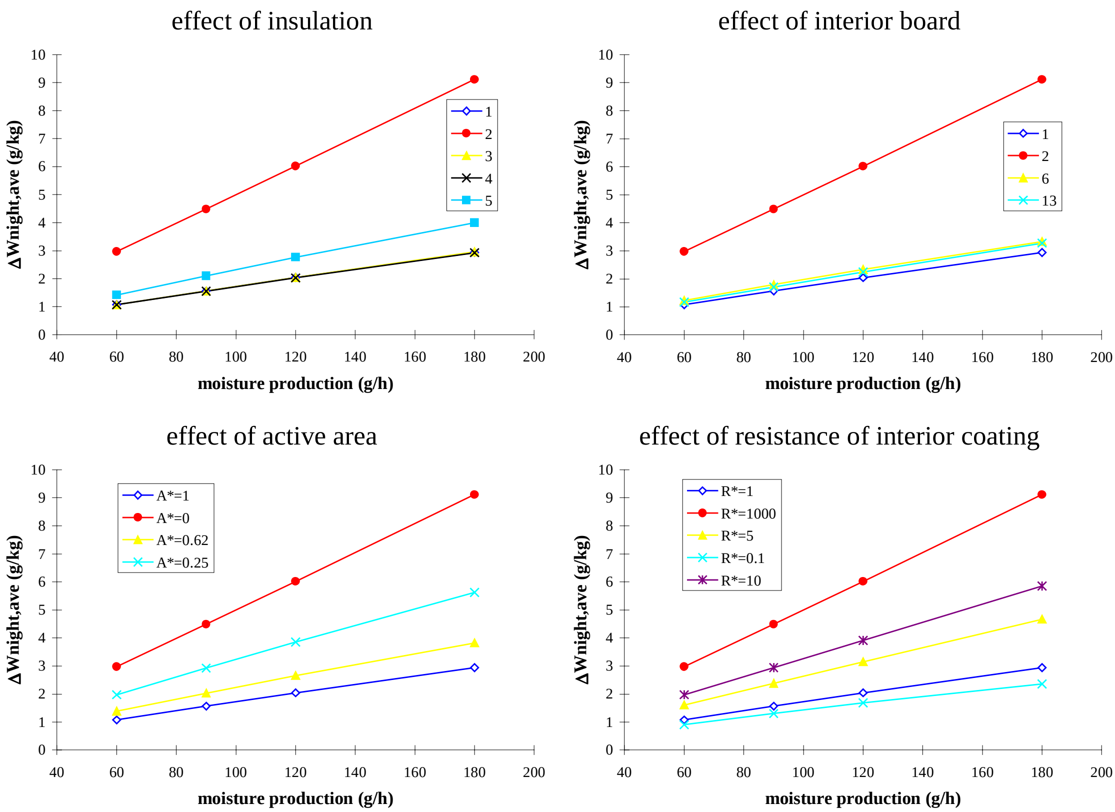

Figure 93. Average increase in absolute humidity during the night for various moisture production rates and different cases.

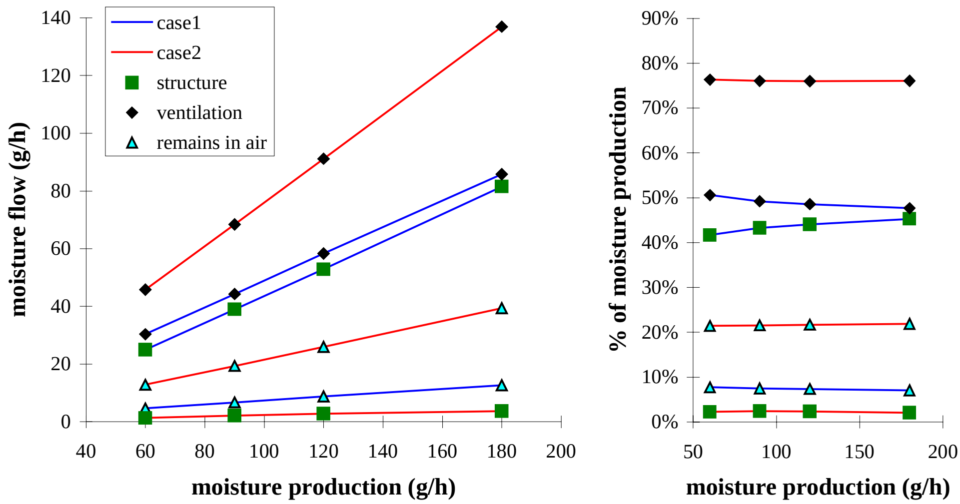

Figure 94. Yearly average moisture flows during the night in Belgium.

4.8.2.2 Time of Poor Performance

Figure 95 shows that as the moisture production increases, the time of unsatisfactory conditions increases for all variables except RH<25%. This is logical because the humidity in the room will increase as the moisture production rate increases. As a result, the time when RH>60% will increase along with the time PD>15% and the time Acc<0. Both the permeable case1 and the impermeable case2 are significantly affected by the moisture production rate, but the impermeable case is more sensitive than the permeable case. The time when RH>60%, PD>15% and Acc<0 are approximately equal in cases 1 and 2 when the moisture production in case1 is about 90 g/h and the moisture production in case2 is 60 g/h. This means that the permeable case can have a 50% higher moisture production than the impermeable case and still have the same number of hours of poor performance.

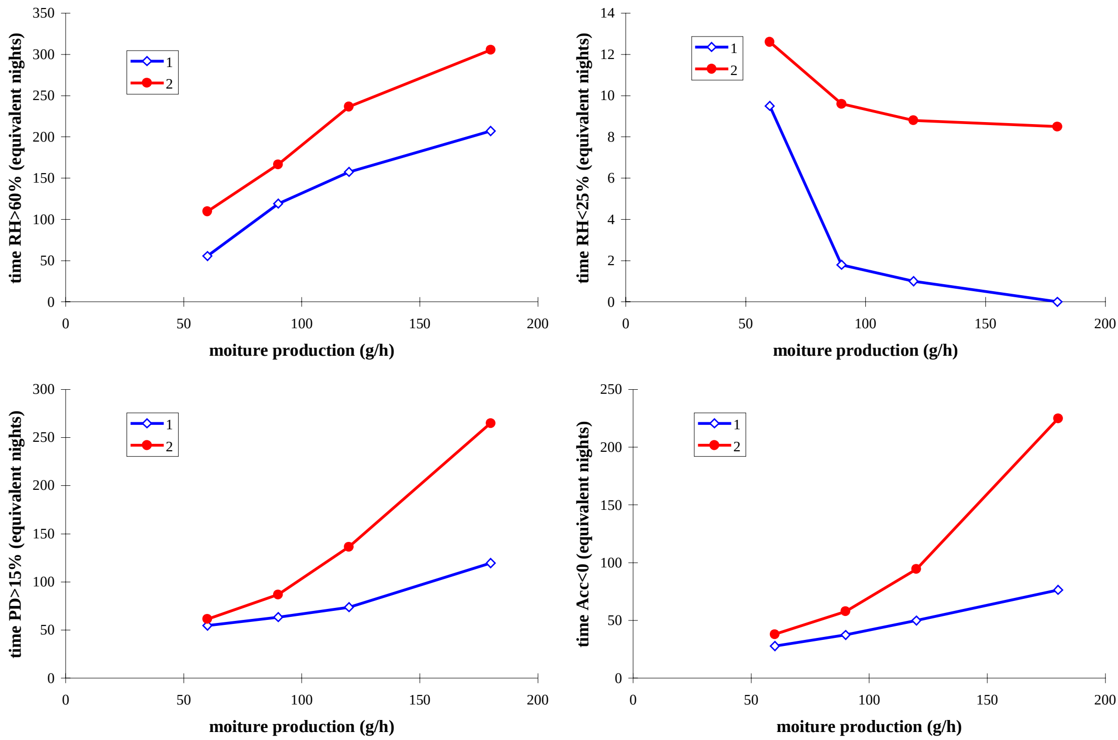

Figure 95. Time that the indoor conditions are outside certain limits during occupation as a function of the moisture production rate (Belgium).

The influence of various parameters on the time of poor performance is shown specifically in Figure 96 to Figure 99. These results show that the time when RH>60%, PD>15% and Acc<0 are more sensitive to the chosen insulation, interior board, active area and interior coating as the moisture production rate increases. Nevertheless, even at a moisture production rate of 180 g/h, the difference between cases 1, 3 and 4 is very small indicating that the insulation is not very critical. However, at a moisture production rate of 180 g/h, case5 (non-hygroscopic wallboard) begins to have more time with RH>60%. Similarly the wooden panel results (case6) begin to deviate from the porous wood fibre board (case1) and gypsum board (case13) results at 180 g/h. The difference between these cases is, however, quite small for PD and Acc.

The time when RH<25% (Figure 97) is more sensitive to the structural characteristics at low moisture production rates because low moisture production rates are more critical for this criteria. It is interesting to note that one case may have more time with RH<25% at a certain moisture production rate, but another may have more time at another. For example at a moisture production rate of 60 g/h, the time when RH<25% is greater for the case with R*=0.1 (a very low vapour resistance) than for the case with R*=1. At a moisture production of 120 g/h, this trend is reversed and the time when RH<25% is greater for R*=1. The reason for this is that as the moisture production increases, the moisture stored in the wall during the night increases and this stored moisture can keep the humidity higher at the beginning of occupation the next evening.

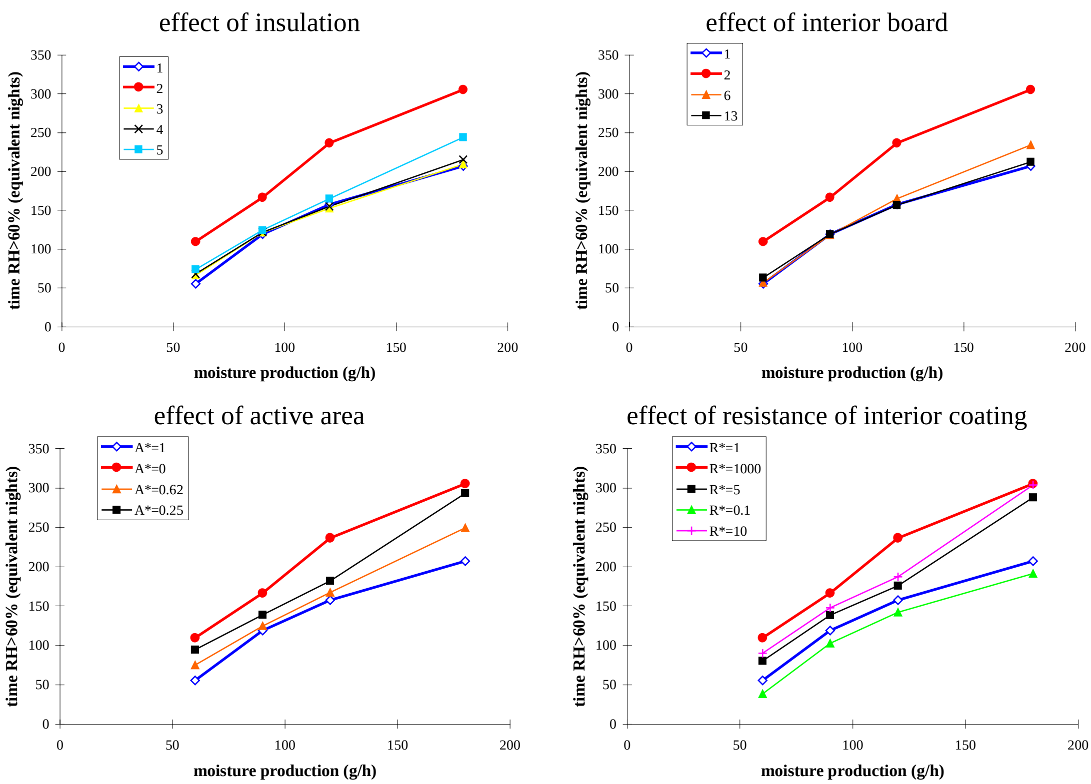

Figure 96. Time that the indoor humidity is greater than 60% RH during occupation as of the function of the moisture production rate (Belgium).

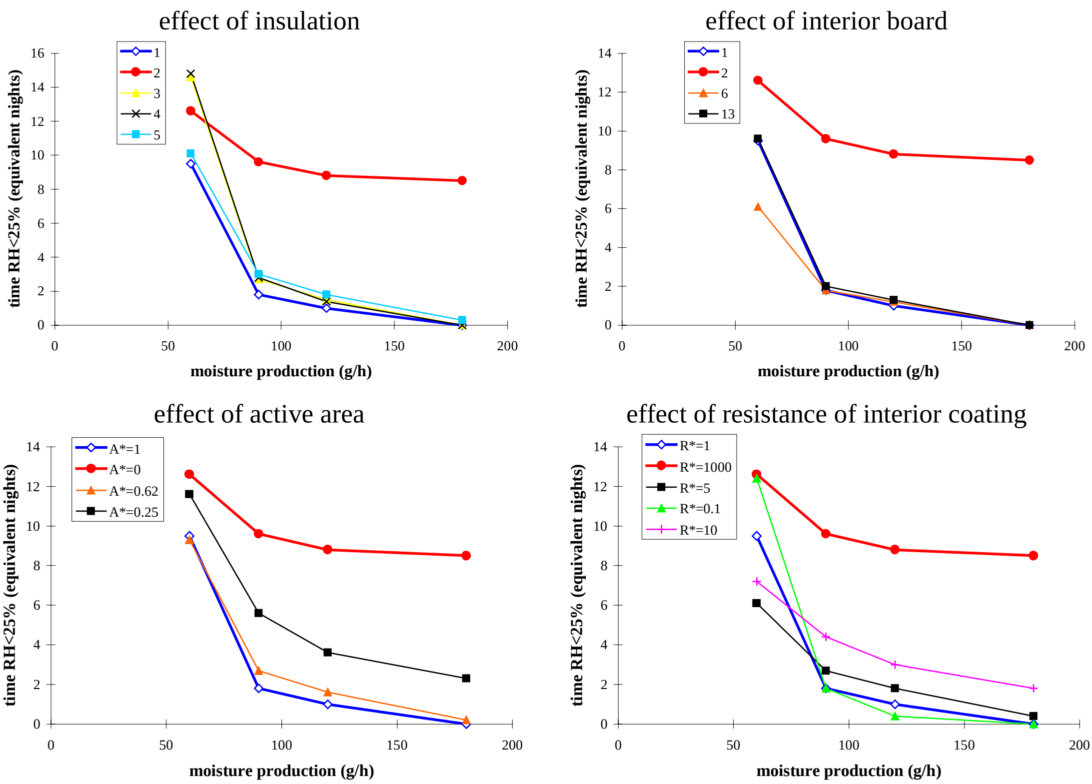

Figure 97. Time that the indoor humidity is less than 25% RH during occupation as a function of the moisture production rate (Belgium).

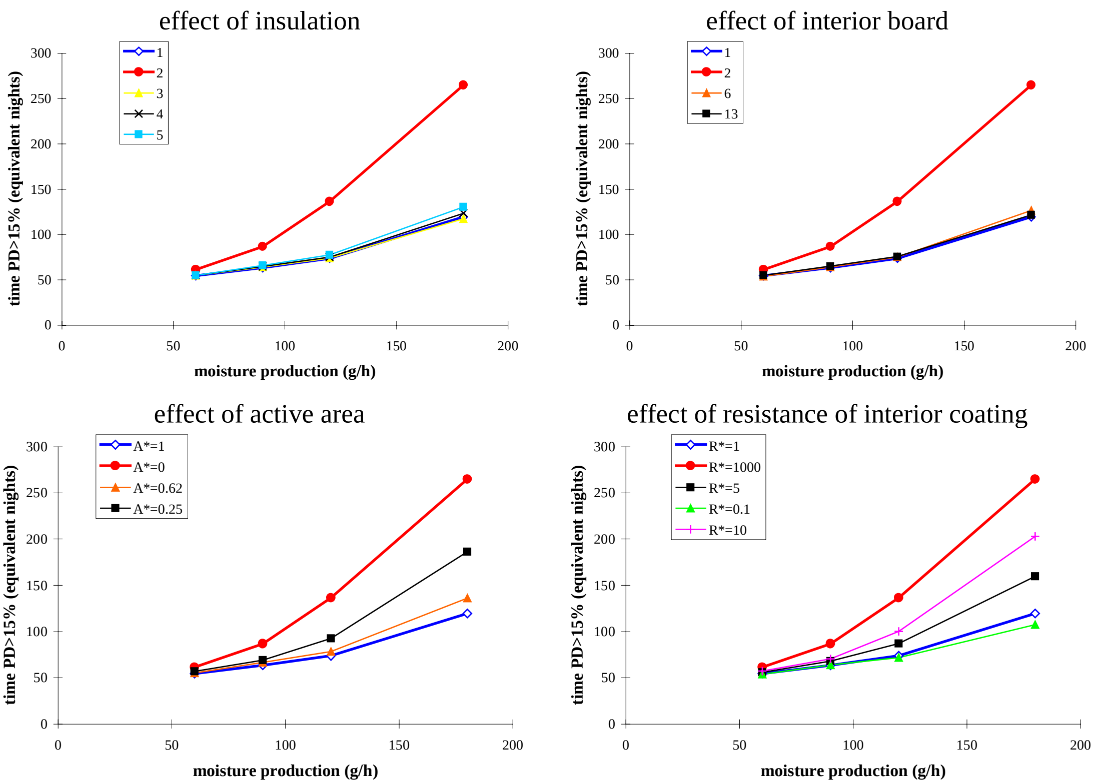

Figure 98. Time that the percent dissatisfied with warm respiratory comfort is greater than 15% during occupation as a function of the moisture production rate (Belgium).

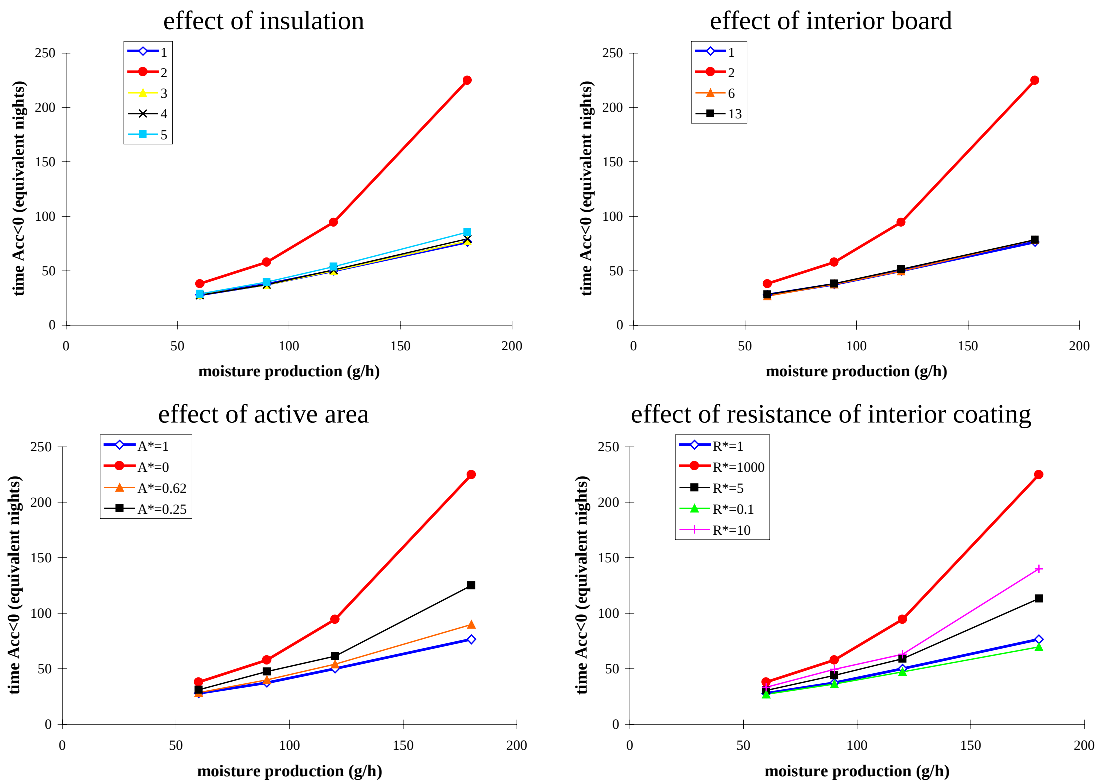

Figure 99. Time that the indoor air quality is unacceptable during occupation as a function of the moisture production rate (Belgium).

4.9 Effect of Climate

The effect of the climate has been shown in previous results, but will be reviewed in this section. The monthly average indoor temperature during occupation (22:00 to 7:00) in cases 1 and 11 and a ventilation rate of 0.5 ach are shown in all climates (ES – Finland, MKE – Belgium, SH – Germany and VMR – Italy) together with the monthly average outdoor temperature in Figure 100. Case11 is shown here because it has the highest thermal mass (200 mm concrete floor and ceiling and 125 mm log on the walls). Despite the large thermal mass in case11, the difference between cases 1 and 11 in Figure 100 is usually less than 1°C, even though the temporal difference can be up to 7°C. The difference between the outdoor temperature and the indoor temperature is quite constant throughout the year and the indoor temperature is always higher because of the internal heat gains (solar radiation, lights and people). The indoor temperature is excessively high in Italy during the summer, which means that cooling will most likely be needed. Even with a large thermal mass such as in case11, the monthly average summer temperature in May, June and July can reduce be reduced only 2°C in Italy. In Italy, the thermal mass reduces the monthly average temperature in August by less than 0.5°C. The maximum monthly temperature in the other climates is between 23°C and 26°C for the lightweight case1 and between 22°C and 25°C for the massive case11.

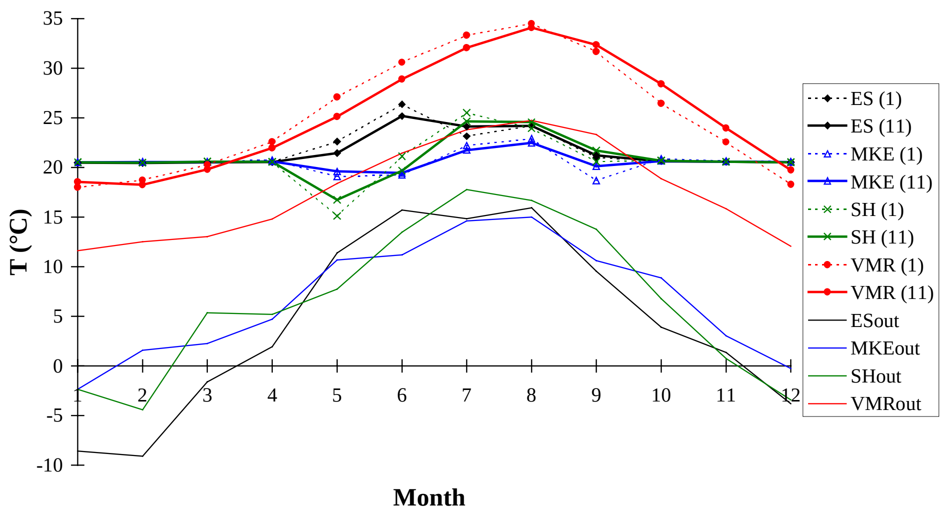

Figure 100. Monthly average indoor temperature during occupation in cases 1 and 11 together with the monthly average outdoor temperature in each climate.

At a ventilation rate of 0.5 ach, the indoor moisture level at the beginning of occupation is approximately equal to the outdoor humidity level. The moisture increase during the night depends on the structure, moisture production and ventilation rate, but is quite independent of the climate. The climate, therefore, affects the level of humidity, but has little effect on the increase during the night. In the cool climates of northern and central Europe, the indoor relative humidity is the highest in the summer and the lowest in the winter (Figure 101), while in the warm climate (Italy), the relative humidity is lower in the summer because the indoor temperature is high. The indoor absolute humidity is always highest in the summer and lowest in the winter as shown in Figure 102. The monthly average indoor absolute humidity is always greater than the outdoor humidity due to the indoor moisture production and the difference is quite constant throughout the year and similar for all climates.

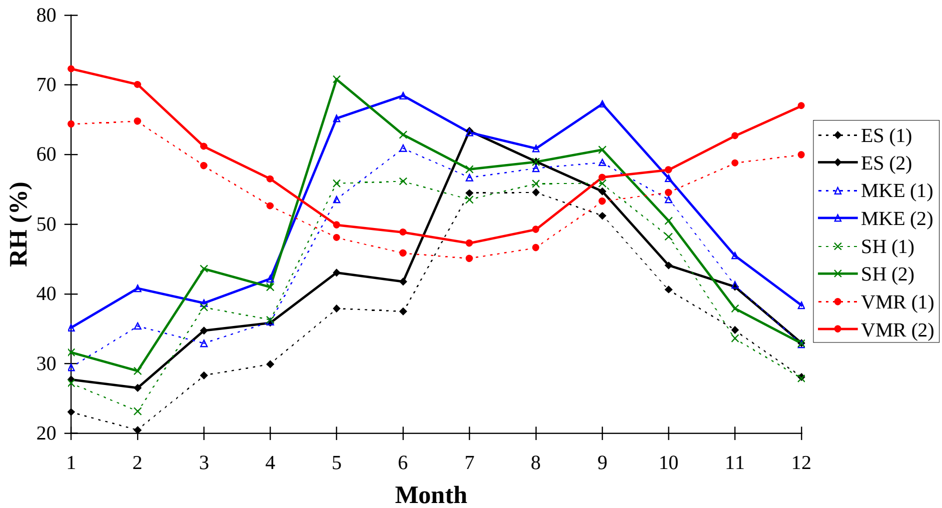

Figure 101. Monthly average indoor relative humidity during occupation in cases 1 and 2.

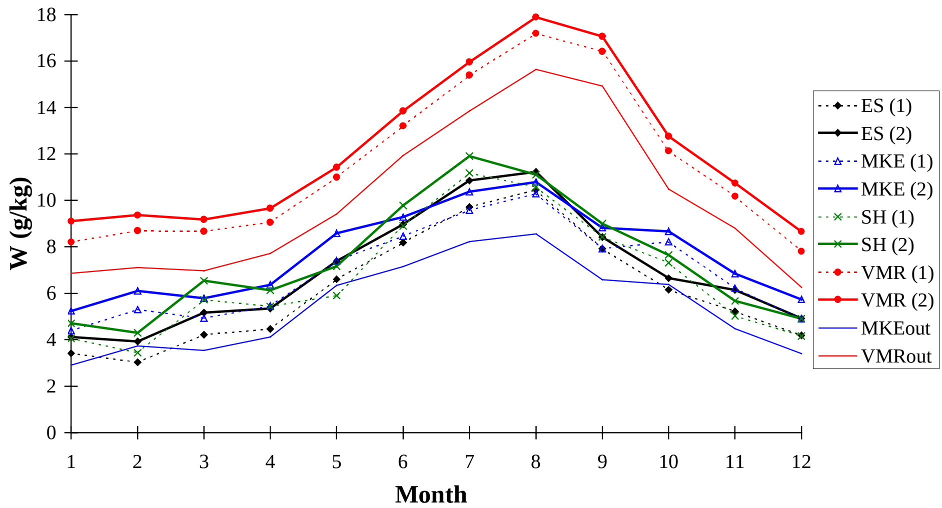

Figure 102. Monthly average indoor humidity during occupation in cases 1 and 2.

Figure 103 shows that the indoor enthalpy is also climate dependent with the southern climate having higher enthalpy values than the northern and central climates. The enthalpy in the impermeable case2 is generally 2 kJ/kg higher than in the permeable case1.

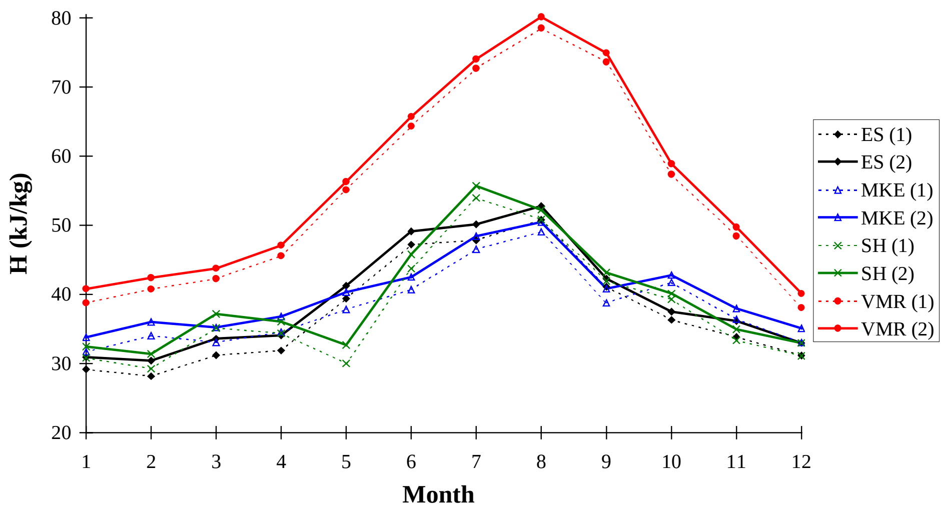

Figure 103. Monthly average indoor enthalpy during occupation in cases 1 and 2.

The indoor comfort and air quality parameters (Figure 104 and Figure 105) are also climate dependent. During the summer in Italy, the percent dissatisfied with warm respiratory comfort is very high and the acceptability of the indoor air is very low during the summer. In the other climates, PD is higher and acceptability lower in the summer than in the winter, but the average PD and acceptability values are not extremely poor. On average, the impermeable case2 has a higher value of PD (2% to 3%) and a lower value of acceptability (0.05 to 0.1) than the permeable case1. In fact, the monthly average of the nightly maximum PD in case1 is lower than the average PD in case2 (Figure 106). Similarly, the monthly average of the nightly minimum acceptability in case1 is higher than the average acceptability in case2 (Figure 107).

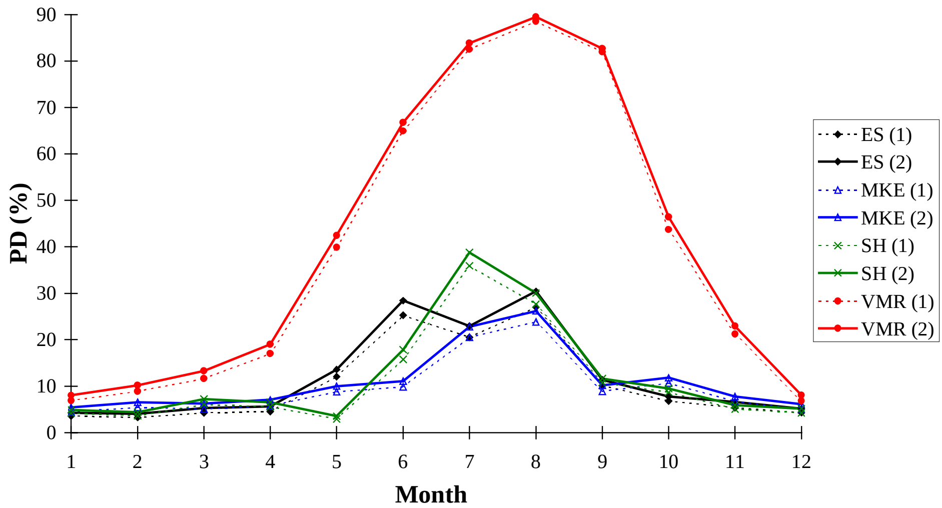

Figure 104. Monthly average percent dissatisfied during occupation in cases 1 and 2.

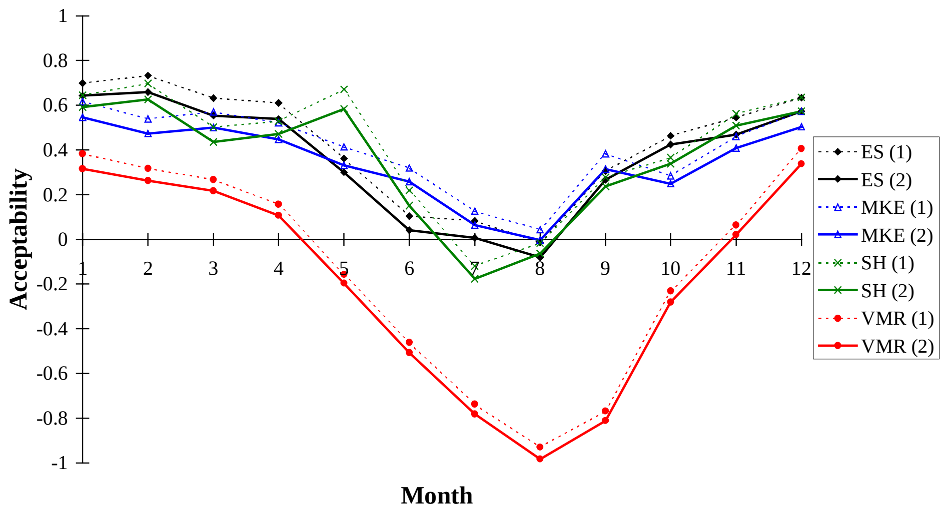

Figure 105. Monthly average acceptability during occupation in cases 1 and 2.

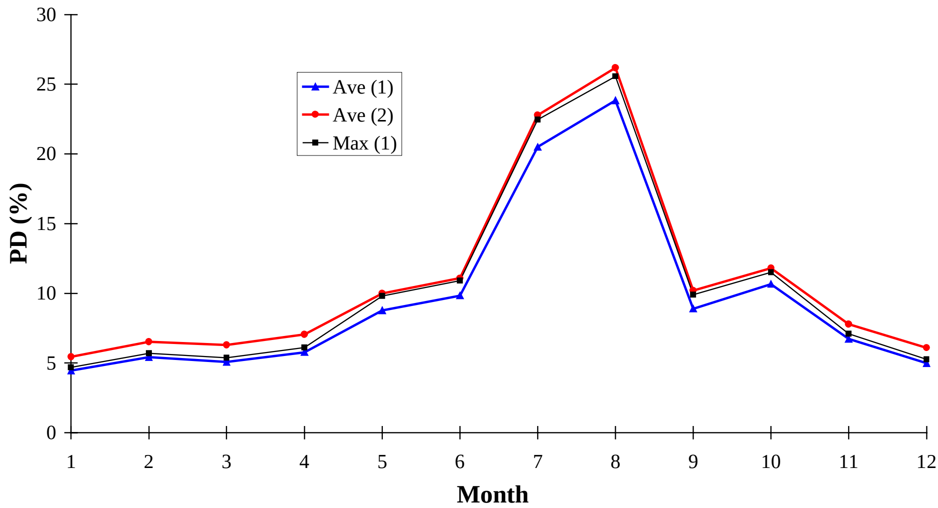

Figure 106. Monthly average PD during occupation in cases 1 and 2 compared to the monthly average of the maximum PD in case1.

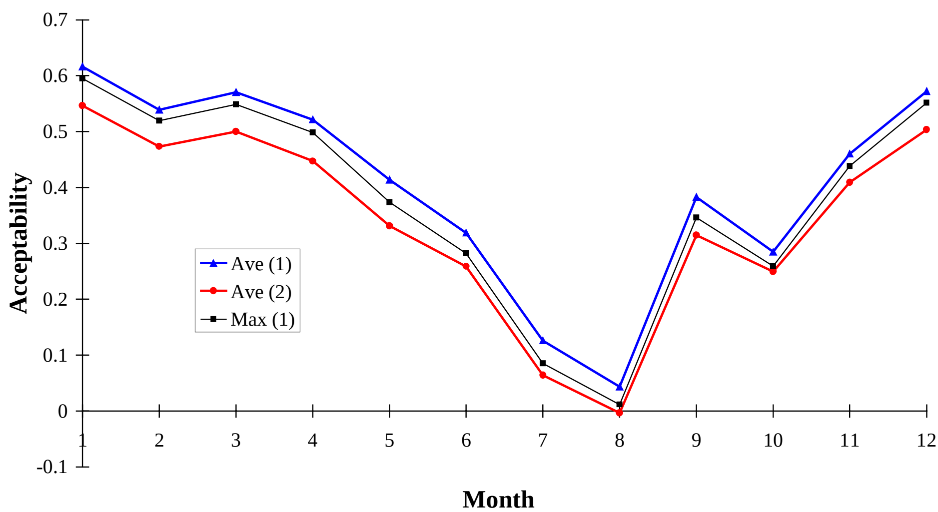

Figure 107. Monthly average acceptability during occupation in case1 compared to the monthly average of the minimum acceptability in case2.

4.10 Longer-term Effects

In order to investigate longer-term effects, the bedroom is simulated with constant outdoor temperature and humidity conditions. The outdoor conditions are constant for 30 days and then changed in step-wise fashion to new conditions, which are maintained for another 30 days. The outdoor temperature and humidity are changed separately and simultaneously as follows (Figure 108):

- 0 to 30 days: 18°C 60% RH 7.7 g/kg
- 30 to 60 days: 18°C 90% RH 11.6 g/kg
- 60 to 90 days: 18°C 60% RH 7.7 g/kg
- 90 to 120 days: 18°C 30% RH 3.8 g/kg
- 120 to 150 days: 18°C 60% RH 7.7 g/kg

- 150 to 180 days: 23°C 60% RH 10.5 g/kg
- 180 to 210 days: 18°C 82% RH 10.5 g/kg
- 210 to 240 days: 23°C 60% RH 10.5 g/kg
- 240 to 270 days: 18°C 60% RH 7.7 g/kg
- 270 to 300 days: 23°C 60% RH 10.5 g/kg
- 300 to 360 days: 18°C 60% RH 7.7 g/kg

As in the previous cases, the room is occupied for 9 hours each night and the ventilation rate is 0.5 ach, but solar radiation is neglected and the room heating system is off.

Figure 109 compares daily average values of indoor RH, T, W, H, PD and Acc during occupation in cases 1 and 2. In general, case1 responds slower to changes in outdoor temperature and humidity than case2 because it has a greater moisture and energy capacity. When the outdoor humidity changes, case1 moderates the change in indoor humidity. This is beneficial when the outdoor humidity increases from moderate to high humidity (day 30) or decreases from moderate to dry (day 90), but is detrimental when the outdoor humidity decreases from high to moderate (day 60).

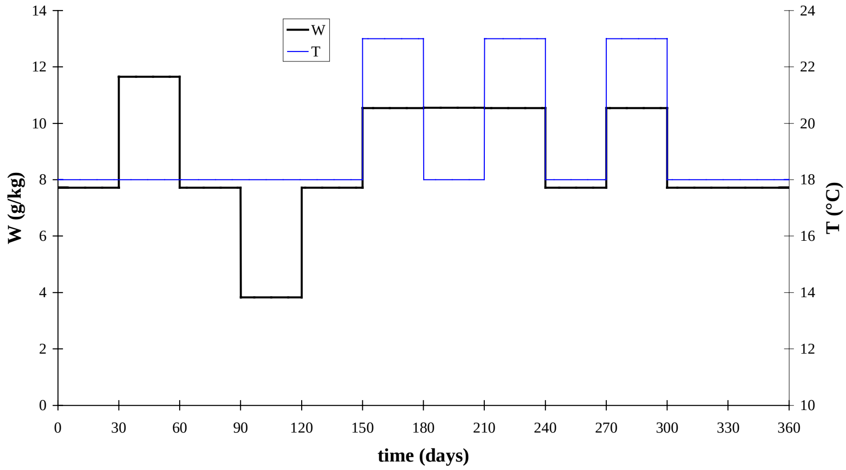

Figure 108. Outdoor humidity and temperature used to investigate longer-term effects.

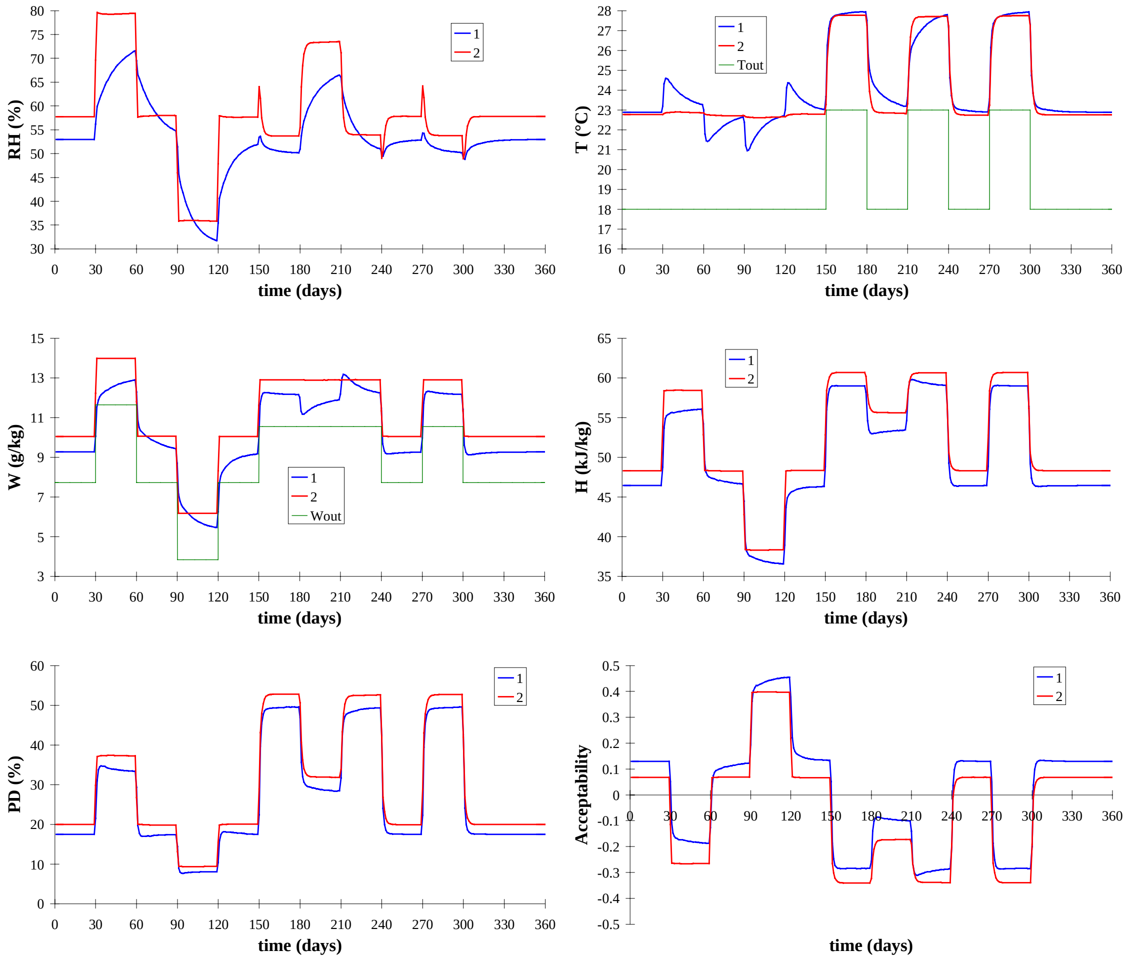

Figure 109. Daily average values of the important indoor air variables during occupation.

After the first step change in outdoor humidity (60% RH to 90% RH at a temperature of 18°C), the indoor relative humidity is always lower in the permeable case than in the impermeable case for the first 20 days and the RH during occupation is lower for the entire 30 days (Figure 110). Furthermore, 15 days after the increase in humidity, the average difference in humidity between cases 1 and 2 during occupation is 10% RH and the maximum difference during occupation is 13% RH. This means that moisture storage has a marked effect on the indoor humidity for about 2 weeks after a change in weather. When the weather changes from moderate to humid, the time that the moisture storage affects the performance is greater because as the humidity increases the moisture storage capacity of wood based materials increases and therefore the difference between cases 1 and 2 is greater. This is evident in Figure 109 because the difference between cases 1 and 2 is greater at the end of the humid period (time=60 days) than at the end of the dry period (time=120 days). This can be seen more clearly in Figure 111, which contains the non-dimensional indoor relative humidity (RH*) and absolute humidity (W*) defined as,

$$RH^* = \frac{RH - RH_{30}}{\Delta RH_{out}} \text{ , and} \tag{28}$$

$$W^* = \frac{W - W_{30}}{\Delta W_{out}} \text{ ,} \tag{29}$$

where RH_{30} and W_{30} are the indoor relative humidity and absolute humidity before the first step change (i.e., on day 30) respectively. The variables ΔRH_{out} and ΔW_{out} are the step changes in outdoor humidity, which are equal to 30% RH and 3.9 g/kg respectively. Figure 111 shows that, after 15 days, the increases in the daily average relative and absolute humidity since the step change are 30% and 15% lower respectively in the permeable case than in the impermeable case.

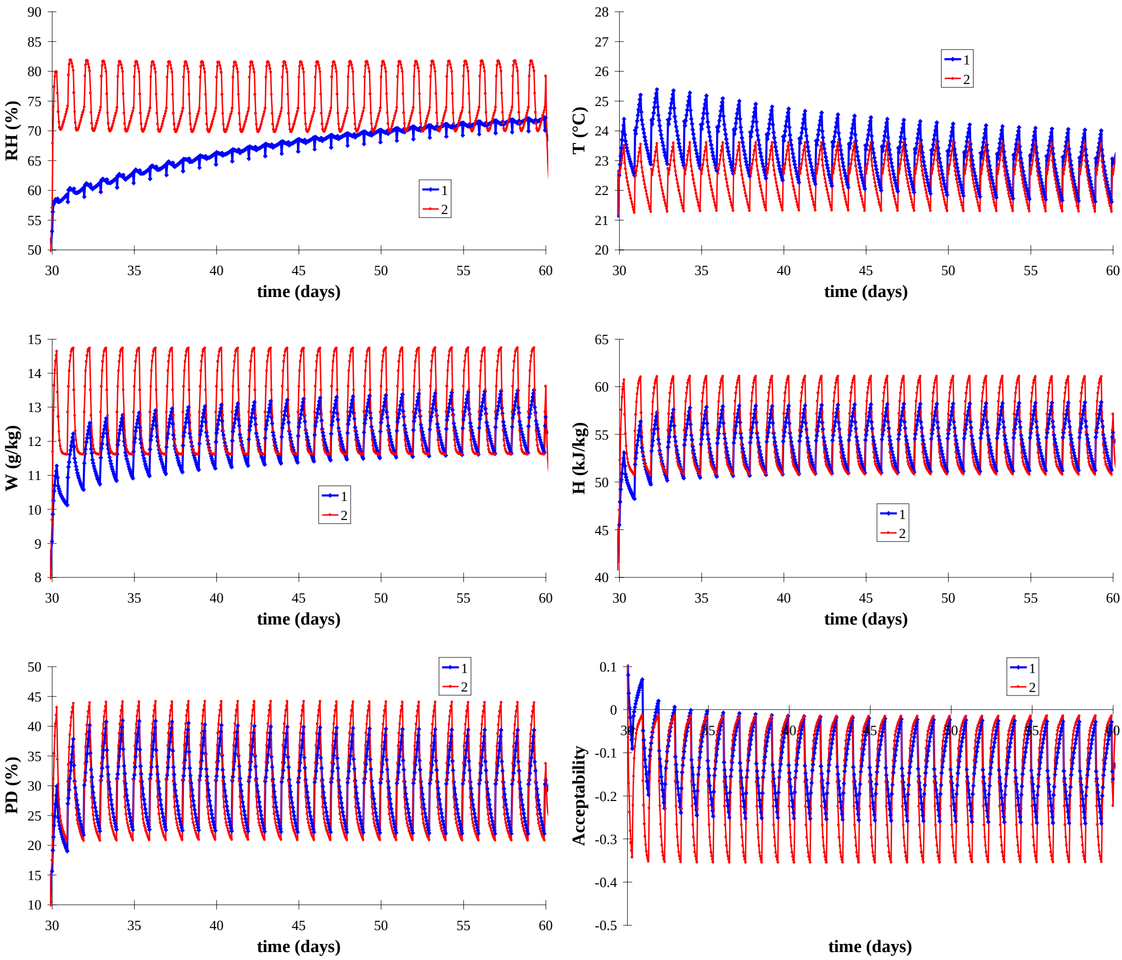

Figure 110. Temporal variation of the important indoor air variables during an increase in outdoor humidity from 60% RH to 90% RH at 18℃.

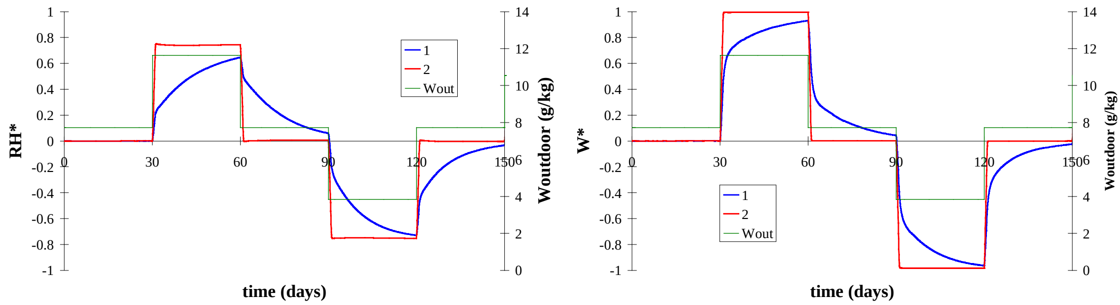

Figure 111. Daily average values of the non-dimensional indoor humidity.

The link between heat and moisture transfer is very clear in Figure 109 and Figure 110. When the outdoor humidity increases with a constant outdoor temperature on day 30, the moisture transfer to the permeable wall increases the indoor temperature by nearly 2°C and when the outdoor humidity decreases on day 60, the moisture transfer from the permeable wall decreases the indoor temperature by nearly 2°C. When the outdoor temperature increases with a constant outdoor absolute humidity (day 210), the indoor RH decreases, which cause moisture transfer from the permeable wall to the indoor air and therefore an increase in the indoor W. Furthermore, when the outdoor temperature changes, the indoor temperature in case1 changes more gradually than in case2. This shows that the moisture transfer affects the heat transfer and effectively increases the thermal mass of the room.

Figure 109 shows that the average RH during occupation is often 5 to 10% RH lower in case1 than in case2, which is an advantage in all cases except after a long dry period (100 to 120 days). The peak differences are much larger (i.e., on the first day after the step change in weather), however, with case2 having as much as 14% higher average indoor RH during occupation than case1 when the outdoor humidity increases and as much as 5% lower RH when the outdoor humidity decreases. Immediately after a decrease in outdoor humidity from humid to moderate, the indoor humidity is greater in case1 than in case2 from day 60 to day 75.

The values of W, H, PD and Acc show similar trends as the RH. The steady state values of PD and Acc are always better in case1 than in case2 and the differences are 3 to 4% for PD and 0.06 to 0.08 for Acc. The differences between case 1 and 2 are greater immediately after a step change than at steady state. When the outdoor humidity increases, the daily average values of PD and Acc are better in case1 (8% for PD and 0.16 of Acc), but when the outdoor humidity decreases the daily average values of PD and Acc are better in case2 (2% for PD and 0.05 for Acc). Comparing the worst case during daily occupation (i.e., the maximum value for PD and the minimum value for Acc) shows even greater differences between the cases. The first day after a change in outdoor humidity PD can be up to 30% higher and Acc up to 0.25 lower in case1 (Figure 110).

Figure 112 and Figure 113 contain plots of the 6 indoor air variables (daily average during occupation) after the outdoor conditions are changed from 60% RH (W=7.7 g/kg) to 90% RH (W=11.6 g/kg) at a constant temperature of 18°C. The effect of the insulation can be seen in Figure 112 and the effect of the interior wallboard can be seen in Figure 113. During the first day, the indoor humidity is nearly the same with hygroscopic insulation (case1), non-hygroscopic insulation (case3) and plastic vapour retarder (case4), while the indoor humidity is slightly higher with a non-hygroscopic wallboard (case5). This means that for the first day the wallboard is the most important hygroscopic material. After the first day, there is a change in the performance curves and the indoor humidity curves are flatter in the cases with active hygroscopic insulation (i.e., cases 1 and 5) than in the cases without active hygroscopic insulation (i.e., cases 3 and 4).

The PD results show that the impermeable case2 has a higher value of PD than the other cases and that the other cases are quite close to each other. Even though the absolute difference between the different cases is quite small, it is interesting to note that case5 (non-hygroscopic wallboard with hygroscopic insulation) has the lowest value of PD from the second day until the fifth day. Case4 (hygroscopic wallboard with plastic vapour retarder), on the other hand, has the highest value of PD from the second to the tenth day. This shows that moisture storage within the structure is useful because it has a smaller effect on the indoor temperature and consequently the percent dissatisfied with warm respiratory comfort.

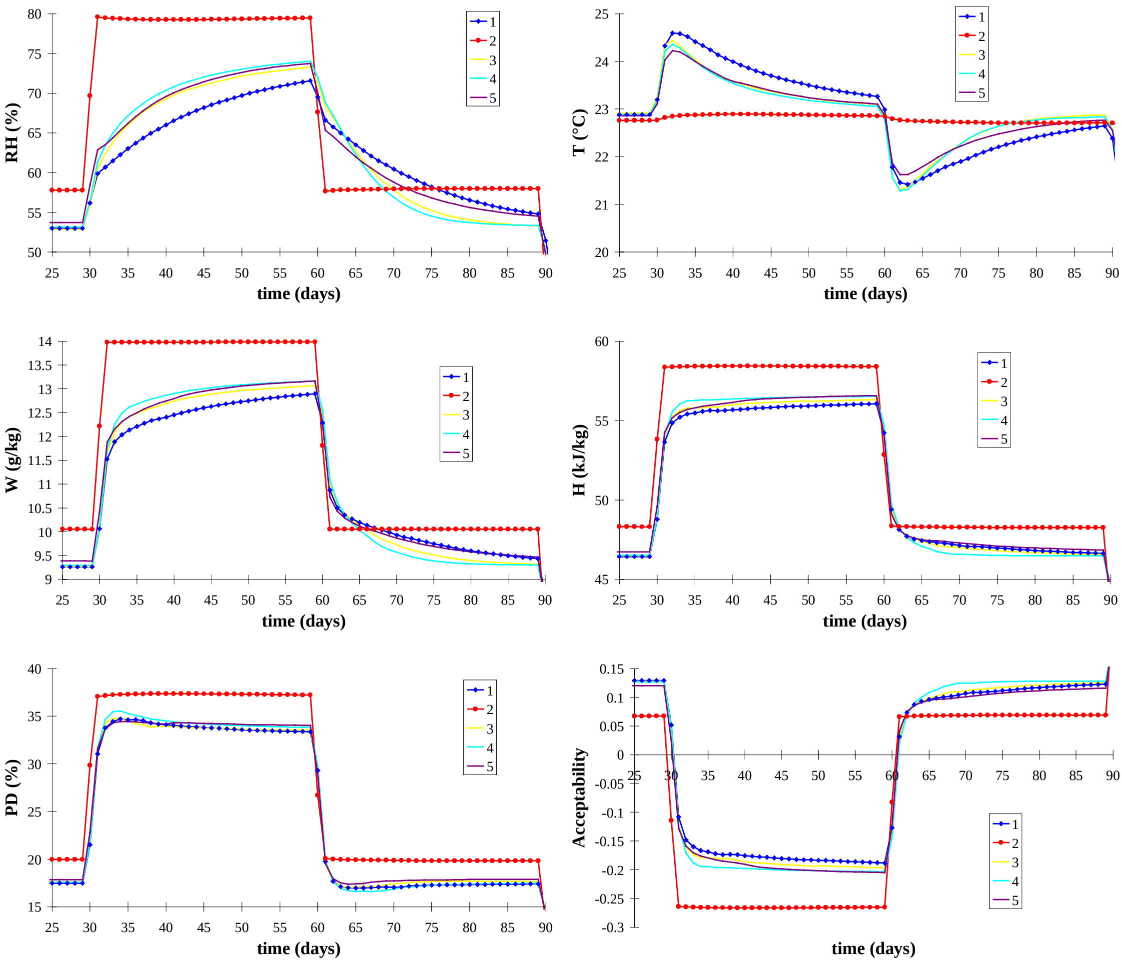

Figure 112. Daily average values of the important indoor air variables during occupation after a step increase and decrease in outdoor humidity showing the effect of insulation.

The results Figure 113 show that case14 (massive log floor, ceiling and walls) has best performance (i.e., lowest values of PD and highest values of Acc) during the first 10 days after an increase outdoor humidity, but the worst performance after a decrease in humidity. The reason for this is that case14 has both thermal and hygroscopic mass. The values of W are quite similar for all cases, but the case with gypsum board (case13) has a slightly higher indoor humidity than the cases with wooden (cases 6 and 14) and with porous wood fibre (case1) interior boards. Meanwhile, the temperature in the massive log case (case14) is much lower than in the other permeable cases for the first 10 days and the result is that PD is lower and Acc is higher in case14 during the first 10 days. After 10 to 15 days, case14 no longer has the best performance and, in fact, case14 has the highest average value of PD during occupation of all the cases (except case2) 15 days after the increase in outdoor humidity.

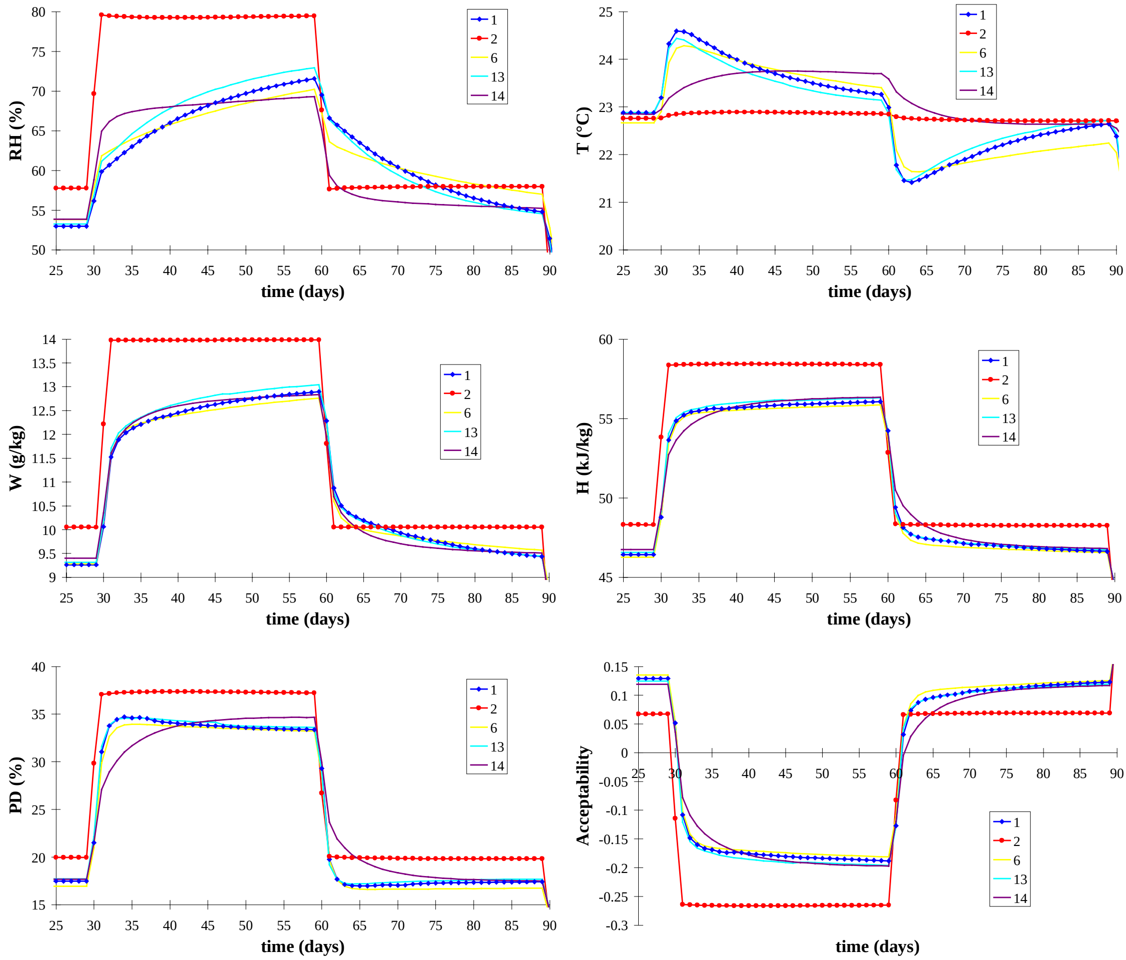

Figure 113. Daily average values of the important indoor air variables during occupation after a step increase and decrease in outdoor humidity showing the effect of the interior wallboard.

5. Conclusions and Future Work

The literature shows that indoor humidity has a significant effect on occupant comfort, perceived air quality, occupant health, building durability, material emissions and energy consumption. The research presented and summarised in this report shows that wood based building materials have the potential to moderate indoor humidity and thereby affect building performance. The main focus of this report is on the ability of wood based materials to damp diurnal changes in indoor humidity and the consequent effect on the indoor climate and perceived air quality and building durability. The effect of moisture transfer on occupant health and building energy consumption are qualified, but not quantified. Emissions from wood based materials were discussed briefly at the international workshop presented in Chapter 2 with the main conclusion being that indoor air problems are generally not caused by wood alone and that wood odour is generally considered pleasant.

To enhance the knowledge of moisture transfer between wood based materials and indoor air, the performance of a bedroom constructed with several combinations of materials, located in different climates and having different ventilation and moisture production rates was studied numerically in this report. The main objective of the simulations is to compare the performance of a bedroom with a permeable wood based structure with one that is impermeable. Also, the purpose of the simulations is to identify the importance of: hygroscopic insulation, hygroscopic wallboard, active area, vapour resistance of the interior coating, thermal mass, ventilation rate, moisture production rate and climate. The simulation results are summarised in the following sections.

5.1 Summary of Numerical Results

The results in this report were obtained by simulating the moisture performance of a bedroom with wood based structural components but neglecting furniture and fabrics. Hourly values of temperature, humidity and solar radiation measured in four European cities (Helsinki, Finland, Saint Hubert, Belgium, Holzkirchen, Germany and Trapani, Italy) were used as outdoor boundary conditions. Two people occupy the bedroom, which has a volume of 32.4 m^3 and an internal surface area of 60 m^2, for 9 hours during the night. The basic input parameters for the simulations are:

- active surface area for moisture transfer of 48 m^2 (walls and ceiling)
- moisture production of 60g/h,
- ventilation rate of 0.5 ach, and
- internal coating on ceiling and walls with a permeance of 5 x 10^{-9} kg/(s·m^2·Pa), which is about 6 times the resistance of convection mass transfer in a well-mixed room.

With these basic input parameters, moisture transfer between indoor air and the building structure is very active and can significantly reduce the peak humidity during the night. However, since moisture transfer affects the indoor temperature and enthalpy, the indoor climate and air quality are improved to a lesser extent. Meanwhile, the risk of mould growth in the structure is low.

5.1.1 Comparison of Permeable and Impermeable Structures

In most situations, the indoor conditions are more favourable when the building structure and coating are permeable than when they are impermeable. This is particularly the case during short periods of increasing outdoor temperature and humidity or during cool and humid weather when there is no heating in the bedroom. During occupation in very cold and dry periods the minimum humidity is higher in the permeable case, but the average humidity is lower in the permeable case, which is not desirable during very dry conditions. During a period of decreasing outdoor temperature and humidity (especially after warm and humid periods) the permeable case may temporally give a poorer performance than the impermeable case. In general, when comparing the permeable and impermeable cases, the permeable case has the following advantages and disadvantages, which are summarised in Table 11.

Table 11. Advantages and disadvantages of the permeable case compared to the impermeable case during occupation. Results are for the basic input parameters (active surface area of 60 m^2, moisture production rate of 60g/h for 9 hours each night and a ventilation rate of 0.5 ach).

	Advantage	**Disadvantage**
RH	• 35% lower max RH in summer • 15% higher min RH in winter • lower ave RH at end of occupation (20% in summer, 10% in winter) • ~7% lower ave RH during summer	• up to 20% higher RH in the summer (few hours at beginning of occupation) • ~5% lower average RH during winter
T	• up to 2°C lower after an increase in outdoor temperature	• up to 2°C higher due to moisture transfer to structure
PD	• 11% to 15% lower depending on the climate (11 to 15 more people satisfied out of 100) • 2% to 3% lower monthly ave • 1% to 2% lower yearly ave	• temporarily 6% to 14% lower value of PD depending on the climate (few hours at beginning of occupation after increase in outdoor humidity)
Acc	• a higher max acceptability (Acc) of 0.2 (scale of –1 to +1) • a higher yearly average (0.06)	• temporarily 0.2 lower values (few hours at beginning of occupation)
W	• on average, nearly 1g/kg lower indoor humidity • 3 times lower increase in indoor humidity during the night	• (max temporal variations of ±3 g/kg with negligible difference between total yearly ave (i.e., including both occupied and unoccupied time))
H	• on average, nearly 2 kJ/kg lower indoor enthalpy	• (max temporal variations of ±5 kJ/kg, similar total yearly ave)
time of poor per-form-ance	• less time with poor performance • 7 to 11 fewer weeks with RH>60% • 1 to 3 fewer weeks with PD>15% • 1 to 3 fewer weeks with Acc<0 (i.e., unacceptable indoor air quality)	• more time with dry indoor conditions • 0 to 4 more weeks with RH<25%
	• lower average of monthly max indoor conditions (even lower than ave values of the impermeable case)	

The permeable case has the following advantages because it has (during occupation):

- up to 35% lower maximum RH in the summer
- up to 15% higher minimum RH during the winter (i.e., at the beginning of occupation)
- a lower average RH at the end of occupation (up to 20% RH in summer, 10% RH in winter)
- about 7% lower average RH during the summer

- up to 2°C cooler indoor temperatures after an increase in outdoor temperature (maximum temporal differences of ±2°C with negligible difference between the yearly averages)

- 11% to 15% lower value of percent dissatisfied with warm respiratory comfort (PD) depending on the climate (11 to 15 more people satisfied out of 100)
- 2% to 3% lower monthly average value of PD
- 1% to 2% lower yearly average value of PD

- a higher maximum acceptability (Acc) by 0.2 (scale of –1 to +1)
- a higher yearly average acceptability (0.06)

- on average, nearly 1g/kg lower indoor humidity during occupation (maximum temporal variations of ±3 g/kg with negligible difference between the yearly averages that include unoccupied time)
- 3 times lower increase in indoor humidity during the night

- on average, nearly 2 kJ/kg lower indoor enthalpy during occupation (maximum temporal enthalpy differences of ±5 kJ/kg with negligible difference between the yearly averages that include unoccupied time)

- less time with poor performance (7 to 11 fewer weeks with RH>60%, 1 to 3 fewer weeks with PD>15% and 1 to 3 fewer weeks with unacceptable indoor air quality (i.e., Acc<0))

- lower average of monthly maximum indoor conditions (even lower than the average values of the impermeable case)

The permeable case has the following disadvantages because it has (during occupation):

- up to 20% higher RH in the summer (usually at the beginning of occupation when the outdoor humidity has recently decreased)
- about 5% lower average RH during the winter (this can cause the indoor humidity to be too low during cold outdoor weather)

- up to 2°C warmer indoor temperatures due to moisture transfer to the structure (maximum temporal differences of ±2°C with negligible difference between the yearly averages)

- temporarily 6% to 14% lower value of PD depending on the climate (usually for a few hours at the beginning of occupation when the outdoor humidity has recently decreased)

- temporarily lower values of acceptability (up to 0.2 lower than the impermeable case, which usually occurs for a few hours at the beginning of occupation when the outdoor humidity has recently decreased)

- more time with dry indoor conditions (0 to 4 more weeks with RH<25%)

5.1.2 Effect of Insulation

Several cases were analysed to reveal the importance of hygroscopic insulation. The results show that either a hygroscopic wallboard or insulation can realise an enhanced moisture performance. Eliminating either the hygroscopic wallboard or hygroscopic insulation increases the indoor humidity during occupation by about 2% RH. Compared to the case with both hygroscopic insulation and a hygroscopic wallboard:

- the case with a hygroscopic wallboard and non-hygroscopic insulation has 2 to 4 weeks more time with RH>60%; and
- the case with hygroscopic insulation and a non-hygroscopic wallboard has 2 to 4 weeks more time with RH>60%.

In Germany, for example, there are 38 to 40 nights (380 to 400 hours) during the year when RH>60% with either a hygroscopic wallboard or hygroscopic insulation, but only 15 nights with both a hygroscopic wallboard and hygroscopic insulation. In this case, the time with RH>60% increases by nearly 3 times when either the insulation or wallboard is non-hygroscopic.

5.1.3 Effect of Interior Wallboard

To determine the effect of the interior wallboard, a thin (11 mm) wallboard of pine wood and gypsum were compared to porous wood fibre board. In each case the insulation was hygroscopic, which will tend to compensate for a poor-performing wallboard and will improve the moisture performance of the case with gypsum board the most significantly. The indoor conditions were very similar in each case, but the time of poor performance during the year showed the following differences.

- The case with wooden panel has the same time with RH<60%, PD>15%, Acc<0 (± few days) as porous wood fibre board.

- The case with wooden panel has about 1 week less time with RH<25% compared to the case with porous wood fibre board.

- The case with gypsum board has 1 or 2 weeks more time with RH>60% compared to the case with porous wood fibre board.

When applying a thick wooden panel (50 mm or 125 mm), the moisture performance is similar to that with a thin wooden panel, but the thermal mass of the thick panel improves the thermal performance of the room. With a thick wooden panel, the time with RH>60% tends to increase slightly, but the time when RH<25% tends to decrease slightly. The time when PD>15% and Acc<0 may increase or decrease depending on the climate. For example in Finland, increasing the wooden panel thickness from 11 mm to 25 mm (and eliminating the moisture transfer to the ceiling) increases the time PD>15% by 1 week, while the same change in Belgium decreases the time PD>15% by 5 days.

5.1.4 Effect of Active Area

The results show that the active area for moisture transfer is very important. In the basic case all the walls and ceiling are active and the results indicate that increasing this active area will provide little improvement. On the other hand, decreasing the active area by coating the exterior wall and ceiling with an impermeable coating (active area 62% of base case) increases the indoor humidity. Further decreasing the active area to 25% of the base case (only the ceiling is active in moisture transfer), causes the performance of the room to be about half way between the impermeable and permeable cases. The effect of active area on the absolute humidity of the indoor air is proportional to the square root of the active area. The results show that the active area has a significant effect on the time when the humidity is high (RH>60%) or low (RH<25%), but a small effect on the time when PD>15% and Acc<0. Increasing the active area, decreases the time when RH>60% during occupation, but increases the time when RH<25% during occupation. Since the performance of the room is quite sensitive to the active area, the difference between different insulations and interior boards is likely more pronounced at lower active areas. This means that if the entire room cannot be made permeable and hygroscopic, the choice of wallboard and insulation may be more critical.

5.1.5 Effect of Vapour Resistance of Interior Coating

In the basic case, all the internal surfaces (except the floor) are coated with a very permeable coating, which increases the water vapour resistance of the internal surface by only 6 times compared to convection mass transfer in a well-mixed room. On the other hand, many coatings increase the vapour resistance of the interior surface by 30 to 2000 times. Results show that the decreasing the resistance of the coating beyond the base value does not have a large effect, but increasing the resistance does. Increasing the resistance of the interior coating increases the time when RH>60% during occupation, but decreases the time when RH<25% during occupation. The resistance of the interior coating is critical to the indoor humidity. However, if a very permeable paint cannot be applied, the active area can be increased to compensate for this.

5.1.6 Effect of Thermal Mass

To simulate the effect of thermal mass, several combinations of thick and thin wooden panel with concrete and wooden floors and ceilings were studied. Similarly as increasing the hygroscopic mass improves the performance, increasing the thermal mass of the structure improves the performance. As expected, thermal mass has the greatest effect on the indoor temperature and the cases with a high thermal mass have about 3 weeks less time with both high and low indoor temperatures (T>26°C and T<18°C). In Italy thermal mass reduces the peak indoor temperature, but affects the time when T>26°C by less than 1 week. Comparison of the massive wooden and concrete structures shows that a similar performance can be realised with massive wood or concrete. Also, the results show that solar shading is important in buildings without mechanical cooling. Closed venetian blinds can reduce the indoor temperature by over 10°C during sunny periods in the summer.

Considering the hygroscopic performance, in general, the massive cases have slightly more time with RH>60%, slightly less time with RH<25%, slightly more time with PD>15% and slightly less time with Acc>0. These trends are, however, climate dependent. The effect of thermal mass on the time of poor performance is very limited in Italy, even though a massive structure can moderate the extreme indoor conditions.

5.1.7 Effect of Ventilation Rate

Outdoor ventilation is an important moisture sink and critical to the moisture performance of the studied room because the absolute humidity of the outdoor air is very seldom higher than the indoor humidity, especially during occupation. On average, 0.5 ach of outdoor ventilation air removes 75% of the moisture produced during the night in the impermeable case and 50% of the moisture produced during the night in the permeable case. Decreasing the moisture transfer to the structure, increases the increase in indoor humidity during occupation, but only by about one third of the reduced moisture transfer to the structure because ventilation removes the rest of the moisture. Comparing the effect of ventilation and the effect of moisture storage on the performance of the room reveals that a similar moisture performance can be realised at different ventilation rates in the permeable and impermeable cases. Often the permeable case can have a similar performance with a lower ventilation rate. For example, comparing the following parameters shows similar performance in the permeable and impermeable cases:

- 0.1 ach in the permeable case gives similar values for the maximum temporal RH in March as 0.5 ach in the impermeable case;

- 0.5 ach in the permeable case gives similar maximum temporal values of PD and ACC in March as 1 ach in the impermeable case; and

- 0.1 ach in the permeable case gives a similar yearly average increase in humidity during occupation as 0.9 ach in the impermeable case.

From these results, it appears possible to reduce the ventilation rate when wood based materials are applied appropriately. This is not totally new because Toftum and Fanger (1999) and Fang et al. (1998a and b and 1999a) have noted that ventilation rates could be decreased notably by maintaining a moderate enthalpy in spaces (provided the minimum ventilation for health is satisfied). Particularly promising is the ability of wood based materials to limit the increase in humidity during the night because in many bedrooms the conditions at the beginning of occupation are the same regardless of the night-time ventilation rate (due to airing or air exchange with the rest of the house during the day). Therefore in practice, a room with a permeable and hygroscopic structure will have a similar moisture performance at a significantly lower ventilation rate than a room with an impermeable or non-hygroscopic structure.

The difference in moisture performance between the different materials and solutions increases as the ventilation rate decreases. For example, the differences in the monthly average of daily maximums between the permeable and impermeable cases are 30% RH, 15% for PD and 0.25 for acceptability when the ventilation rate is 0.1 ach, while the differences decrease to 15% RH, 3% for PD and 0.1 for acceptability when the ventilation rate is 0.5 ach. Also the difference between the time of poor performance in the different cases increases as the ventilation rate decreases.

5.1.8 Effect of Moisture Production

As expected, the results are quite sensitive to the moisture production rate during the night. The increase in humidity during the night is linearly proportional to the moisture production rate. Similarly, the moisture removed by the ventilation air and stored in the permeable structure is proportional to the moisture production rate. The results show that a similar indoor climate can be realised with different moisture production rates in the permeable and impermeable cases. Generally, the permeable and hygroscopic structure can withstand higher moisture production rates than the impermeable structure as listed below.

- The maximum temporal RH in March is nearly the same in the permeable case when the moisture production is 180 g/h as in the impermeable case when the moisture production is 60 g/h. For this comparison, the permeable case can withstand a 3 times higher moisture production rate.

- The temporal values of PD and acceptability are similar in the permeable case with 180 g/h as in the impermeable case with 90 g/h. For this comparison, the permeable case can withstand twice as much moisture production.

- The time of poor performance during the year (i.e., the time when RH>60%, PD>15% and the indoor air is unacceptable) is similar in the permeable case with 60 g/h as in the impermeable case with 90 g/h. The permeable case can withstand a 50% higher moisture production rate.

- The increase in humidity during occupation is similar in the permeable case when the moisture production is 180 g/h as in the impermeable case when the moisture production is 60 g/h

5.1.9 Effect of Climate

The moisture and thermal storage in wood based materials can decrease the maximum and increase the minimum indoor humidity and temperature. The increase in absolute humidity and temperature during the night is quite independent of the climate. However, the indoor absolute humidity is close to the outdoor humidity at the beginning of occupation when the room is unoccupied during the day and the ventilation rate is 0.5 ach. Therefore, the climate typically affects the level of indoor temperature and humidity, but not the change during occupation. The results in this report show that passive methods of controlling the indoor climate are more successful in moderate climates than in hot and humid climates. In southern Italy, the indoor climate and air quality are unacceptable for most of the year, while in the central and northern European climates, they are acceptable for most of the year. This also indicates that the comfort criteria for northern and central Europe may not be applicable in southern Europe.

5.1.10 Longer-term Effects

Longer-term effects of moisture storage are simulated by setting a constant outdoor temperature and humidity for 30 days and then changing the outdoor temperature and humidity in a step-wise fashion to a new level and holding it constant for 30 days. In general, the permeable and hygroscopic cases respond slower to changes in outdoor temperature and humidity than the impermeable case because they has a greater potential to store moisture and energy. When the outdoor humidity changes, a permeable and hygroscopic structure moderates the change in indoor humidity. This is beneficial when the outdoor humidity increases from moderate to humid or decreases from moderate to dry, but is detrimental when the outdoor humidity decreases from humid to moderate. When the outdoor humidity increases from 60% RH to 90% RH at a temperature of 18°C, the indoor relative humidity is always lower in the permeable case than in the impermeable case for the first 20 days and the RH during occupation is lower for the entire 30 days. Fifteen days after the step change, the average indoor humidity during occupation is still 10% RH lower in the permeable case and the increase in daily average absolute humidity since the step change is 15% lower in the permeable case than in the impermeable case. These results indicate that moisture storage has a noticeable effect on the indoor humidity for about 2 weeks after a change in weather. Increasing the hygroscopic mass above that in the base case naturally improves the ability of the structure to moderate the indoor humidity, but the higher hygroscopic mass becomes noticeable only about

10 days after a step change in outdoor humidity. The best performance during the first 10 to 15 days after an increase outdoor humidity is realised with a permeable structure that has a large thermal and moisture storage capacity. The results also show that, during the first day after a change in weather, the wallboard is the most important hygroscopic material, but the importance of the insulation increases with time.

5.2 Future Work

As discussed in the introduction, the main purpose of this report is to investigate the possibility of using wood based materials to improve the indoor humidity conditions as well as thermal comfort, perceived air quality and other factors. An international workshop was held to discuss these issues and the conclusions from the workshop include a list of future research activities, which the experts agreed are important. Most of the participants at the workshop are interested in actively pursuing research in this field; the main question is in which forum the research should take place. This bodes well for international collaboration in phase II of this project. Since the future research activities listed in the workshop summary are very general and cover a wider range of activities, this section will focus on activities that are most appropriate for the wood industry in Finland.

The results in this report show that moisture transfer between indoor air and structures is important and several wood based materials are appropriate. An interesting finding, which needs experimental confirmation, is that either a hygroscopic wallboard or hygroscopic insulation can play a significant role alone. One of the most important findings is that the vapour resistance of the interior coating and the active area are very important and can be used to compensate each other. This means that in new and retrofit buildings it may be possible to apply surface texturing to increase the active area or small but highly active modules as shown in Figure 114. These modules could employ natural or forced convection and could take up a small fraction of the internal surface area of the room, but have an internal surface area that would be comparable to the entire surface area of the room. Since the local airflow and mixing will have a large impact on the performance of very small modules, large rooms with poor mixing may need several modules distributed throughout the room.

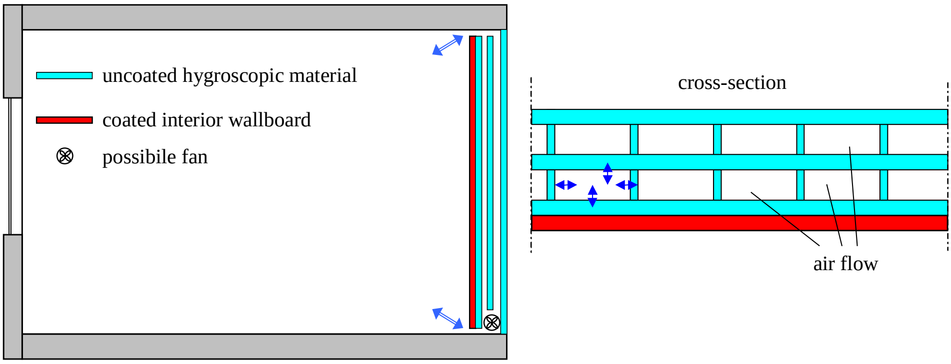

Figure 114. A possible small but highly active moisture storage device.

Another aspect that has become evident in this research is that moisture is an important comfort and indoor air quality parameter and that the comfort and perceived indoor air quality can be improved when applying permeable and hygroscopic materials. It appears possible to provide similar indoor climate and perceived air quality conditions with a smaller ventilation rate when permeable and hygroscopic materials are correctly applied. To quantify the amount that ventilation can be reduced when applying wood based materials in real buildings would be a long and difficult task, but future research in the area of indoor climate and air quality could focus on defining appropriate ways to quantify the effect of humidity on IAQ. This work would, in the beginning, mainly include a review of existing literature and indoor air quality standards to more thoroughly determine the effect of humidity on comfort and IAQ. Later on, if the results are extremely promising, laboratory studies could be conducted to study human response. In a similar way, the effect of humidity on occupant health could be quantified from the literature. It is expected that health affects would create additional arguments for the application of hygroscopic wood based materials.

It is known that the durability of building materials and the risk of mould growth are affected by moisture. Results in this report and other investigations (Simonson, 2000 and Simonson and Ojanen, 2000) show that it is possible to design a permeable envelope with good moisture performance. In fact a permeable envelope made of wood based materials is less susceptible to condensation and mould growth at the internal surface of thermal bridges because the peak indoor humidity is lower when applying hygroscopic wood based materials. Furthermore, if there is a faulty air barrier and exfiltration air flows through the envelope, the risk of moisture damage is likely smaller with a permeable and hygroscopic envelope. This requires further research to ascertain.

The results in this report show that the phase change energy temporarily increases or decreases the indoor temperature by 2°C. In addition, the indoor enthalpy is on average 2 kJ/kg lower during occupation in the summer when a permeable envelope is applied. If the control system is designed to account for this enthalpy storage during occupation, the energy consumption in mechanically cooled buildings could be decreased. Simulations that properly include the interactions between building materials, indoor air and HVAC systems are needed to estimate the energy savings possible when applying wood based materials.

5.2.1 Phase II

If phase II research and development work is initiated, it is expected to include several research activities and research partners. As shown in Figure 115, the research work could lead to the development of new products and the demonstration of wooden buildings with enhanced performance, which could increase the application of wood based materials in Finland and abroad. Since there are possibly several researchers and institutes involved in Phase II, a strong co-ordinator is needed to co-ordinate the individual tasks. Individual tasks, which have arisen through this research and its evaluation by the reviewers (see Appendix D) and steering group, could include:

- investigation of rooms with higher moisture production and ventilation (e.g., kitchens, bathrooms, meeting rooms, saunas and rooms with pools);

- investigation of the importance of furniture and fabrics;

- small-scale experiments to confirm the calculated results;

- the development of correction factors to account for the complexities (non-Fickian behaviour, hysteresis and difference in diffusion coefficients during adsorption and desorption) that exist in some wood based materials;

- review of the literature to better quantify the effect of moisture transfer on comfort, indoor air quality and occupant health and incorporate these results into indoor comfort and air quality standards and classifications;

- the enhancement of a building simulation tool (i.e., including moisture storage in building structures) to allow the estimation of the potential for wood based materials to reduce the energy consumption in buildings;

- detailed moisture performance analysis (risk of mould growth) of permeable and impermeable envelopes constructed with realistic faults;

- determining the effect of moisture on material emissions;

- optimisation of the location of vapour resistant layers for good indoor air climate and safe moisture performance;

- the demonstration of wood based materials in buildings (field testing and show homes);
- the development and testing of highly active modules for new and retrofit application in residential and other buildings; and
- the development of design methods for applying wood based materials in buildings with enhanced performance.

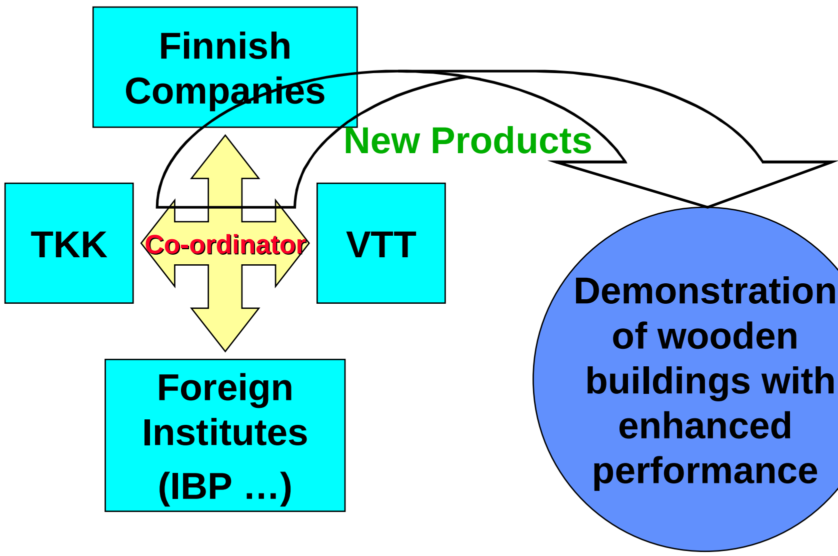

Figure 115. Collaboration between researchers and practitioners from several institutes will increase the research potential but will require an effective co-ordinator.

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Appendix A: Property Data

This appendix presents the property data that is used in the LATENITE simulation model when simulating the performance of the test bedroom. The important property data are the sorption isotherm, water vapour permeability and thermal conductivity and these are given for the different materials in Figure A.1 to Figure A.9. These figures also include the tabulated values of vapour permeability for each material and thickness at a relative humidity of 50% RH, the moisture capacity calculated as follows:

$$Cm = (u_{60\%RH} - u_{40\%RH})\rho V 1000 / 20 \qquad \text{(A.1)}$$

and the moisture diffusivity calculated as follows:

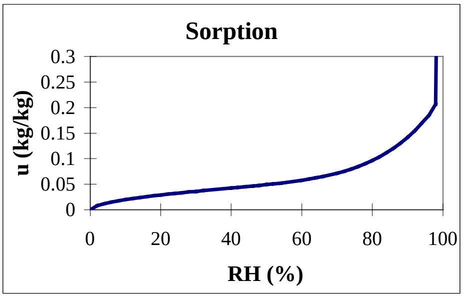
$$\alpha_m = \frac{kd}{Cm/(1000V)\frac{100}{P_{v,sat}}} \quad , \qquad \text{(A.2)}$$

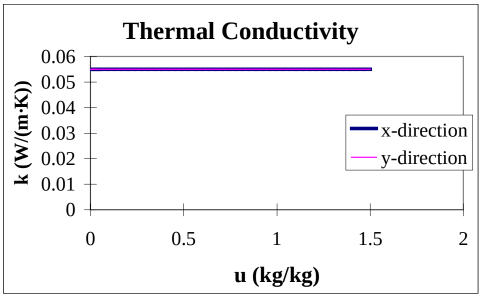
where $P_{v,sat}$ is the saturation pressure for water vapour at 22°C.

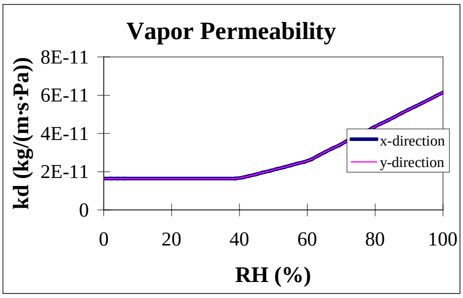
Figure A.10 to Figure A.25 list the geometry and materials used in each case as well as the internal and external permeance in kg/(s·m^2·Pa) and the surface area of each wall.

POROUS WOOD FIBRE BOARD

ρ = 310 kg/m^3	Cp = 2100 J/(kg·K)







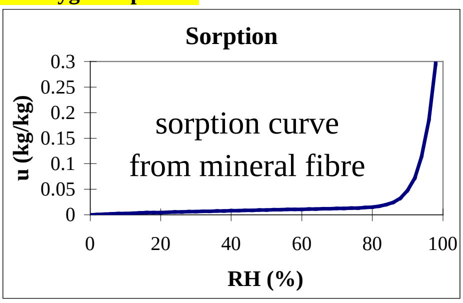
t (mm)	11	
A (m^2)	1	
vapor perm-x (g/(d·Pa))	0.169	8.9 x Rair
moisture capacity (g/%RH)	2.60	
Rt-x ((m^2·K)/W)	0.200	
C (J/K)	7161	
αt (m^2/s)	8.4E-08	
αm (m^2/s)	2.4E-09	

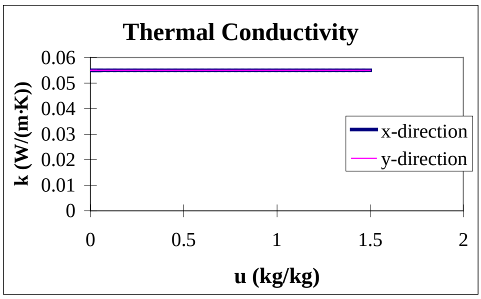
Figure A.1. Material properties for porous wood fibre board.

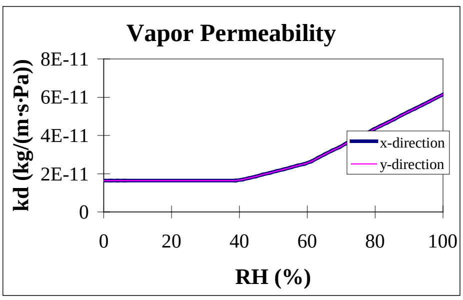
POROUS WOOD FIBRE BOARD

non-hygroscopic

ρ = 310 kg/m^3	Cp = 2100 J/(kg·K)





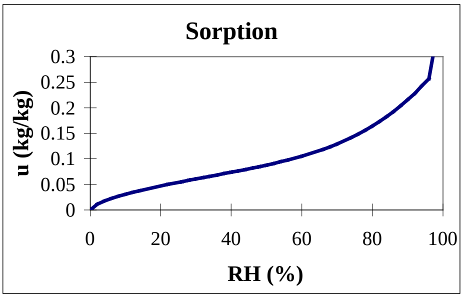


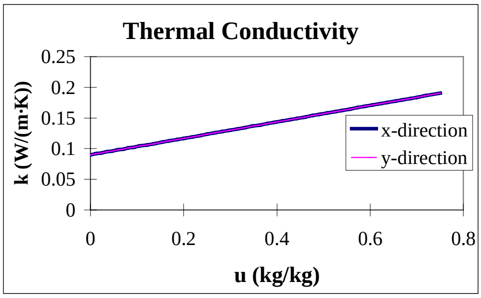
t (mm)	11	
A (m^2)	1	
vapor perm-x (g/(d·Pa))	0.169	8.9 x Rair
moisture capacity (g/%RH)	0.49	
Rt-x ((m^2·K)/W)	0.200	
C (J/K)	7161	
αt (m^2/s)	8.4E-08	
αm (m^2/s)	1.3E-08	

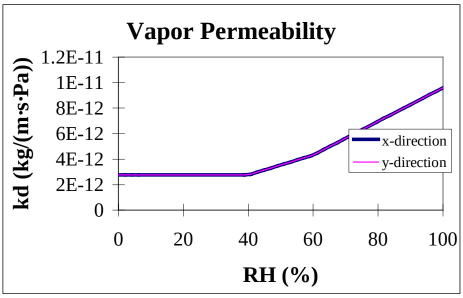
Figure A.2. Material properties for “non-hygroscopic” porous wood fibre board.

PINE WOOD

ρ =	425	kg/m^3	Cp =	2390	J/(kg·K)





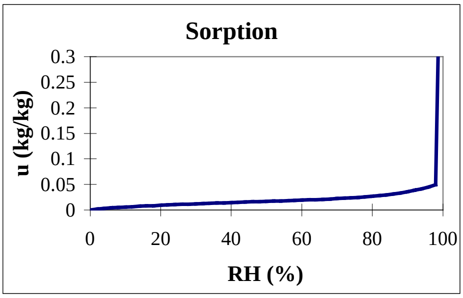


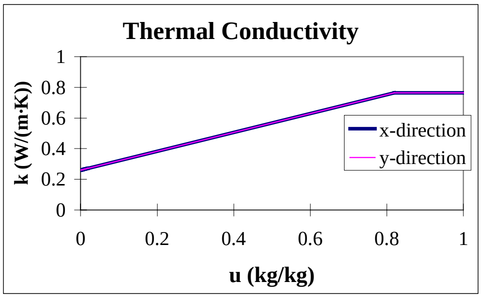
t (mm)	11	
A (m^2)	1	
vapor perm-x (g/(d·Pa))	0.028	52.5 x Rair
moisture capacity (g/%RH)	7.37	
Rt-x ((m^2·K)/W)	0.122	
C (J/K)	11173	
αt (m^2/s)	8.9E-08	
αm (m^2/s)	1.4E-10	

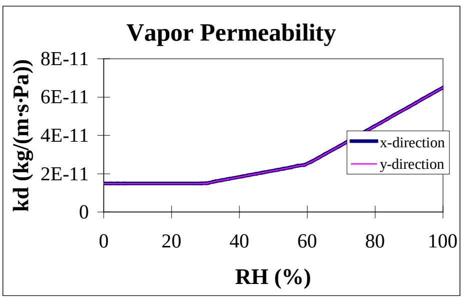
Figure A.3. Material properties for pine wood.

GYPSUM1 BOARD

ρ =	620	kg/m^3	Cp =	840	J/(kg·K)





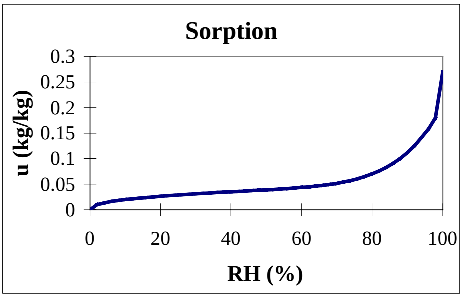


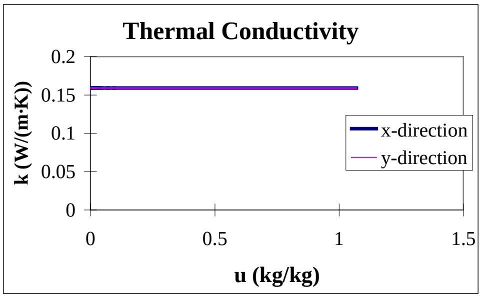
t (mm)	11	
A (m^2)	1	
vapor perm-x (g/(d·Pa))	0.173	8.6 x Rair
moisture capacity (g/%RH)	1.63	
Rt-x ((m^2·K)/W)	0.042	
C (J/K)	5729	
αt (m^2/s)	5.0E-07	
αm (m^2/s)	3.9E-09	

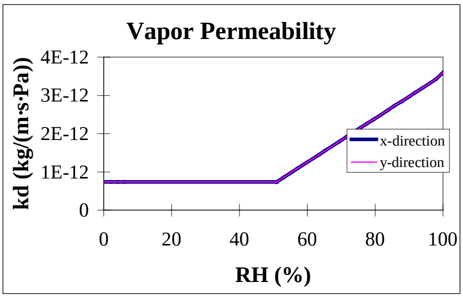
Figure A.4. Material properties for gypsum board.

BUILDING PAPER

ρ =	840 kg/m^3	Cp =	1256 J/(kg·K)





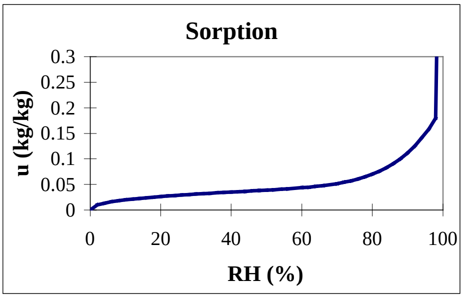


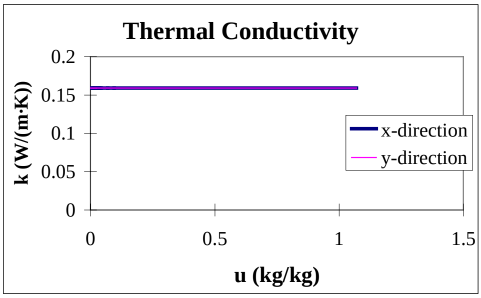
t (mm)	0.3	
A (m^2)	1	
vapor perm-x (g/(d·Pa))	0.213	257 x Rair
moisture capacity (g/%RH)	0.11	
Rt-x ((m^2·K)/W)	0.002	
C (J/K)	317	
αt (m^2/s)	1.5E-07	
αm (m^2/s)	5.5E-11	

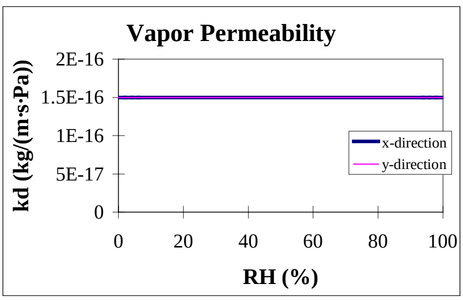
Figure A.5. Material properties for building paper.

POLYETHYLENE SHEET 6-MIL

ρ =	840 kg/m^3	Cp =	1256 J/(kg·K)





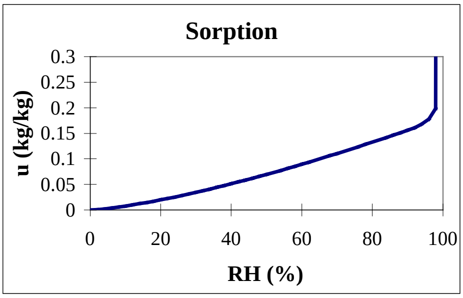


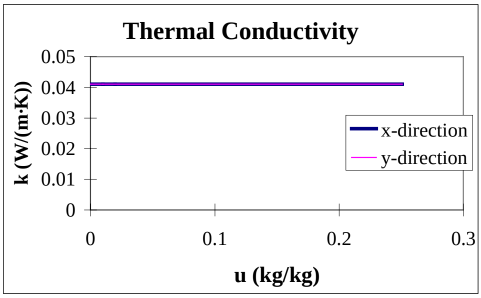
t (mm)	0.3	
A (m^2)	1	
vapor perm-x (g/(d·Pa))	0.000	1E+06 x Rair
moisture capacity (g/%RH)	0.11	
Rt-x ((m^2·K)/W)	0.002	
C (J/K)	317	
αt (m^2/s)	1.5E-07	
αm (m^2/s)	1.1E-14	

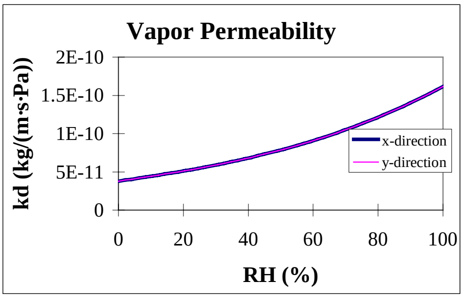
Figure A.6. Material properties for polyethylene plastic.

CELLULOSE1

ρ =	30	kg/m^3	Cp =	1400	J/(kg·K)





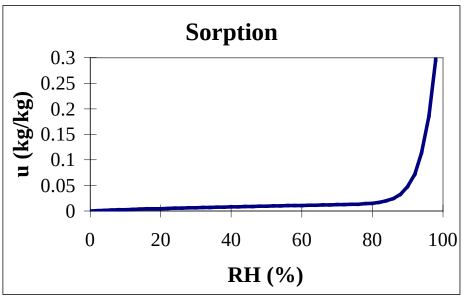


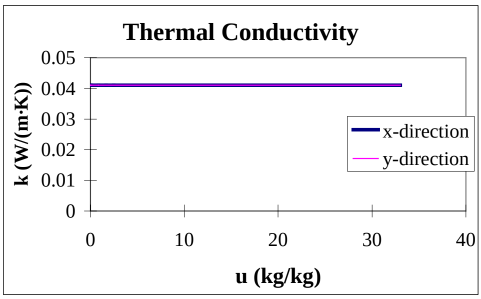
t (mm)	75	
A (m^2)	1	
vapor perm-x (g/(d·Pa))	0.092	2.4 x Rair
moisture capacity (g/%RH)	4.29	
Rt-x ((m^2·K)/W)	1.829	
C (J/K)	3150	
αt (m^2/s)	9.8E-07	
αm (m^2/s)	3.7E-08	

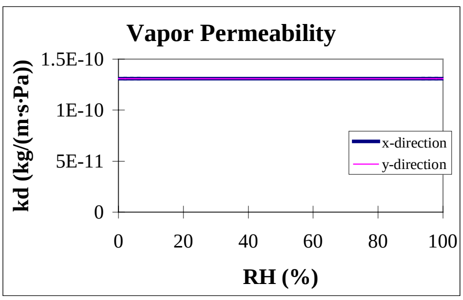
Figure A.7. Material properties for cellulose insulation.

MINERAL FIBRE

ρ =	30	kg/m^3	Cp =	840	J/(kg·K)





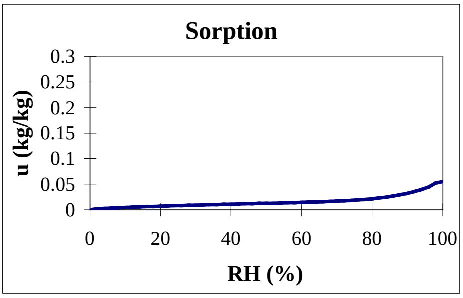


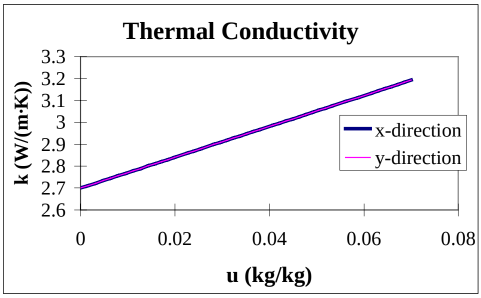
t (mm)	75	
A (m^2)	1	
vapor perm-x (g/(d·Pa))	0.151	1.5 x Rair
moisture capacity (g/%RH)	0.33	
Rt-x ((m^2·K)/W)	1.829	
C (J/K)	1890	
αt (m^2/s)	1.6E-06	
αm (m^2/s)	8.0E-07	

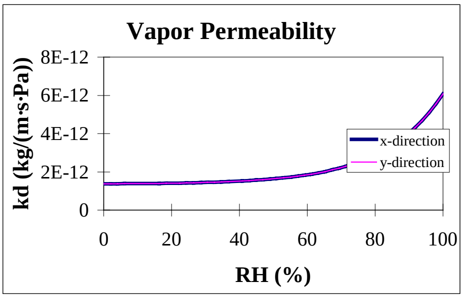
Figure A.8. Material properties for mineral fibre insulation.

CONCRETE

ρ =	2200 kg/m^3	Cp =	840 J/(kg·K)







t (mm)	11	
A (m^2)	1	
vapor perm-x (g/(d·Pa))	0.013	115 x Rair
moisture capacity (g/%RH)	4.22	
Rt-x ((m^2·K)/W)	0.004	
C (J/K)	20328	
αt (m^2/s)	1.5E-06	
αm (m^2/s)	1.1E-10	

Figure A.9. Material properties for concrete.

CASE 1

	ext. perm.																																	int. perm.
ext. wall	1.5E-07	4	4	4	42	42	42	2	2	2	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
215.3		4	10	4	4	17	4	4	4	3	3	6	10	14	20	20	20	14	12	10	8	6	4	2	1	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	6.3		**18**			**25**			**11**									**150**									**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	8.1															**75**											**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
ceiling	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**11**			
floor	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	5.0E-12
103.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	6	12	6	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**28**			

LEGEND: 2 porous wood fibre board; 4 pine wood; 3 gypsum; 8 concrete; 42 air; 21 building paper; 17 polyethylene; 16 cellulose; 5 mineral fibre

Figure A.10. Grid size and materials for case 1 (permeable).

CASE 2

	ext. perm.																																	int. perm.
ext. wall	1.5E-07	4	4	4	42	42	42	2	2	2	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-12
215.3		4	10	4	4	17	4	4	4	3	3	6	10	14	20	20	20	14	12	10	8	6	4	2	1	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	6.3		**18**			**25**			**11**									**150**									**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-12
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-12
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	8.1															**75**											**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-12
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
ceiling	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-12
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**11**			
floor	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	5.0E-12
103.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	6	12	6	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**28**			

LEGEND: 2 porous wood fibre board; 4 pine wood; 3 gypsum; 8 concrete; 42 air; 21 building paper; 17 polyethylene; 16 cellulose; 5 mineral fibre

Figure A.11. Grid size and materials for case 2 (impermeable).

CASE 3

	ext. perm.																																	int. perm.
ext. wall	1.5E-07	4	4	4	42	42	42	2	2	2	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	21	21	21	2	2	2	2	2	5.0E-09
215.3		4	10	4	4	17	4	4	4	3	3	6	10	14	20	20	20	14	12	10	8	6	4	2	1	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	6.3		**18**			**25**			**11**									**150**									**0.3**				**11**			
int. wall	1.0E-18	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
int. wall	1.0E-18	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	8.1															**75**											**0.3**				**11**			
int. wall	1.0E-18	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
ceiling	1.0E-18	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**11**			
floor	1.0E-18	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	21	21	21	4	4	4	4	4	5.0E-12
103.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	6	12	6	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**28**			

LEGEND: 2 porous wood fibre board; 4 pine wood; 3 gypsum; 8 concrete; 42 air; 21 building paper; 17 polyethylene; 16 cellulose; 5 mineral fibre

Figure A.12. Grid size and materials for case 3 (mineral fibre).

CASE 4

	ext. perm.																																	int. perm.
ext. wall	1.5E-07	4	4	4	42	42	42	2	2	2	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	17	17	17	2	2	2	2	2	5.0E-09
215.3		4	10	4	4	17	4	4	4	3	3	6	10	14	20	20	20	14	12	10	8	6	4	2	1	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	6.3		**18**			**25**			**11**									**150**									**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	17	17	17	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	17	17	17	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	8.1															**75**											**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	17	17	17	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
ceiling	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	17	17	17	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**11**			
floor	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	17	17	17	4	4	4	4	4	5.0E-12
103.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	6	12	6	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**28**			

LEGEND: 2 porous wood fibre board; 4 pine wood; 3 gypsum; 8 concrete; 42 air; 21 building paper; 17 polyethylene; 16 cellulose; 5 mineral fibre

Figure A.13. Grid size and materials for case 4 (plastic vapour retarder).

CASE 5

	ext. perm.																																	int. perm.
ext. wall	1.5E-07	4	4	4	42	42	42	2	2	2	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
215.3		4	10	4	4	17	4	4	4	3	3	6	10	14	20	20	20	14	12	10	8	6	4	2	1	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	6.3		**18**			**25**			**11**									**150**									**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	8.1															**75**											**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
ceiling	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**11**			
floor	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	5.0E-12
103.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	6	12	6	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**28**			

LEGEND: 2 porous wood fibre board; 4 pine wood; 3 gypsum; 8 concrete; 42 air; 21 building paper; 17 polyethylene; 16 cellulose; 5 mineral fibre

Figure A.14. Grid size and materials for case 5 (non-hygroscopic wallboard).

CASE 6

	ext. perm.																																	int. perm.
ext. wall	1.5E-07	4	4	4	42	42	42	2	2	2	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	5.0E-09
215.3		4	10	4	4	17	4	4	4	3	3	6	10	14	20	20	20	14	12	10	8	6	4	2	1	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	6.3		**18**			**25**			**11**									**150**									**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	8.1															**75**											**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
ceiling	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**11**			
floor	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	5.0E-12
103.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	6	12	6	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**28**			

LEGEND: 2 porous wood fibre board; 4 pine wood; 3 gypsum; 8 concrete; 42 air; 21 building paper; 17 polyethylene; 16 cellulose; 5 mineral fibre

Figure A.15. Grid size and materials for case 6 (wooden panel).

CASE 7

	ext. perm.																																	int. perm.
ext. wall	1.5E-07	4	4	4	42	42	42	2	2	2	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-12
215.3		4	10	4	4	17	4	4	4	3	3	6	10	14	20	20	20	14	12	10	8	6	4	2	1	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	6.3		**18**			**25**			**11**									**150**									**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	8.1															**75**											**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
ceiling	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-12
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**11**			
floor	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	5.0E-12
103.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	6	12	6	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**28**			

LEGEND:

2 porous wood fibre board	4 pine wood	3 gypsum	8 concrete / 42 air
21 building paper	17 polyethylene	16 cellulose	5 mineral fibre

Figure A.16. Grid size and materials for case 7 (interior walls only).

CASE 8

	ext. perm.																																	int. perm.
ext. wall	1.5E-07	4	4	4	42	42	42	2	2	2	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-12
215.3		4	10	4	4	17	4	4	4	3	3	6	10	14	20	20	20	14	12	10	8	6	4	2	1	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	6.3		**18**			**25**			**11**									**150**									**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-12
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-12
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	8.1															**75**											**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-12
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**				**11**			
ceiling	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**11**			
floor	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	5.0E-12
103.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	6	12	6	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**				**28**			

LEGEND:

2 porous wood fibre board	4 pine wood	3 gypsum	8 concrete / 42 air
21 building paper	17 polyethylene	16 cellulose	5 mineral fibre

Figure A.17. Grid size and materials for case 8 (ceiling only).

CASE 9

	ext. perm.																																	int. perm.
ext. wall	1.5E-07	4	4	4	42	42	42	2	2	2	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	1.0E-09
215.3		4	10	4	4	17	4	4	4	3	3	6	10	14	20	20	20	14	12	10	8	6	4	2	1	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	6.3		**18**			**25**			**11**									**150**									**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	1.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**										**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	1.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	8.1															**75**										**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	1.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**										**0.3**				**11**			
ceiling	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	1.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	12															**75**										**0.3**				**11**			
floor	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	5.0E-12
103.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	6	12	6	2	<= t (mm)
A (m^2) =	12															**75**										**0.3**				**28**			

LEGEND:

2 porous wood fibre board	4 pine wood	3 gypsum	8 concrete	42 air
21 building paper	17 polyethylene	16 cellulose	5 mineral fibre	

Figure A.18. Grid size and materials for case 9 (paint).

CASE 9mp

	ext. perm.																																	int. perm.
ext. wall	1.5E-07	4	4	4	42	42	42	2	2	2	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-08
215.3		4	10	4	4	17	4	4	4	3	3	6	10	14	20	20	20	14	12	10	8	6	4	2	1	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	6.3		**18**			**25**			**11**									**150**									**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-08
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**										**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-08
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	8.1															**75**										**0.3**				**11**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-08
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**										**0.3**				**11**			
ceiling	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-08
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	12															**75**										**0.3**				**11**			
floor	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	5.0E-12
103.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	6	12	6	2	<= t (mm)
A (m^2) =	12															**75**										**0.3**				**28**			

LEGEND:

2 porous wood fibre board	4 pine wood	3 gypsum	8 concrete	42 air
21 building paper	17 polyethylene	16 cellulose	5 mineral fibre	

Figure A.19. Grid size and materials for case 9mp (more permeable paint).

CASE 9lp

	ext. perm.																																	int. perm.
ext. wall	1.5E-07	4	4	4	42	42	42	2	2	2	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-10
215.3		4	10	4	4	17	4	4	4	3	3	6	10	14	20	20	20	14	12	10	8	6	4	2	1	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	6.3		**18**			**25**			**11**									**150**									**0.3**			**11**				
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-10
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**			**11**				
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-10
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	8.1															**75**											**0.3**			**11**				
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-10
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**			**11**				
ceiling	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-10
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**			**11**				
floor	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	5.0E-12
103.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	6	12	6	2	<= t (mm)
A (m^2) =	12															**75**											**0.3**			**28**				

LEGEND:

2	porous wood fibre board	4	pine wood	3	gypsum	8	concrete	42	air
21	building paper	17	polyethylene	16	cellulose	5	mineral fibre		

Figure A.20. Grid size and materials for case 9lp (less permeable paint).

CASE 10

	ext. perm.																																	int. perm.
ext. wall	1.5E-07	4	4	4	42	42	42	2	2	2	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
215.3		4	10	4	4	17	4	4	4	3	3	6	10	14	20	20	20	14	12	10	8	6	4	2	1	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	6.3		**18**			**25**			**11**									**150**									**0.3**			**11**				
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**			**11**				
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	8.1															**75**											**0.3**			**11**				
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	2	2	2	2	2	5.0E-09
86.3		4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	0	0	0	2	2	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**											**0.3**			**11**				
ceiling	1.0E-18	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	5.0E-12
100		4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	<= t (mm)
A (m^2) =	12															**76**											**9**			**15**				
floor	1.0E-18	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	5.0E-12
100		4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	<= t (mm)
A (m^2) =	12															**76**											**9**			**15**				

LEGEND:

2	porous wood fibre board	4	pine wood	3	gypsum	8	concrete	42	air
21	building paper	17	polyethylene	16	cellulose	5	mineral fibre		

Figure A.21. Grid size and materials for case 10 (concrete).

CASE 11

	ext. perm.																																	int. perm.
ext. wall	1.5E-07	4	4	4	42	42	42	2	2	2	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	4	4	4	4	4	5.0E-09
329.3		4	10	4	4	17	4	4	4	3	3	5	10	20	37	37	20	10	5	3	0	0	0	5	10	25	40	20	10	6	4	3	2	<= t (mm)
A (m^2) =	6.3		**18**			**25**			**11**									**150**				**0**									**125**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	4	4	4	4	4	5.0E-09
200.3		4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	0	0	0	5	10	25	40	20	10	6	4	3	2	<= t (mm)
A (m^2) =	10.8															**75**						**0**									**125**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	4	4	4	4	4	5.0E-09
200.3		4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	0	0	0	5	10	25	40	20	10	6	4	3	2	<= t (mm)
A (m^2) =	8.1															**75**						**0**									**125**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	4	4	4	4	4	5.0E-09
200.3		4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	0	0	0	5	10	25	40	20	10	6	4	3	2	<= t (mm)
A (m^2) =	10.8															**75**						**0**									**125**			
ceiling	1.0E-18	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	5.0E-12
100		4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	<= t (mm)
A (m^2) =	12															**100**											**9**				**15**			
floor	1.0E-18	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	5.0E-12
100		4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	<= t (mm)
A (m^2) =	12															**100**											**9**				**15**			

LEGEND: 2 porous wood fibre board; 4 pine wood; 3 gypsum; 8 concrete; 42 air; 21 building paper; 17 polyethylene; 16 cellulose; 5 mineral fibre

Figure A.22. Grid size and materials for case 11 (125 mm log).

CASE 12

	ext. perm.																																	int. perm.
ext. wall	1.5E-07	4	4	4	42	42	42	2	2	2	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	4	4	4	4	4	5.0E-09
254.3		4	10	4	4	17	4	4	4	3	3	5	10	20	37	37	20	10	5	3	0	0	0	2	3	5	8	10	10	5	3	2	2	<= t (mm)
A (m^2) =	6.3		**18**			**25**			**11**									**150**				**0**									**50**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	4	4	4	4	4	5.0E-09
125.3		4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	0	0	0	2	3	5	8	10	10	5	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**						**0**									**50**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	4	4	4	4	4	5.0E-09
125.3		4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	0	0	0	2	3	5	8	10	10	5	3	2	2	<= t (mm)
A (m^2) =	8.1															**75**						**0**									**50**			
int. wall	1.0E-18	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	4	4	4	4	4	4	4	4	4	4	5.0E-09
125.3		4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	0	0	0	2	3	5	8	10	10	5	3	2	2	<= t (mm)
A (m^2) =	10.8															**75**						**0**									**50**			
ceiling	1.0E-18	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	5.0E-12
100		4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	<= t (mm)
A (m^2) =	12															**100**																		
floor	1.0E-18	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	5.0E-12
100		4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	<= t (mm)
A (m^2) =	12															**100**											**9**				**15**			

LEGEND: 2 porous wood fibre board; 4 pine wood; 3 gypsum; 8 concrete; 42 air; 21 building paper; 17 polyethylene; 16 cellulose; 5 mineral fibre

Figure A.23. Grid size and materials for case 12 (50 mm log).

CASE 13

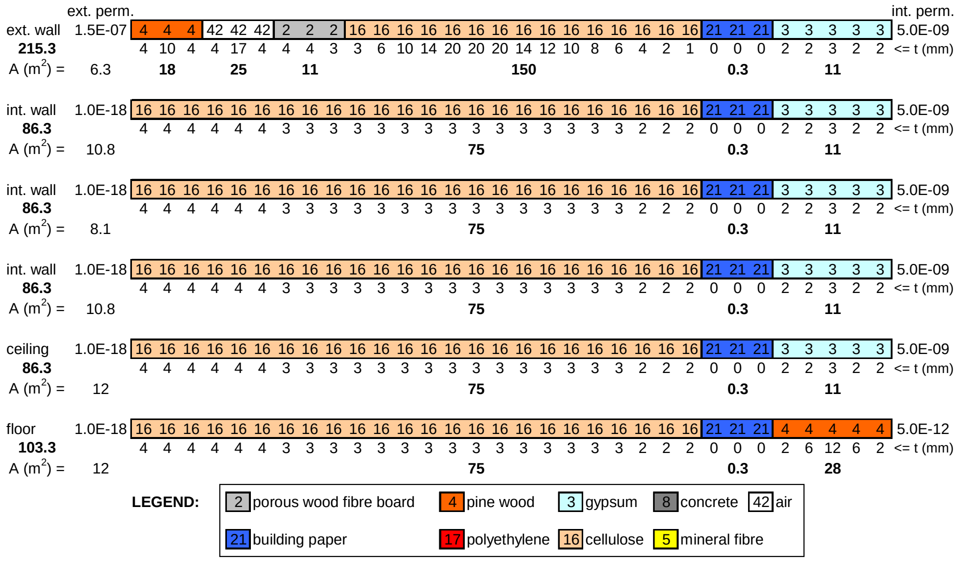


Figure A.24. Grid size and materials for case 13 (gypsum).

CASE 14

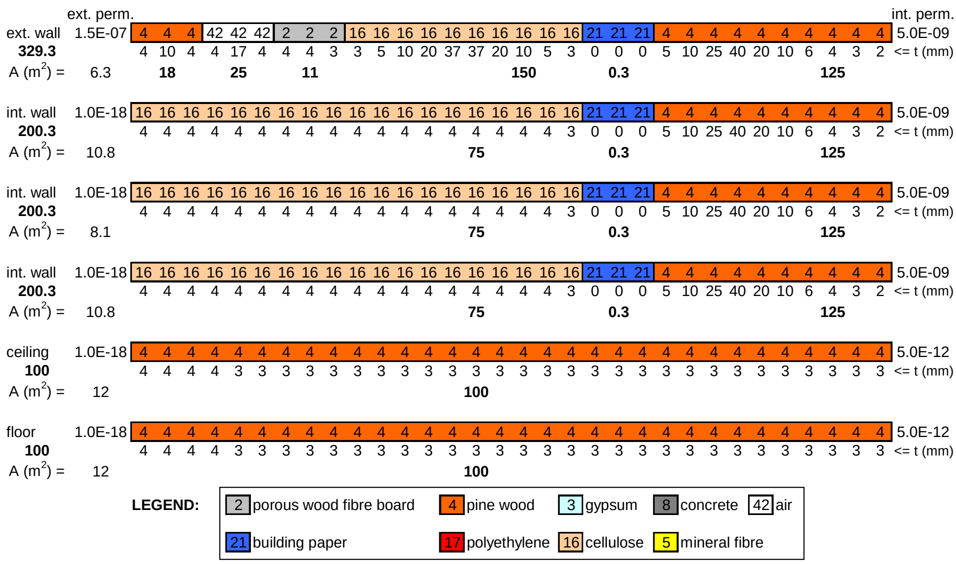


Figure A.25. Grid size and materials for case 14 (all log).

Appendix B: Temporal Variations of T, RH, W, H, PD and Acc in Permeable Case1 and Impermeable Case2 in all Climates

This Appendix contains detailed results, which demonstrate the difference between the permeable case1 and impermeable case2 in all climates.

B.1 Northern Climate

B.1.1 Moderate weather (Finland)

The time chosen for this analysis is a ten day period at the beginning of July when the outdoor temperature varies between 10°C and 20°C and the outdoor humidity is between 6 and 10 g/kg (Figure B.1). During this time, the indoor temperature varies between 19°C and 24°C and the permeable case (case1) has higher indoor temperatures as shown in Figure B.2. The higher temperature in case1 is a result of the phase change energy that is released when moisture is accumulating in the building structures. Figure B.2 also contains the relative humidity for the permeable and impermeable cases and shows that the indoor humidity is significantly higher for the impermeable case. During the first three days, the relative humidity in the impermeable case increases above the permeable case during the night, but decreases below the permeable case during the day. However, from 4.7 to 9.7, when the outdoor humidity begins to increase slightly, the indoor relative humidity is consistently higher for the impermeable case. The peak humidity during the night is 20% to 25% RH greater for the impermeable case than for the permeable case. However, the indoor temperature is slightly higher in the permeable case, which will tend to lower the relative humidity.

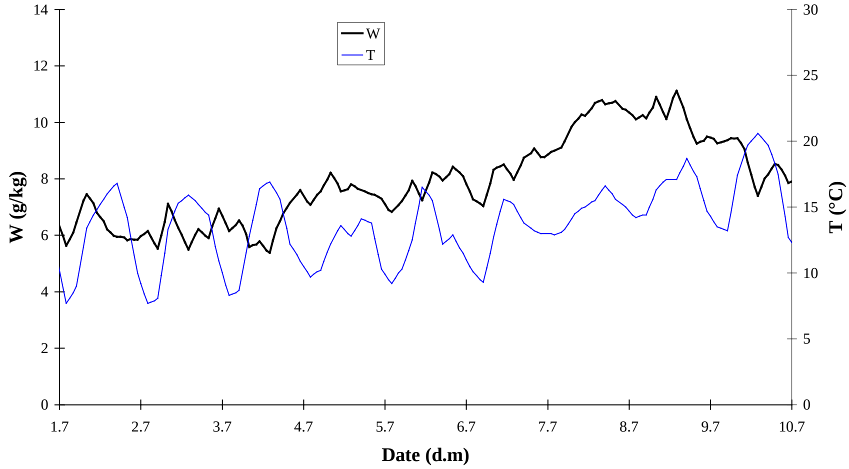


Figure B.1. Outdoor humidity and temperature during a moderate period in Finland.

Figure B.2 also presents the absolute humidity and enthalpy of the indoor air for the same period (1.7 to 10.7). The absolute humidity results are very similar to the relative humidity results. Again the indoor absolute humidity is consistently higher in impermeable case for 4.7 to 9.7. The enthalpy of the indoor air is greater during the night for the impermeable case than for the permeable case. Since, the temperature and humidity affect both comfort and perceived air quality, the percent dissatisfied and acceptability of the indoor air are included in Figure B.2.

The percent dissatisfied with respiratory cooling is nearly always higher during the night for impermeable case (case1) than for the permeable case (case2). The peak value of PD is typically in the morning and at this time case2 will have 5% more people dissatisfied with respiratory comfort. During the day (unoccupied period) PD is very similar for both cases. The acceptability results are quite similar to the PD results and show that the indoor air is typically more acceptable in the permeable case than in the impermeable case. For example, during the night of 7.7, the indoor air quality is unacceptable (i.e., acceptability < 0) from 4:00 to 7:00 in case2, while case1 has an acceptability of 0.18 to 0.12 during the same time.

These results show that a permeable structure is able to improve the indoor humidity, comfort and perceived air quality.

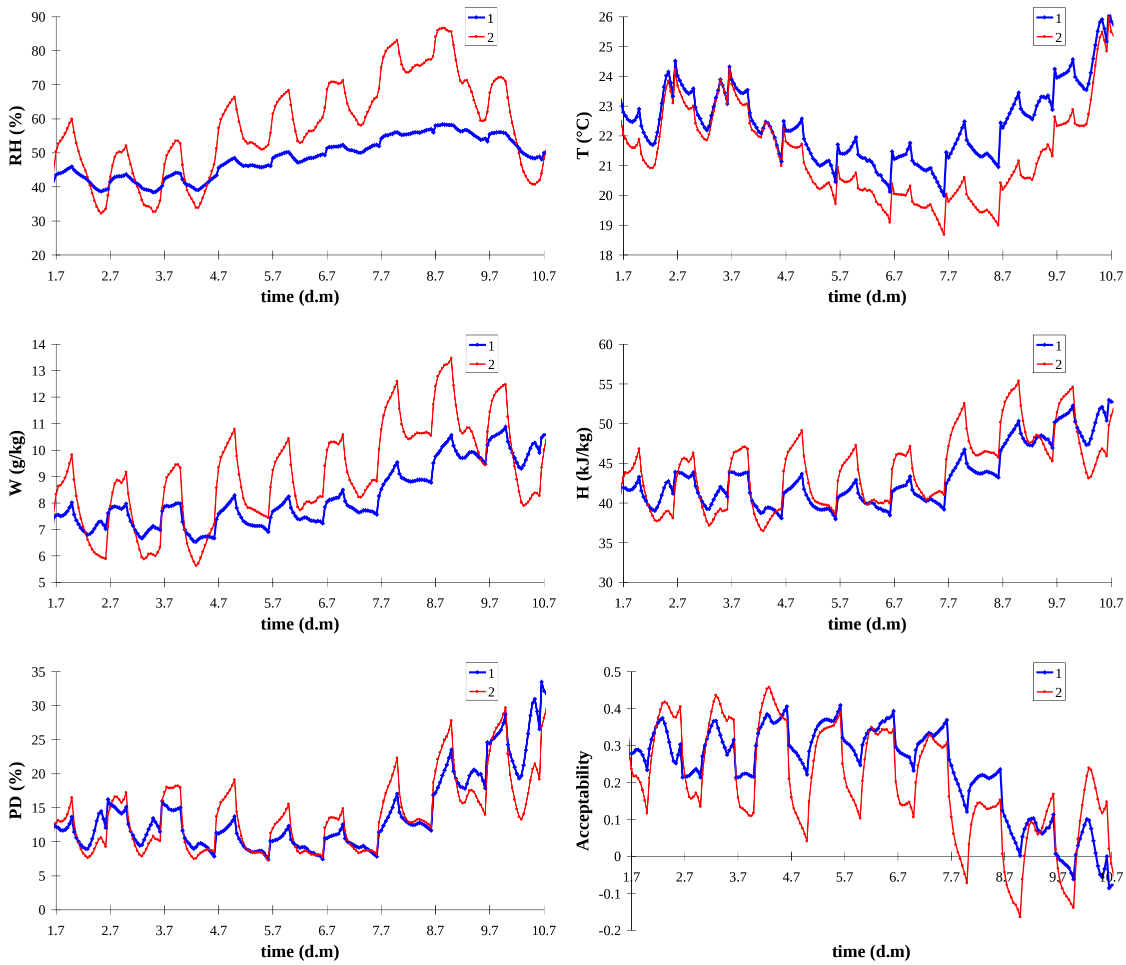


Figure B.2. Temporal variation of the important indoor air variables during a moderate period in Finland.

B.1.2 Humid period (Finland)

The highest outdoor humidity in Helsinki is about 12 g/kg and therefore the performance of the room is presented during a period where the outdoor humidity is between 10 and 12 g/kg for a week and then decreases to below 8 g/kg. The time period is in August and the outdoor temperature fluctuates between 15°C and 25°C as shown in Figure B.3. Once again the indoor temperature and relative humidity, absolute humidity and enthalpy and percent dissatisfied and acceptability are presented (Figure B.4).

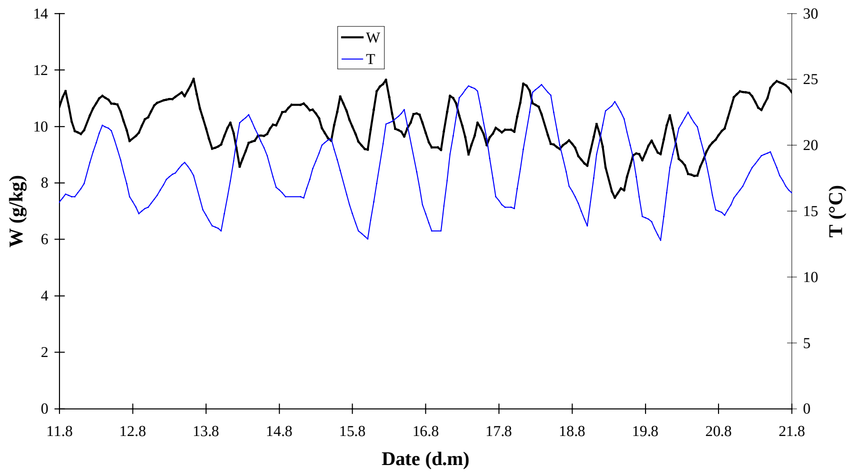


Figure B.3. Outdoor humidity and temperature during a humid period in Finland.

The indoor temperature it typically greater in case1 (permeable case) from 11.8 to 16.8 and greater in case2 (impermeable case) from 17.8 to 21.8. On 17.8, the outdoor humidity decreases (Figure B.3) causing the indoor humidity to decrease and therefore the permeable structure to dry. Since energy is required to evaporate moisture from the structure, the indoor air temperature decreases. During the night of 19.8, the maximum temperature in case1 is 28°C, while the maximum temperature in case2 is 29.5°C. However, during this time the indoor humidity is 15% RH higher in case1. The peak indoor relative humidity is greater in case1 than in case2 for only 2 of the 10 nights. When the indoor temperature is nearly equal (16.10), the relative humidity in case2 is 5% higher than in case1.

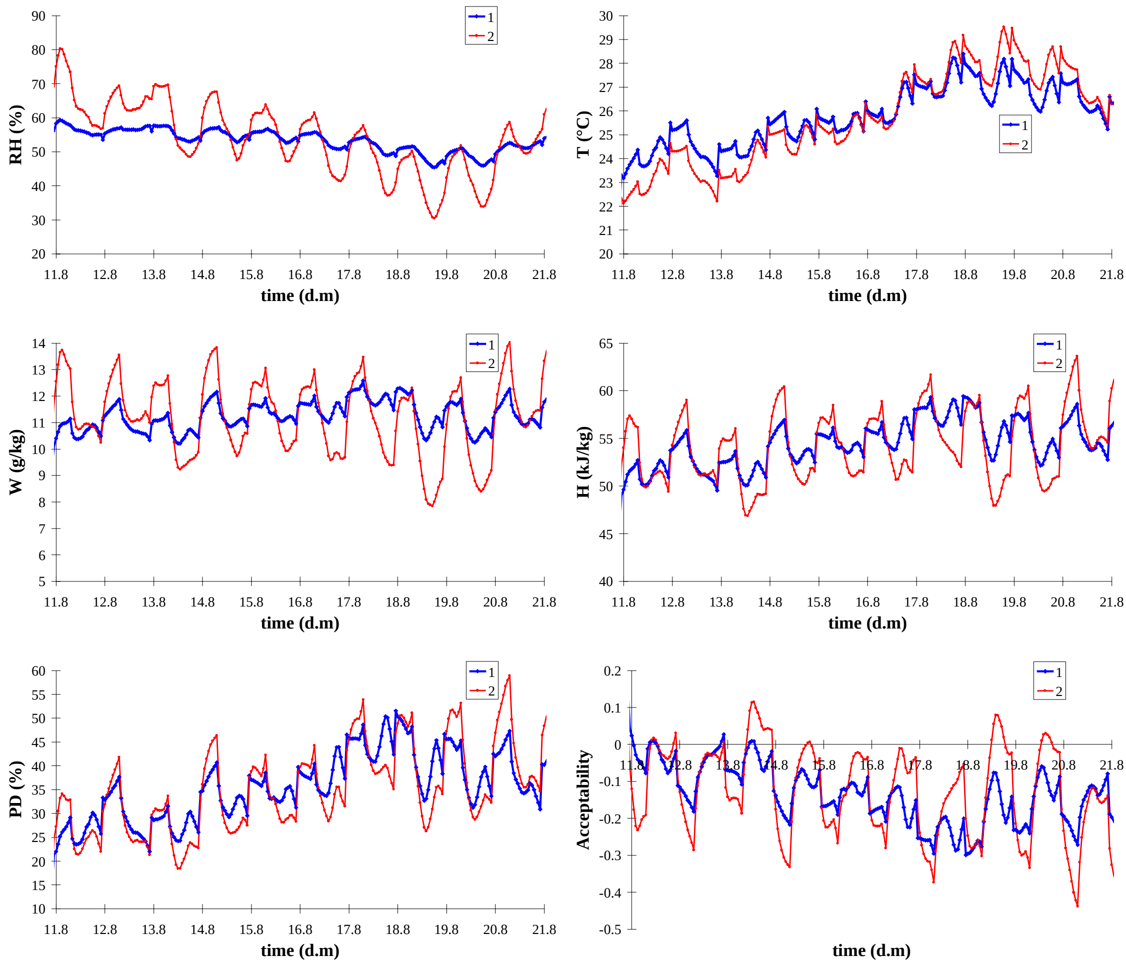


Figure B.4. Temporal variation of the important indoor air variables during a humid period in Finland.

The indoor absolute humidity and enthalpy results are similar to the temperature and relative humidity results. The absolute humidity and enthalpy of the indoor air is usually higher during the night in case2 than in case1, except for when the outdoor humidity decreases (nights of 18.8 and 19.8).

The results in Figure B.4 show that PD is quite high and the acceptability is quite low in both cases. During occupation (night), the comfort and air quality are better for the permeable case (case1) than for the impermeable case (case2), except during 18.8 and 19.8. In the morning of 14.8 and 20.8 there will be 6% and 14% more occupants dissatisfied with the comfort conditions in case2 than in case1, while in the morning of 18.8 there will be 3% more occupants dissatisfied with comfort conditions in case1 than in case2.

B.1.3 Dry period (Finland)

At the end of March, the outdoor temperature is near 0°C and the outdoor humidity is about 3 g/kg (Figure B.5). During this time, the indoor temperature is quite constant and the indoor relative humidity is moderate as can be seen in Figure B.6. The maximum indoor humidity is 25% RH higher in case2 than in case1. The indoor humidity in case2 is higher during the occupied period (night) and lower during the unoccupied period (day) than in case1. Similarly, the absolute humidity and enthalpy in case2 are higher during the night and lower during the day. The net results is that the indoor climate and air quality are better in case1 during occupied hours and better in case2 during unoccupied hours. On average, PD during occupation is about 4% in case1 and about 7% in case2.

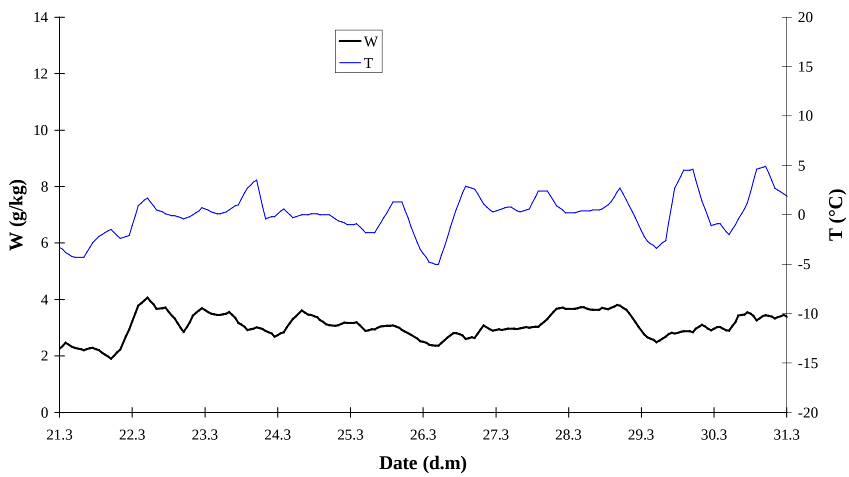


Figure B.5. Outdoor humidity and temperature during a cold and dry period in Finland.

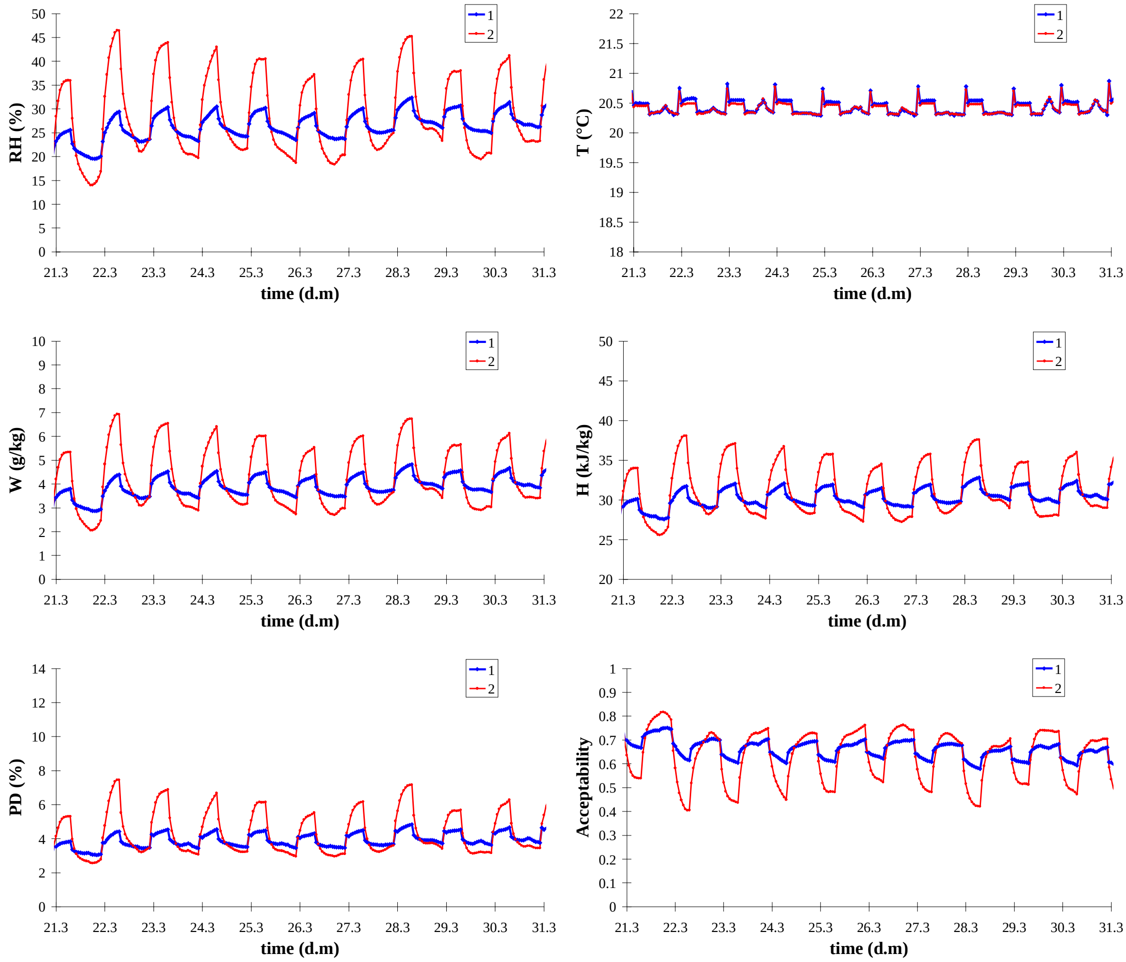


Figure B.6. Temporal variation of the important indoor air variables during a cold and dry period in Finland.

B.1.4 Very dry period (Finland)

The outdoor humidity in Finland goes very low (below 1 g/kg) in January when the outdoor temperature is very low (–20°C) as shown in Figure B.7. Because the outdoor humidity is very low, the indoor air becomes very dry as can be seen in Figure B.8. However, the indoor humidity in case2 increases above 40% RH on 8.1 when the outdoor temperature and humidity increase to 0°C and 3 g/kg respectively. As with the dry period, the comfort and air quality conditions are better in case1 when the bedroom is occupied and better in case2 when the bedroom is not occupied. However, the difference between the cases is smaller than in the dry period and respiratory comfort and air quality are good for both cases. It is important to note that the correlation used to estimate the warm respiratory comfort is based on providing adequate cooling of the mucous membranes in the upper respiratory tract. At the low humidities in Figure B.8 cooling will be adequate, but dryness may occur and the general thermal discomfort may be greater than the warm respiratory discomfort.

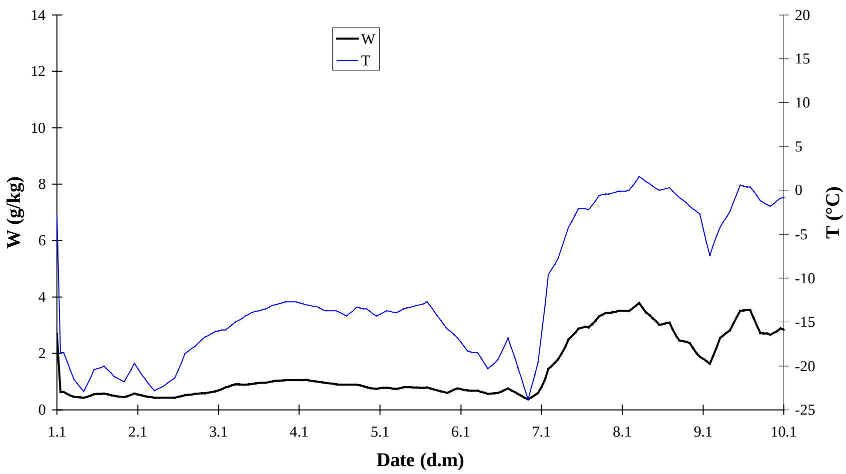


Figure B.7. Outdoor humidity and temperature during a very cold and dry period in Finland.

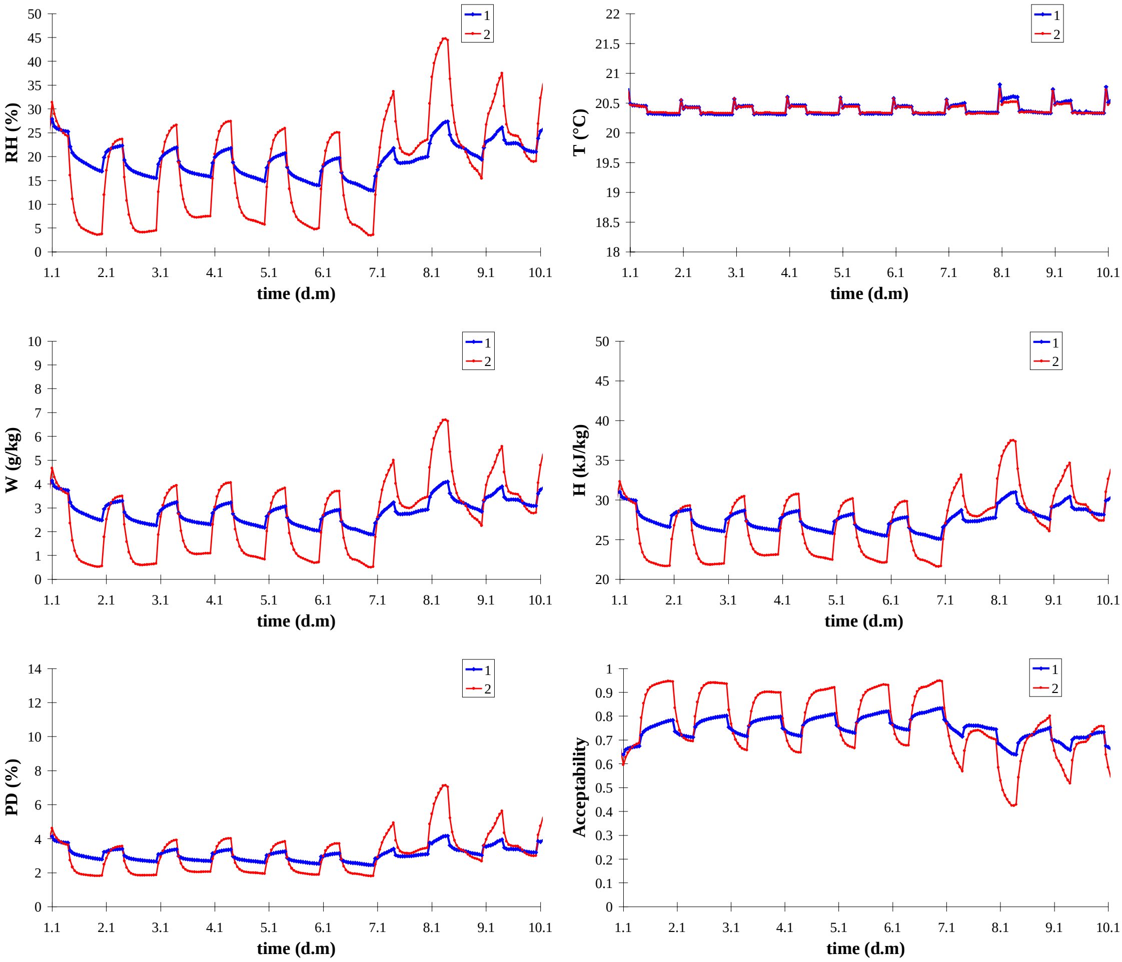


Figure B.8. Temporal variation of the important indoor air variables during a very cold and dry period in Finland.

B.1.5 Increasing outdoor humidity (Finland)

The results in Figure B.9 and Figure B.10 are for increasing outdoor humidity in October. These results show that as the outdoor humidity increases, the difference between the permeable and impermeable cases increases. On the night of 8.10, case2 has a maximum humidity that is 11% RH higher than case1, while on the night of 11.10 case2 has a maximum humidity that is 20% RH higher than case1. The temperature difference between case1 and case2 also peaks on the night of 11.10, when the outdoor humidity is the highest. The difference in PD is not as dramatic. On 8.10, 3% more of the occupants will be dissatisfied with the conditions in case2, while on 11.10, 5% more of the occupants will be dissatisfied with the conditions in case2.

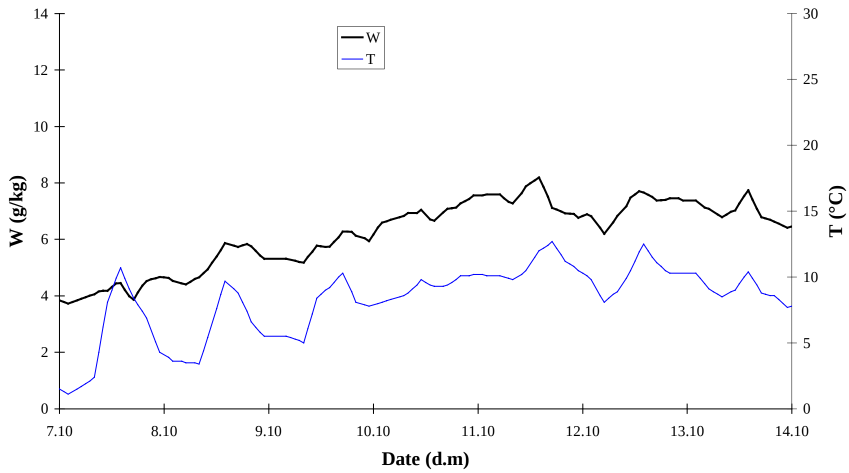


Figure B.9. Outdoor humidity and temperature during a period of increasing outdoor humidity in October in Finland.

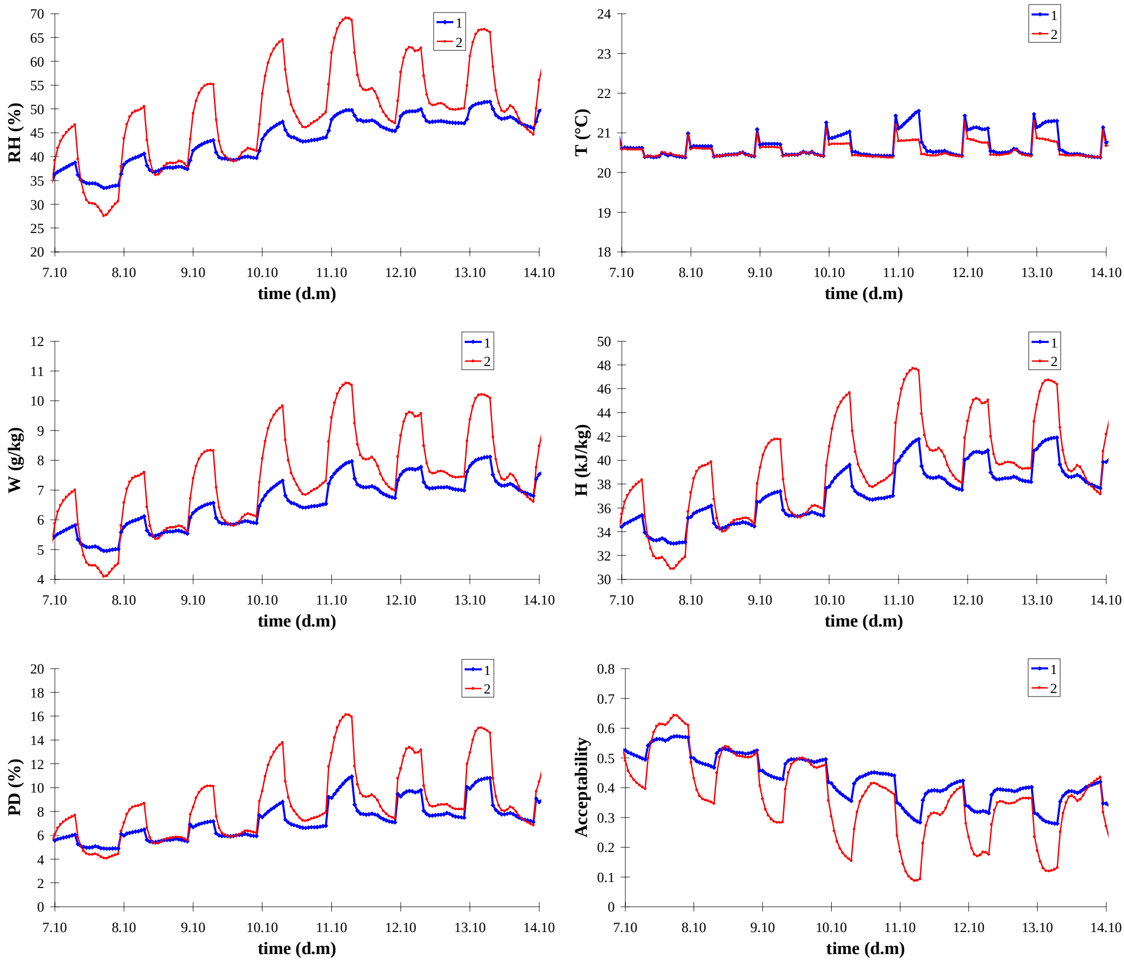


Figure B.10. Temporal variation of the important indoor air variables during a period of increasing outdoor humidity in October in Finland.

B.2 Maritime Climate

B.2.1 Moderate weather (Belgium)

Just after the heating season in Belgium, the temperature is quite moderate (10°C to 15°C) and the outdoor humidity is quite moderate (6 g/kg) as shown in Figure B.11. As a result, the indoor temperature is quite low and the indoor relative humidity is quite high (Figure B.12). The minimum indoor temperature is 2°C higher in case1 than in case2 and the maximum relative humidity is 35% RH higher in case2 than in case1. The indoor humidity is above 60% RH for only a few hours in case1, but is almost always above 60% RH during occupation in case2. The indoor absolute humidity and enthalpy are higher during occupation in case2 than in case1. Figure B.12 also shows that PD is quite low and the acceptability is quite high in both cases. PD is about 3% higher in case2 than in case1. During these conditions respiratory cooling will be adequate, but the high humidities in case2 may lead to other humidity related problems (e.g., asthma, mould, mites).

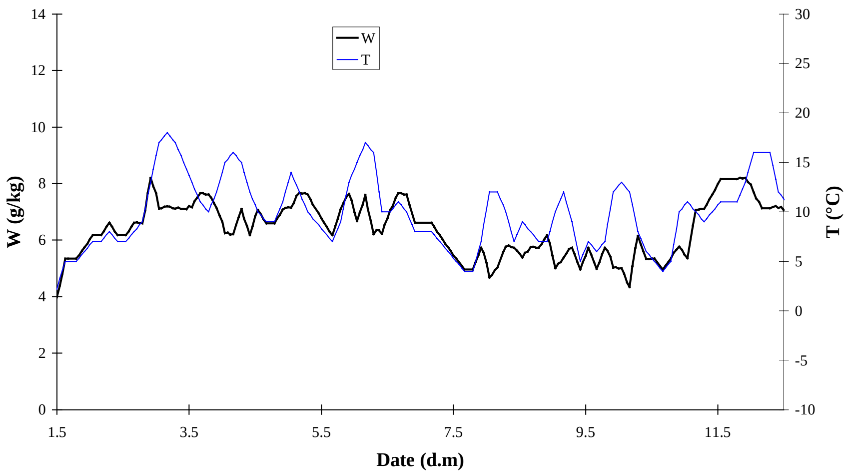


Figure B.11. Outdoor humidity and temperature during a moderate period in Belgium.

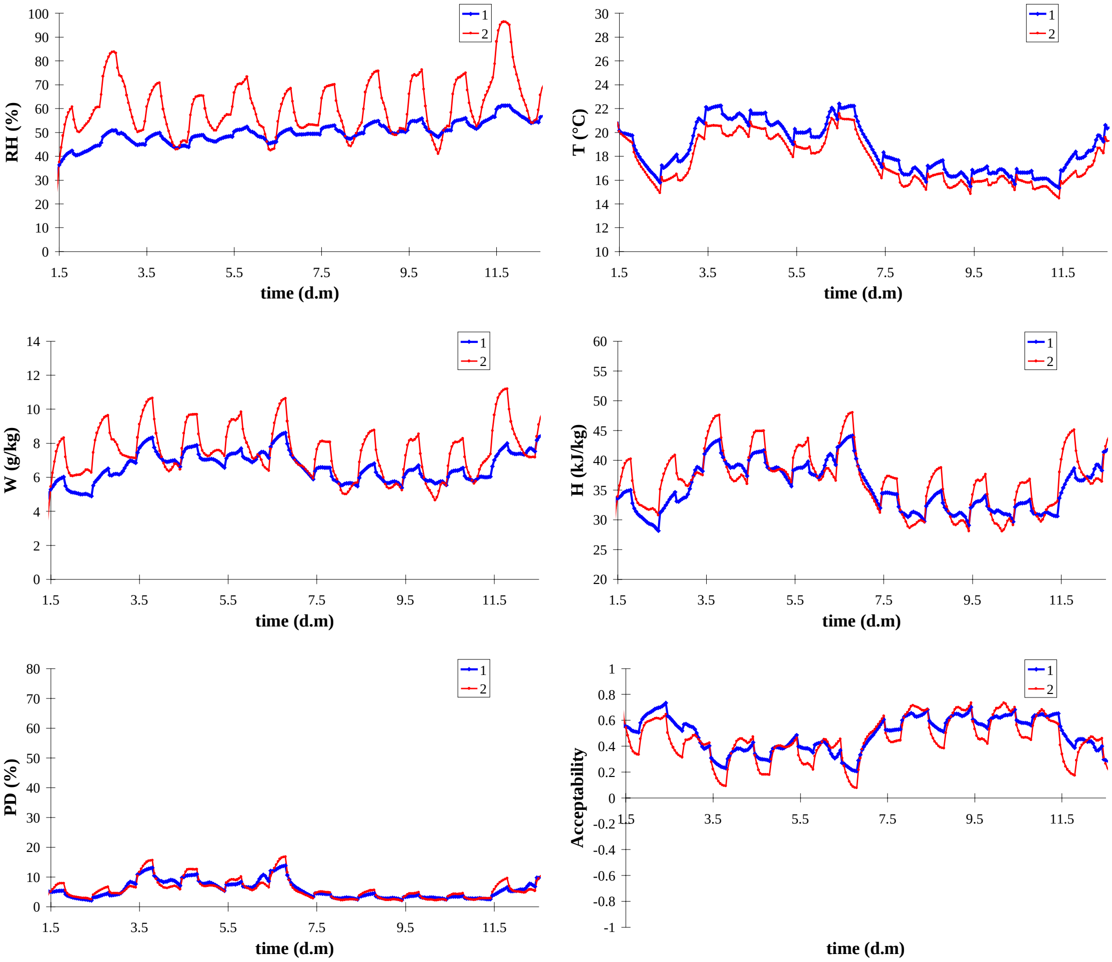


Figure B.12. Temporal variation of the important indoor air variables during a moderate period in Belgium.

B.2.2 Humid weather (Belgium)

Since the following results (Figures B.13 to B.20) are quite similar to the previous results from the northern climate, the graphs will be presented without explanation.

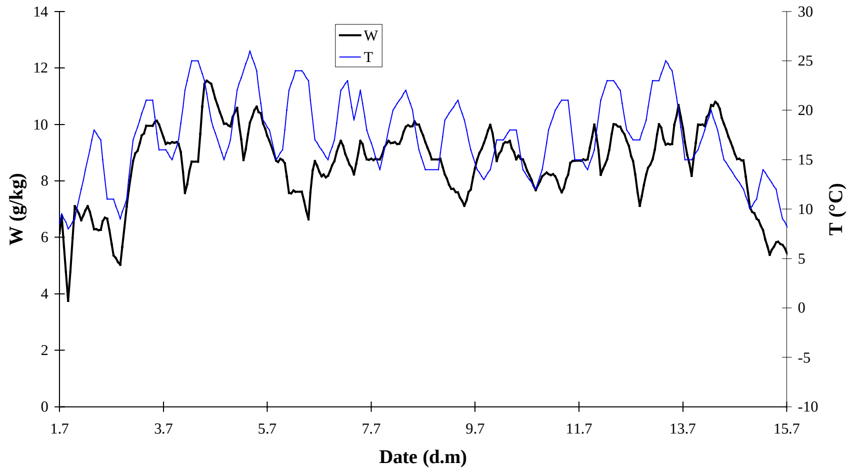


Figure B.13. Outdoor humidity and temperature during a humid period in Belgium.

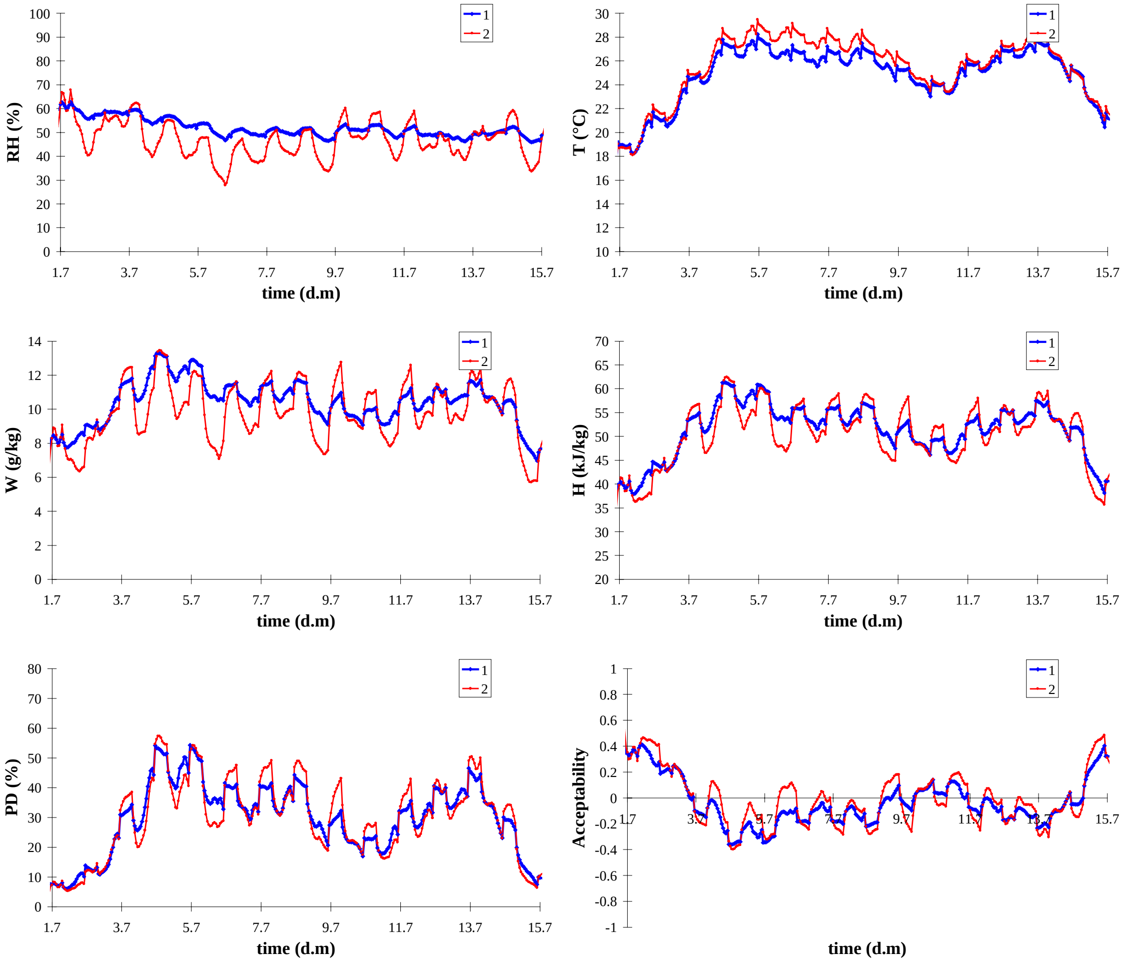


Figure B.14. Temporal variation of the important indoor air variables during a humid period in Belgium.

B.2.3 Cold weather (Belgium)

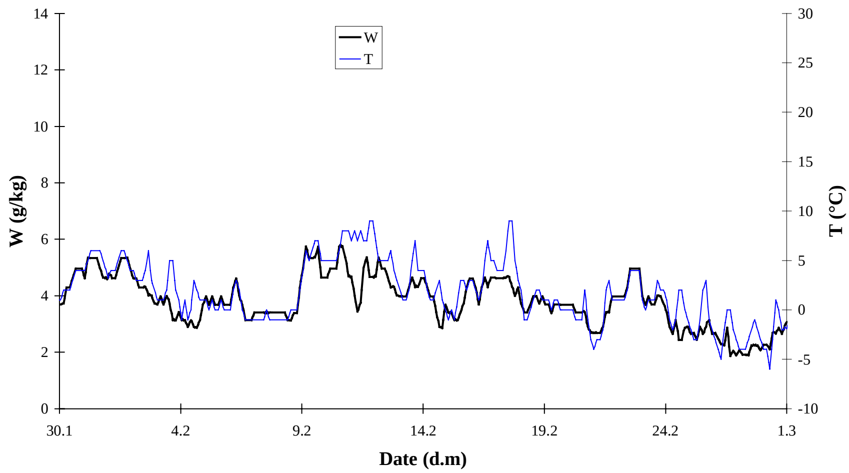


Figure B.15. Outdoor humidity and temperature during a cold period in Belgium.

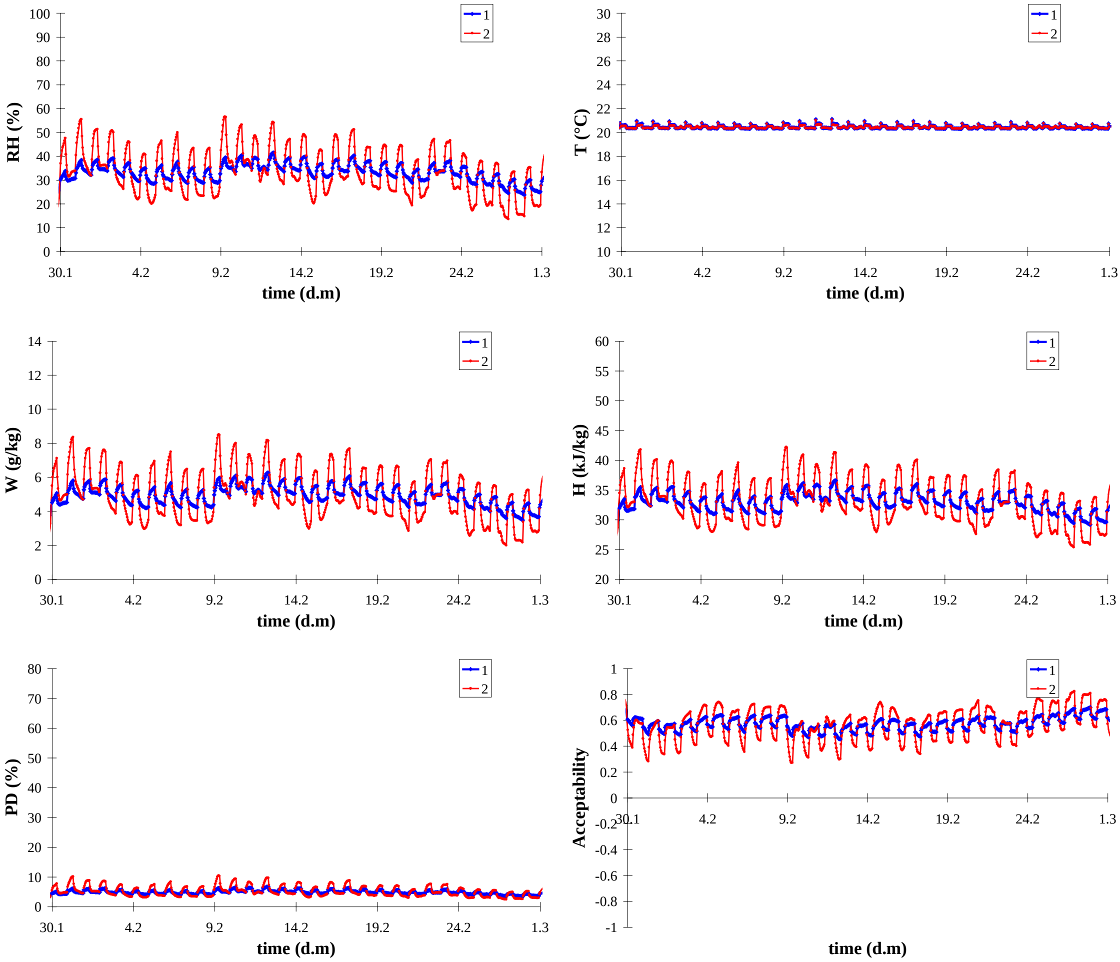


Figure B.16. Temporal variation of the important indoor air variables during a cold period in Belgium.

B.2.4 Increasing outdoor humidity (Belgium)

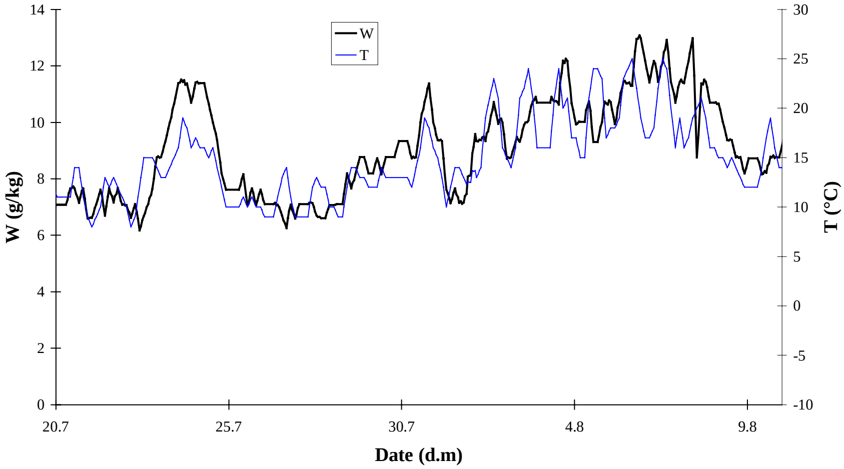


Figure B.17. Outdoor humidity and temperature during a period of increasing outdoor humidity in Belgium.

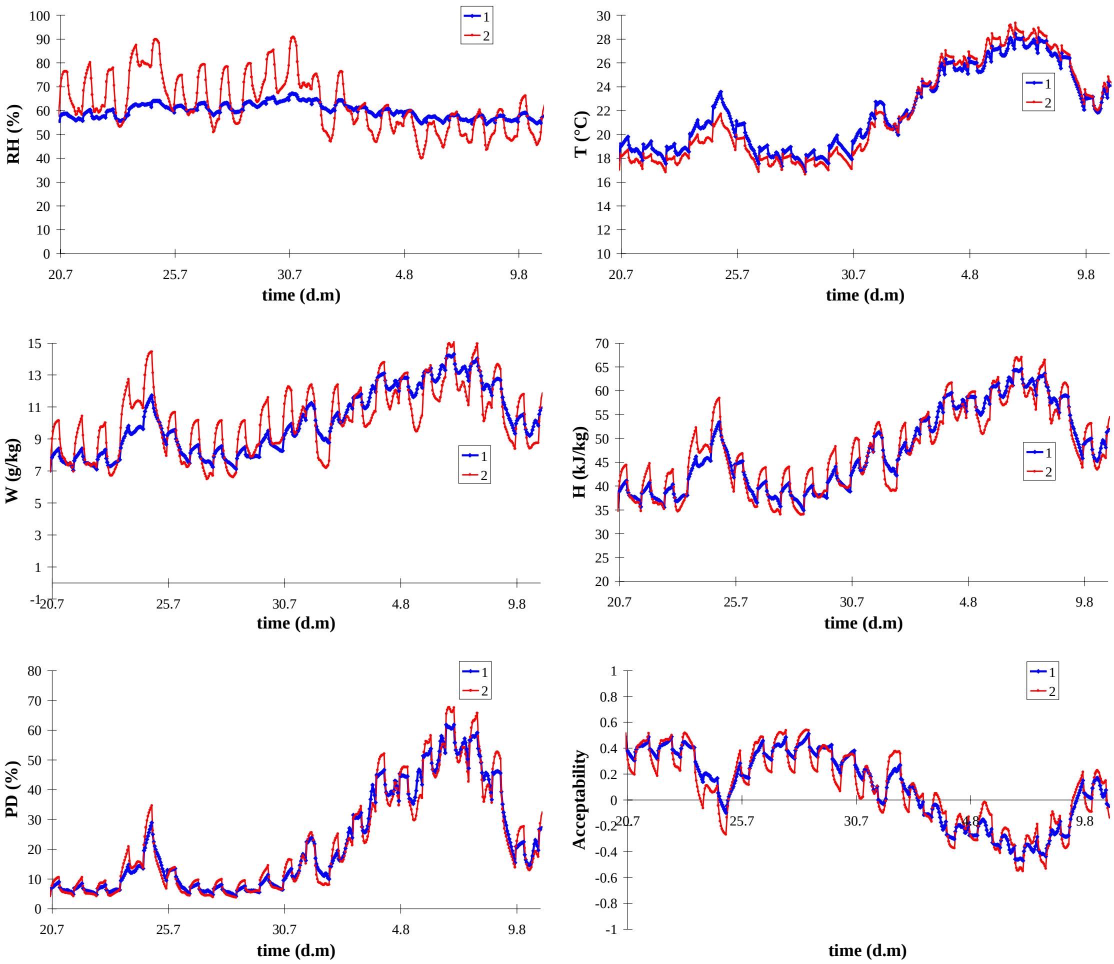


Figure B.18. Temporal variation of the important indoor air variables during a period of increasing outdoor humidity in Belgium.

B.2.5 Decreasing outdoor temperature and humidity (Belgium)

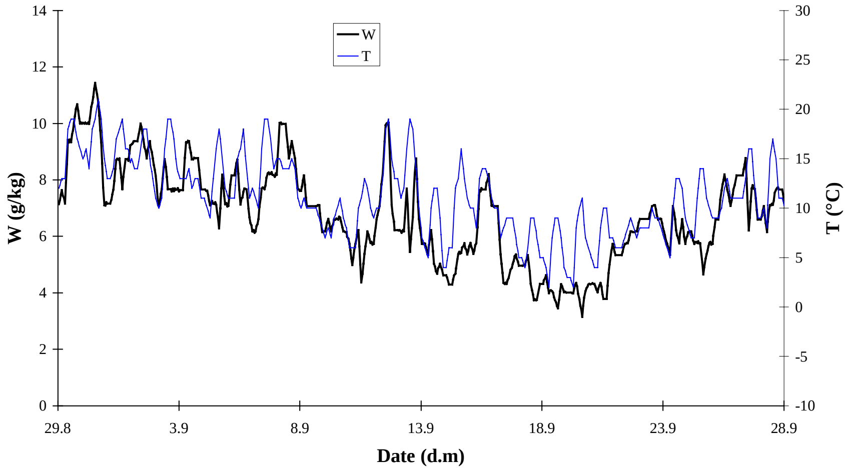


Figure B.19. Outdoor humidity and temperature during a period of decreasing outdoor temperature and humidity in Belgium.

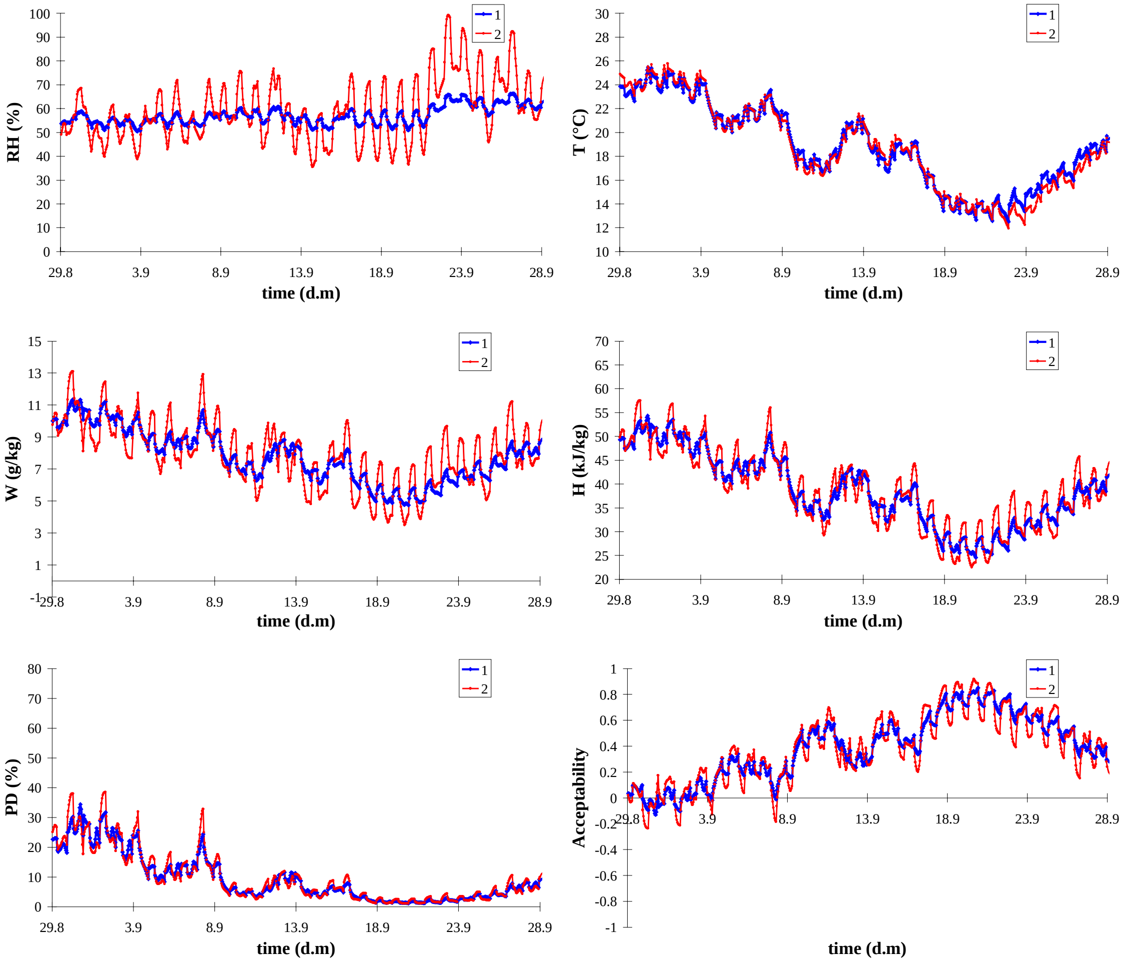


Figure B.20. Temporal variation of the important indoor air variables during a period of decreasing outdoor temperature and humidity in Belgium.

B.3 Central Climate

The graphs presented in this section (Figures B.21 to B.28) are for various stages of weather in Holzkirchen, Germany. Since the weather in Holzkirchen tends to change less rapidly than in the other cities studied in this report, some of the results in this section will be for longer-term trends. The graphs contain the outdoor temperature and humidity and the indoor relative humidity, temperature, absolute humidity, enthalpy, percent dissatisfied with warm respiratory comfort and the acceptability of clean indoor air. The results are presented without discussion.

B.3.1 Moderate weather (Germany)

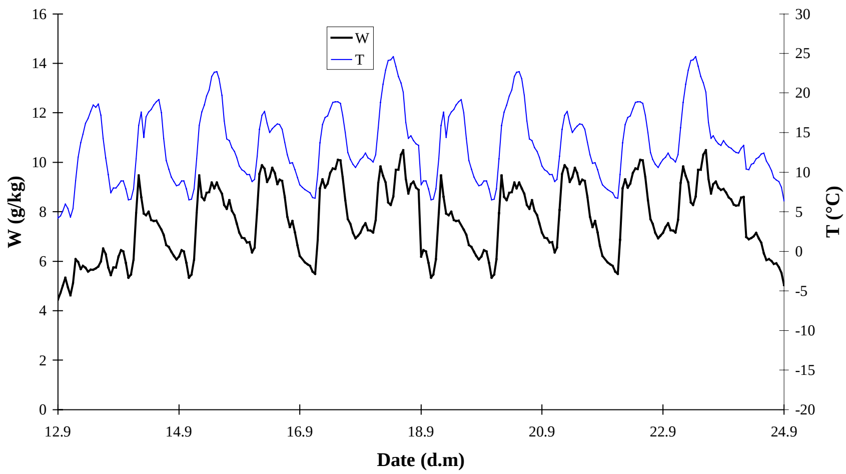


Figure B.21. Outdoor humidity and temperature during a moderate period in Germany.

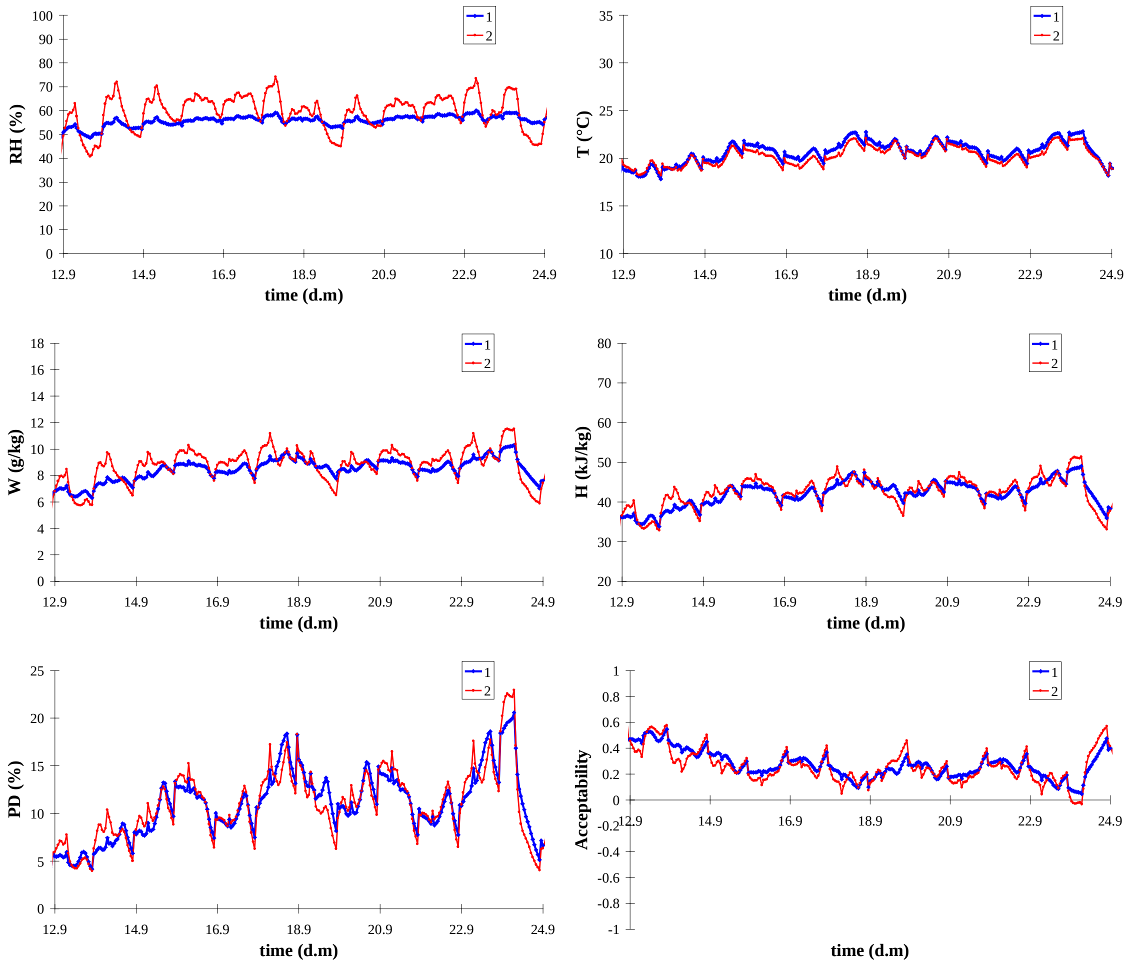


Figure B.22. Temporal variation of the important indoor air variables during a moderate period in Germany.

B.3.2 Humid weather (Germany)

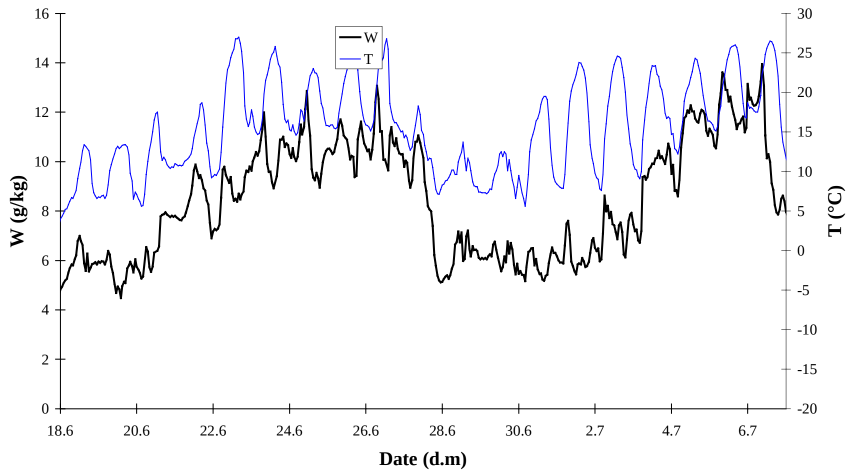


Figure B.23. Outdoor humidity and temperature during a humid period in Germany.

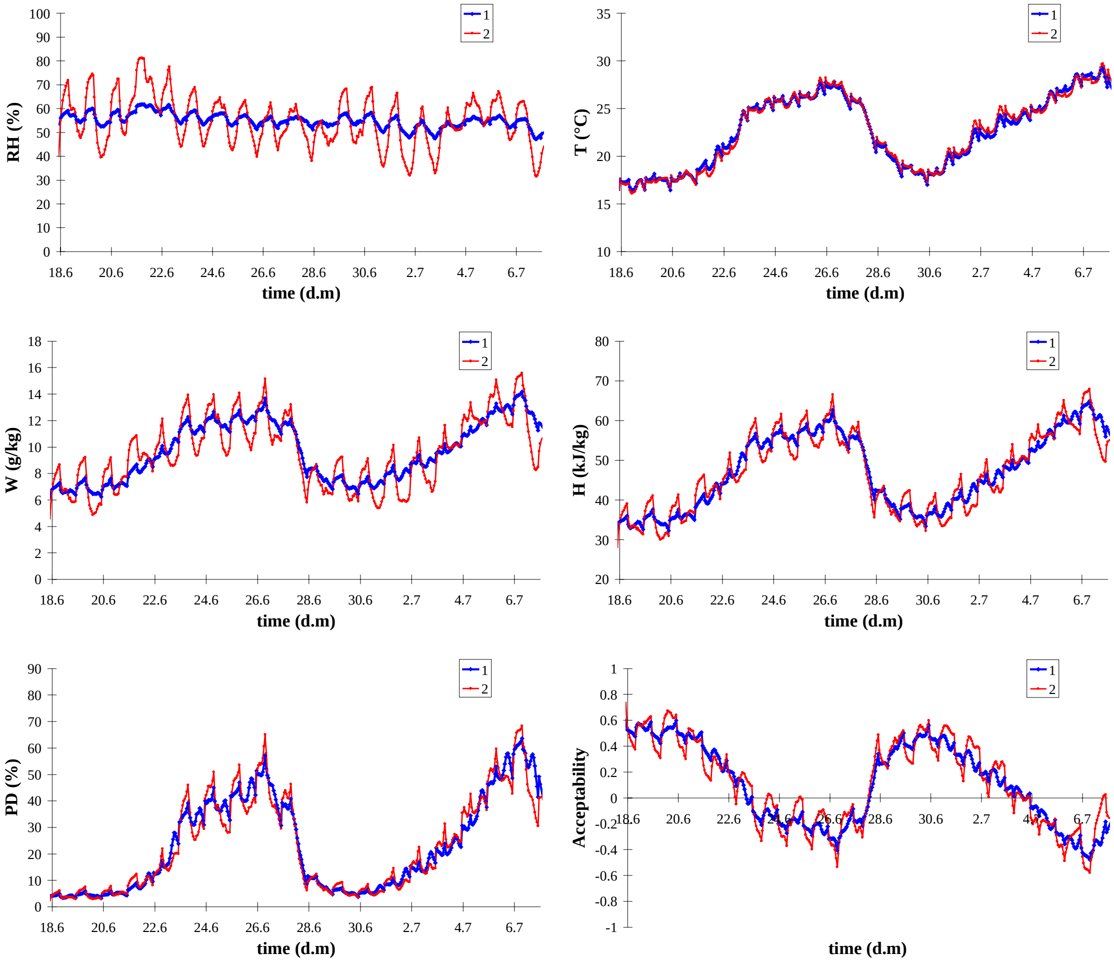


Figure B.24. Temporal variation of the important indoor air variables during a humid period in Germany.

B.3.3 Cold weather (Germany)

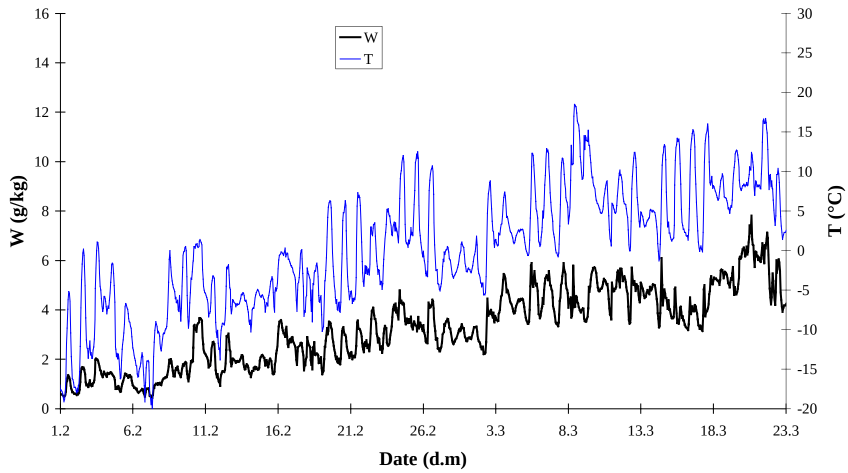


Figure B.25. Outdoor humidity and temperature during a cold period in Germany.

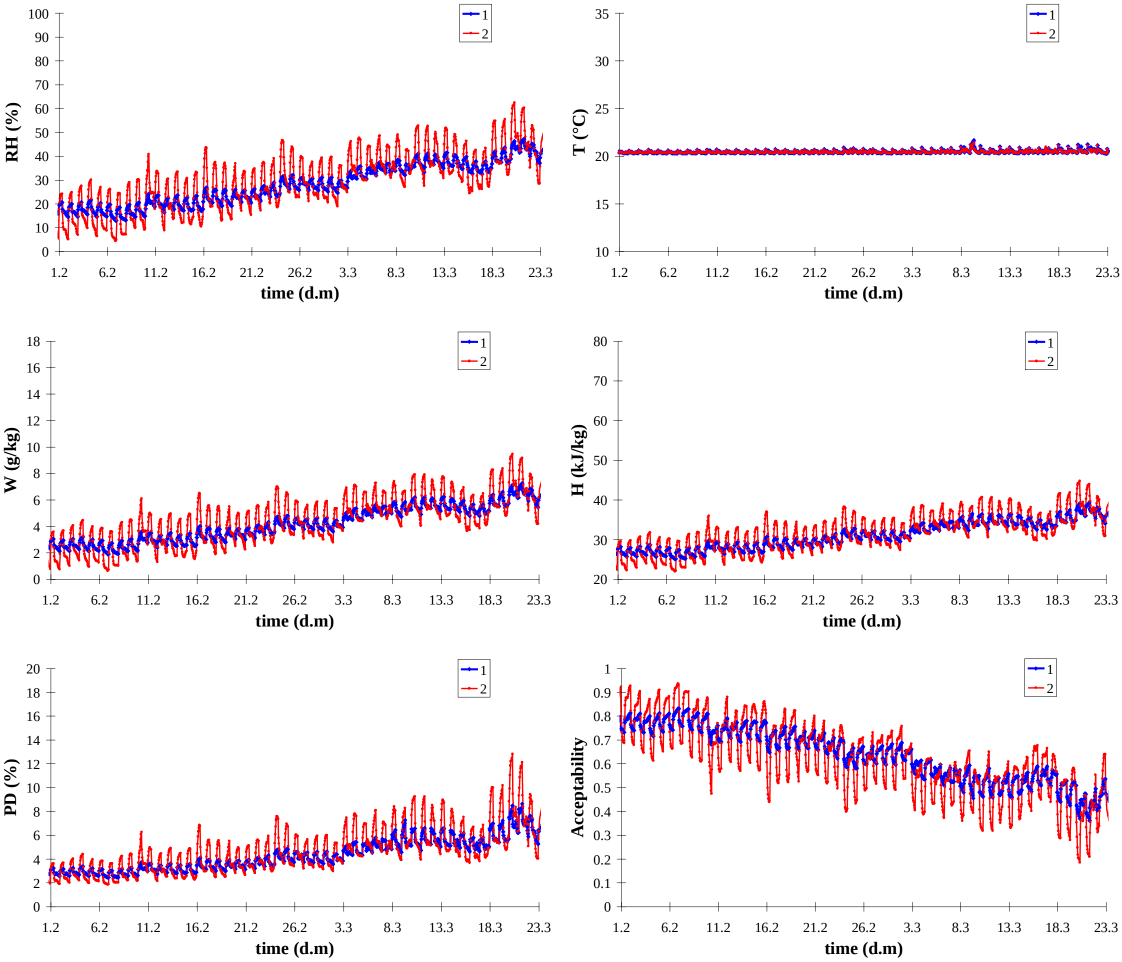


Figure B.26. Temporal variation of the important indoor air variables during a cold period in Germany.

B.3.4 Increasing outdoor humidity (Germany)

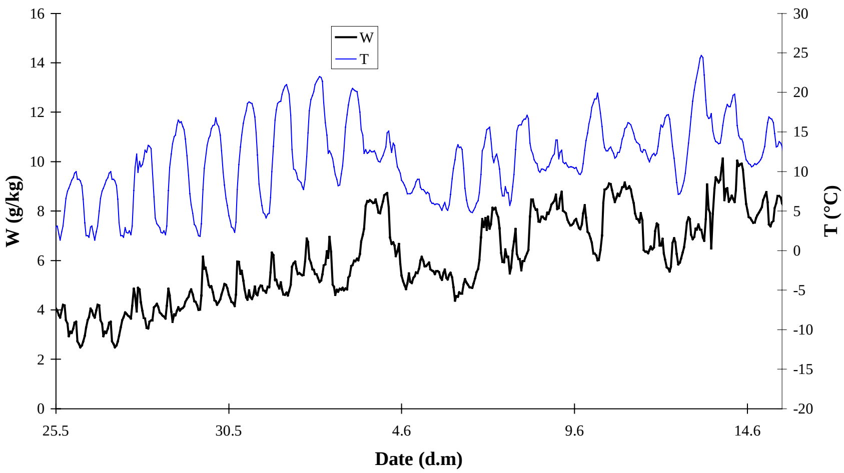


Figure B.27. Outdoor humidity and temperature during a period of increasing outdoor humidity in Germany.

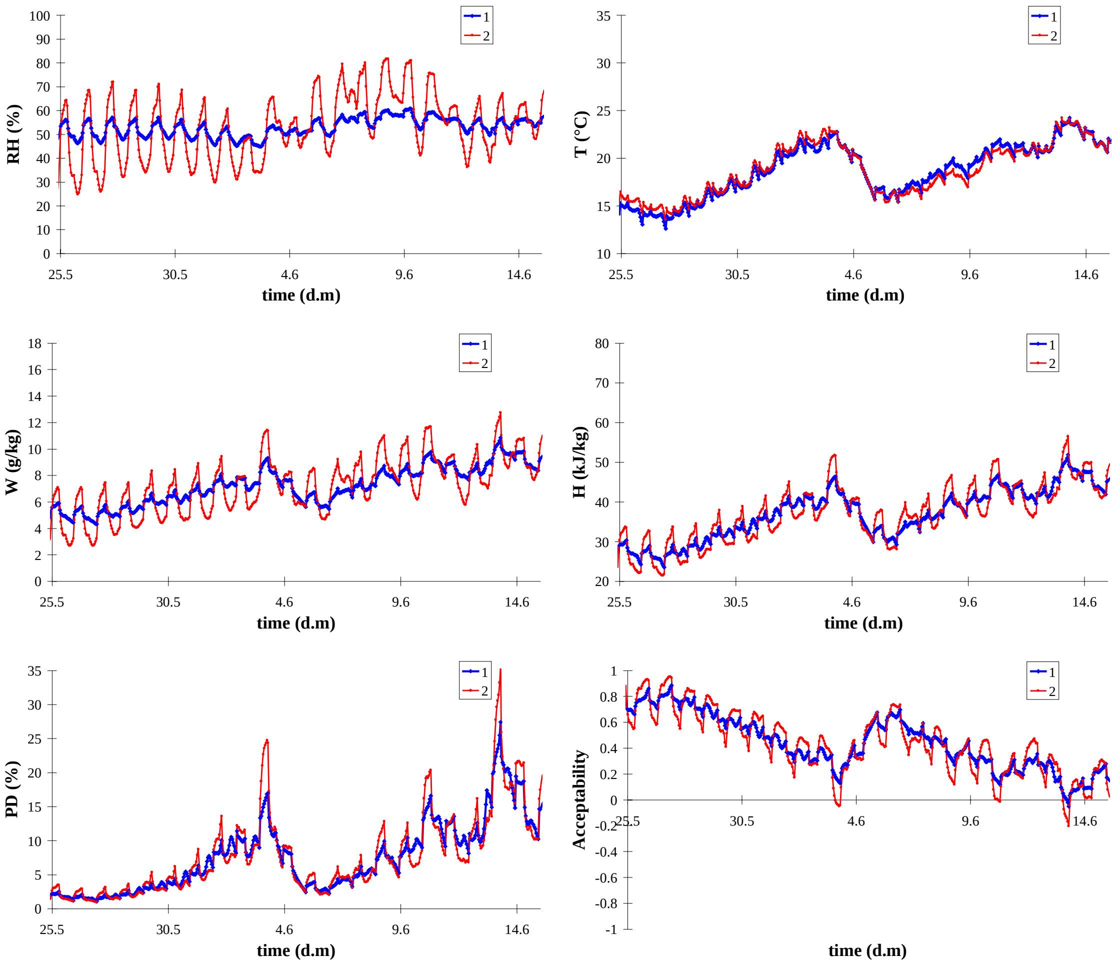


Figure B.28. Temporal variation of the important indoor air variables during a period of increasing outdoor humidity in Germany.

B.4 Southern Climate

The results for various weather conditions in southern Italy (Trapani) are presented in this section (Figures B.29 to B.38) without explanation.

B.4.1 Moderate weather (Italy)

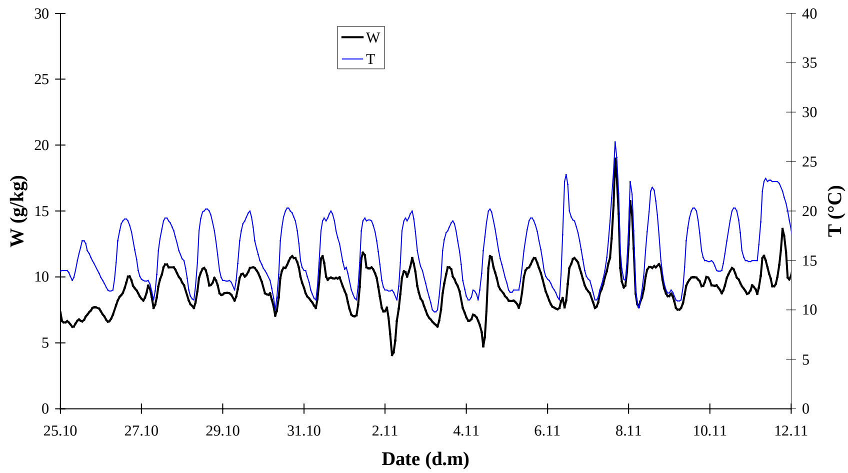


Figure B.29. Outdoor humidity and temperature during a moderate period in Italy.

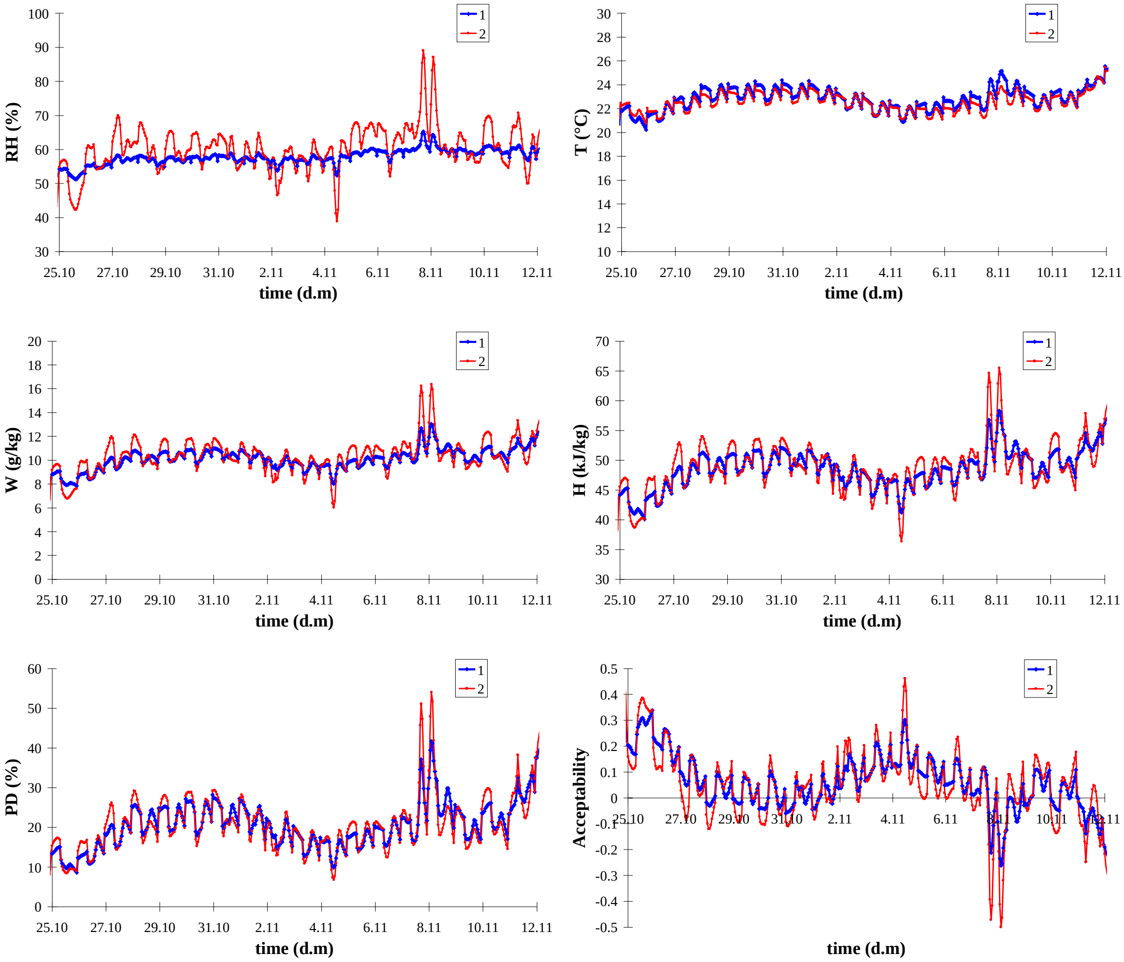


Figure B.30. Temporal variation of the important indoor air variables during a moderate period in Italy.

B.4.2 Hot and humid weather (Italy)

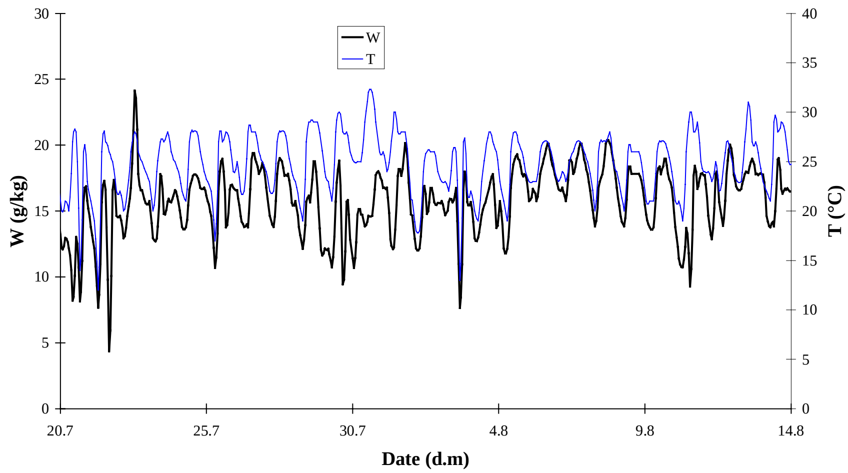


Figure B.31. Outdoor humidity and temperature during a hot and humid period in Italy.

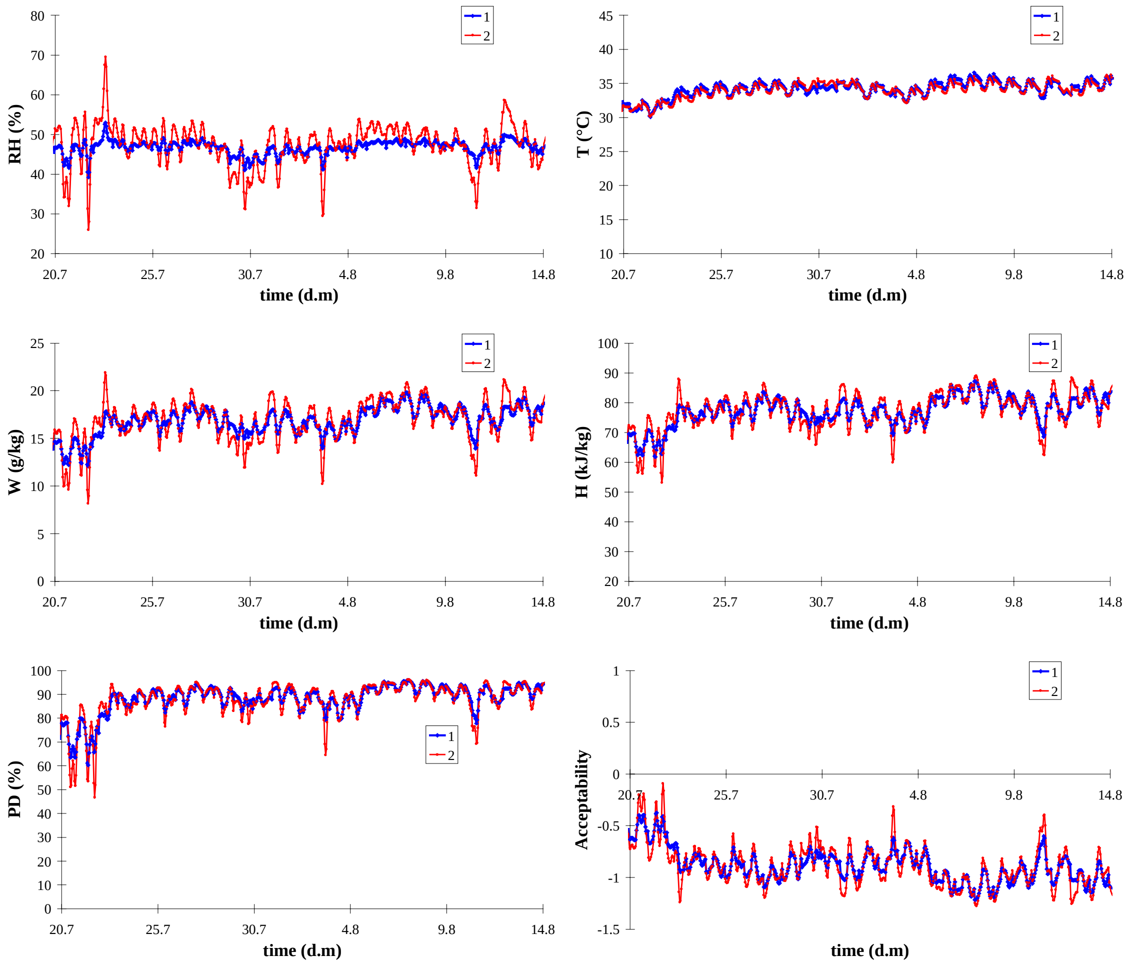


Figure B.32. Temporal variation of the important indoor air variables during a hot and humid period in Italy.

B.4.3 Humid weather (Italy)

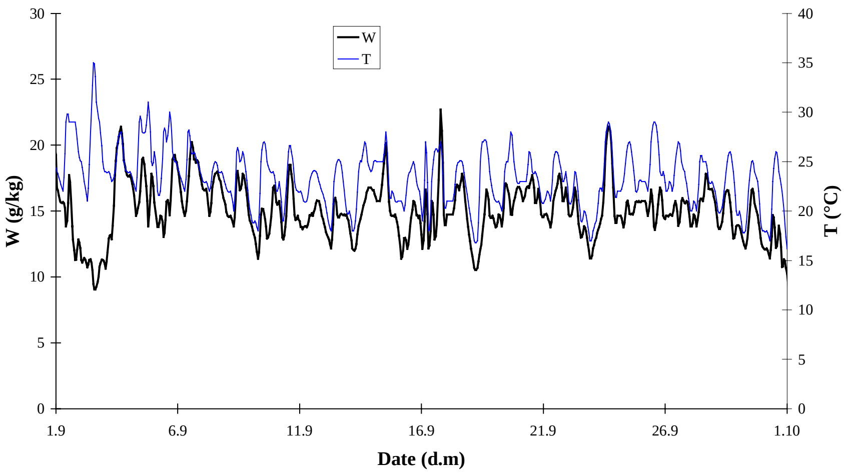


Figure B.33. Outdoor humidity and temperature during a humid period in Italy.

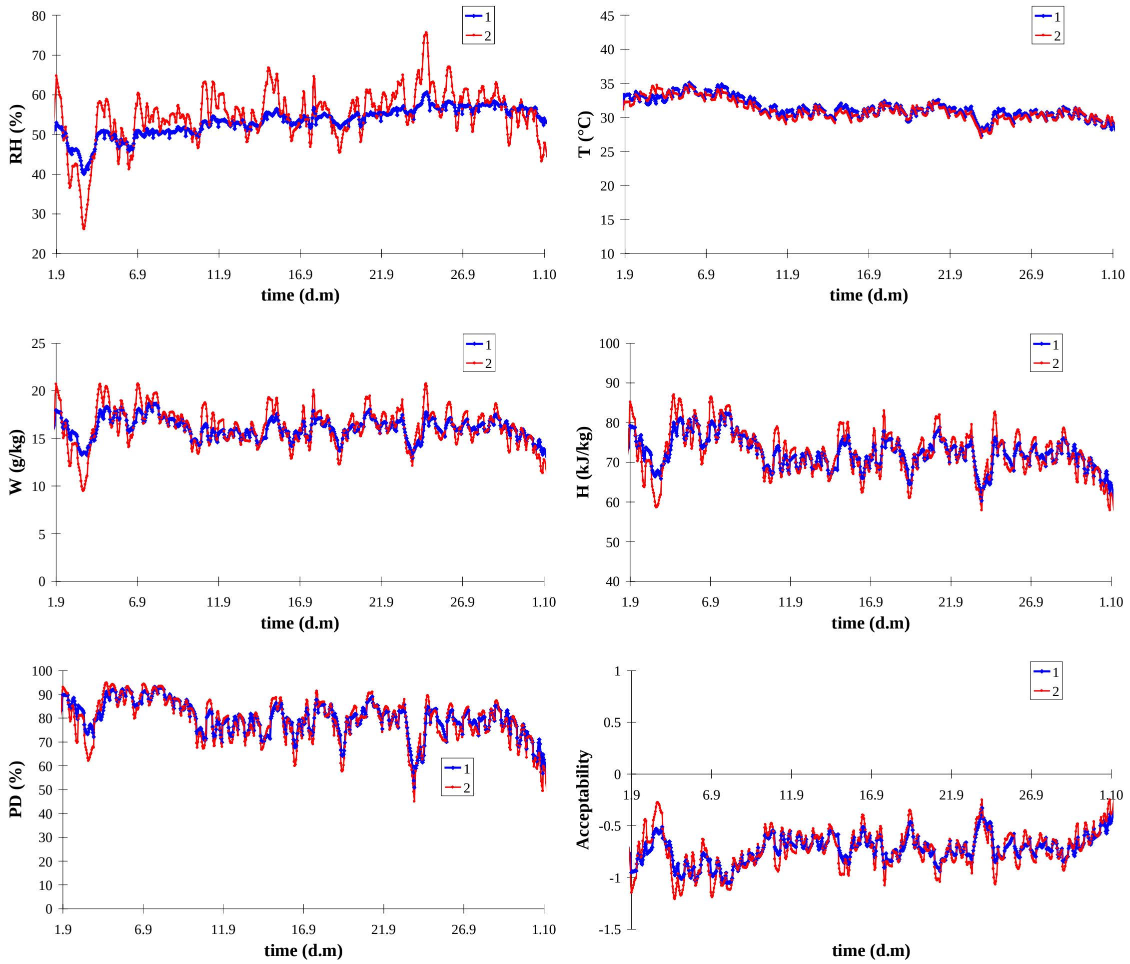


Figure B.34. Temporal variation of the important indoor air variables during a humid period in Italy.

B.4.4 Cold weather (Italy)

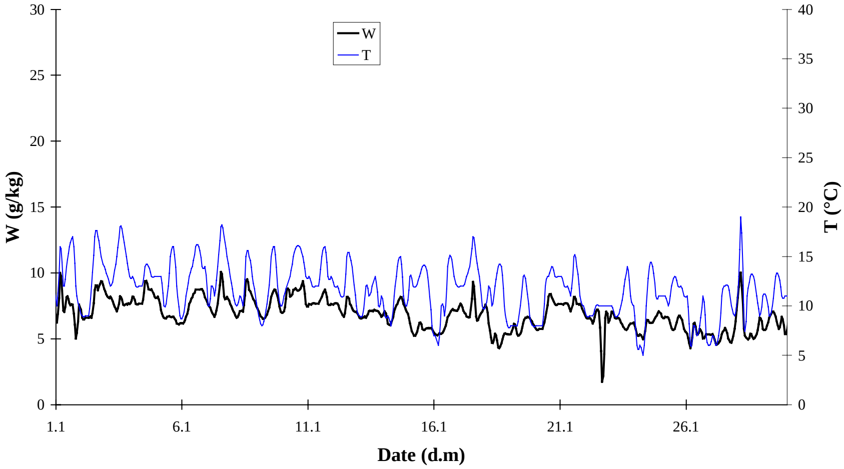


Figure B.35. Outdoor humidity and temperature during a cold period in Italy.

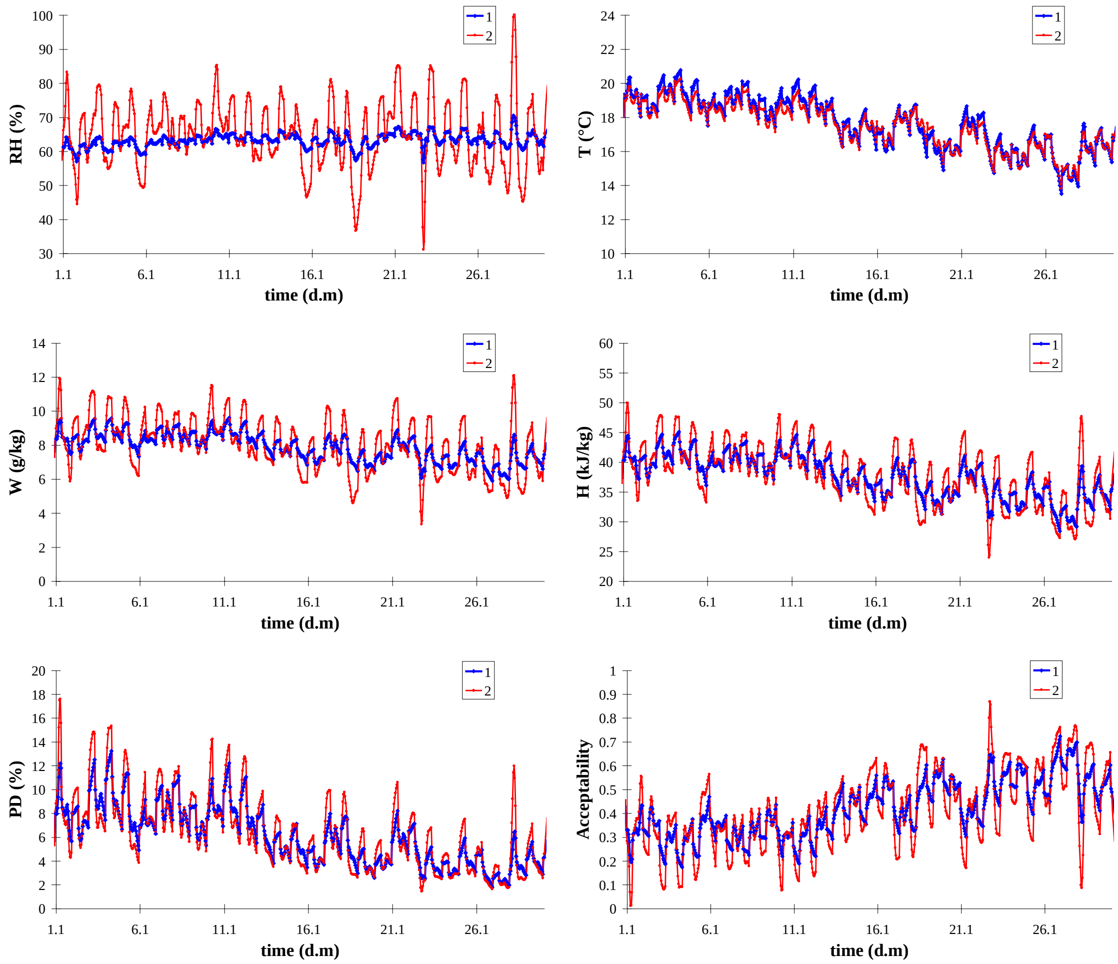


Figure B.36. Temporal variation of the important indoor air variables during a cold period in Italy.

B.4.5 Changing outdoor humidity (Italy)

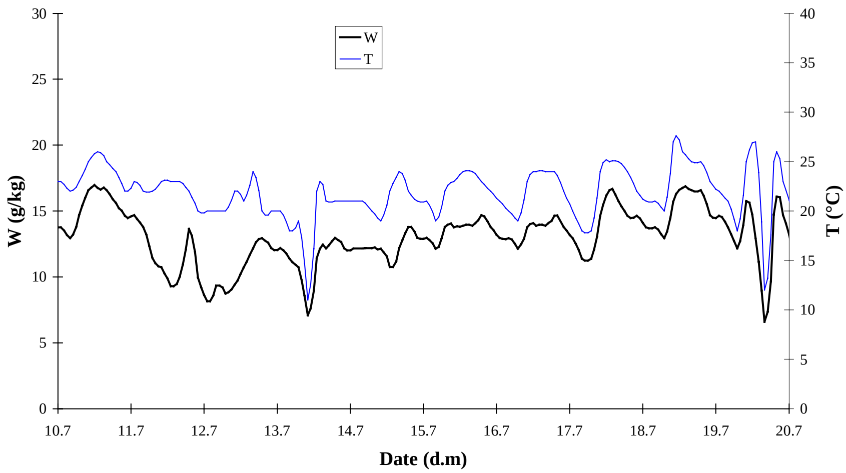


Figure B.37. Outdoor humidity and temperature during a period of changing outdoor humidity in Italy.

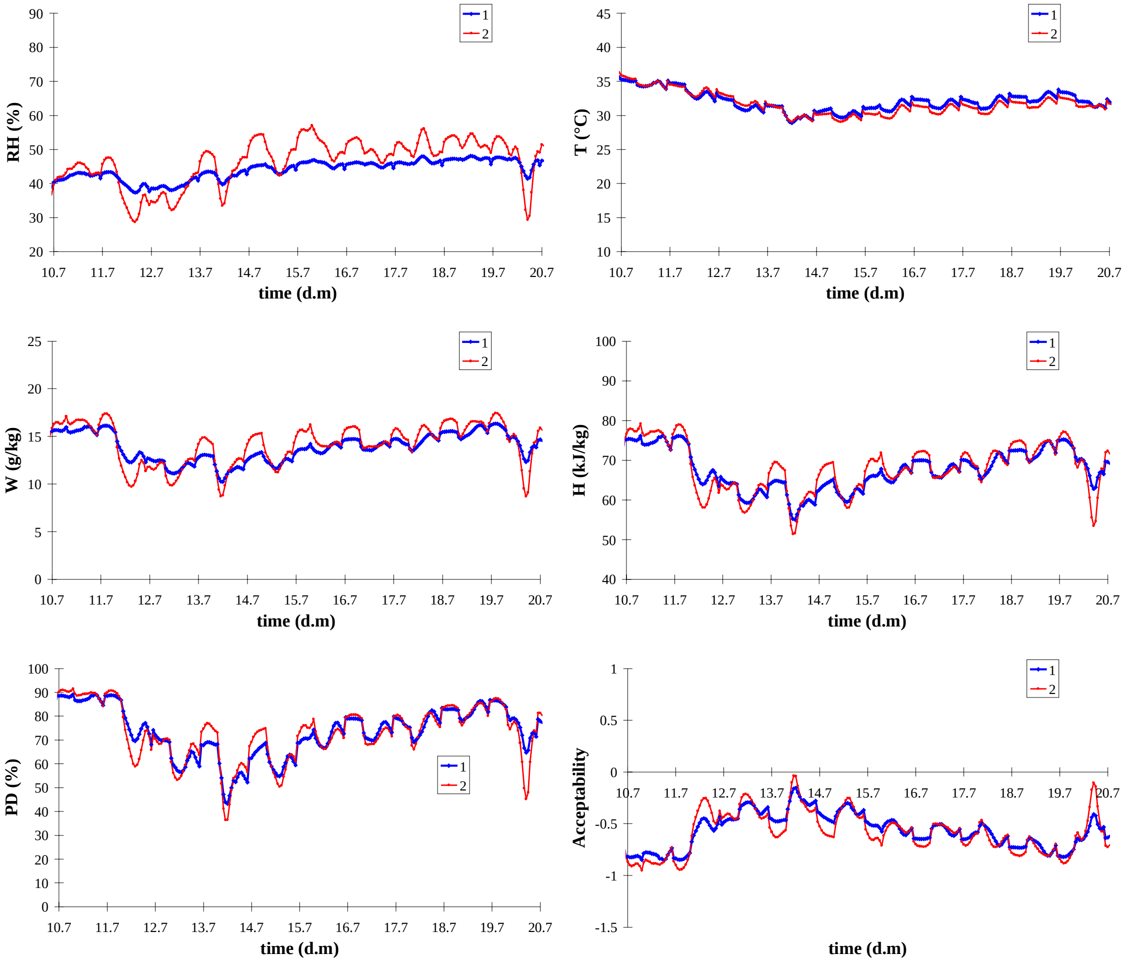


Figure B.38. Temporal variation of the important indoor air variables during a period of changing outdoor humidity in Italy.

Appendix C: Results Demonstrating the Effect of Certain Parameters on the Performance of the Room

The results in this Appendix supplement the results and discussion in sections 4.2 to 4.6 and are presented without discussion.

C.1 Effect of Insulation

Table C.1. Simulation cases which show the effect of insulation.

Case	Internal coating	Interior wallboard (11 mm)		Air/vapour barrier (0.3 mm)	Insulation (150 mm)
	permeance	hygroscopicity	permeability	permeability	hygroscopicity
1	high (v. perm. paint)	high (porous wood	high fibre board)	high (paper)	high (cellulose)
2	low (v. tight paint)	high (porous wood	high fibre board)	high (paper)	high (cellulose)
3	high (v. perm. paint)	high (porous wood	high fibre board)	high (paper)	low (mineral fibre)
4	high (v. perm. paint)	high (porous wood	high fibre board)	low (plastic)	high (cellulose)
5	high (v. perm. paint)	low (wood fibre board with	high mineral fibre sorption)	high (paper)	high (cellulose)

C.1.1 Mild Period in Belgium (May)

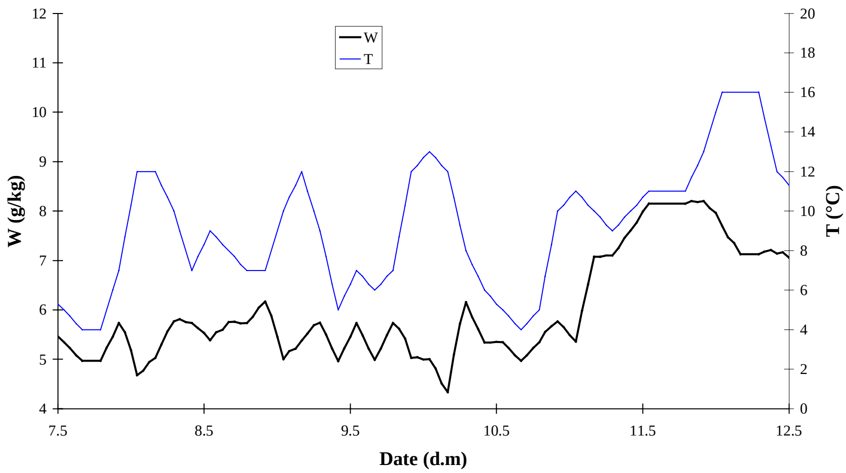


Figure C.1. Outdoor humidity and temperature during mild weather in Belgium.

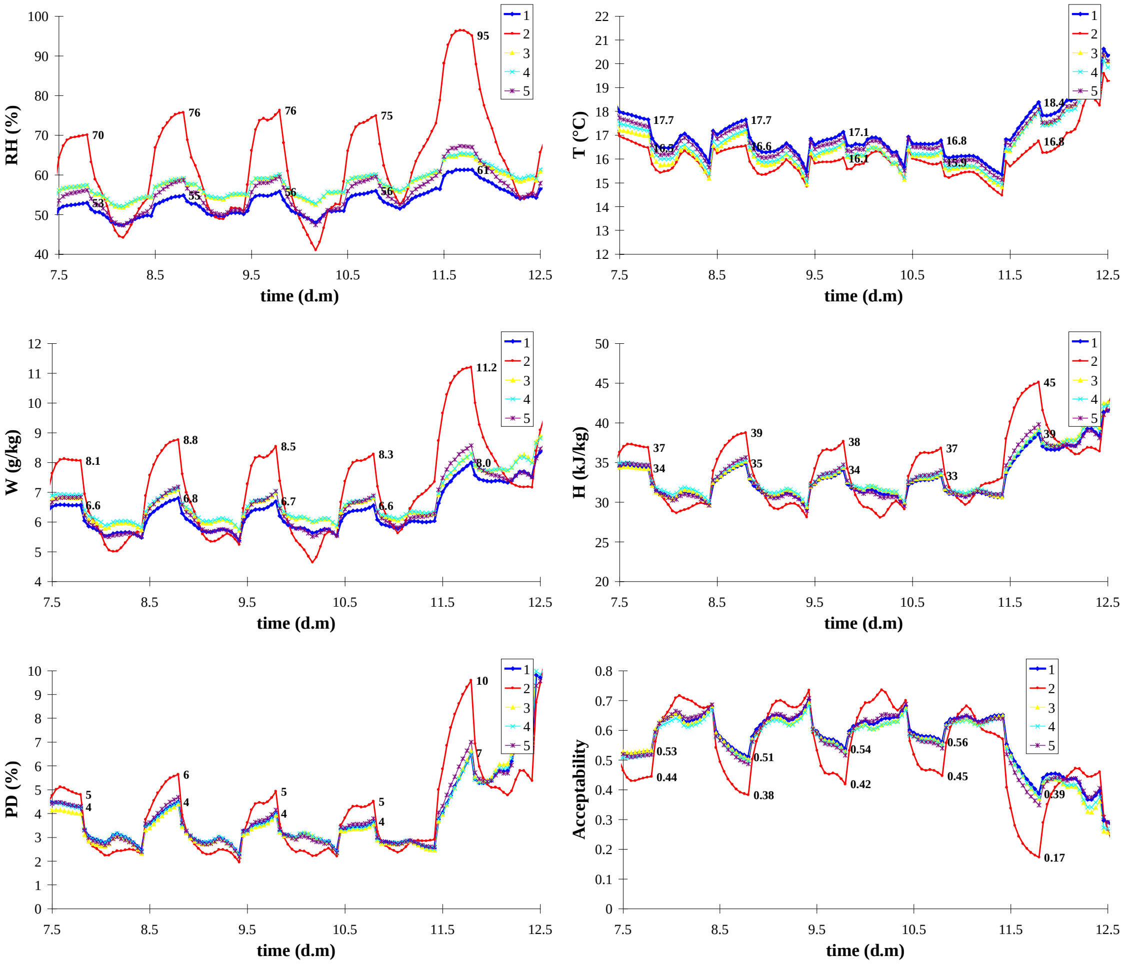


Figure C.2. Temporal variation of the important indoor air variables during mild weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

C.1.2 Dry Period in Belgium (February)

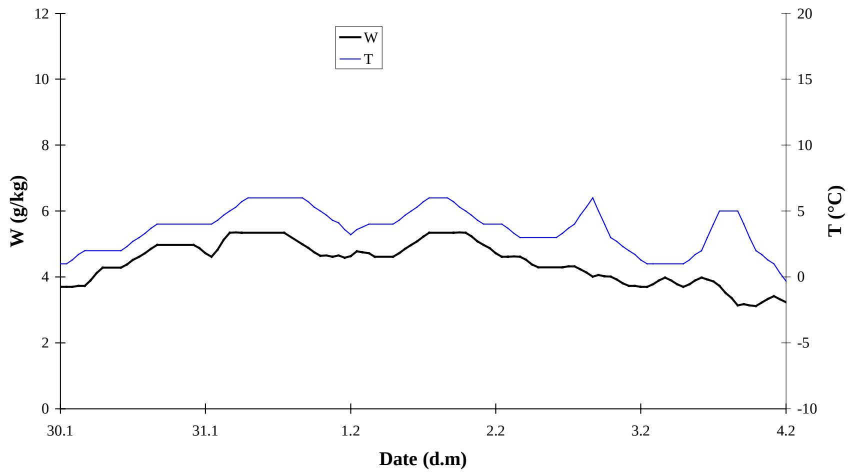


Figure C.3. Outdoor humidity and temperature during a dry period in Belgium.

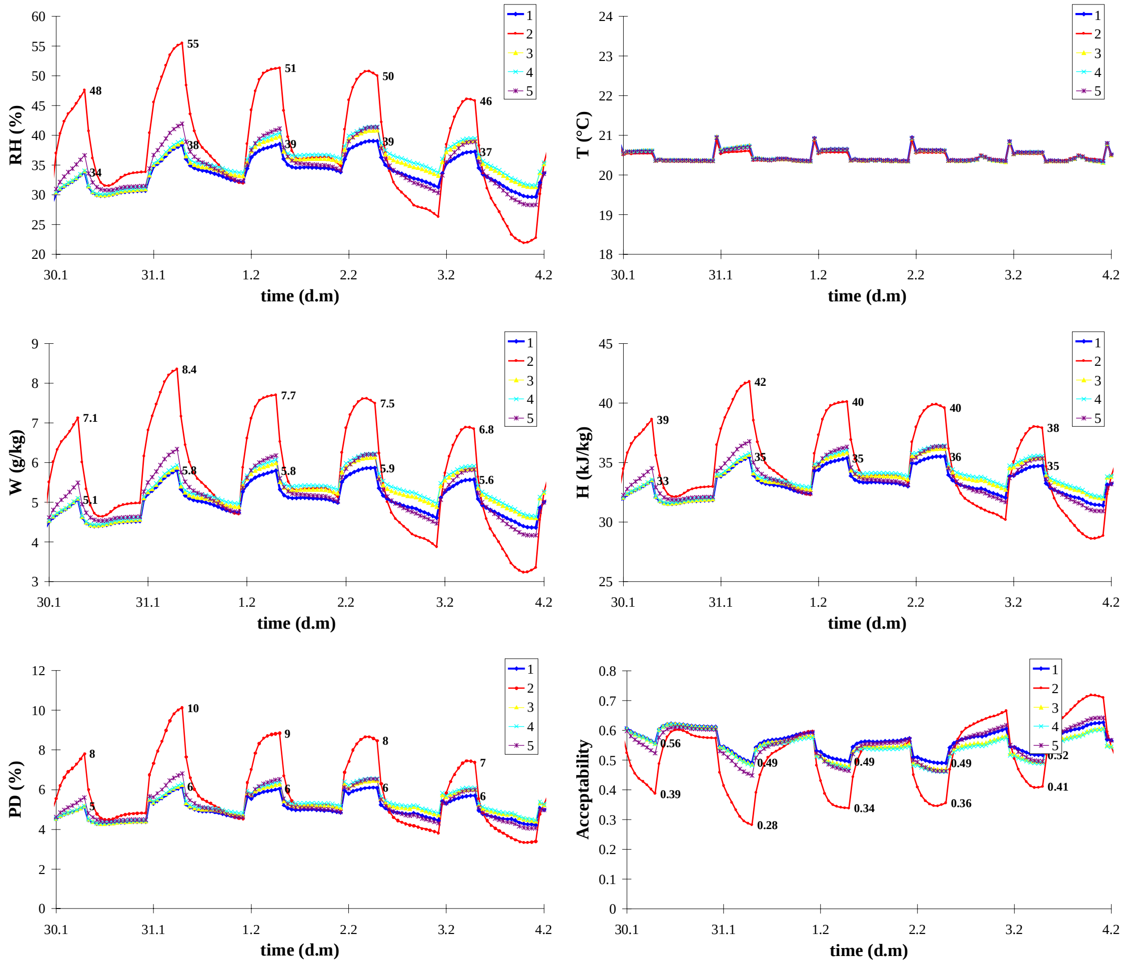


Figure C.4. Temporal variation of the important indoor air variables during dry weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

C.1.3 Performance during Occupation

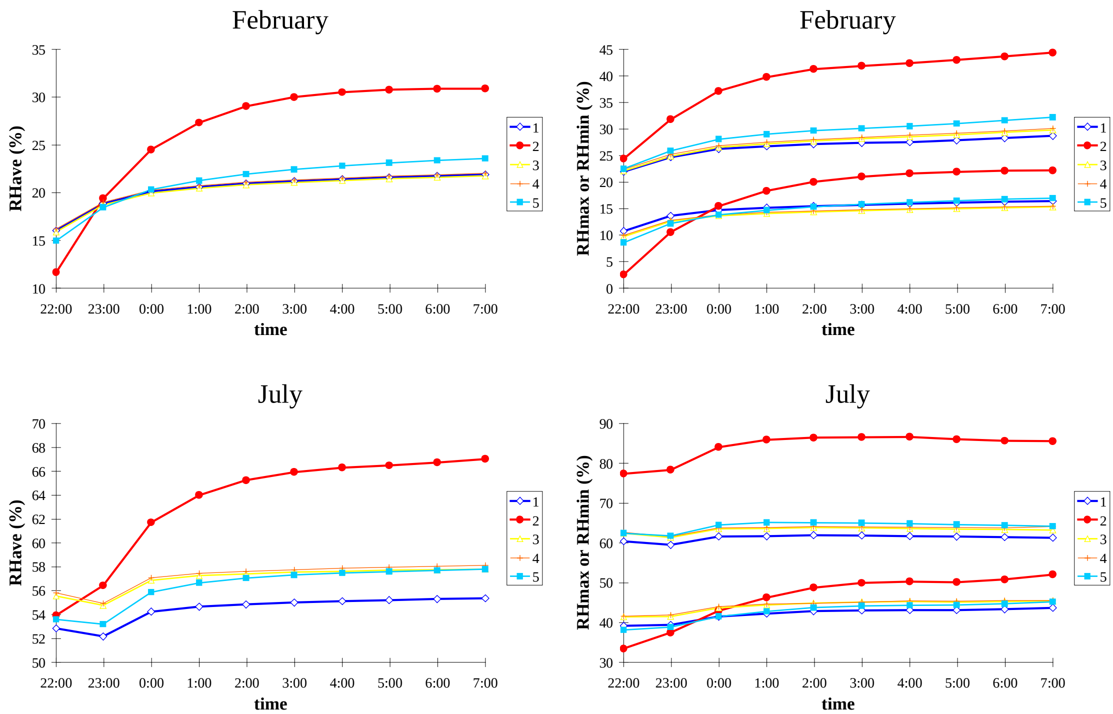


Figure C.5. Average, maximum and minimum relative humidity for each occupied hour during February and July in Finland.

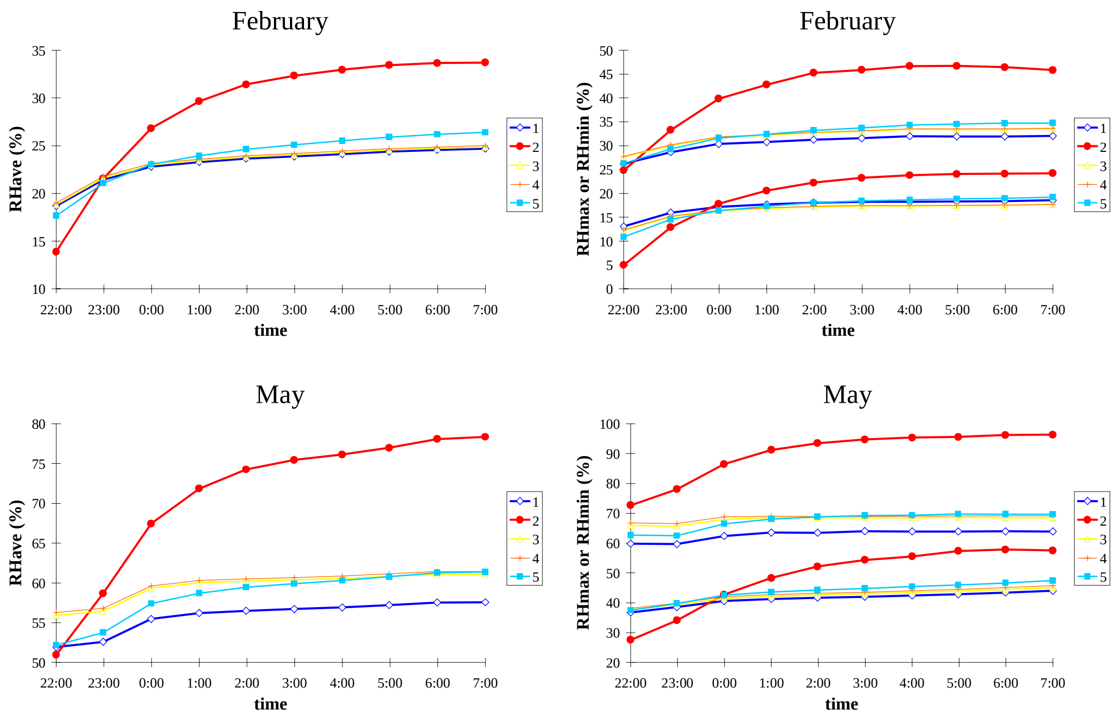


Figure C.6. Average, maximum and minimum relative humidity for each occupied hour during February and May in Germany.

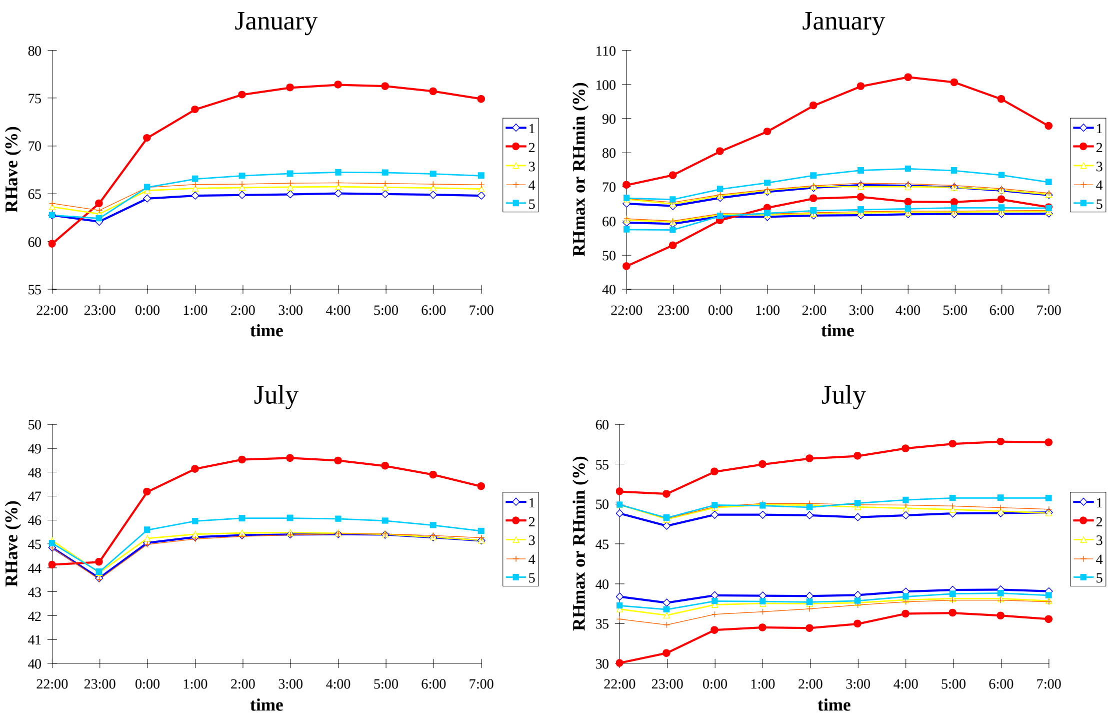


Figure C.7. Average, maximum and minimum relative humidity for each occupied hour during January and July in Italy.

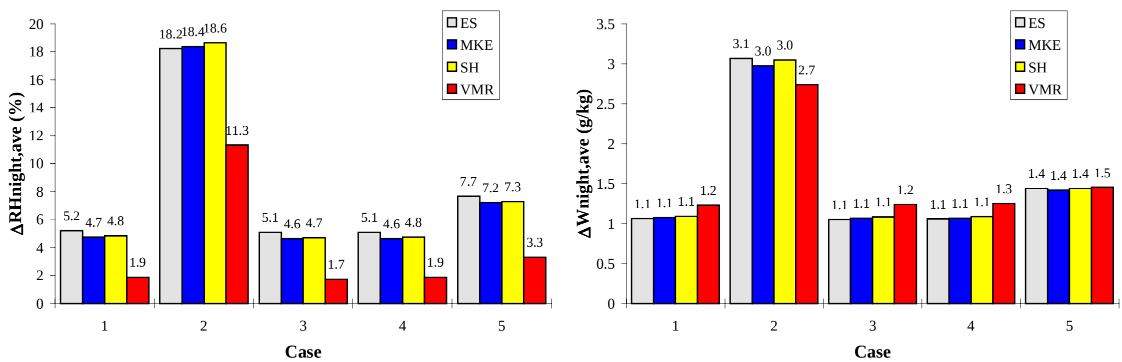


Figure C.8. Average increase in relative and absolute humidity during the night for cases 1 to 5 in all climates.

C.2 Effect of Interior Wallboard

Table C.2. Simulation cases which show the effect of the interior wallboard.

Case	Internal coating	Interior wallboard (11 mm)		Air/vapour barrier (0.3 mm)	Insulation (150 mm)
	permeance	hygroscopicity	permeability	permeability	hygroscopicity
1	high (v. perm. paint)	high (porous wood fibre board)	high	high (paper)	high (cellulose)
2	low (v. tight paint)	high (porous wood fibre board)	high	high (paper)	high (cellulose)
6	high (v. perm. paint)	high (wooden panel)	low	high (paper)	high (cellulose)
13	high (v. perm. paint)	moderate (gypsum board)	high	high (paper)	high (cellulose)

C.2.1 Mild Period in Belgium (May)

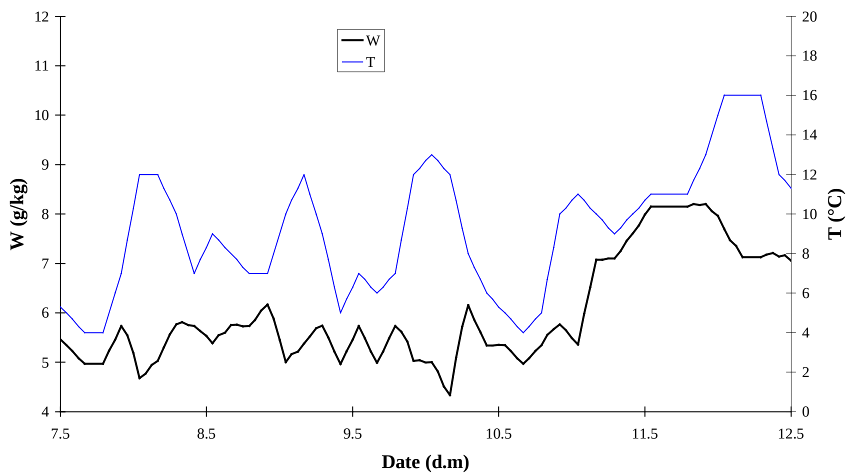


Figure C.9. Outdoor humidity and temperature during mild weather in Belgium.

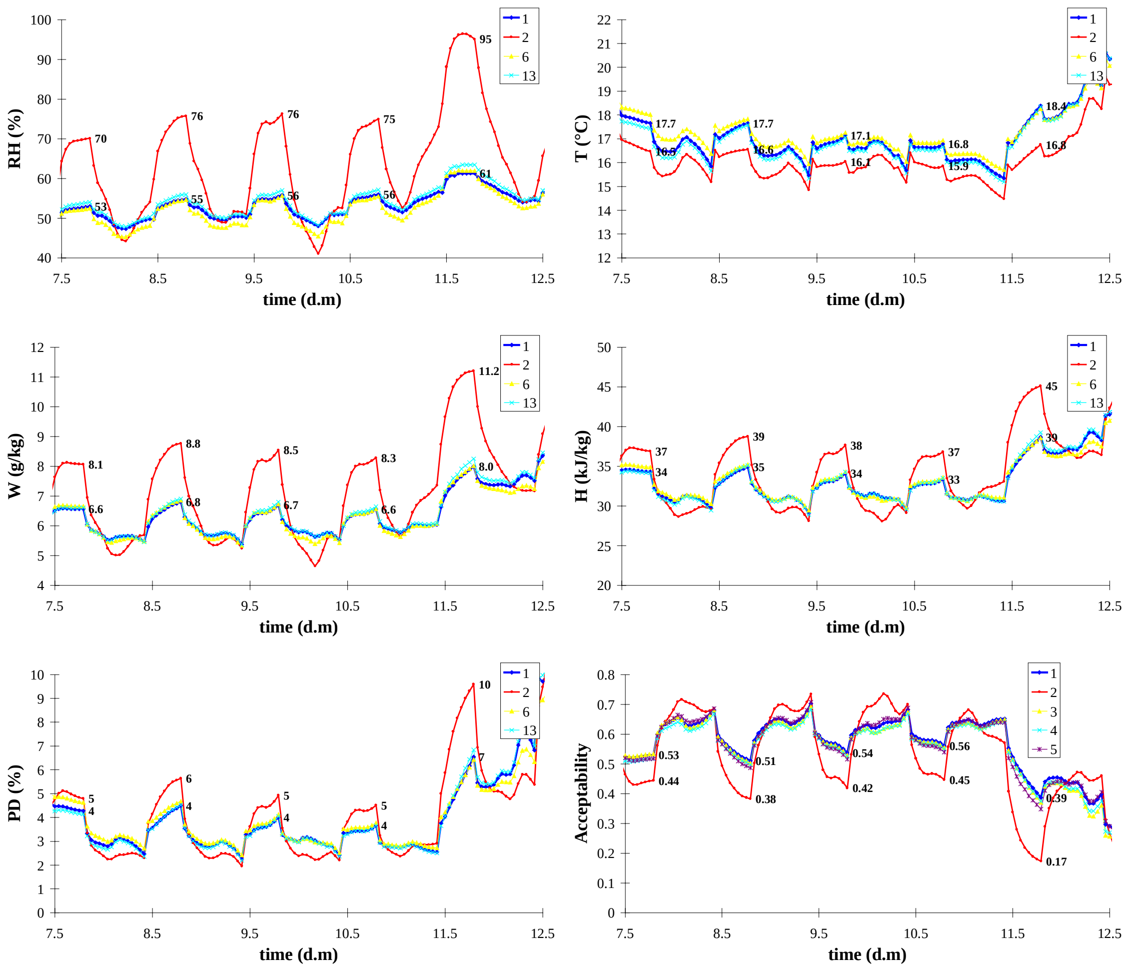


Figure C.10. Temporal variation of the important indoor air variables during mild weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

C.2.2 Dry Period in Belgium (February)

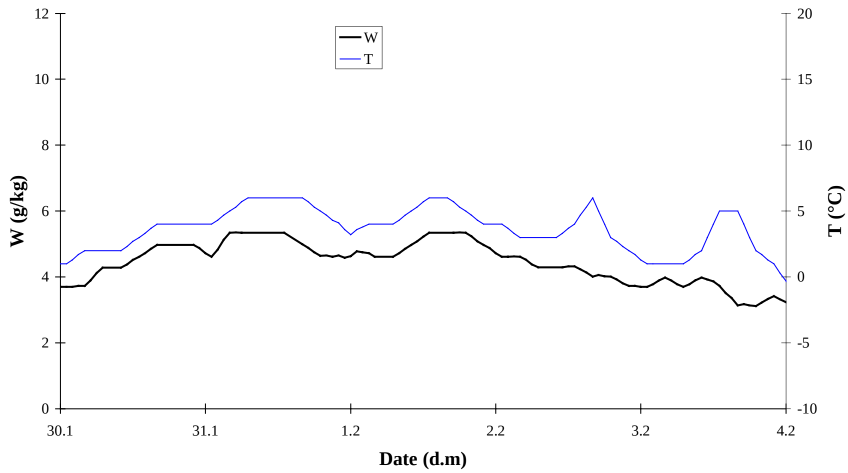


Figure C.11. Outdoor humidity and temperature during a dry period in Belgium.

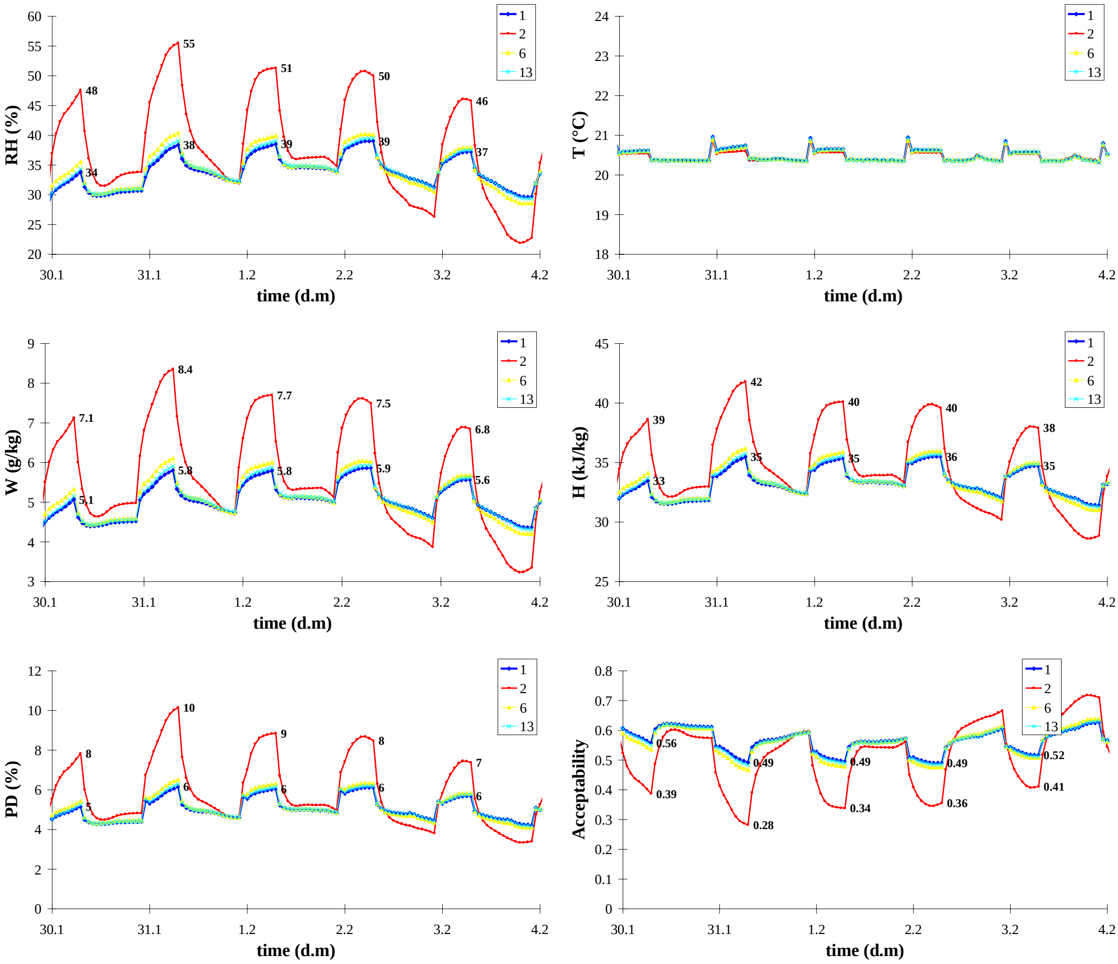


Figure C.12. Temporal variation of the important indoor air variables during dry weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

C.3 Effect of Active Area

The effect of the active area is studied in case7 and case88. In case7, the external wall and ceiling have a vapour tight paint (active area 62% of case1) and in case8, all walls have a vapour tight paint while the ceiling is permeable (active area 25% of case1). The ratio of active area of each case relative to case1 (A*) is defined as,

$$A^* = \frac{A_i}{A_1} \quad . \tag{C.1}$$

C.3.1 Mild Period in Belgium (May)

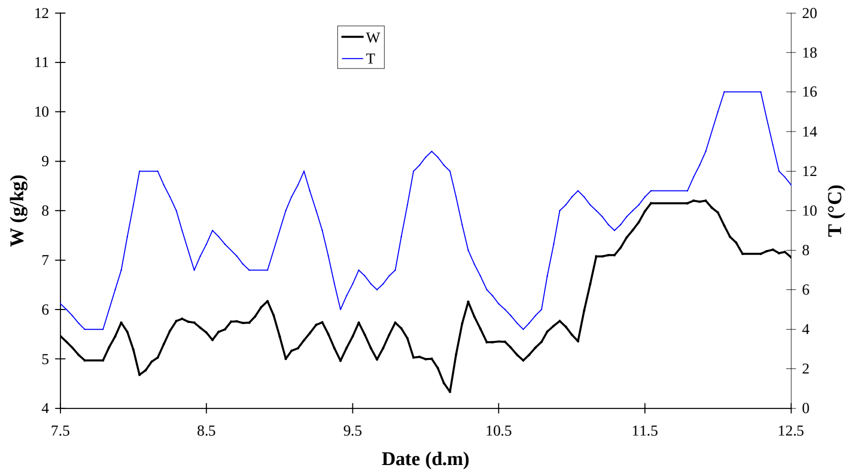


Figure C.13. Outdoor humidity and temperature during mild weather in Belgium.

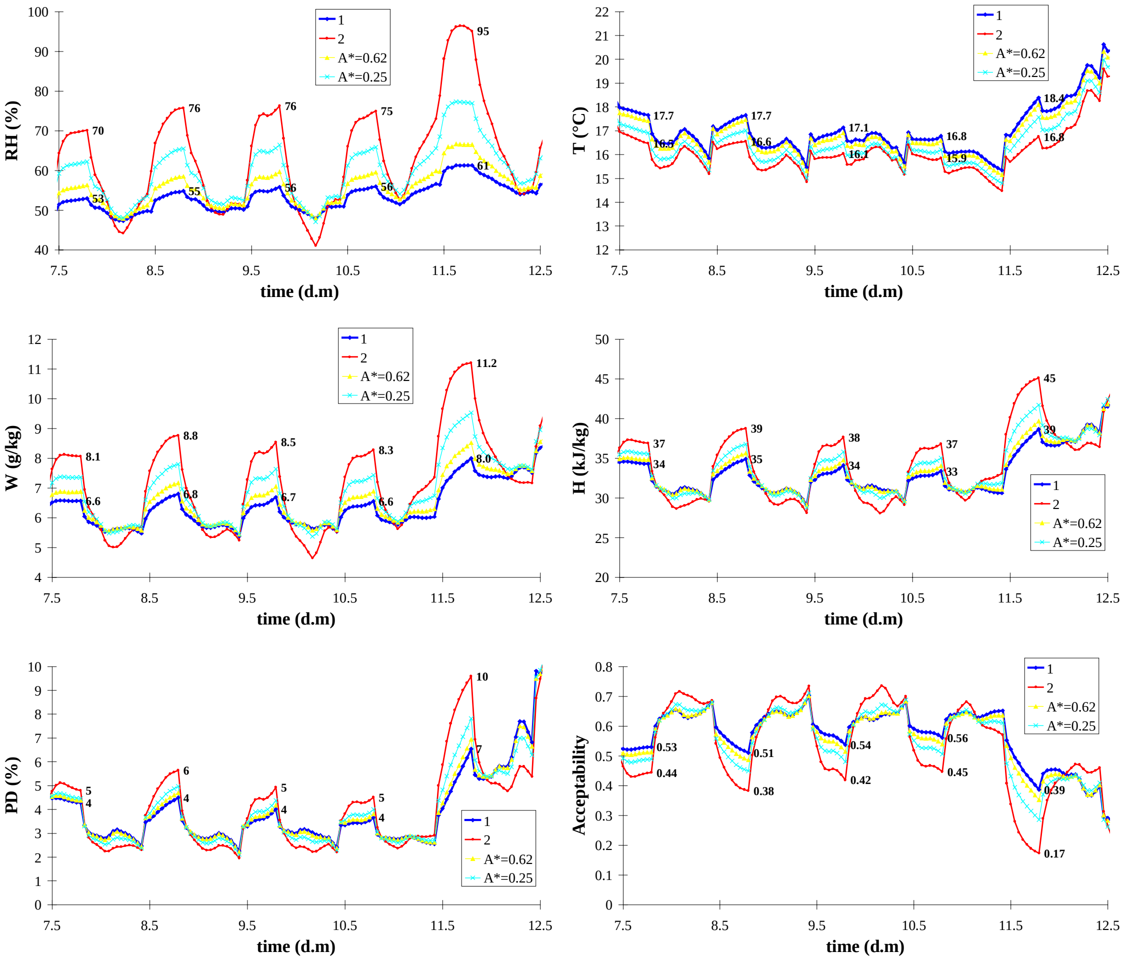


Figure C.14. Temporal variation of the important indoor air variables during mild weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

C.3.2 Dry Period in Belgium (February)

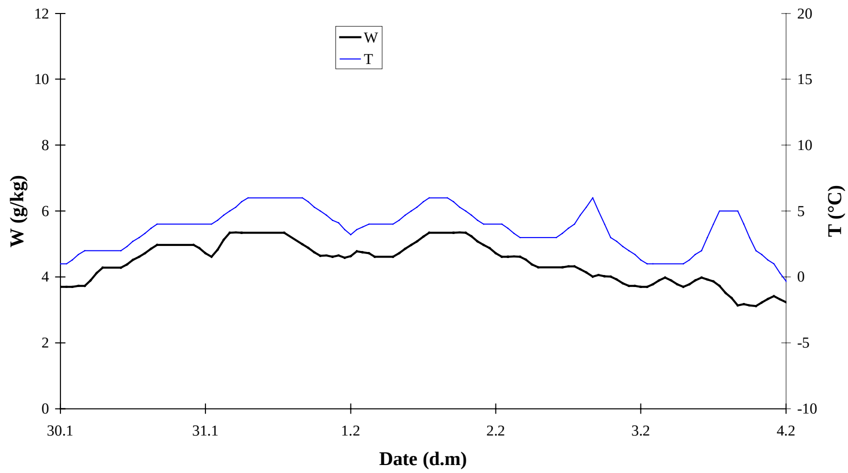


Figure C.15. Outdoor humidity and temperature during a dry period in Belgium.

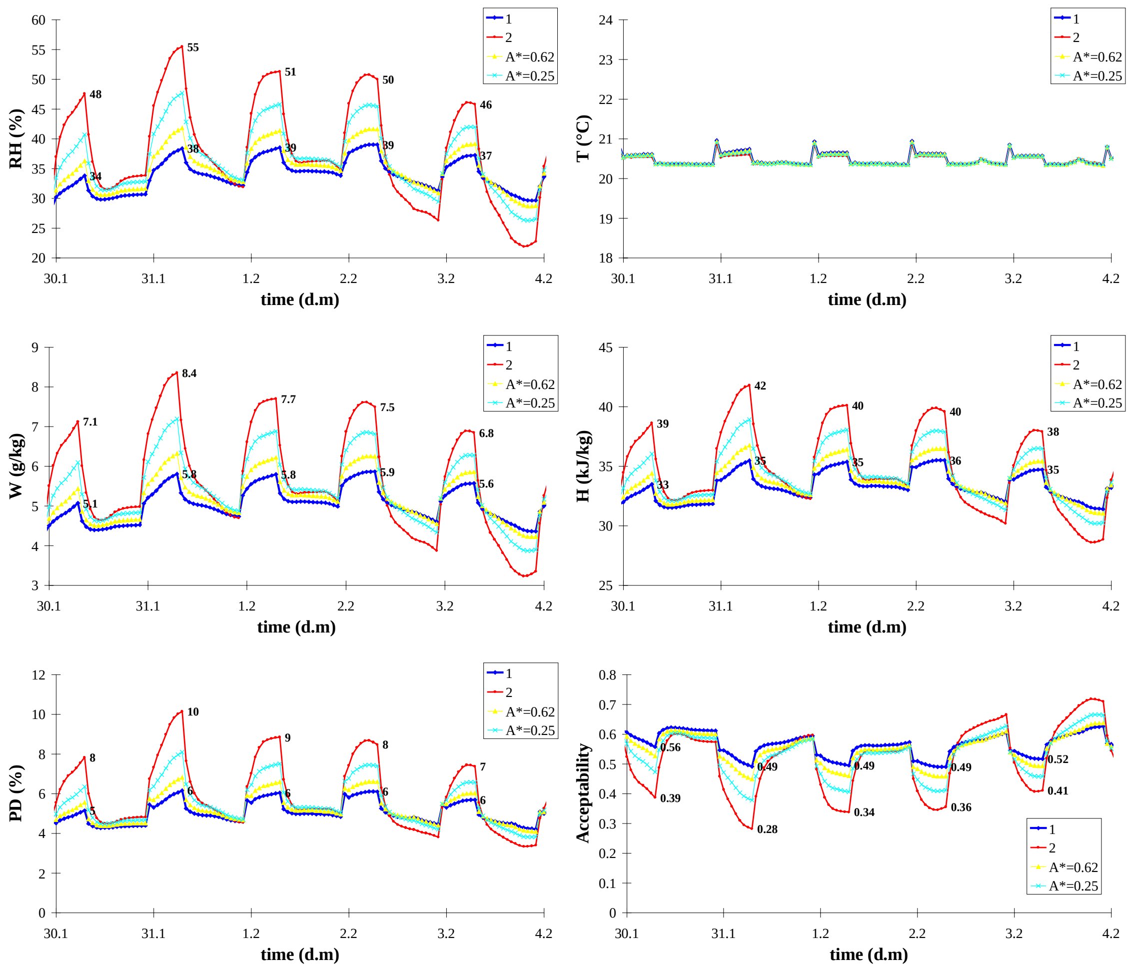


Figure C.16. Temporal variation of the important indoor air variables during dry weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

C.4 Effect of the Interior Coating

The ratio of the coating vapour resistance chosen for the sensitivity study to the ratio of the coating in case 1 (R*), will be used to distinguish between different cases, where

$$R^* = \frac{R_i}{R_1} = \frac{1}{k^*} = \frac{kd_1}{kd_i} \quad . \tag{C.2}$$

The permeability in the various cases and the values of R* and k* are as follows:

case9mp:	kd = 5 x 10^{-8} kg/(s·m^2·Pa)	R* = 0.1	k* =10
case1:	kd = 5 x 10^{-9} kg/(s·m^2·Pa)	R* = 1	k* = 1
case9:	kd = 1 x 10^{-9} kg/(s·m^2·Pa)	R* = 5	k* =0.2
case9lp:	kd = 5 x 10^{-10} kg/(s·m^2·Pa)	R* = 10	k* = 0.1
case2:	kd = 5 x 10^{-12} kg/(s·m^2·Pa)	R* = 1000	k* = 0.001

It should be noted that for convection mass transfer in a well-mixed room, the permeance of the surface is expected to be 3 x 10^{-8} kg/(s·m^2·Pa) (R*=0.16).

C.4.1 Mild Period in Belgium (May)

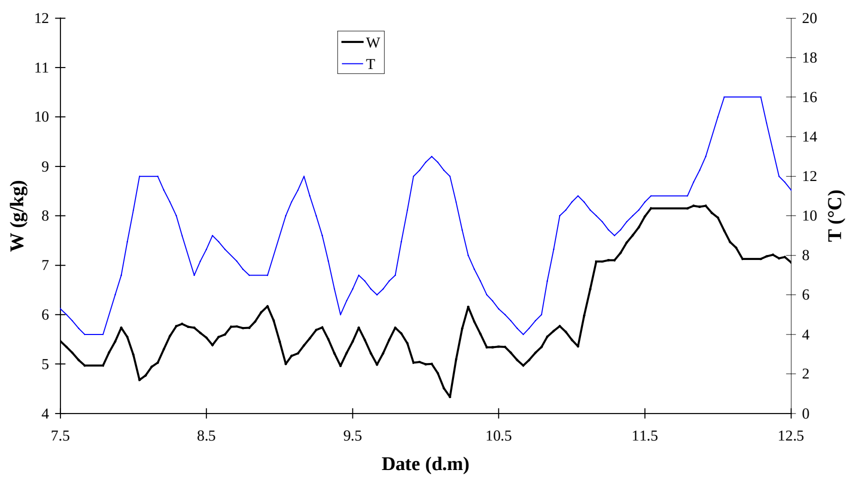


Figure C.17. Outdoor humidity and temperature during mild weather in Belgium.

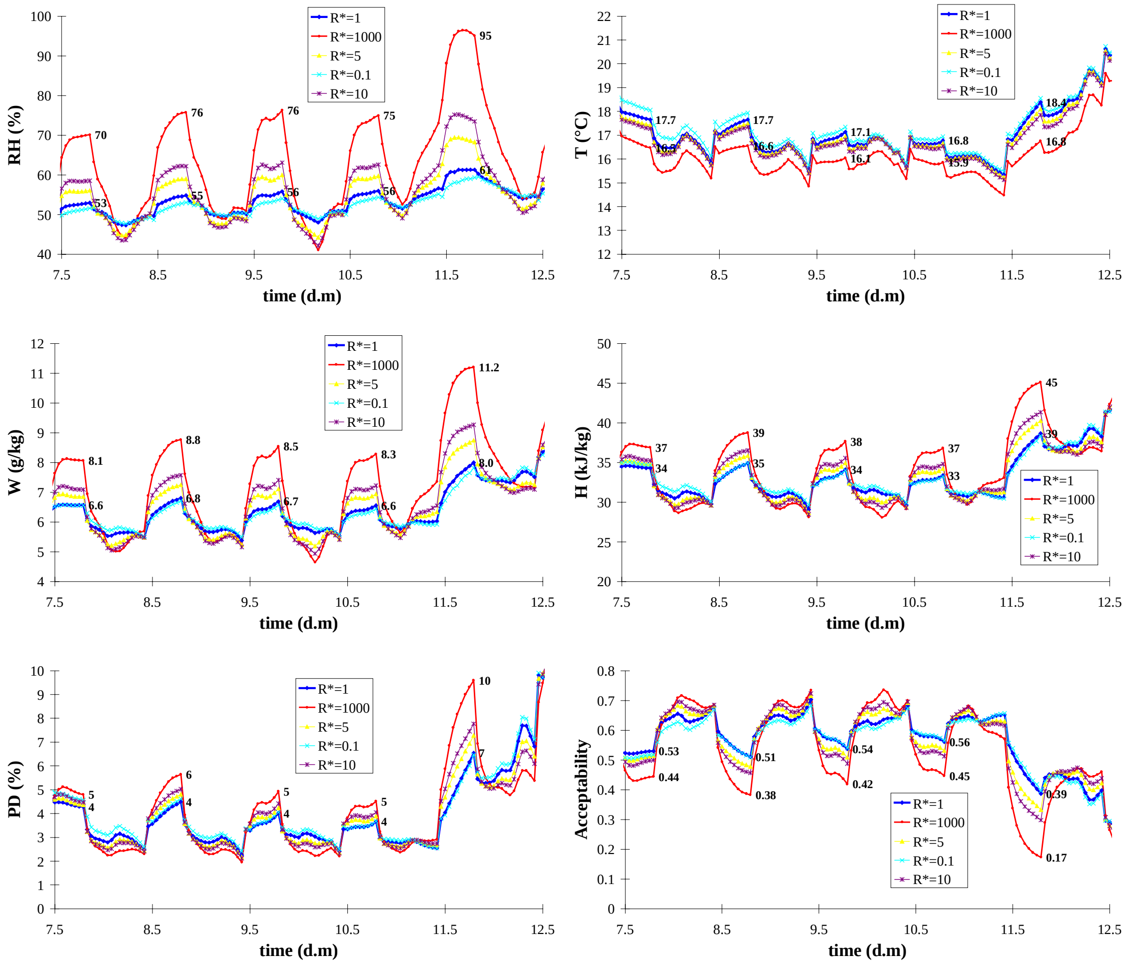


Figure C.18. Temporal variation of the important indoor air variables during mild weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

C.4.2 Dry Period in Belgium (February)

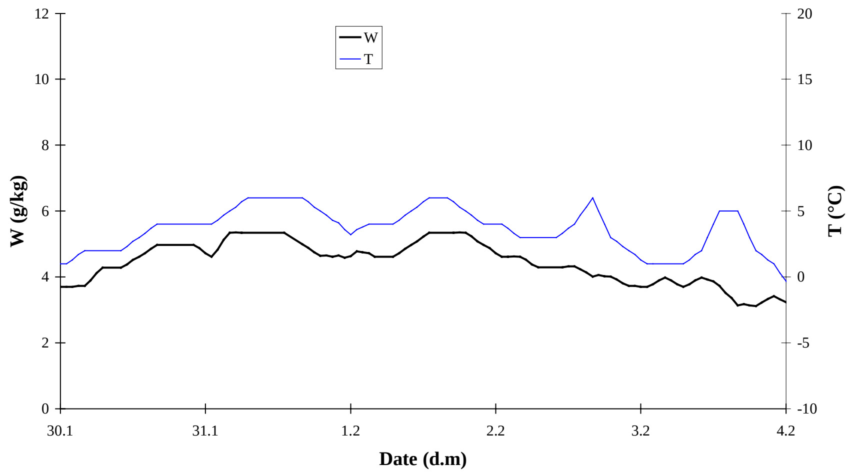


Figure C.19. Outdoor humidity and temperature during a dry period in Belgium.

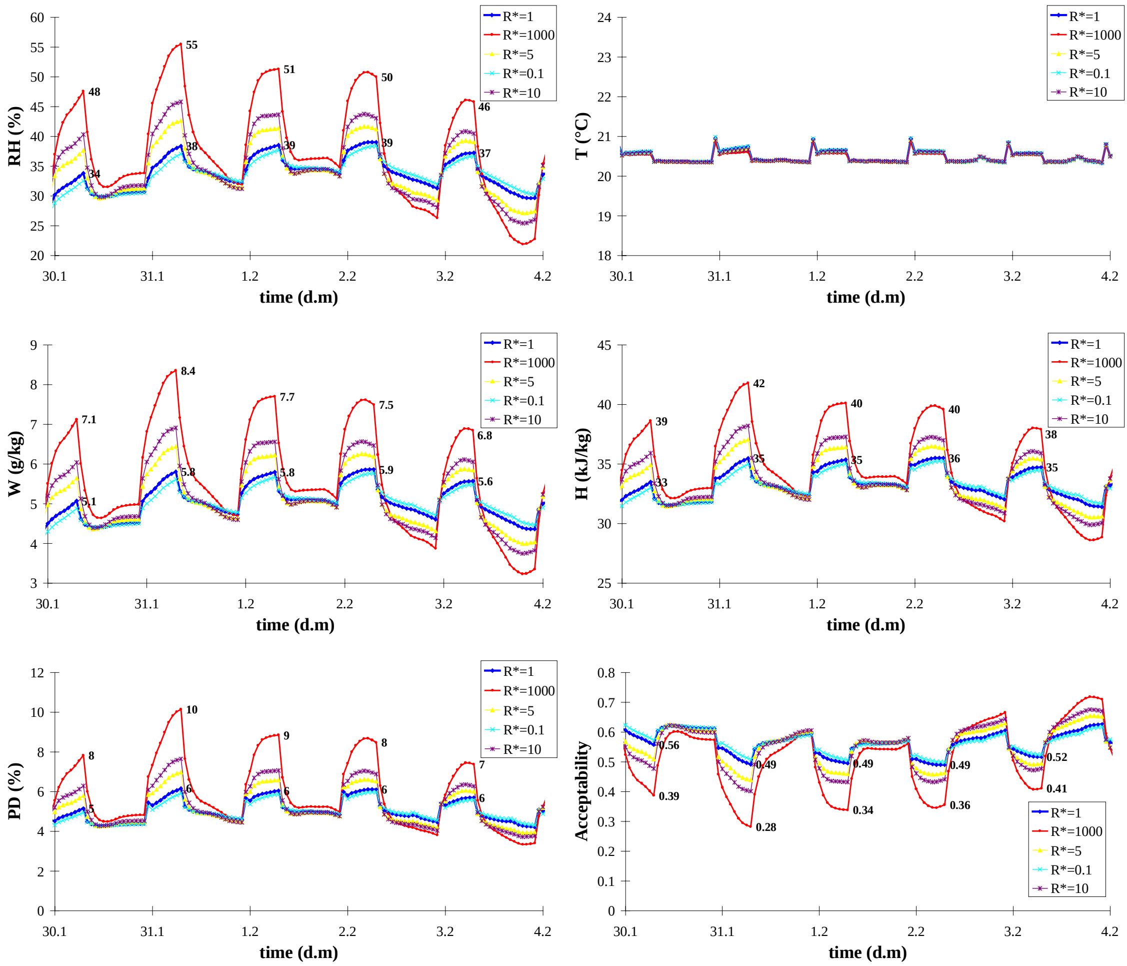


Figure C.20. Temporal variation of the important indoor air variables during dry weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

C.5 Effect of Thermal Mass

Table C.3. Simulation test cases showing the effect of thermal mass.

Case	Internal coating	Interior wallboard (11 mm)		Air/vapour barrier (0.3 mm)	Insulation (150 mm)
	permeance	hygroscopicity	permeability	permeability	hygroscopicity
1	high (v. perm. paint)	high (porous wood fibre board)	high	high (paper)	high (cellulose)
2	low (v. tight paint)	high (porous wood fibre board)	high	high (paper)	high (cellulose)
10	Same as case1, except the floor and ceiling are massive (i.e., 200 mm of concrete) with impermeable coatings				
11	Same as case10, except the interior wallboard is massive wood (125 mm log)				
12	Same as case10, except the interior wallboard is less massive wood (50 mm log)				
14	Same as case11, except the massive ceiling and floor are wood (200 mm)				

C.5.1 Mild Period in Belgium (May)

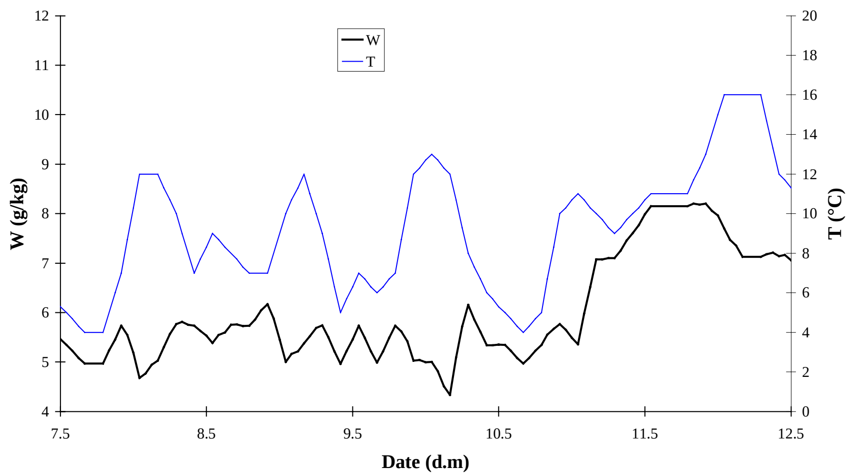


Figure C.21. Outdoor humidity and temperature during mild weather in Belgium.

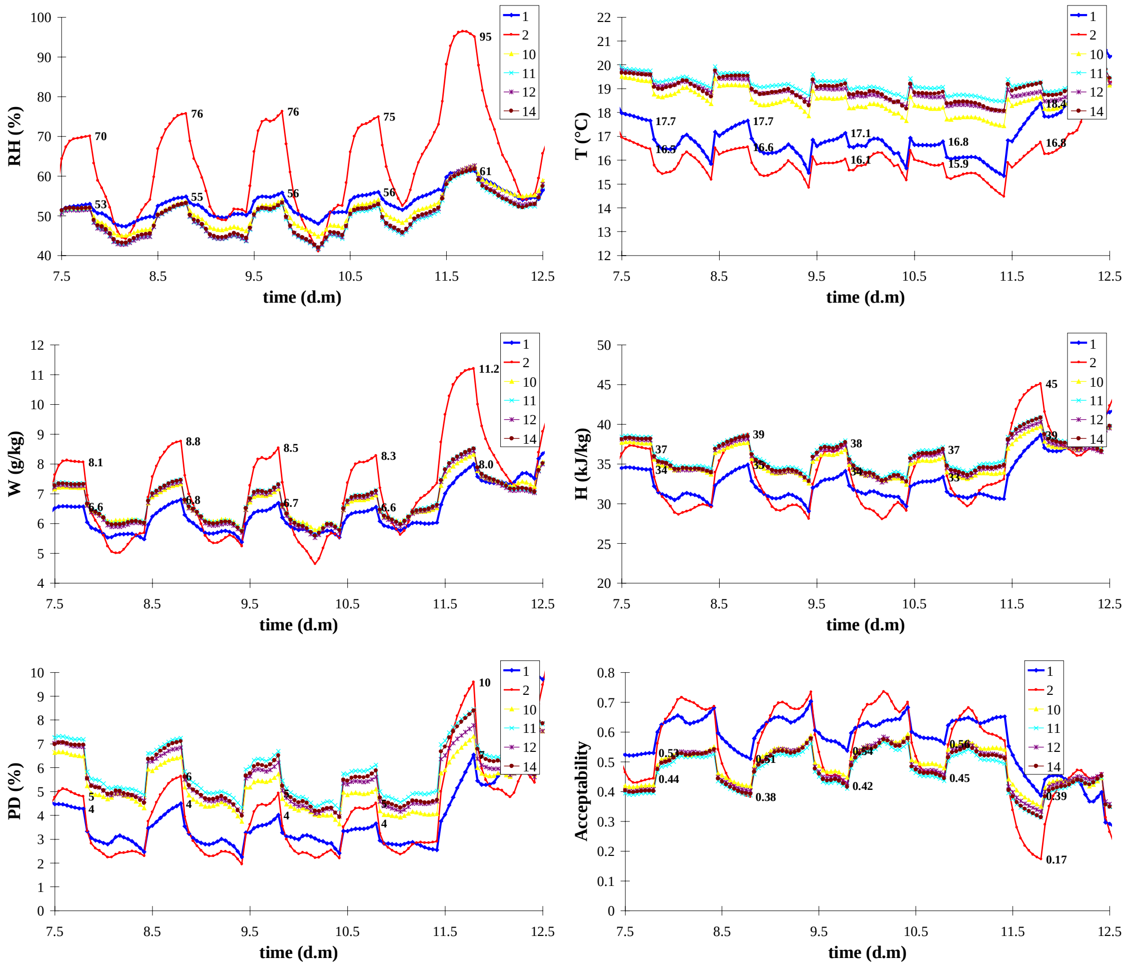


Figure C.22. Temporal variation of the important indoor air variables during mild weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

C.5.2 Dry Period in Belgium (February)

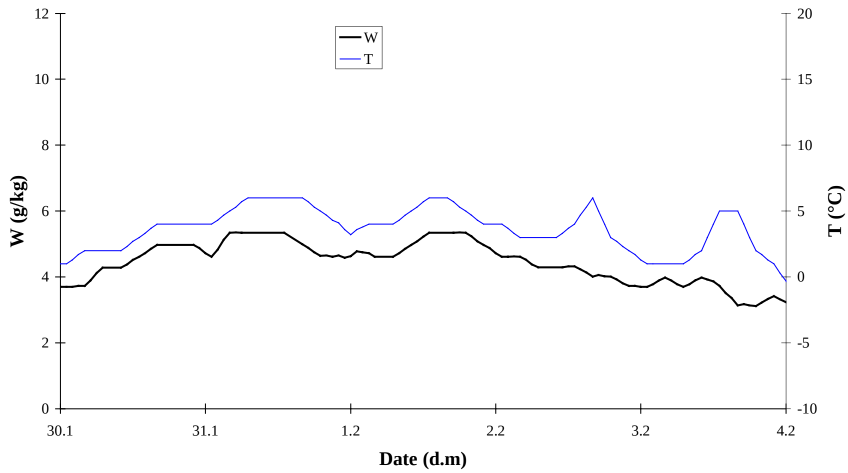


Figure C.23. Outdoor humidity and temperature during a dry period in Belgium.

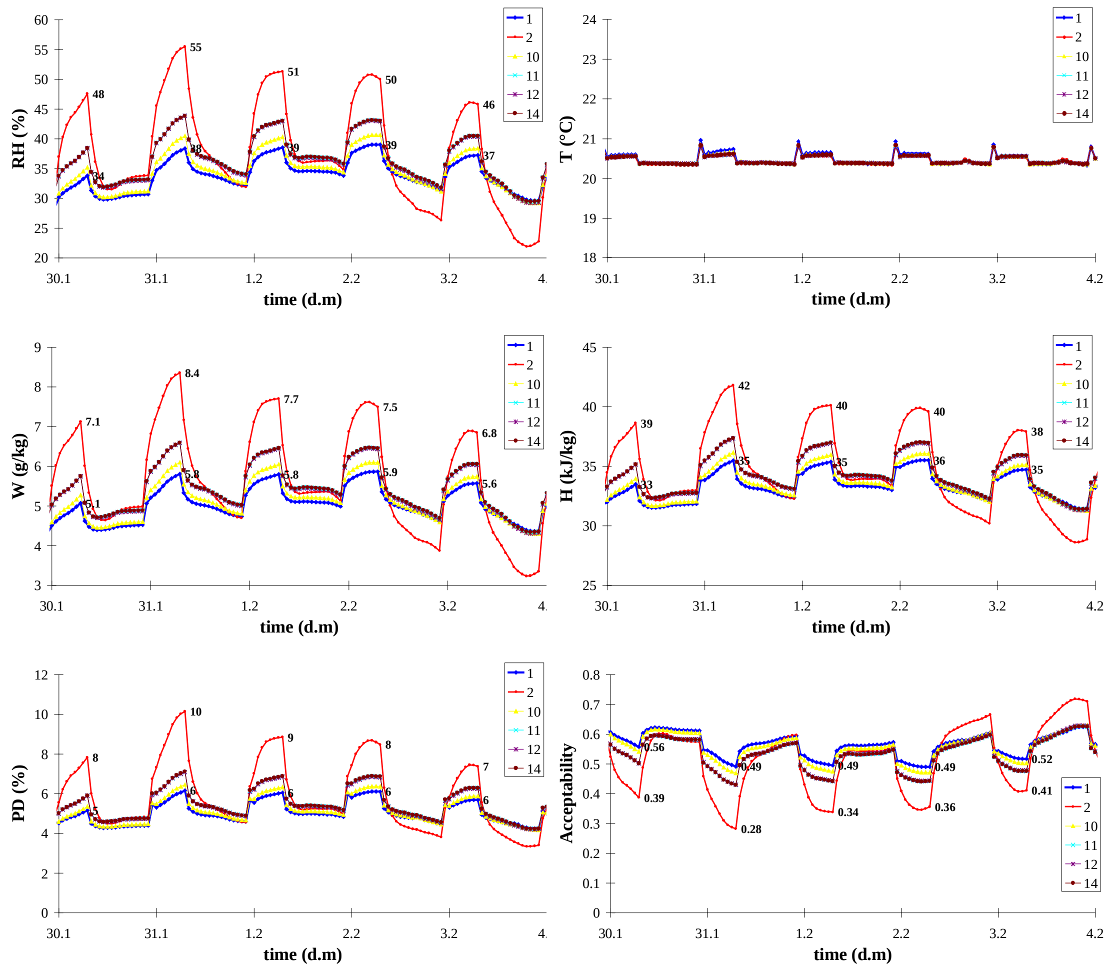


Figure C.24. Temporal variation of the important indoor air variables during dry weather in Belgium. (The values at the end of occupation (7:00) are in each graph.)

Appendix D: Reviewers' Evaluations

This report has been reviewed and evaluated by the following researchers and their comments are included in this appendix:

- Dr. Hartwig M. Künzel, Fraunhofer Institut Bauphysik, Holzkirchen, Germany;

- Dr. Jarek Kurnitski, Helsinki University of Technology, HVAC-Laboratory, Espoo, Finland; and

- Simo Koponen, Helsinki University of Technology, Laboratory of Structural Engineering & Building Physics, Espoo, Finland.

D.1 Dr. Hartwig M. Künzel, Fraunhofer Institut Bauphysik, Holzkirchen, Germany

D.1.1 General remarks

This report is an innovative attempt to estimate the importance of the vapor sorption capacity of wood based building materials for indoor comfort conditions. Because building engineers are realizing that the transient behavior of buildings and building components cannot be adequately described by steady state methods the importance of thermal mass is now widely acknowledged. However, most practitioners are unaware of the importance of moisture capacity. Therefore the work described in this report should be disseminated and continued in order to introduce this new concept to building scientists and architects.

D.1.2 Introduction

The introduction stresses the importance of the indoor air humidity for human comfort, both thermal comfort and perceived air quality. The fact that a change of 5 % R.H. has a similar effect on percentage of dissatisfied as a temperature change of 1 K and that a lot of energy is needed to remove latent heat might be common knowledge in North America but it is rather new to most European building practitioners. The introduction contains valuable information and explains why passive control of the temperature and humidity conditions in dwellings could help to save energy compared to active control by HVAC systems.

D.1.3 Healthy Buildings 2000, Workshop 10

This workshop dealt with the effect of wood based materials on indoor air quality and climate. Experts from many different countries agreed that the moderating effect of wood based materials on the indoor climate is likely to improve human comfort conditions compared to non hygroscopic and vapor retarding envelope materials. It was felt that more research is necessary in order to quantify and optimize the passive indoor climate control. The project report appears to be a first successful step in order to answer some of the questions put forward by the conclusions of workshop 10.

D.1.4 Input Data and Numerical Model

The division of this chapter into different topics is not rigorous, e.g. indoor climate related data appear in 3.1 and 3.3 (heat and moisture sources).

D.1.4.1 Description of Bedroom

Due to the rather simple description of the occupation conditions (people who sleep are unlikely to severely alter the ventilation and moisture production in the room and if they do not sleep they will normally not stay in the room for long) a bedroom appears to be a good choice to start realistic numerical simulations. The bedroom has a wall surface to volume ratio (A/V) of 1.2 and an external wall with a window facing west. If ceiling and floor consist of the same materials as the walls the total humidity buffering envelope area is ca. 60 m² (A/V = 1.9). The solar radiation into the window is reduced to 25% by venetian blinds. The absorption coefficient of the wall represents with 0.8 (dark color) a worse case scenario for summer conditions (dark wall colors are for obvious reasons rarely applied in Southern Italy). The hygrothermal capacity of the envelope materials is the only storage quantity considered. Furniture, clothes, blankets and mattresses which are generally present in a bedroom will provide additional humidity buffering capacity and also some thermal mass to the whole room.

D.1.4.2 Indoor and Outdoor Climate

The indoor temperature is set to at least 20 °C during the heating season. According to a representative investigation in 2000 German dwellings the mean bedroom temperature was 15.5 °C ± 3 K [1]. Even lower bedroom temperatures are reported from the United Kingdom [2]. A lower indoor air temperature leads to a higher relative humidity which means that the simulation results represent a worst case scenario concerning the air dryness during the heating season. The fact that the only moisture production source in the bedroom are the 2 persons sleeping there, points in the same direction. In reality there might be additional sources like plants, moisture from cleaning or bathrobes and humid air infiltration from other rooms. Also additional internal heat sources might be present like TV, radio, etc. This could have a negative effect in summertime which seems, however, covered by the worse case scenario “dark external wall color”.

The outdoor climate data seem well chosen to represent typical conditions in Western Europe. However, a more detailed presentation of the meteorological data employed for the simulation would be desirable (e.g. typical diurnal variation of temperature and relative humidity, solar radiation incidence) in order to get a feeling for the climate differences in Europe. It should be pointed out that the West orientation is probably the worst case for a bedroom under summer conditions.

D.1.4.3 Numerical Model

The explanation of the extended LATENITE model for the hygrothermal building simulation is very vague. It would be interesting to know how the latent heat effects are treated (e.g. heat of evaporation/condensation + average heat of sorption for employed materials) and how large is their influence on the energy balance of the bedroom ? Is the solar radiation absorbed by the floor only or is it distributed over the whole envelope? A flow chart would help to understand how the extended model works and what input data are required. The material parameters employed are taken from the LATENITE database. It would be interesting to see how the practical range of material parameters influences the calculation results (stochastic analysis).

D.1.5 Numerical Results

The calculation results are plausible. However, an experimental validation of the results for one or two cases would be desirable. Without such a validation the results can only assess qualitatively the real hygrothermal behavior of a bedroom. However, the experience with hygrothermal simulations has shown that even without experimental validation, the comparison of effects from different parameters can be done rather accurately. This means that the differences in the calculated hygrothermal behavior due to alternative envelope materials can be expected to be realistic provided that the material data are realistic.

D.1.6 Conclusions

It is always tricky to draw general conclusions from a specific case study, especially when only calculation results are available. The conclusions indicate how the calculation results translate into practice under the selected boundary conditions. However, some questions remain:

Could the effect of the hygroscopic insulation material be overestimated considering that a bedroom contains a lot of sorption capacity in its furniture, etc. ? The result that the hygroscopicity of the insulation might be as important for indoor comfort as a wall board envelope is difficult to grasp.

In Italy massive constructions are a tradition because they assure more thermal comfort than light weight structures. The result that under Italian conditions the influence of thermal mass on the performance of the bedroom is limited indicates that the comfort criteria for Northern and Central Europe might not be entirely applicable.

The longer-term effects are very important. In general the air change rate depends on the outdoor air temperature because people open the windows more often when it is warmer outside. This would probably alleviate some of the negative influences of moisture buffering materials.

D.1.6.1 Future work

To create inaccessible air spaces within a wall assembly in order to enhance the moisture buffering capacity of a room may have some serious drawbacks. Dust and dirt can accumulate there and insects have good hiding places. An alternative would be a surface texture of the building element that increases the absorption capacity.

Phase II: The results of this report show that the future tasks indicated in 5.2.1 would be a good starting point for gaining more insight into hygrothermal interactions between the indoor air and the envelope. Especially the correct treatment of vapor buffering building components in future building simulation tools seems an urgent task considering the potential of wood based materials to passively improve human comfort conditions in buildings.

The future work should also focus on rooms where moisture production and ventilation are usually considerably higher (e.g. kitchens, bathrooms, rooms with saunas and pools) and on whole buildings where infiltration of humidity from one room to another is possible. Furthermore it seems advisable to compare the humidity dampening capacity of light weight structures with that of massive structures commonly used in Germany or other parts of Central Europe. Since massive walls have a bonus concerning thermal mass it might be important to show that the same is not necessarily true for the sorption capacity.

References

[1] Künzel, H.: Repräsentativumfrage über das Heizen und Lüften in Wohnungen. IBP-Mitteilung 7 (1979), Nr. 47.

[2] Sanders, C.: Environmental Conditions. Final report volume 2, IEA-Annex 24, Leuven 1996.

D.2 Dr. Jarek Kurnitski, Helsinki University of Technology, HVAC-Laboratory, Espoo, Finland

D.2.1 Originality of the study

This report presents an advanced approach in building science to design a building as a whole, by taking into account the interactions between the building envelope and indoor climate. Commonly, these issues are kept separate due to independent structural design and design of heating and ventilating. However, in reality buildings function according to natural laws and, therefore, it is important to know such interactions, for example, for constructing healthier buildings with better indoor climate.

The report studies how significantly indoor relative humidity and temperature, which are key the parameters of indoor climate, may be affected by the moisture and heat capacities of wooden based materials. This is important since a too high temperature and relative humidity will cause discomfort, and the passive means described are a strong alternative to mechanical air conditioning for achieving an acceptable comfort level. In apartment buildings and houses, passive measures in combination with the air change rate are very often the only way to control indoor climate as mechanical cooling systems are not used in such buildings.

It is known that the heat and mass transfer between air and structures has some effect on indoor climate. The heat capacity of structures is used to some extent in practice, for example, in office buildings by means of night cooling, where efficient ventilation during the night is used to cool down the building. It is also well known that massive structures will offer a better protection against temperature peaks in the summer compared to lightweight structures.

D.2.2 Methodology

This report endeavours to find out what extra effects, in addition to the heat capacity effects, may be provided by active moisture transfer between indoor air and the building structure. Due to interactions between heat and moisture transfer these effects are studied simultaneously. The main issues studied are the following:

- To what extent can the maximum relative humidity be decreased in the summer
- To what extent can the minimum relative humidity be increased during the winter
- To what extent can the temperature be decreased in the summer
- Are the effects the same in different climates?

To study the above mentioned problems, parametric simulations are used in which the following main parameters are varied:

- Moisture capacity of hygroscopic thermal insulation (in the case of permeable interior coating)
- Moisture capacity of interior wallboard
- Vapour resistance of interior coating
- Thermal mass of structures
- Ventilation rate
- Climate

The simulations are carried out for one well-defined set up – a bedroom occupied by two people for nine hours during the night. With the basic input parameters, moisture transfer between indoor air and building structures is very active. This situation is compared to impermeable structures, which is the case where no moisture transfer between indoor air and structures occurs. The software 'LATENITE' used in this study incorporates an RC-network model which allows to perform simultaneous dynamic simulations of heat and mass transfer and fluid flow including phase change effects. The model was validated in previous studies and the measured data concerning the studied bedroom was also available from the previous study.

The studied set up is simplified as the bedroom has no furniture or textiles and there are some other minor simplifications, but this is justified for the first phase of the study. The simulation model and input parameters as well as the whole study methodology are basically correct for the study carried out. The parametric simulations have been comprehensive and carefully done. However, varying a large number of parameters leads to a huge amount of results which are not easy to read. There is also a lot of repetition since the same calculations are performed for different climates. The climate related performance is important, but the interpretation of the results is tricky as building traditions depend strongly on climate and the structures studied will mainly suit a cold climate. Perhaps it would have been possible to select fewer cases for the reporting of the study or at least some less important results should have been presented in appendixes. Some of the results are presented in very illustrative 2D performance maps, but the majority of the results are plotted as quite raw data. Duration curves, which are essential way for presenting of annual data, are not used. This is a minor detail but it has some effect on reading and analysing the results.

When the results are analysed, dissatisfaction criteria are used to determine thermal comfort. The use of the criterion for the general thermal comfort is correct. The effect of humidity is not very significant in the studied set up as the metabolic rate is as low as 0.8 MET for sleeping people. The role of humidity is more important at higher metabolic rates. It is doubtful whether the criteria for respiratory thermal comfort and acceptability are appropriate for steady state conditions (such as occupancy indoors) because their determination has been based on rapidly changing laboratory conditions. It is recommendable not to stress the dissatisfaction results calculated with these criteria and to stress the results calculated with general comfort criteria. In addition, there are some limitations in the use of the comfort criteria in a warm climate as the criteria developed for buildings with air conditioning may provide unrealistic results in buildings with natural ventilation, especially in warm climate.

D.2.3 The main results and future work

The studied set up has provided valuable results and it proves the enhanced performance of permeable structures. The most important findings concerning permeable case are the following:

- Up to 35 % lower maximum relative humidity during the summer
- About 7 % lower average relative during the summer
- Up to 2 °C cooler indoor temperatures during the summer
- Up to 15 % higher minimum relative humidity during the winter in a cold climate
- Enhanced moisture performance can be realised either by using hygroscopic wallboard or insulation
- Air change of 0.1 ach provides the same moisture performance as 0.5 ach in the impermeable case

It has to be emphasized that the studied set up with a bedroom at night time is important, but as a particular case it cannot provide a complete description of the extent of enhancements achieved by active moisture transfer between indoor air and structures. In future work it is important:

- To study a “daily” case of a living room, where temperature and relative humidity variations are studied during the daytime
- To perform small-scale experiments to confirm the calculated results
- To use local structural solutions in the calculations if the climate is varied
- To determine an optimum ventilation strategy, where the air change rate is varied, for example, between 0.2 – 2 ach based on CO_2 control which is necessary for achieving good indoor air quality, and temperature and humidity control which is necessary for achieving an optimal thermal comfort
- To analyse the extent of enhancements in respect of the indoor air quality and climate classifications, i.e. to find out whether it is possible to achieve a higher class of indoor climate combining passive measures and improved ventilation strategy

In respect of the evaluation of indoor climate not only is the night time in the bedroom important, but the daily conditions in other occupied rooms are as well. Daily conditions in the living rooms are especially important, because the highest temperature peaks in the summer occur usually in the afternoons.

Combining the ventilation system and passive measures is very important since ventilation can destroy or enforce the enhancements depending on outdoor climate. When the outdoor air is hot and humid the ventilation should be reduced to its minimum speed determined by CO_2 control. If vice versa, i.e. outdoor air can be used for cooling purposes, the ventilation rate should be increased to maximum speed or the speed determined by temperature and humidity control. Such a ventilation system which may provide a significantly better performance can be easily realised in practice by adding only a control unit to the conventional ventilation system, which does not cause significant extra costs.

In general, it is also important to produce scientific data related to humidity conditions in occupied rooms and possibilities to control humidity conditions by passive measures. When such data is available, it can be used for developing existing indoor climate guidelines and classifications. Therefore, it is important to show in a future study which issues should be included in guidelines and classifications in order to provide a better control of indoor climate.

D.3 Simo Koponen, Helsinki University of Technology, Laboratory of Structural Engineering & Building Physics, Espoo, Finland

In the near future healthy and energy efficient building solutions will have increasing share in the European building business. In addition, the ability to control temperature and humidity level and variation to obtain more comfortable living conditions will be a positive argument. The Finnish wood product industry will have chance to increase the use of wood, to increase extend of value added products and to obtain new and better functions of the products.

Phase I of the study “A Wooden Building with Comfortable Temperature and Humidity Conditions” is the first step to investigate the feasibility and limiting factors of wood based products to achieve the new positive arguments. The report includes essential building physical fundamentals and indoor air quality criterions at the required level to provide solid base for the numerical analysis of indoor air quality.

The numerical analysis is made using existing model LATENITE. It combines the heat, air, moisture and contaminant balance of indoor air with the hygrothermal performance of the building envelope parts.

LATENITE is used to conduct transient analyses of the effects of geographical location (climate), solar radiation, and ventilation rate and to show the role different building materials. The material parameters are mostly based on LATENITE database. Based on numerous calculation results presented in the report, LATENITE seems to be efficient tool to analyze indoor air quality.

The report concludes that the wood based building materials have the potential to moderate indoor humidity and thereby improve the building performance. It is shown that moisture technically active materials significantly reduce the peak humidity during night. Also the risk of mould growth is low. Advantages and disadvantages of permeable and impermeable structures are analyzed. As a disadvantage it is obtained up to 2°C temporarily warmer indoor temperatures due to moisture transfer (latent heat). According to calculated results the indoor temperature is affected by the thermal mass but the solar shading (venetian blinds) is also important. The mechanical cooling is very inefficient thus the new solutions to keep indoor air temperature within comfortable range are important especially in southern climate and during summer time.

In the moisture balance of indoor air ventilation rate plays an important role (50-75%). Using rates of 0.1 ach, 0.5 ach and 0.9 ach shows this. It is also shown that by using permeable and impermeable materials similar increase in humidity is obtained. Thus it is concluded that it is possible to reduce ventilation rate. Therefore heating energy loss by ventilation is important to reduce and it is beneficial to use permeable material. However, the minimum ventilation for health has to be satisfied.

The potentiality of the wooden building to obtain comfortable humidity conditions is not fully proven in Phase I. At least verification and possibly modification of the calculation model should be done. The experimental validation of the building physical behavior is essential to be considered in the planning of Phase II. This should be done by laboratory experiments but also using full-scale tests. The effects of the carpets and furnishing materials have to be taken into account. The models of moisture technical material properties used in the simulations do not fully describe the complex transient moisture transfer phenomenon. Generally material properties are based on steady state material tests, but the studied cases are transient. The effect of hysteresis typical for wood products has to be taken into account. In the worst case using average sorption isotherm can lead to about five to ten times too high hygroscopic activity. The moisture transfer is modeled based on Fickian theory. In certain transient conditions wood and wood products do not obey Fick's second law. The importance of hysteresis and possible non-Fickian behavior has to be defined as mentioned in the conclusions of the report.

In the promotion of the use of wood, also the other aspects have to be considered. In the workshop WS10 emissions of VOC's were mentioned. The emissions are observed to increase with increasing indoor humidity (Fang et al. 1999) but does the varying humidity increase emissions even more? In the near future the heating energy consumption's has to be reduced. The chance of wood based system solutions having multiple functions to meet all these needs is important to consider.

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Title

Improving Indoor Climate and Comfort with Woden Structures

Abstract

In this report, the moisture performance of a bedroom in a wooden apartment building is studied numerically using hourly weather data from 4 different cities (Helsinki, Finland, Saint Hubert, Belgium, Holzkirchen, Germany and Trapani, Italy). The bedroom is occupied for 9 hours by two adults during the night (22:00 to 7:00), the volume is 32.4 m^3 and the wall surface area is 60 m^2. With the basic input parameters (moisture production of 60g/h, ventilation rate of 0.5 ach and a permeable internal coating on the ceiling and walls) the moisture transfer between indoor air and the building structure is very active. With these parameters, the moisture transfer between indoor air and structures can significantly improve the indoor climate and air quality compared to the case where the internal coating is vapour tight. Moisture storage in wood based materials can reduce the peak humidity during the night and this moisture can then be removed by ventilation air during the following day. In general (at a ventilation rate of 0.5 ach), the indoor humidity is close to the outdoor humidity when the occupants enter the room (22:00) for all structures and materials. The increase in absolute humidity during the night is quite independent of the climate, but the amount of time when the indoor climate and air quality are unsatisfactory is very dependent on the climate. Passive methods of controlling the indoor climate are naturally more successful in moderate climates than in hot and humid climates, even though they provide benefits in all climates.

With the basic input parameters, there are many materials that can realise an enhanced moisture performance. For example, either a hygroscopic wallboard or hygroscopic insulation can provide good performance. However, when there is a hygroscopic wallboard, the insulation behind the wallboard has little effect on the performance. Therefore, the indoor moisture level of a room with a hygroscopic wallboard is quite insensitive to the hygroscopicity of the insulation and the vapour resistance of the elements behind the wallboard. When there is hygroscopic insulation behind a non-hygroscopic and permeable wallboard (most wallboard materials have some hygroscopicity), the performance is only slightly worse than when there is a hygroscopic wallboard. These results are for the basic input parameters and the difference between different materials and solutions becomes more important when: the moisture production increases, the ventilation rate decreases, the active area decreases, the vapour resistance of the paint increases or during long term weather changes. With the basic parameters, the risk of mould growth is low, but the risk increases as the moisture production rate increases.

The simulation results in this report demonstrate that thermal mass and solar shading are important for moderating indoor temperatures in northern and central European climates, but even a structure with a high thermal mass performs poorly in southern Europe when there is no heating or cooling. A room with a massive wooden floor and ceiling (200 mm) has a similar thermal performance as a room with a concrete floor and ceiling (200 mm). Also, moisture transfer can help cool the room when the outdoor temperature increases.

The sensitivity of the ventilation rate is analysed and the results show that ventilation is very important for removing moisture, especially when an impermeable coating is applied. The increase in humidity during the night becomes greater as the ventilation rate decreases for all cases. With a permeable paint and a ventilation rate of 0.1 ach, the indoor air humidity increases on average by 7.4 g/h during the night, which is equivalent to the humidity increase when the ventilation rate is 0.9 ach and the paint is impermeable. Nevertheless, the amount of time that the indoor humidity exceed 60% RH during occupation, decreases as the ventilation rate decreases because the indoor temperature increases as the ventilation rate decreases. The thermal comfort and perceived indoor air quality at the end of occupation can be similar with 0.1 ach and a permeable paint as with 0.25 ach and an impermeable paint.

As the moisture production increases, the fraction of the produced moisture that is stored in the wall increases very slightly. The moisture removed by the ventilation air, the moisture removed by the hygroscopic structure and moisture that remains in the indoor air are nearly linearly dependent on the rate of moisture production.

Keywords

indoor air quality, indoor climate, wooden structures, construction, moisture, mass transfer, heat transfer, building envelope, thermal comfort, fungi, apartment buildings, ventilation

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Tekijä(t)

Simonson, Carey J., Salonvaara, Mikael & Ojanen, Tuomo

Nimeke

Sisäilmaston ja viihtyisyyden parantaminen puurakenteilla

Tiivistelmä

Tässä raportissa tarkastellaan sisäilman kosteustasoja ja kosteusteknistä toimintaa. Tarkastelu tehtiin numeerisesti puurakenteisen kerrostalon makuuhuoneelle käyttäen reunaehtoina neljän eri paikkakunnan tunneittain ilmoitettuja ulkoilman olosuhteita. Tarkastellut paikkakunnat olivat Helsinki, Saint Hubert Belgiassa, Holzkirchen Saksassa ja Trapani Italiassa. Tarkastellun makuuhuoneen koko on 32,4 m^3 ja sen seinäpinta-ala on 60 m^2. Sisäilman kosteuskuormitus (60 g/h) aiheutuu kahden hengen 9 tuntia kestävästä oleskelusta huonetilassa (klo 22:00 - 07:00). Huoneen ilmanvaihtokerroin on 0,5 1/h. Kun seinä- ja kattorakenteiden sisäpinnat ovat hyvin vesihöyryä läpäiseviä, on kosteusvirtaus sisäilman ja rakenteiden välillä hyvin aktiivista. Näissä olosuhteissa kosteusvirtaus sisäilman ja rakenteiden välillä voi olennaisesti parantaa sisäilman laatua verrattuna tapaukseen, jossa rakenteiden sisäpinta on höyrytiivis. Kosteuden varastoituminen puupohjaisiin materiaaleihin voi alentaa sisäilman suhteellisen kosteuden yöllisen kuormitustilanteen aikaisia huippuarvoja ja varastoitunut kosteus voidaan poistaa rakennuksesta ilmanvaihdon avulla seuraavan päivän aikana. Yleensä, rakenteista ja materiaaleista riippumatta, ilmanvaihdon ollessa 0,5 1/h sisäilman kosteustaso on lähellä ulkoilman vastaavaa tasoa kun huonetilan kuormitus alkaa (klo 22:00). Sisäilman absoluuttisen kosteustason nousu kuormituksen aikana ei juurikaan riipu ilmastosta, mutta se aika, jonka sisäilman laatu on epätyydyttävä, on voimakkaasti ilmastosta riippuva. Passiiviset menetelmät sisäilman olosuhteiden säätelemiseksi ovat luonnollisesti toimivampia leudoissa ilmastoissa kuin kuumissa ja kosteissa oloissa, vaikkakin ne kaikissa ilmastoissa parantavat sisäilman tilaa.

Oletuksen mukaisessa tilanteessa useilla materiaaleilla voidaan aikaansaada sisäilman kosteuden kannalta hyvä vuorovaikutus. Tällaisia materiaaleja ovat esimerkiksi hygroskooppinen (kosteutta materiaaliin sitova) sisäverhouslevy tai hygroskooppinen lämmöneristys. Kuitenkin lämmöneristeellä, joka on hygroskooppisen sisäverhouslevyn takana, on vain pieni vaikutus sisäilman kosteuteen. Sen vuoksi sisäilman kosteustaso ei juurikaan riipu hygroskooppisen sisäverhouslevyn takana olevan lämmöneristeen hygroskooppisuudesta tai levyn takana olevan kerroksen vesihöyrynvastuksesta. Kun ei-hygroskooppisen (kosteutta heikosti sitovan) ja kosteutta hyvin läpäisevän sisäverhouslevyn (useimmat seinälevymateriaalit kuitenkin ovat hygroskooppisia) takana on hygroskooppinen lämmöneristys, kosteusvaikutus sisäilmaan on vain hiukan heikompi kuin tapauksessa, jossa on pelkästään hygroskooppisen sisäverhouslevy. Nämä tulokset pätevät edellä esitetyillä perusoletuksilla ja erot eri materiaalien ja sovellutusratkaisujen välillä tulevat edellistä merkittävämmiksi silloin kun: kosteustuotto kasvaa, ilmanvaihto pienenee, aktiivinen pinta-ala pienenee tai sisäverhouksen maalin vesihöyrynvastus kasvaa sekä pitkäaikaisten, useita päiviä tai viikkoja kestävien säämuutosten aikana. Perusoletuksen mukaisissa tapauksissa riski homeen kasvusta rakenteissa on pieni, mutta riski lisääntyy kun sisäilman kosteuskuormitus kasvaa.

Tässä raportissa esitetyt numeeriset simulointitulokset osoittavat, että terminen massa ja auringon varjostus ovat tärkeitä tekijöitä sisäilman lämpötilahuippujen tasoittamisessa Pohjois- ja Keski-Euroopan ilmastoissa. Sen sijaan Etelä-Euroopassa rakenteiden suurikaan terminen massa ei yksinään riitä varmistamaan sisäilman viihtyisyyttä, jollei rakennuksessa ole lämmitystä ja jäähdytystä. Jos huoneessa on massiivinen puulattia ja katto (200 mm), sen lämpötekninen toimivuus on samanlainen kuin vastaavan paksuisten betoniseinämien kanssa. Myös kosteuden siirtyminen voi auttaa huoneen jäähdytyksessä silloin kun ulkoilman lämpötila nousee.

Ilmanvaihtomäärän vaikutukset on analysoitu ja tulokset osoittavat, että ilmanvaihto on hyvin tärkeä tekijä kosteuden poistamisessa sisäilmasta erityisesti silloin, kun huoneen seinämät on käsitelty vesihöyryä läpäisemättömiksi. Kuormituksen aikainen huoneilman kosteustason muutos (kasvu) suurenee kaikissa tapauksissa silloin kun ilmanvaihtomäärä laskee. Kun seinämissä on vesihöyryä läpäisevä maalipinta ja ilmanvaihtokerroin on 0,1 1/h, kasvaa sisäilman kosteustaso yön aikana keskimäärin 7,4 g/h. Tämä vastaa kosteustason muutosta tilanteessa, jossa seinämien sisäpinta on käsitelty vesihöyryä läpäisemättömäksi ja ilmanvaihtokerroin on 0,9 1/h. Tästä huolimatta, se aika, jona sisäilman suhteellinen kosteus ylittää yöaikana tason 60 % RH (viihtyisyysraja) on ilmanvaihdon laskiessa lyhyempi kuin normaali-ilmanvaihdolla. Tämä johtuu sisäilman lämpötilan kohoamisesta pienellä ilmanvaihdolla. Sisäilman terminen viihtyisyys ja aistittavissa oleva ilman laatu voivat olla samat kuormitustilanteen lopussa ilmanvaihdolla 0,1 1/h ja läpäisevällä maalipinnalla tai kun ilmanvaihto on 0,25 1/h ja seinämien maalipinta on vesihöyryä läpäisemätön.

Kun kosteudentuotto sisäilmassa kasvaa, rakenteisiin varastoituneen kosteuden osuus koko kosteustuotosta kasvaa vain hyvin vähän. Ilmanvaihdon poistaman, rakenteisiin varastoituneen ja sisäilmaan jäävän kosteuden määrät riippuvat jokseenkin lineaarisesti kosteuden tuotosta sisäilmaan.

Avainsanat

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