Czech Technical University in Prague

Faculty of Civil Engineering

Department of Building Structures

Bachelor thesis

2018 LUKÁŠ KOTRBATÝ

ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE
Fakulta stavební
Thákurova 7, 166 29 Praha 6

ZADÁNÍ BAKALÁŘSKÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

Příjmení: Kotrbatý Jméno: Lukáš Osobní číslo: 440810

Zadávající katedra: K124

Studijní program: Stavební inženýrství

Studijní obor: Konstrukce pozemních staveb

II. ÚDAJE K BAKALÁŘSKÉ PRÁCI

Název bakalářské práce: Vlhkostní vlastnosti dřeva a jejich využití pro analýzu obalových konstrukcí moderních dřevostaveb

Název bakalářské práce anglicky: Hygric properties of wood and their use for analysis of envelope structures in modern timber buildings

Pokyny pro vypracování:
Změřte sorpční izotermu smrkového dřeva (obsah vlhkosti v závislosti na relativní vlhkosti). Dále z dostupných zdrojů zjistěte vlhkostní závislost faktoru difuzního odporu dřeva. Obě tyto vlastnosti zadejte jako vstupní parametry do vhodného numerického softwaru (např. WUFI) a proveďte analýzu a případně i optimalizaci obalových konstrukcí moderních dřevostaveb.

Seznam doporučené literatury:
ČSN EN ISO 12571 - Tepelně-vlhkostní vlastnosti stavebních materiálů a výrobků - Stanovení hygroskopických sorpčních vlastností
KurtKielsgaard Hansen, SORPTION ISOTHERMS - A Catalogue, 1986
Zillig, Moisture transport in wood, PhD thesis, 2009

Jméno vedoucího bakalářské práce: Ing. Kamil Staněk, Ph.D.

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Údaj uveďte v souladu s datem v časovém plánu příslušného ak. roku

Podpis vedoucího práce Podpis vedoucího katedry

III. PŘEVZETÍ ZADÁNÍ

Beru na vědomí, že jsem povinen vypracovat bakalářskou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je nutné uvést v bakalářské práci a při citování postupovat v souladu s metodickou příručkou ČVUT „Jak psát vysokoškolské závěrečné práce" a metodickým pokynem ČVUT „O dodržování etických principů při přípravě vysokoškolských závěrečných prací".

21.2.2018

Datum převzetí zadání Podpis studenta(ky)

I hereby declare that this bachelor thesis was composed by myself only under the professional guidance of Ing. Kamil Staněk, Ph.D.

I also confirm that I have not used any other sources than those identified as references.

……………………………

signature

Acknowledgement:

I take this opportunity to show my gratitude to all the people who supported me during the completion of this bachelor thesis. Namely, I would like to express my sincere thankfulness to Ing. Kamil Staněk, Ph.D. for his valuable guidance and encouragement. I am also extremely grateful to Ing. Jan Richer for enabling me to perform research and sharing his expertise. Last but not least, I could have not finished this work without my parents who provided me with the priceless opportunity to study university.

Hygric properties of wood and their use for analysis of envelope structures in modern timber buildings

Vlhkostní vlastnosti dřeva a jejich využití pro analýzu obalových konstrukcí moderních dřevostaveb

Abstract:

The main goal of this thesis was to thoroughly analyse the moisture behaviour of the most common external walls in modern timber buildings. This was performed by dynamic simulation in WUFI® Pro 6.1 software, mainly focusing on the moisture content of wood fibreboards. In order to make realistic approximations, the experimentally measured sorption isotherm of wood was inserted into the computational model. Also, specific factors were considered in the calculations, *e.g.* the dependence of diffusion resistance factor of wood and OSB board on relative humidity, solar radiation, rain and liquid transport. The results of the detailed analysis were compared with the results of a simplified simulation relevant to stationary model in TEPLO 2010, which is an ordinarily used software for hygrothermal assessment. Among other outcomes, this work has shown that the dependence of the diffusion resistance factor of OSB board on the relative humidity plays a non-negligible role in the moisture behaviour of a particular type of construction. The obtained results are intended as a stimulus for further discussions.

Keywords: *moisture, timber buildings, sorption isotherm, wood, diffusion resistance factor*

Anotace:

Hlavním cílem této práce bylo podrobně analyzovat vlhkostní chování nejběžnějších obvodových stěn v moderních dřevostavbách. Toto bylo provedeno pomocí dynamické simulace v softwaru WUFI® Pro 6.1, ve kterém byl zkoumán průběh hmotnostní vlhkosti v závislosti na čase, nejčastěji u dřevovláknitých desek. Aby se výsledky co nejvíce příblížily reálnému chování, do výpočetního modelu byla zadána experimentálně změřená sorpční izoterma smrkového dřeva. Dále byly uvažovány závislost faktoru difuzního odporu dřeva a OSB desky na relativní vlhkosti, vliv solární radiace, deště a kapilárního transportu vody v konstrukci. Výsledky této analýzy byly porovnány s výsledky ze zjednodušené simulace odpovídající běžnému stacionárnímu posudku v softwaru TEPLO 2010. Tato práce mimo jiné ukázala, že závislost faktoru difuzního odporu OSB desky na relativní vlhkosti hraje nezanedbatelnou roli ve vlhkostním chování daného typu konstrukce.

Klíčová slova: *vlhkost, dřevostavby, sorpční izoterma, dřevo, faktor difuzního odporu*

Contents

List of symbols

c	[J/kgK]	heat capacity
d	[m]	thickness of material
D	[$m^2 \cdot s^{-1}$]	vapour diffusion coefficient
D_a	[$m^2 \cdot s^{-1}$]	vapour diffusion coefficient of air
EMC	[$kg \cdot kg^{-1}$]	equilibrium moisture content
gradp	[Pa/m]	gradient of partial pressure
J	[$kg/m^2 \cdot s$]	mass diffusion flux
m_a	[kg]	mass of adsorbed sample
m_b	[kg]	mass of aluminium bowl
m_{dry}	[kg]	mass of dry material
m_w	[kg]	mass of the adsorbed moisture in the material
M	[$kg.mol^{-1}$]	molar mass of water
M_c	[$kg \cdot m^{-2} \cdot a^{-1}$]	amount of condensed water vapour
M_{ev}	[$kg \cdot m^{-2} \cdot a^{-1}$]	amount of evaporable water vapour
MC	[$kg \cdot kg^{-1}$]	moisture content
p_w	[Pa]	partial pressure of water vapour
p_{ws}	[Pa]	saturation pressure of water vapour
r	[m]	pore radius
R	[J/Kmol]	gas constant
RH	[%]	relative humidity
s_d	[m]	equivalent air layer thickness
T	[K]	temperature
V_{bulk}	[m^3]	total volume
V_p	[m^3]	open pore volume
w	[$kg \cdot kg^{-1}$]	volume moisture content
γ	[N/m]	surface tension
δ	[$kg/m \cdot s \cdot Pa$]	vapour diffusion permeability
$Ø$	[-]	open porosity
λ	[W/mK]	thermal conductivity
ρ_l	[kg/m^3]	density of water
ρ_b	[kg/m^3]	bulk density

μ	[-]	diffusion resistant factor
Θ	[°]	contact angle of meniscus

List of abbreviations

a.s.l.	above sea level
CLT	cross laminated timber
CTU	Czech technical university
DVS	dynamic vapour sorption
FSP	fibre saturation point
OSB	oriented strand board
UCEEB	University centre for energy efficient buildings CTU in Prague
VIS	“vapour impermeable“ structure
VPS	“vapour permeable“ structure

1 Introduction

1.1 Background

In recent years, there has been a huge expansion of timber buildings in Czechia, i.e. those buildings in which the load-bearing structure is mostly made of wood or wooden materials. [1] The 92 wooden houses which were built in 1999 represented only 1,12% of all family houses built in that year. However, the most recent data show that the number of wooden dwellings has significantly increased. In 2016, there were 2013 wooden houses constructed, that is equal to 14,37 % out of all new family houses. [2]

The statistics also show which type of the load-bearing system is the most common. *Frame construction/Panel construction* that consists of wooden ribs of squared sections and a stabilizing sheathing is the most attractive system that formed the core of more than 80% of all family dwellings built in 2016. (1634 out of 2013). For this system, prefabricated panels (*Panel construction*) slightly dominate over the in-situ construction (*Frame construction*). [2]

Unlike the family houses, the amount of administration and civic buildings with wooden load-bearing system is still considerably small in the Czech Republic. One of the biggest issues, when designing a multi-storey timber structure, is the need to follow the strict regulations for fire safety. The Czech legislation states, that in wooden buildings, the height between the surface of the ground floor and the surface of the top floor must not exceed 12 m. Hence, this requirement limits builders to design max. 5 storey buildings. [3] This hinders the Czech market from even steeper growth of timber structures, whereas engineers from some other countries break the records in the maximal heights of wooden high-rise buildings. [4][5]

However, the construction of family houses made of wood as the loadbearing material is on a steady rise because of many factors which relate with each other:

- First of all, there is an evident trend in sustainable and energy efficient construction. People are becoming aware of potential “destruction“ of our Earth, if they keep living in today´s consumerism, especially considering the fact of growing population. There are numerous theories predicting shortages of water, oil, phosphorus and other natural resources on the planet in relatively near future. [6][7][8]
- Therefore, the intention of the large part of advanced society is to consume as little primary energy as possible, to reduce the production of pollutants, to use local

recyclable resources, etc. Modern timber buildings offer a partial solution for this issue. When designing a wooden structure, there is a great emphasis on using mostly recyclable natural materials. Moreover, those new buildings are often designed with heat recovery ventilation. All these aspects contribute to both, diminishing of the energy consumption and comfortable indoor environment. To sum up, the construction and utilization of energy efficient buildings built of wood-based materials belongs to sustainable way of living.

- The second reason is related to the first one. The pollutants-free indoor air is one of the key indicators of general well-being. It is known, that people spend most of the time indoor. Therefore, if a user of a wooden house feels relaxed at home, he/she shares positive experience or recommends the modern wooden dwelling to his/her friends, colleagues etc. Consequently, the satisfaction of individual users can also stimulate the escalation of wooden family-houses in the Czech Republic.
- When the demand increasing, the supply replies in the same way. Accordingly, a lot of new companies are emerging on the market and they are offering modern developed structures. [2]
- Thanks to the rivalry between the firms, the purchase prices of wooden houses may drop and thus become more affordable in comparison with the brick houses. Furthermore, if the house is designed as energy efficient building, there is a huge difference in the operating cost.
- Another immense advantage is the speed of construction. After the casting a concrete slab which functions as foundation, the total construction time is usually not longer than 6 months. [9]
- Last but not least, the economic situation in the Czech Republic has slightly improved in the recent years. As a consequence, the number of all new family houses has increased annually in 2016 after the 8-year decline. [2]

1.2 Motivation

Even though, there would not be any problem to find some other advantages of modern wooden houses, it also brings some risks and concerns of the users. The fire resistance issues were already mentioned. Another trouble may be caused by rodents. People believe that natural materials which are used in wooden houses attract rats and mice. Theoretically, those animals could damage the wall but usually it does not happen because the structure is still too thick for them. Moreover, the possibility of destroying the wooden-house-wall by rodents is not bigger than in autoclaved aerated concrete construction. (Note: Currently, Autoclaved aerated concrete is common material for family houses in the Czech Republic). [10]

Finally, the often discussed issue related to the modern timber buildings is **moisture**, which can appear either in a liquid form or as a water vapour. There are several sources whence those two forms of moisture can endanger the structure (see Fig. 1).

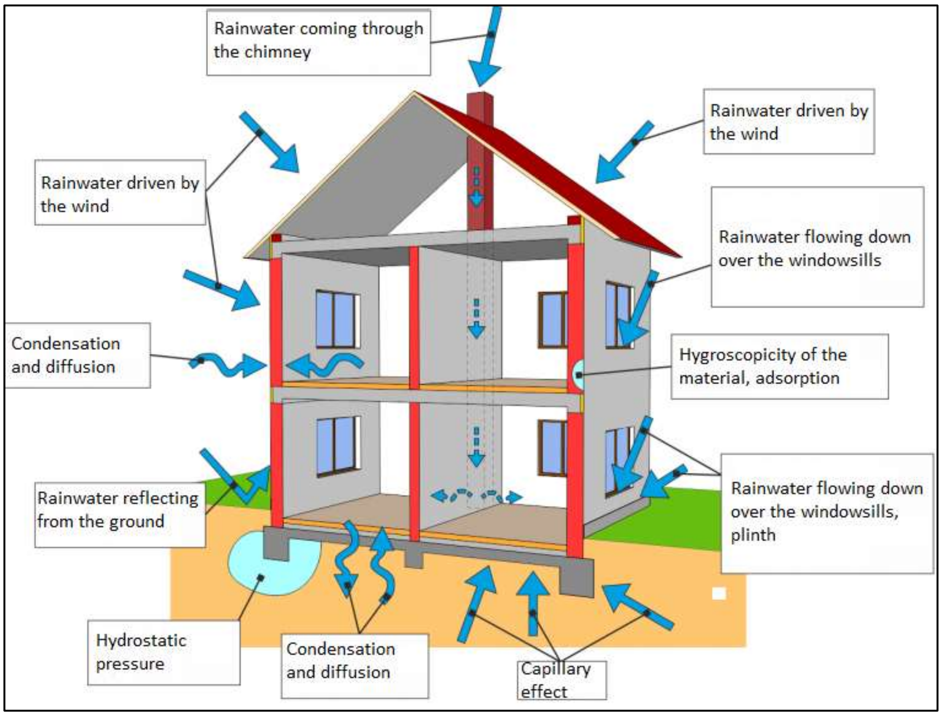

Figure 1: Sources of moisture [11]

When focusing on design of new wooden houses, preventing the both rainwater and rising groundwater from the penetrating into the structure is usually solved by waterproofing layer (or coating) and is not relatively big issue for engineers. However, the diffusion of water vapour and possible condensation within the structure can cause huge problems and the solutions for avoidance are more complicated.

Those problems can turn into enormous ones primarily for two reasons: First, all diffusion processes are happening inside the structure. Thus, the moisture problem can be invisible for a long time, until it appears on the wall surface. When recognizing a wet spot on the surface, it can be too late because the wall can be already largely damaged. Second, the wood-based materials are highly hygroscopic, which means that it takes on a big amount of moisture from the surrounding environment. [12] The excessive humidity negatively influences the mechanical and thermal properties of wood and wood-based materials, which is highly undesirable. This is discussed in detail in the following chapter.

In order to disable the moisture to damage the structure, two important assumptions must be fulfilled: Correct design and flawless realization. Whereas the precision of realization always depends on the individual qualities and attitudes of workers, the hygrothermal simulations may help us to predict how the construction will behave in times of its existence. Furthermore, a basic hygrothermal analysis must be a part of every single project, because Czech Technical Standards ČSN 37 0540 and ČSN EN ISO 13788 determinate thermal and moisture requirements for all building elements.

1.3 Standard requirements

More precisely, ČSN 37 0540 states that the amount of condensed water vapour (M_c) within the structure including wooden elements must not exceed the lower value out of 0,10 kg/(m^2·a) per year and 3% of area density of the material, in which the condensation appears, if the bulk density exceeds 100 kg/m^3. For material with its $\rho \leq$ 100 kg/m^3, the limit is 6% of its area density. [13] Normally, the requirement on the limited value of 0,10 kg/(m^2·a) is considered as the reference, because it represents the lower value for the most of the layers.

Simultaneously, considering an annual cycle, the amount of condensed water vapour $M_{c,a}$ [kg/(m^2·a)] must be lower than the amount of evaporable water vapour $M_{ev,a}$ [kg/(m^2·a)]:

$$M_{c,a} < M_{ev,a} \tag{1}$$

In other words, the amount of water vapour within the structure must not constantly increase.

Furthermore, bearing in mind wood and/or wood-based materials in construction, ČSN 73 0540-2/Z1, referring to ČSN EN 14220, gives another criterium. It states, if the moisture content of wood or wood-based materials within the structure exceeds 18 %, the structure does not fulfil its function. Therefore, moisture content of those materials must be kept under 18 %. [14]

1.4 Aim

Most likely, all external walls of modern timber buildings should meet the Standard requirements. The question is whether the elementary simulations which are normally run by producers are sufficiently accurate and safe in the determination of the real behaviour of the structure. In other words, how does the basic simulation diverge from the real state? If it diverges, which aspects cause the difference? Should these factors be considered in the ordinary design? Is it possible, that those factors could cause exceeding of Standard limits? If so, are the Standard requirements too strict or can the external walls be negatively affected by moisture? For instance, some measurements show that the diffusion resistant factor (μ value) of wood and wood-based materials varies according to relative humidity of the environment it is exposed to (see Fig. 8). How does this factor influence the amount of moisture in the structure? Is the result significantly different from the case at which the value is expressed as a constant?

This thesis is aimed to give the answers to all the questions posed above. To sum it up, the main goals are listed:

- To prove (by regular assessment) that the most typical external walls in all kinds of construction of modern wooden houses meet the Standard requirements (stated in ČSN 37 0540 and ČSN EN ISO 13788) related to the moisture inside the structure.
- To subject those walls to the both detailed hygric analysis and simplified analysis corresponding to the regular assessment
- To compare results from both simulations; i.e. to state which factors not included in the regular simulation play a significant role in the moisture behaviour.
- To determinate if those factors could influence the moisture behaviour as much as the wall assemblies would not meet the Standard requirements, or/and could be threatened by excessive moisture.

2 Theory

In this part, fundamental physical principles of moisture transport through the building components are described. The greatest emphasis is placed on moisture content (MC) of wood-based materials. It is because hygroscopicity of these materials may affect numerous physical and mechanical characteristics of wood such as dimensions, load-bearing capacity, thermal conductivity, water vapour diffusion *etc*. [12] To gain deeper understanding of this issue, the definition of sorption isotherm is necessary. Finally, various measurement methods for determination of sorption isotherm are discussed.

2.1 Sorption processes

All buildings are surrounded by ambient air which contains certain amount of water vapour. This amount is expressed by relative humidity (RH), which is defined as the ratio of the partial pressure of water vapour (p_w) to the saturation pressure of water vapour (p_{ws}) at a given temperature (*T*). [15] (see Eq. 2).

$$RH = \frac{p_w}{p_{ws}} * 100\% \qquad (2)$$

In other words, RH indicates how much humidity is in the air compared to the air which would be saturated. The saturated air contains the maximal amount of water vapour that is possible. Thus, its RH is 100 % and the condensation occurs. However, RH is closely related to temperature of the air. With temperature increases, RH decreases and conversely. The temperature, at which the air becomes saturated and water vapour condensates, is defined as the dew point. [12]

The fact, that the temperature and the RH of the ambient air constantly change, has a huge impact on porous building materials. Most common materials, such as wood, brick, concrete, or OSB board, have a high value of porosity (Ø), which is defined by the ratio of the volume of pores (V_p) to the total volume of the dry material (V_{bulk}). [16]

$$Ø = \frac{V_p}{V_{bulk}} \qquad (3)$$

It is important to distinguish between two different types of porosity. Whereas closed porosity includes pores which are not connected to the surface of the material, the open porosity (Eq. 3) refers to pores linked to the surface of the given material. However, it is only the open porosity which influences the moisture transport through materials.

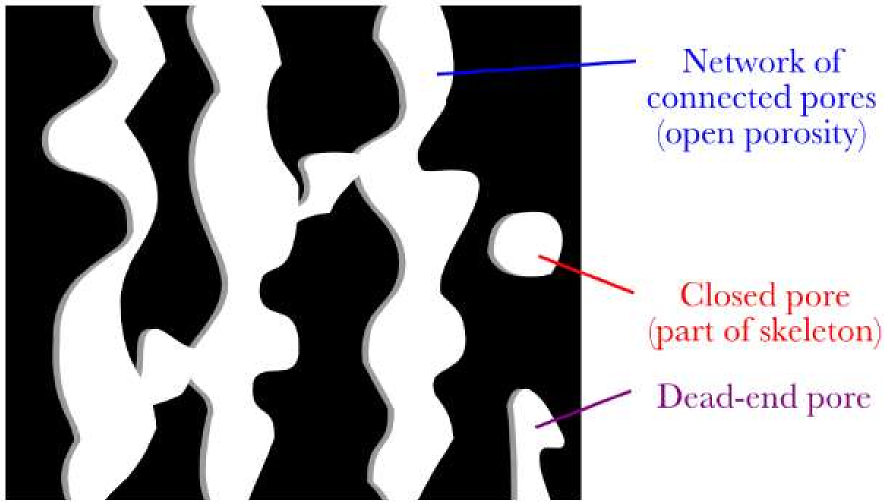

Figure 2: Types of pores in porous medium [17]

The process, in which the water vapour molecules move between the porous material and surrounding air, is called water vapour sorption. It is also important to mention, that during the water vapour sorption in pore systems, the physically bond water is released, and so it does not influence the material structure, unlike chemically bound water. [18]

When a pre-dried material is exposed to the environment with a constantly increasing RH, the water molecules from the ambient air become attached to the surface of the open pores of the material. This phenomenon is called monomolecular adsorption and it occurs because of Van der Waals forces which are present between the hygroscopic material and the water vapour molecules.

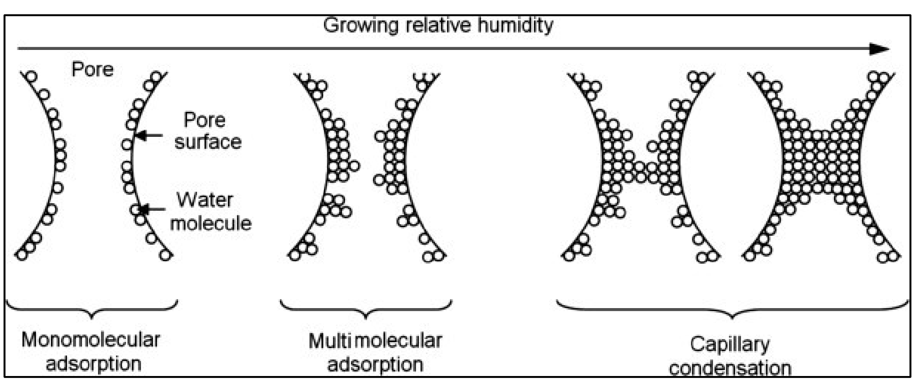

Figure 3: Different stages of the adsorption process [19]

When the RH grows further, the first layer of molecules becomes saturated and additional layers are formed. During this phase of the adsorption process, which is called multimolecular adsorption, the molecules are not as strongly connected to each other as they are in the first layer linked to the material surface. During the exposure to the high RH values (but still less than 100%), water in liquid state can be found inside the pores. This phenomenon is caused by capillary condensation. [19] [20]

Once, the amount of adsorbed water is too high, a homogeneous layer is created. The greater amount of water vapour molecules is present within the narrow pore, the stronger the Van der Waals interactions are and if a certain amount of water in the pores is attained, a condensation occurs, despite the fact that, the saturation vapour pressure of the pure liquid has not been reached. Immediately after that, menisci are formed at the interface of the liquid and the vapour phase, and their surface tension enables to achieve equilibrium. The physical process of capillary condensation is described by putting Kelvin´s law and Young-Laplace equation together: (Eq. 4)

$$RH = \frac{p_w}{p_{ws}} = exp\left(\frac{-2\gamma}{r\rho_l RT}cos(\theta)\right) \qquad (4)$$

where γ [N/m] is the surface tension, r [m] is the pore radius, ρ_l [kg/m^3] is density of water, R [J/Kmol] is the universal gas constant, T [K] is the temperature and θ *[°]* is the contact angle of meniscus. [16] Consequently, there is an influence of the meniscus shape upon the rate of capillary condensation.

To get better understanding of the whole adsorption process, sorption isotherm is presented.

2.1.1 Sorption isotherm

Sorption isotherm describes thermodynamic relationship between the equilibrium moisture content (EMC) and the RH values at a constant temperature and pressure. [18] In a general model of sorption isotherm, adsorption process is divided into three different zones (see Fig. 4).

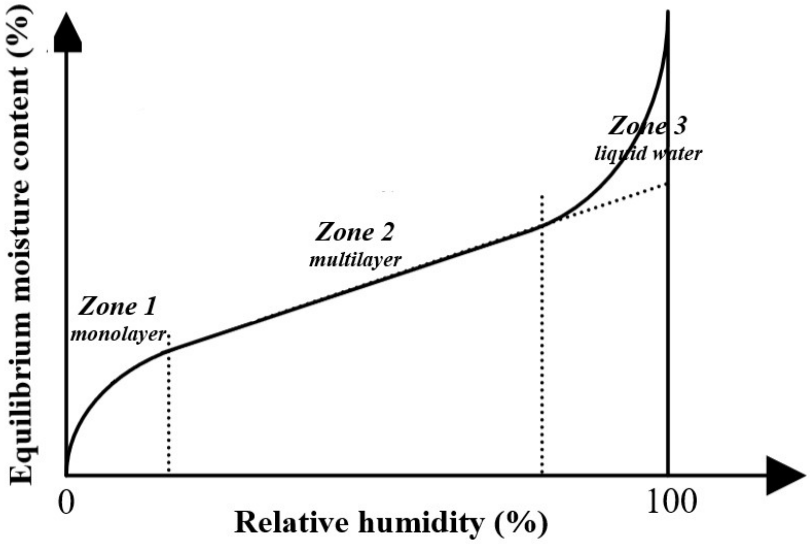

Figure 4: Zones of sorption isotherm [21]

The slope of the curve is not steep in the zone 2, when the multimolecular sorption occurs. This is given by small interactions among the layers of the vapour molecules. Thus, in the middle of the RH values, the materials do not adsorb much physically bound water in comparison with the first and third zone, where the interactions are much stronger.[21]

When exposing a material to an environment with a stable RH, the adsorption process proceeds as described in the previous chapter. At one point, the balance between surrounding air and the material occurs. Although the process of sorption never ceases, the number of adsorbed molecules is equal to the number of molecules which are leaving the pores. For this equilibrium state, the amount of adsorbed water in the material is called the equilibrium moisture content (EMC).

Moisture content (MC) can be determined as:

$$MC = \frac{m_w}{m_{dry}} \; [kg/kg], \tag{5}$$

where m_w is the mass of the adsorbed moisture in the material and m_{dry} is the weight of dry material. The definition of a dry material for building physics purposes is given by the Czech technical standard ČSN EN ISO 12 570 and it is discussed in the following chapter. Sometimes the MC is multiplied by 100% to give percentage ratio.

Another calculation method how to express amount of moisture is volumetric moisture content (w):

$$w = \frac{m_w}{V_{bulk}} \; [kg/m^3], \tag{6}$$

where V_{bulk} refers to the total volume of dry material. This expression is used for the interpretation of moisture storage function in certain moisture design tools such as WUFI.

There is a simple relationship between the mass MC and the volumetric MC. If bulk density ρ_b is defined as the ratio of weight and the volume of dry material:

$$\rho_b = \frac{m_{dry}}{V_{bulk}} \; [kg/m^3], \tag{7}$$

the relation between the mass MC and the volumetric MC is given as:

$$w = \rho_b * MC \; [kg/m^3] \tag{8}$$

2.1.2 Desorption isotherm, hysteresis

When discussing sorption isotherms, the difference between adsorption and desorption curve is necessary to mention. The hysteresis phenomenon is caused by several effects, from which the "ink bottle effect" is considered as the main one. The principle of this process is based on the fact that bigger pores are part of the pore system only via smaller pores. When the RH of ambient air decreases, the bigger pores remain filled with water until the smaller pores become empty. [22] This causes that for some materials the EMC values at a given RH vary between adsorption and desorption. (see Fig. 5)

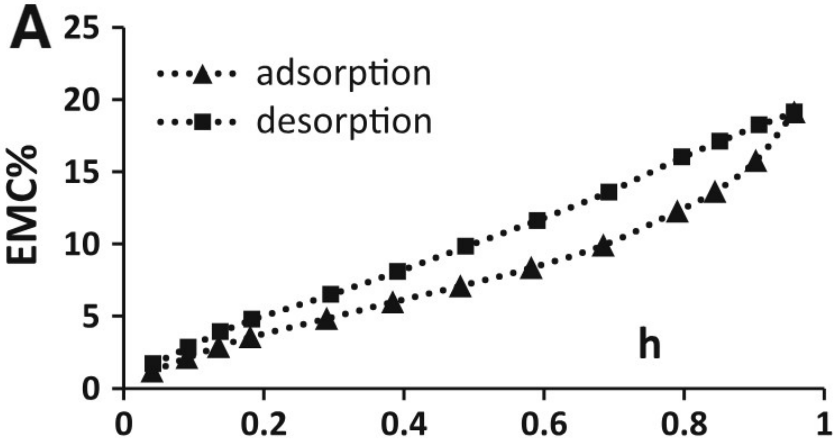

Figure 5: Wood moisture sorption hysteresis, native A. mangium at 25 °C [23]

However, desorption curve is not dealt within the frame of this thesis because the software in which the detailed moisture analysis is simulated does not work with this difference.

2.2 Wood and moisture relationship

Substantial fact is that adsorption and desorption processes greatly influence various characteristics of hygroscopic materials. Thus, each material behaves differently according to the RH of the surrounding environment that it is exposed to. In order to investigate the moisture behaviour of external walls in the modern wooden buildings, fundamental characteristics of wood, in dependence on humidity, are discussed.

2.2.1 Wood structure

Concerning moisture, wood is a very specific material. That is mainly because wood is a natural matter obtained from living trees which need water for their growth. As all plants, trees are capable of synthesising sugar glucose by performing the photosynthesis. When thousands of individual glucose units link together, the fundamental structural component of a wood cell, *cellulose* is built:

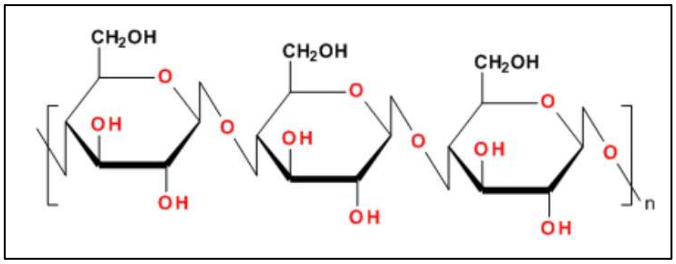

Figure 6: Cellulose

Cellulose chains form elementary fibres which are then gathered into the microfibrils. These components, visible by electron microscope, play the key role in water sorption processes.[24]

2.2.2 Moisture capacity of wood

To define the amount of water inside the wood, the MC value in percentage is used (definition of MC described in the previous chapter) MC of freshly cut log varies from 45% to more than 200% depending on the tree species. [24] Values above 100% mean that the water inside the wood is heavier than the completely dry wood. For instance, the MC value of 200% describes wood with moisture weight twice higher than is the weight of the dry wood. Naturally, different MC values affect the changes of dimensions of the wood.

2.2.3 Shrinkage and swelling

It is necessary to describe what exactly is happening with the wood during its complete drying. There are two forms of water that exist in the wood structure. Firstly, it is the free water, which is found in cell cavities called lumens. And secondly, it is the bound water retained in the cell walls. [24]

When drying the wood, the free water leaves the lumens first. Nevertheless, this process does not influence the change of the wood shape and it proceeds until all free water is desorbed. This point called fibre saturation point (FSP) is characterized by the highest MC at which only bound water is present. [25] The average FSP is approximately 26 %, but it may differ from the average value according to the species. [24] When continuing the drying process below FSP, the bound water is gradually desorbed. But because the bound water has been an integral part of cell wall, when it leaves the cell, a movement of microfibrils is induced (Fig. 7 b) and as a result, wood shrinkage can be observed.

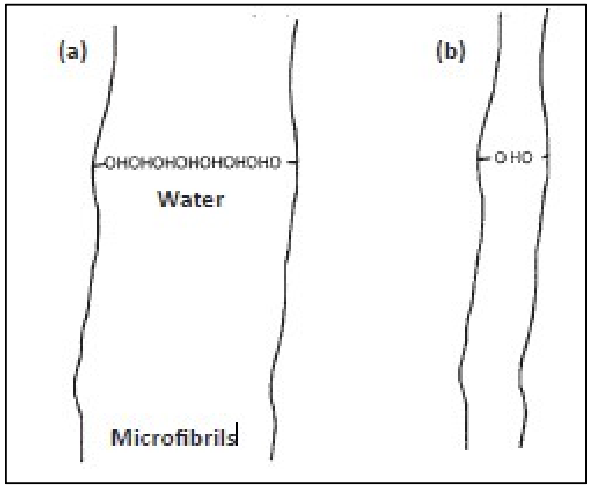

Figure 7: Changing of the shape of microfibrils according to the moisture content [24]

Conversely, if wood is completely dried out and water vapour molecules are constantly adsorbed, the specimen of wood swells until it reaches the FSP. This happens because bound water comes back into the cell wall and as a consequence, the microfibrils outspread themselves. (Fig.7 a) The adsorption of free water after reaching FSP does not have impact on shrinkage nor swelling. [24]

Also, the rate of shrinkage depends on the direction of wood fibres. It leads the wood to the tendency to warp. [24] Both shrinkage/swelling and twisting can have a negative effect for logs kept in the construction. Therefore, designers should be aware of which conditions the wood will be subjected to. Wood should be sufficiently conditioned in advance. It means that it has to be exposed to the environment with the RH, in which it will be placed in the construction, until the EMC is reached.

2.2.4 Diffusion characteristics of wood

The humidity does not influence only dimension change. Also, a certain dependence between RH and water vapour diffusion resistance factor (μ) can be observed. First, principle of water vapour diffusion through construction is briefly described.

2.2.4.1. Diffusion

A wall represents barrier between two environments with different features. If absolute humidity, defined as an amount of water vapour per cubic meter of air [g/m^3], varies from one another, partial pressure of water vapour differs as well. The water molecules are forced to move from air with higher partial pressure through the wall to the other side with lower partial pressure to reach equilibrium. This movement is called diffusion and its rate is described by the following relation (see Eq. 9). [26]

$$J = -\delta \; gradp \tag{9}$$

where J represents the mass diffusion flux and grad$p$ is a gradient of partial pressure. Those two quantities are in a proportional relationship. The constant of proportion is expressed by permeability for vapour pressure gradients (δ).

The most common parameter describing the diffusion transport through building materials is the water vapour diffusion resistance factor (μ). To derive the μ value from δ, definition of water vapour diffusion coefficient (D) is necessary:

$$D = \frac{\delta RT}{M}, \; [m^2 \cdot s^{-1}] \tag{10}$$

where M is the molar mass of water [0,018 kg·mol^{-1}], R is universal gas constant [8,314 J·mol^{-1}·K^{-1}] and T is absolute temperature [K]. [27]

Finally, the μ which is given by a manufacturer for each building material can be defined as:

$$\mu = \frac{D_a}{D}, \; [-] \tag{11}$$

where D_a is the water vapour diffusion coefficient in the air [2,3 x 10^{-5} m^2·s^{-1}]. Thus, μ expresses the relation between diffusion through given material and diffusion which would occur in the air under the same boundary conditions. [27]

For some vapour barriers, the equivalent air layer thickness (s_d) is stated. The value of s_d indicates the thickness of static air layer that has the same μ as the building material of thickness d [m]. (see Eq. 12) [27]

$$s_d = \mu \cdot d \; [m] \tag{12}$$

In other words, s_d gives us a clue how thick would an air layer be, if we used it instead of the building material. For instance, if we apply a 15mm-thick OSB board with $\mu = 200$, then its

$s_d = 3$ m. Consequently, 3m-thick air layer would be needed to reach the same diffusion characteristics.

2.2.4.2. Dependence of μ value on RH

However, the diffusion of water vapour in wooden materials is also dependent on the RH of environment where it is placed. This relationship is often neglected when analysing the structure. Manufactures mostly state only a constant μ value for a material. The dependence of μ on RH of spruce wood can be seen in the Figure 8.

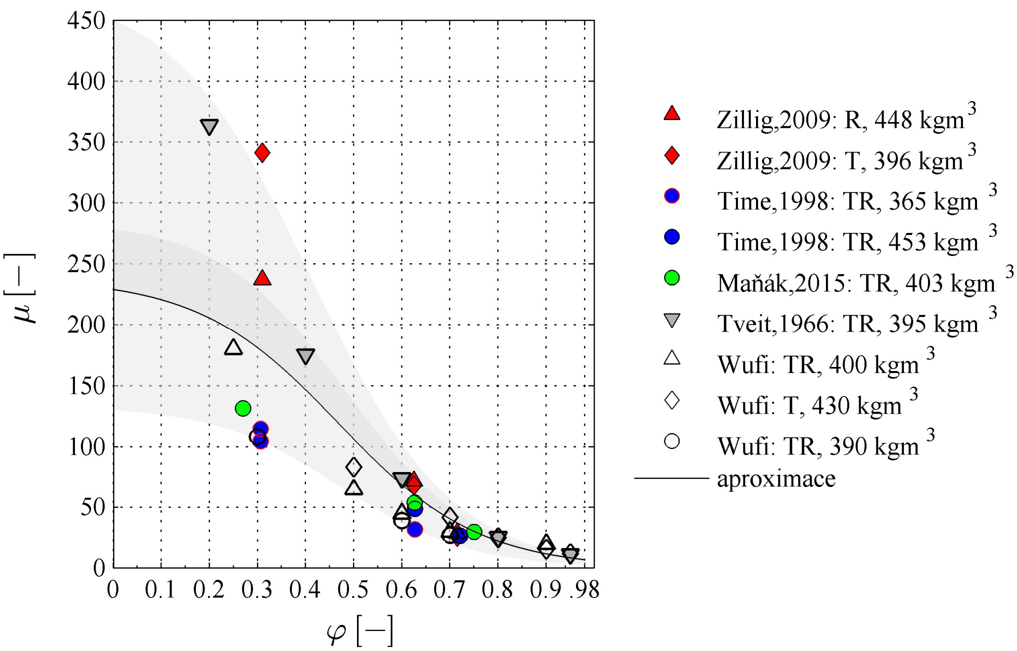

Figure 8: Approximation of dependence of μ value of spruce to the RH (i.e. φ) [28]

It is important to mention, that the curve is only approximation from collected values published by various laboratories. Those measured values are interpreted by colourful points in the chart.

2.2.5 Influence of moisture on wood-based thermal insulation

When designing a modern wooden house, a trend is to use as many natural materials as possible to reduce the environmental impact. Therefore, instead of classic thermal insulation made of mineral wool, wood fibre insulation can be used, which has similar values of thermal conductivity (λ), e.g. around 0,040 W/m*K. However, the λ value is also dependent on amount of water adsorbed in the material. Those wood fibre boards are used for thermal insulation, because of their high value of porosity, thus they contain an air, which is a very good thermal insulating layer. Nevertheless, when exposing the wood-fibre board to a high RH, sorption of water vapour molecules happens and water can fulfil open pores (detailed described above). In this case, thermal insulating characteristics of the wood-fibre board get worse, because water is better thermal conductor than air. [29][30]

2.2.6 Mould growth

Growth of mould fungi can occur on wooden material under certain conditions:

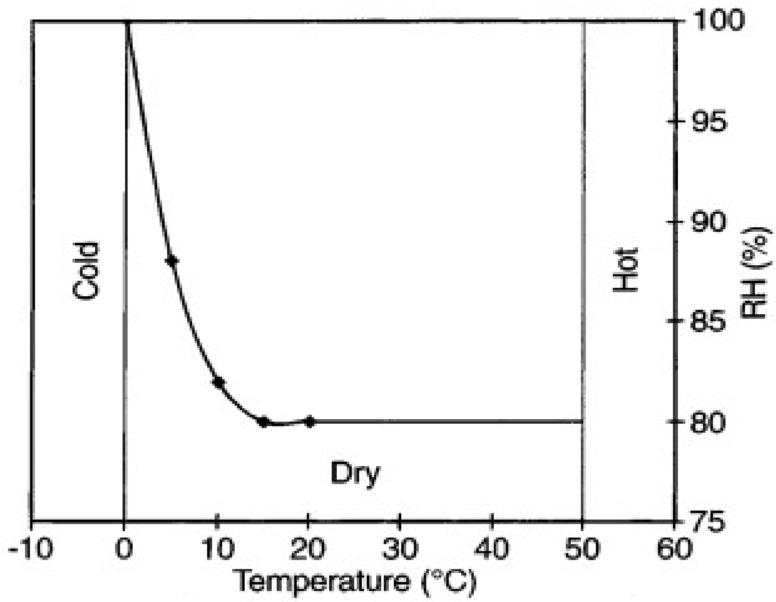

Figure 9: Conditions favourable for initiation of mould growth on wooden material as a mathematical model

The mathematical model (Fig. 9) shows that favourable temperature range for initiation of mould growth is 0-50 °C and critical RH is dependent on the temperature. When it is above 20 °C, the boundary RH is 80%. When temperature is lower, the RH rises. There is a certain time, usually several weeks, needed for mould growth. It varies according to RH and temperature, to which the wood is exposed. [31] Among other things, the mould growth is associated with possible health implications such as asthma. [32]

2.3 Measurement methods for determination of sorption isotherm

Sorption isotherm is measured in order to gain the moisture storage capacity in hygroscopic range (0 – 98% RH). [18] In this subchapter, different methods for determination of this essential moisture characteristic are shown.

2.3.1 Static gravimetric test

2.3.1.1. Principle

There is a conservative method called static gravimetric test, which is based on exposing the specimens to various environments with saturated salt solutions, each giving different RH. [33]

2.3.1.2. Procedure

First, the samples had to be completely dried out according to the ČSN EN ISO 12 570. [34] This Standard states that the attainment of complete drying is achieved when three consecutive weightings, at intervals of at least 24 hours, do not display any mass decrease higher than 0,1% of the sample weight. There are two methods, how to attain a completely dry state, either by a carrying out desiccant drying or by vacuum drying. The first approach takes place in a desiccator, where samples are enclosed with a desiccant such as silica gel or molecular sieves (usually zeolite). The drying process can be accelerated by placing the desiccator into a heated oven. [33] However, it is necessary to take into consideration that structures of certain materials may be damaged when they are exposed to high temperatures. Secondly, vacuum drying runs on the principle of creating vacuum around the specimens, and so the pressure is decreased below the partial vapour pressure of water. Consequently, the boiling point of water inside the material declines and the evaporation accelerates.[35]

After drying, samples are put into desiccators where they are exposed to environments with gradually increasing RH. This is controlled by various saturation salt solutions, which have the ability to indicate particular RH values when placed in the enclosed space.

The samples are periodically weighted in order to observe the mass growth. Again, ČSN EN ISO 12 571 indicates that if the mass increase is not higher than 0,1 % of the sample weight during three weighting at intervals of at least 24 hours, achieved equilibrium is considered. [36] From the measured mass value, EMC is derived. Then, the specimen is exposed to an air of higher RH, until it reaches 98 % of RH.

2.3.2 Dynamic vapour sorption (DVS) analysers

The static gravimetric test, which was described above, is simple, but time-consuming. According to the size of the analysed material, the whole procedure may last from a month to a year.

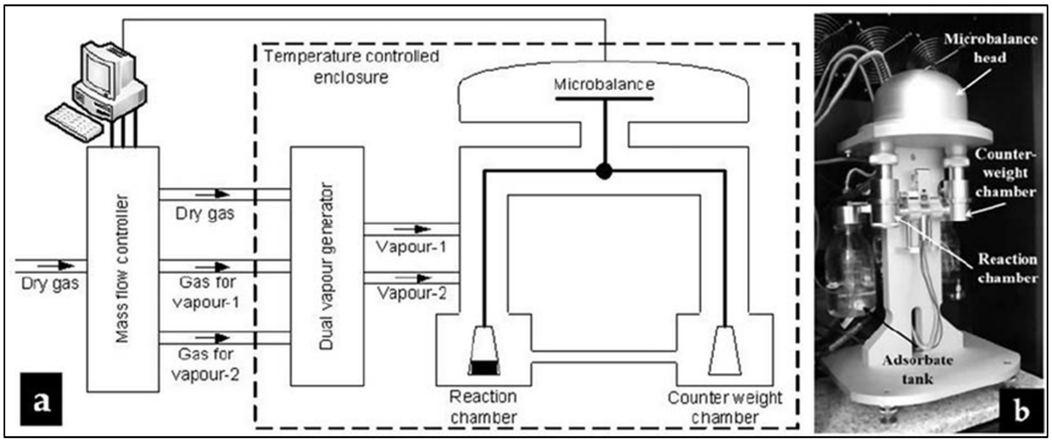

Figure 10: Scheme of DVS analyser. [35]

The dynamic vapour sorption (DVS) is a fairly new and faster modern method. It is based on changing the water vapour concentration in the air flow, which surrounds the specimen, and on subsequent, measuring the weight change directly inside the box. The whole process takes place in a fully automated instrument DVS analyser, which operates under PC control. A scheme of DVS instrument is shown in the Fig. 10.

There are two substantial advantages of this technique. First, the achievement of more accurate measurements is possible as the samples do not have to be removed from the instrument for weighting, unlike in the static gravimetric test. Second, considerably shorter time is required in comparison with the first method. Because of the accurate microbalance, the samples can be small, typically 10 mg. This leads to the minimalization of the time, which is required for reaching the equilibrium. [38]

3 Experiment

In this chapter, my own measurement of the sorption isotherm of wood is described. This experiment was held at UCEEB in 2018 during which the moisture storage capacity of wood was investigated. The stimulus for carrying out such experiment was that the storage capacity plays an important role in water vapour transport through external walls in wooden buildings. Subsequently, the resulting data were entered into the WUFI® Pro 6.1 software so that further detailed hygric analysis was carried out.

3.1 Methods

The static gravimetric test was chosen because it is generally considered as a proven method. The fundamental principle has been explained in the previous chapter. In this chapter, a detailed procedure of the experiment is shown.

3.1.1 Preparatory phase

First of all, three pieces of spruce were drawn from different parts of a tree trunk (bottom, centre, top). In order to accelerate the experiment, each of the three pieces was cut into smaller splinters of approximate dimensions 40 x 7 x 3 mm. The splinters from each piece were divided into five open aluminium bowls. These bowls do not report the change of their mass while exposing them to the air with different RH, which is important for exactness of the whole experiment.

Table 1: Initial mass [g] of all 15 samples taken from three different pieces of one spruce trunk (SOR 0, SOR 3, SOR5)

[g]	**SOR 0**	**SOR 3**	**SOR 5**
1	11.959	12.223	11.849
2	11.978	12.206	11.844
3	11.971	12.047	11.930
4	11.981	11.859	11.847
5	11.836	12.025	11.893

Thus, in total, 15 samples, each weighing approximately 12 g, were prepared. The mass refers to the correctness of the weighing scales, which works on accuracy of 0,001 g. Consequently, a totally dry specimen should not show its mass below 10 g.

3.1.2 Drying

All of the samples were put into a desiccator with a molecular sieve. To improve air circulation, two small ventilators were installed into the desiccator. The airtightness was achieved by putting sealing compound based on butyl on the top of the cover and a thin layer of vaseline between the body and the cover of the desiccator.

Figure 11: Samples of spruce wood in the desiccator

The specimens were weighted twice per week until they reached the EMC values according to the Standard ČSN EN ISO 12 570. [34] During the weighing process, the samples were covered by other aluminium bowls, so that any undesired effects of the surrounding environment were minimized. In order to dry out the samples properly, molecular sieves were regenerated once every two weeks. This was carried out at temperatures of 210 °C for periods of 6 hours. After

38 days, the samples were considered to be entirely dry, and thus ready for the adsorption procedure.

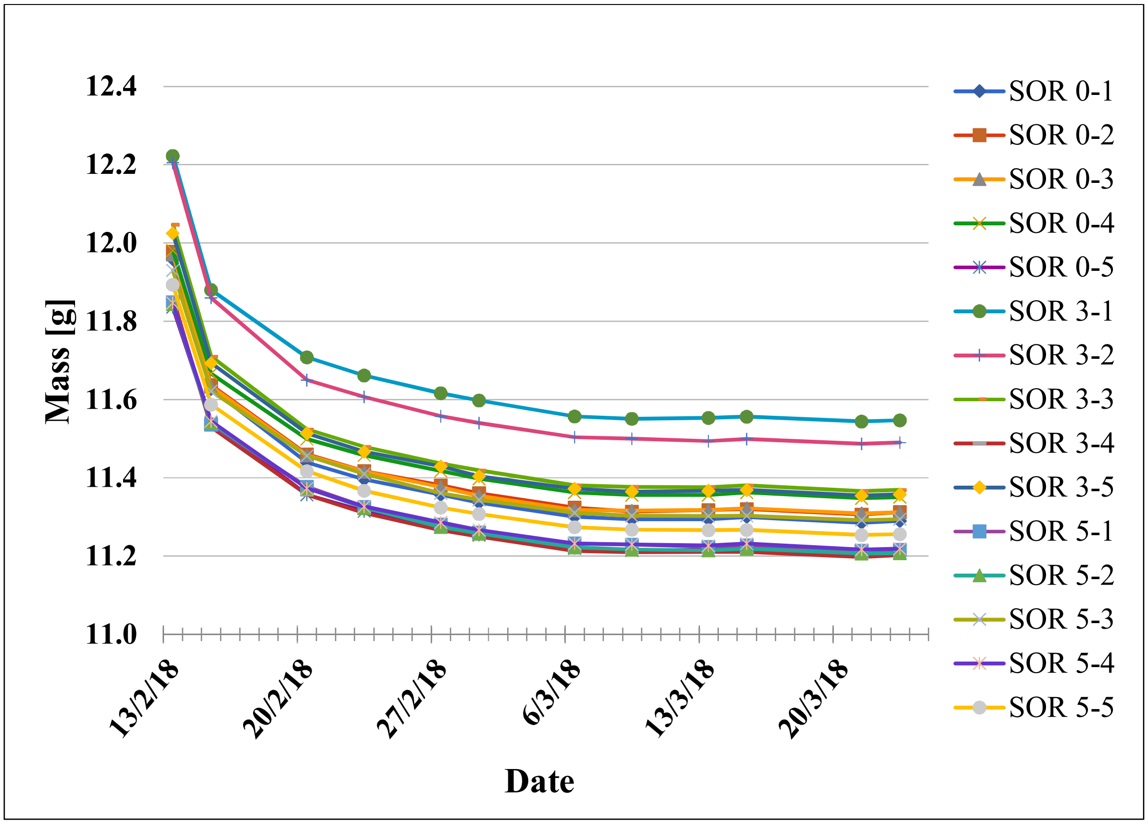

Figure 12: Drying of spruce wood for determination of sorption isotherm, mass decrease upon time

3.1.3 Adsorption process

After the drying procedure, the samples were divided into five desiccators, each of them with different salt solution ensuring specific RH. (see Table 2).

Table 2: RH given by a salt solution may change according to the ambient air temperature. Those values are assumed for 23°C, which is corresponding to the temperature at the laboratory during the experiment

Salt solution	RH [%]	Samples
CH_3COOK	22.8	SOR 0 - 1, SOR 3 - 1, SOR 5 - 1
NaCl	75.4	SOR 0 - 2, SOR 3 - 2, SOR 5 - 2
KCl	84.7	SOR 0 - 3, SOR 3 - 3, SOR 5 - 3
KNO_3	94.0	SOR 0 - 4, SOR 3 - 4, SOR 5 - 4
K_2SO_4	97.7	SOR 0 - 5, SOR 3 - 5, SOR 5 - 5

Again, the samples were weighted twice a week until they reached the desired EMC, according to the ČSN EN ISO 12 571. [36] The process of adsorption, which lasted 28 days, can be seen in the Figure 13.

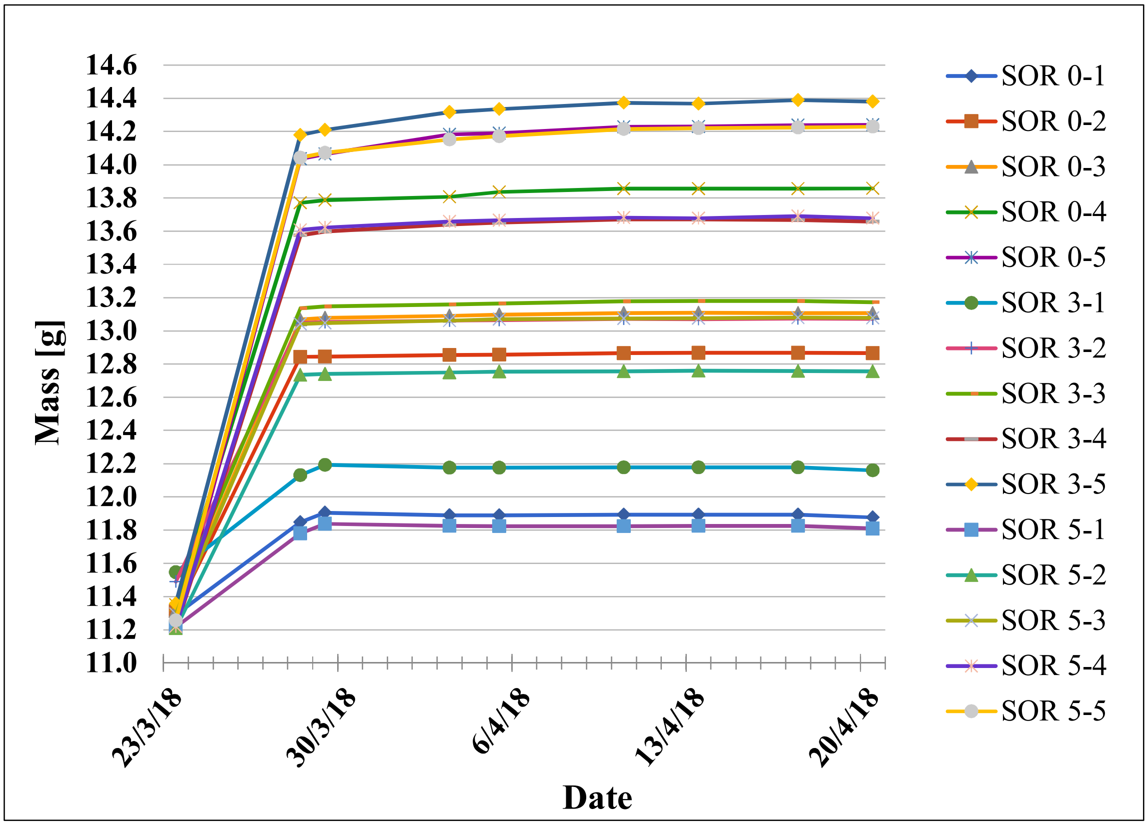

Figure 13: Adsorption process of spruce wood, mass increase upon time

3.1.4 Calculations

Once the mass of all the samples was stabilized (according to the ČSN EN ISO 12 571), the individual values of EMC [kg/kg] were calculated from the measured data:

$$EMC = \frac{(m_a - m_b) - (m_{dry} - m_b)}{(m_{dry} - m_b)} \; [kg/kg] \qquad (13)$$

where:

m_a … mass of the adsorbed sample reported during the last weighing of adsorption process

m_{dry} … mass of totally dry sample reported during the last weighing of drying process

m_b … mass of the aluminium bowl

3.2 Results and discussion

All the obtained EMC values, together with the average values of the three different pieces (SOR 0, SOR 3, SOR 5) are displayed in the Table 3.

Table 3: Resulting EMC values

Samples	RH [%]	SOR 0	SOR 3	SOR 5	AVERAGE
-	**0.0**	0.00	0.00	0.00	**0.00**
1	**22.8**	0.05	0.05	0.05	**0.05**
2	**75.4**	0.14	0.14	0.14	**0.14**
3	**84.7**	0.16	0.16	0.16	**0.16**
4	**94.0**	0.22	0.22	0.22	**0.22**
5	**97.7**	0.27	0.27	0.26	**0.27**

From the Table 3, we can conclude, that the EMC values are almost identical for all the three pieces. For that reason, the average values could be rendered into a sorption isotherm curve.

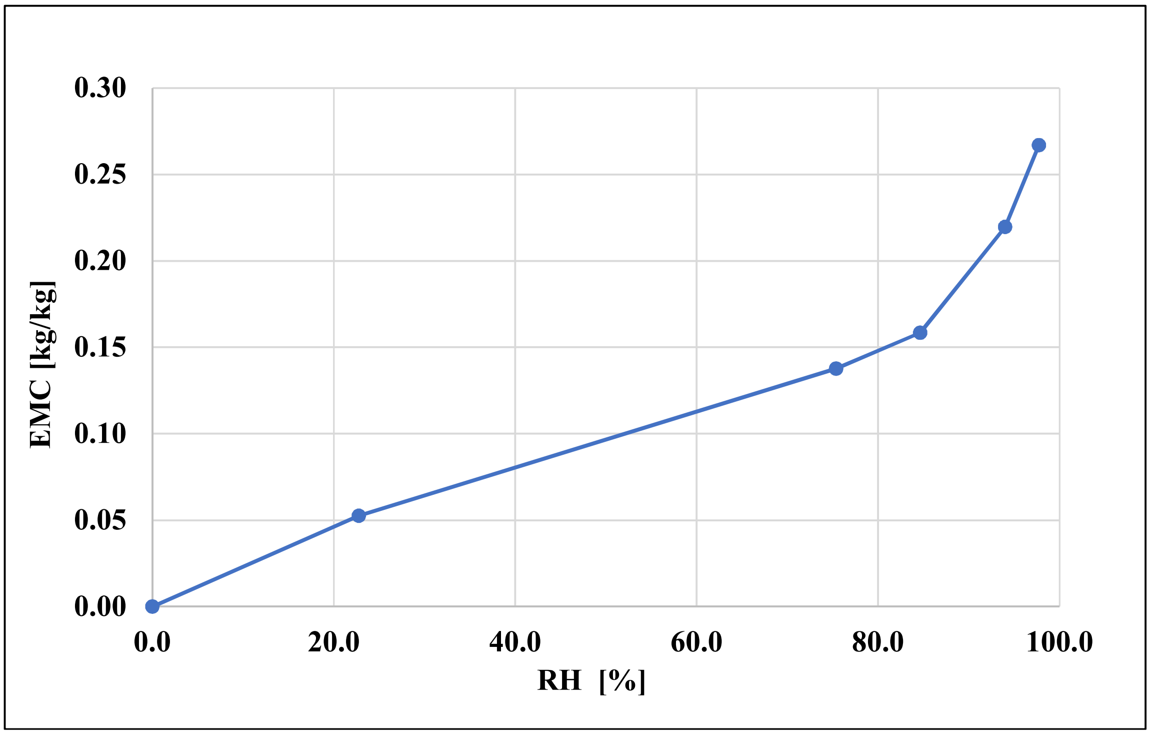

Figure 14: Sorption isotherm of spruce wood, UCEEB 2018

The measured sorption isotherm reports a typical three-zone shape (monolayer adsorption, multilayer adsoprtion and capillary condensation). Moreover, our result was compared with a reputable sorption curve published in the Wood Handbook – Wood as an Engineering Material, FPL, 2010, Chapter 4, p. 4-3. [12]

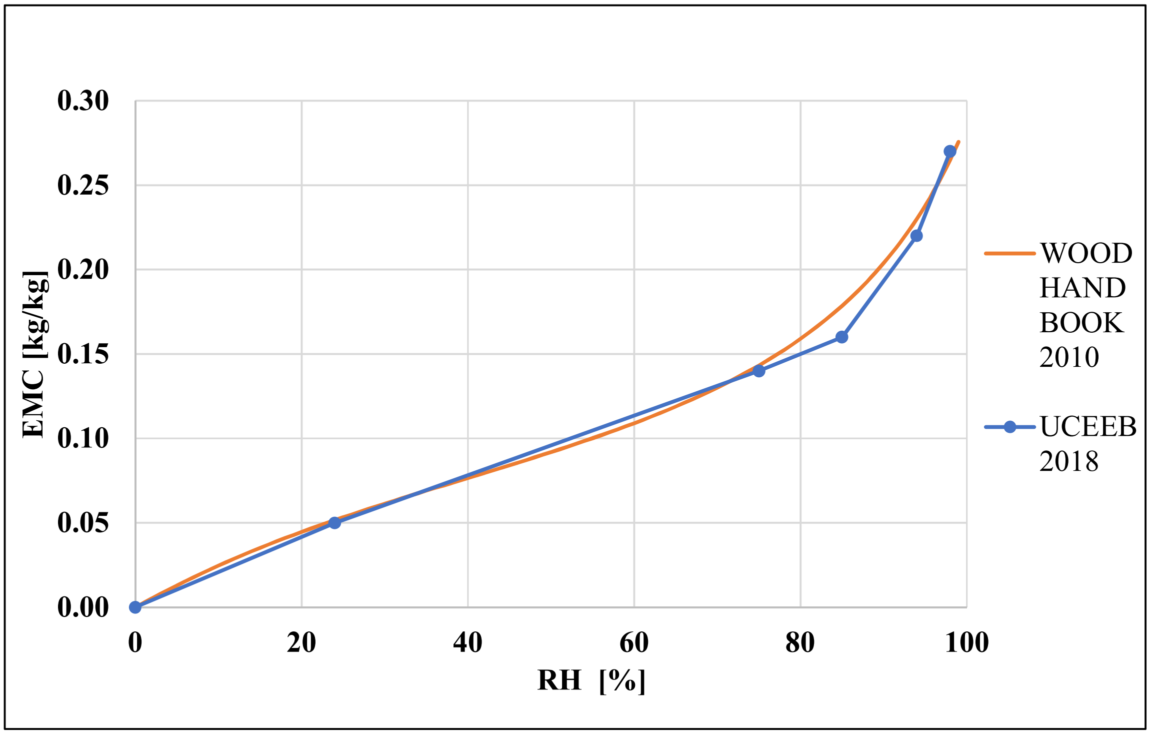

Figure 15: Comparison of the measured sorption isotherm with the reference curve

The nuance between those two curves is negligible. The subtle difference in the higher RH value of our isotherm could have been caused by two possible aspects. Either, we had prepared the solution incorrectly, thus the samples were exposed to a slightly different RH value. Or, the more probable explanation is that the reference curve from the Wood HandBook is actually an average of various measurements of different spruce wood.

Because the experiment was successful, the measured sorption isotherm was exported to the WUFI® Pro 6.1 software for the dynamic analysis of the most common external walls of modern wooden houses.

4 Research of external walls in modern timber buildings

For detailed hygric analysis, five fundamental external walls of modern wooden family houses were chosen; each representing one load-bearing system. Only in cases of frame and log construction, two assemblies were considered. That is because those systems behave differently in terms of water vapour transport. All the five selected structures are nowadays offered by several companies operating on the Czech market, while the sixth structure was designed by myself. All the structures were represented by ideal one-dimensional cross sections.

4.1 Methods

The research of the external walls was mainly focused on the current Czech market. Therefore, various companies supplying modern wooden houses in the Czech Republic were identified and their offers of external walls assemblies were checked. The book "Adresář výrobců a dodavatelů dřevostaveb 2018" was used as the source of the companies. [39] It is annually published booklet by the magazines DŘEVO&stavby and sruby&roubenky and provides a wide range of companies which deal with wooden houses. All the found suppliers were then divided into several categories according to the structural systems they are focusing on.

Table 4: List of the companies offering wooden houses on Czech market [37], modified

Company name	Frame/Panel constr.		Solid timber constr.	Log constr.
	VPS	VIS		
3AE / Novahome			■	
ALFAHAUS	■	■		
ALLSTAV CZ	■	■		
ARCHCON atelier	■		■	
Atrea	■			
A T R I U M	■			
Avanta Systeme spol.	■	■		
BARTOŠ DŘEVOSTAVBY	■		■	■
CEDAR HOME				■
CERTIKO	■	■		
DBH	■			
DOMY D.N.E.S.	■			
Dřevostavbybidlo	■	■		
Dřevostavby Biskup			■	■
Dřevostavby MC Novák			■	
Dřevostavby Mlčoch	■	■		
DUMRAZDVA	■	■		
EKOPANELY CZ	■			
FACHKAS stavební spol.	■	■		
GOOPAN BUILDING	■	■		
Hass Fertigbau Chanovice	■	■		
HK-DŘESTAV	■	■		
HUTCHHOUSE - modulové domky	■	■		
KANADSKÉ SRUBY TÁBOR				■
Kontio Loghouses				■
LUCERN stav	■	■		
Neat-Houses Dřevostavby	■	■		
NEMA Dřevostavby			■	
OK PYRUS			■	■
Origis	■		■	
PALIS Plzeň	■			
PENATUS			■	
Prodesi/Domesi	■		■	
Profi-Gips	■	■		
QUICKHAUS	■	■		
RD Rýmařov	■	■		
Roman Střihavka - Roubenky				■
RUDOLF EKODOMY	■			
Sruby Masiv				■

Sruby Pacák	■	■		■
Sruby Rajec				■
STAVEX KUTNÁ HORA	■	■		
Stavitelství Kašpar		■		
STORA ENSO WOOD PRODUCTS			■	
Tesařství Tůma	■		■	
Tesařství Urban				■
TFH dřevěné skeletové domy	■		■	
VEXTA	■	■		
VS DOMY	■	■		
WALFER				■
WOLF SYSTEM	■	■		
WOOD STEP	■	■		
WOOD SYSTEM	■	■		
WOOD-LIFE CZ				■
Total number of the companies offering the construction:	**37**	**25**	**13**	**13**

VPS ... "Vapour permeable structures"
VIS ... "Vapour impermeable structures"

It can be seen that most companies offer frame and panel construction at which “vapour permeable“ wall is the most common case (see Table 4).

Then, the most typical wall assembly, or two assemblies, for each system was/were selected and an own structure was designed.

4.2 Discussion and results

In the following part, the types of loadbearing systems are briefly characterized and all the selected structures are described. Also, the difference between the “vapour permeable“ and the “vapour impermeable“ systems are discussed.

4.2.1 Frame construction / Panel construction

For both frame and panel construction, the loadbearing system consists of wooden ribs of rectangular sections and a sheathing (OSB board, plywood...) for its stabilization. The only difference is that the frame construction is built completely *in situ*, whereas prefabricated panels are assembled in advance and then imported onto the construction site. When dealing with family houses, the construction is often called *2x4 (two by four) construction*, because of the fundamental dimensions of the wooden ribs 2´´ x 4´´.

Due to their different hygric performance, it is important to distinguish between these two types of external walls:

4.2.1.1. "Vapour permeable" construction

This construction enables the water vapour to permeate through the wall structure, thus the wall naturally "breathes". For most of the year, the water vapour circulates from inside to outside. For that reason, a general rule applies that the μ value of particular materials should be decreasing outwards (from interior to exterior). Otherwise the water vapour could condensate on the boundary of the two layers which would be highly problematic. In the "vapour permeable" system, a vapour semi-permeable layer is usually placed near to the inner surface. Normally, OSB board or plywood sheathing performs this function.

This type of construction is widely used, mainly due to its breathable character and a possibility to use a large scale of wood-based materials. However, mineral wool as the thermal insulation layer is still generally preferred over the wood fibre insulation.

As a typical structure, the wall assembly offered by Lucern company was selected (Figure 16). [40] The insulation cavity is filled with mineral insulation and the inner surface is clad by gypsum plasterboard. At the outer surface, there is a wood-fibre board performing both the reinforcing and thermal resistant function. This is covered by silicone plaster.

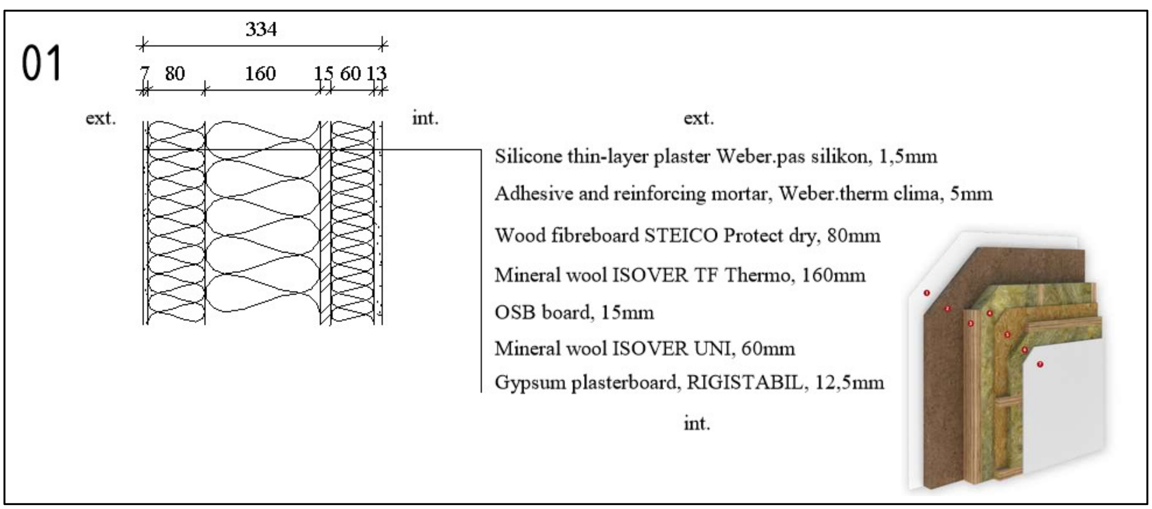

Figure 16: STRUCTURE 01 [38]

4.2.1.2. “Vapour impermeable“ construction

In this system, a vapour barrier typically made of polyethene is installed by the inner surface. Its function is to protect the construction from water vapour transport, to avoid any condensation. In other words, the membrane does not allow the water vapour molecules to go through the structure. Even though, this construction is very efficient solution for avoiding condensation (described in detail in the following chapters), it is currently not as popular as the “vapour permeable“ system. There are two main reasons for it: First, most of users of wooden houses prefer to live in a healthy environment surrounded by natural materials. Second, even the slightest leakage in the vapour barrier would cause huge intensification of vapour pressure at that spot and moisture problems within the structure would arise.

For the following analysis, *DNK Economy* wall was chosen as the typical “vapour impermeable“ construction. [41]

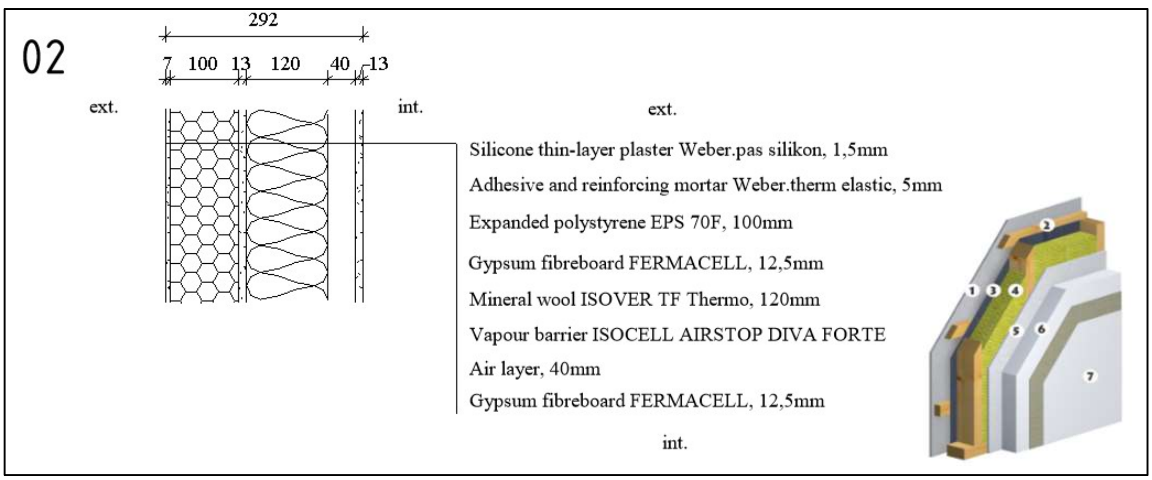

Figure 17: STRUCTURE 02 [39]

This structure also demonstrates that a wooden house may consist only of loadbearing logs, while other materials can be inorganic.

4.2.2 Solid timber construction

Another system, that is currently becoming popular, uses solid wood panels as the loadbearing component. This solid wall is usually made of Cross Laminated Timber (CLT) and possesses excellent mechanical and acoustic features. In terms of moisture process, the structure behaves similarly to the “vapour permeable“ system in Frame construction. Wooden panel takes over the role of semi-permeable layer. The only disadvantage can be in a large consumption of material (wood) leading to higher costs.

There are few certificated systems of CLT panels, for instance NOVATOP, which is fairly often distributed by many Czech companies.

One of the typical NOVATOP external walls was selected. [42] It is a ventilated wall with a wooden cladding at the external surface. All the thermal insulation layers are made of wood-fibre insulation.

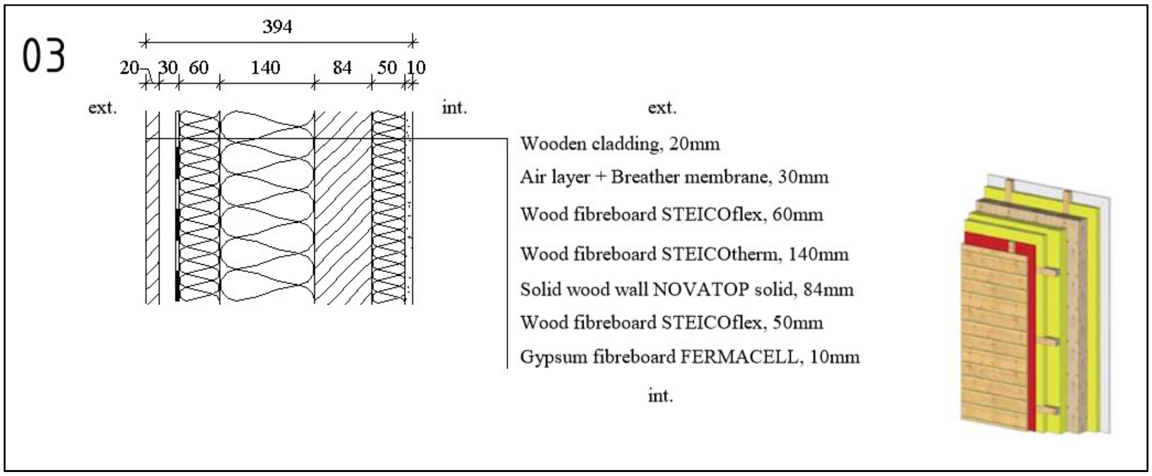

Figure 18: STRUCTURE 03 [40]

4.2.3 Log construction

This type of construction is historically the oldest structural system of timber houses. Simple assembly consists of only massive wooden logs which are placed on top of each other. Those logs can have either a rectangular or a circular cross section. Currently, log structures are not designed on a large scale, mainly due to the increasing demand of a low heat transfer coefficient (U value) of building envelopes. Today, the requirement of ČSN 73 0540-2 for U value of the external walls is 0,30 W/m^{2}K, and thus the wood-log structures have to be thick enough to keep this coefficient below the limit. For instance, OK Pyrus company builds the log houses with a 280 mm thick external wall. This structure was analysed as the number four. [43]

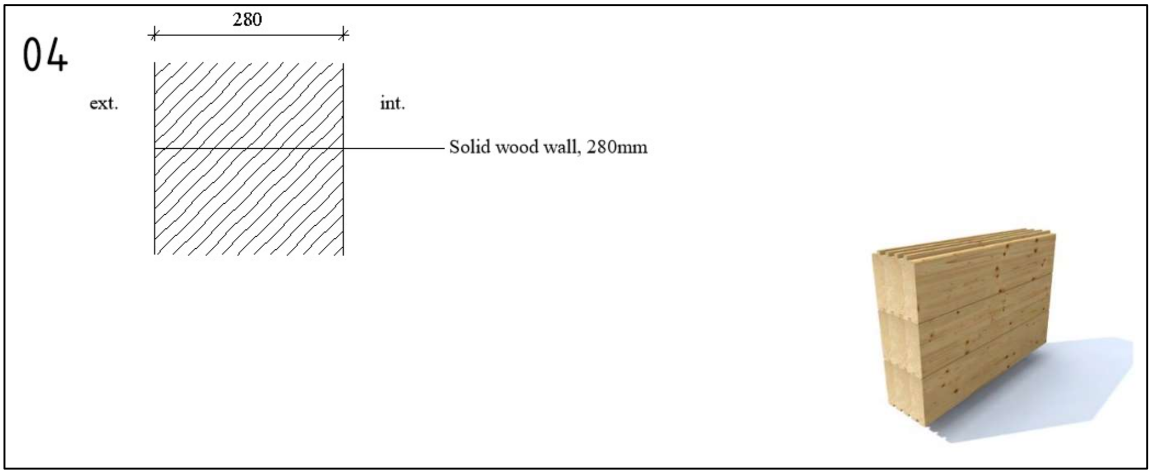

Figure 19: STRUCTURE 04 [41]

In order to enhance the thermal resistance of the wall, mineral wool as the insulating layer is added. Among others, OK Pyrus offers the following structure.

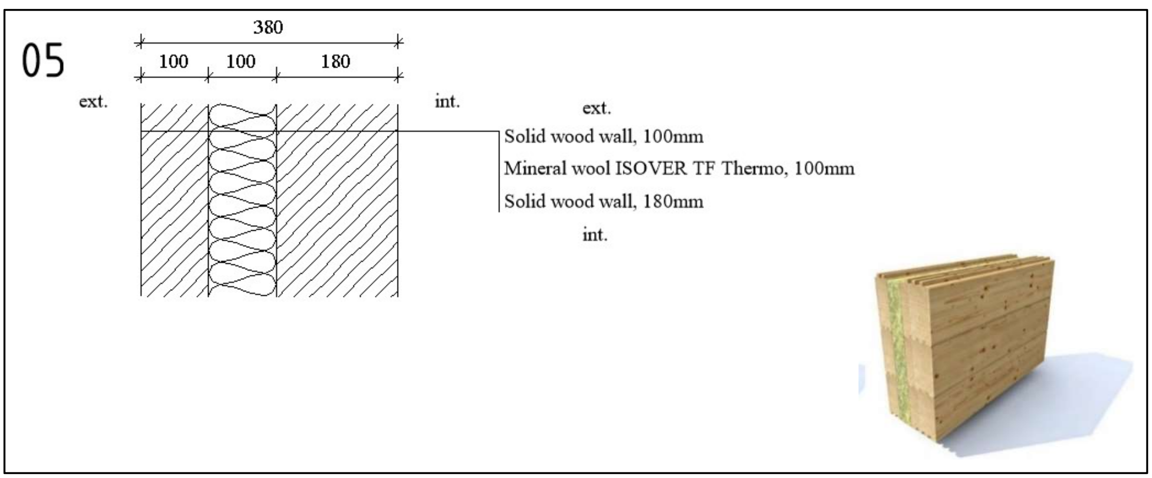

Figure 20: STRUCTURE 05 [41]

4.2.4 Frame construction - my own structure

This structure is designed as "vapour permeable" for the frame/panel construction. Unlike the other assemblies of this type containing mineral wool as a thermal insulation layer, in this structure, wood fibre board is used.

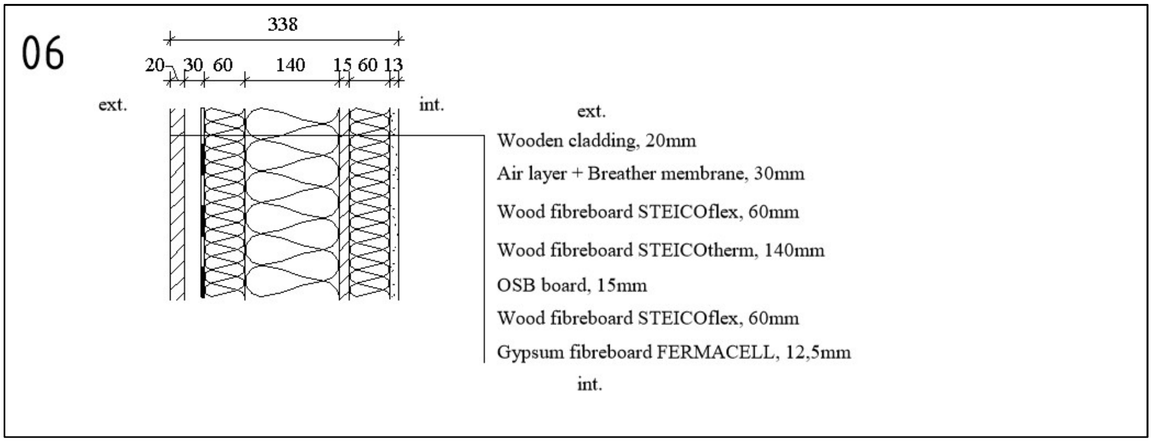

Figure 21: STRUCTURE 06

I designed this structure for the analysis because I consider the 2x4 construction with "vapour permeable" external walls as an effective and healthy way for low-energy houses. Moreover, I believe that as many organic materials as possible should be used within the assembly.

4.3 Résumé

One typical assembly for each type or category of external walls in modern timber houses, which were described above, was chosen. Plus, one wall assembly was designed, using the maximum number of wood-based materials. All the chosen structures are summarized in the Table 5.

Table 5: Summary of the analysed structures

Structure label	**Type of constr.**	**Category**	**Note**	
			External surface	**Main thermal insulation**
STRUCTURE 01	Frame constr.	vapour permeable	plaster	mineral wool
STRUCTURE 02		vapour impermeable	plaster	EPS
STRUCTURE 03	Solid timber constr.	CLT panels	wooden cladding	wood fibreboard
STRUCTURE 04	Log constr.	traditional	-	-
STRUCTURE 05		with insulation layer	-	mineral wool
STRUCTURE 06	Frame constr.	vapour permeable	wooden cladding	wood fibreboard

These walls were subjected to the detailed analysis of their hygric performance.

5 Hygric Analysis

5.1 Methods

The analysis of all chosen structures was carried out in three steps. First of all, a classic assessment (**TEPLO**) was performed in TEPLO 2010 software, which is used by the majority of companies for hygrothermal analysis of a construction. Second, WUFI® Pro 6.1 software, as the tool for dynamic analysis, was used. However, in the beginning, a simple model in WUFI® Pro 6.1 was created (**WUFI 01**). In this phase, materials were characterized by the identical properties as they were in TEPLO, and boundary conditions remained unchanged. Thirdly, WUFI® Pro 6.1 software was applied for detailed hygric analysis (**WUFI 02**), which was expected to show as realistic behaviour of construction as possible. Consequently, where applicable, the dependence of material characteristics upon a change of RH, rain, solar radiation and capillary transport were here considered.

In order to conduct a deeper investigation of the difference between the classic assessment (TEPLO, WUFI 01) and the realistic model (WUFI 02), several steps had to be added into the analysis. These intermediate stages were running only on the most common wall assembly, which is the structure 01.

5.1.1 TEPLO

TEPLO 2010 software is an elementary tool used for technical assessments of building constructions in terms of transport of heat and transport of water vapour through the structure. Besides the determination of the heat transfer coefficient (*U*-value), this software can also determine the amount of the condensed water vapour within the construction. Also, it solves how much water can evaporate. The calculation procedure is valid according to the standard ČSN 730540-4 and ČSN EN ISO 13788. The resulting data are presented both annually and monthly; and they are compared with the ČSN 730540-2 and EN ISO 13788.

Generally, TEPLO 2010 is used as the only one method for moisture assessment when designing a building. Although, it is a stationary test (*i.e.* not changing in time) and calculates with constant characteristics of materials.

Material characteristics

In TEPLO, each material is described by four specific values:

λ ... Thermal conductivity [W/mK]

ρ ... Bulk density [kg/m^3]

c ... Heat capacity [J/kgK]

μ ... Water vapour diffusion resistance factor [-]

According to those input parameters, the software determines how much water can appear within the structure. Those properties, mainly drawn from technical data sheets of producers (spruce from WUFI Fraunhofer-IBP database), are stated in the *Appendix 01* for all the used materials in the analysed structures.

Boundary conditions

Surface transfer coefficients

At both exterior and interior surface, standard values for external walls were considered. For the exterior surface, the heat resistance is 0,059 m^{2}K/W, for the interior resistance, it is 0,13 m^{2}K/W.

Climatic data

Outdoor climate

Climatic data for external surface were drawn from Meteonorm, a world-wide meteorological database collecting data from ground stations all around the world. Hradec Kralove (50,18° N; 15,83° E, 285 m a.s.l.) was chosen as the representative place for the Czech climatic conditions. Monthly averages of temperature and RH were exported from Meteonorm and entered into the TEPLO 2010 software.

Indoor climate

Indoor climate was considered according to the ČSN 73 0540, which indicates the mean temperature to be 21 °C and the RH to be of a value of 50 %. The calculation was done in the Humidity class 3, representing environment with medium humidity in the residential buildings with a small number of occupants.

5.1.2 WUFI

WUFI® Pro 6.1 software, developed by Fraunhofer-IBP, is a 1D dynamic programme for the evaluation of moisture conditions in building envelopes. One of the available outputs of WUFI is the determination of the MC within each layer of the structure, along a specific period of time. The results are comparable with the standard ČSN 730540-2/Z1, which allows the MC value of 18 % in wood-based materials.[14]

5.1.2.1. WUFI 01

In the first phase, a model was created similarly to TEPLO model in order to find out whether the results from these two programmes are relevant to each other. Thus, all of the used materials were characterized by four fundamental values: λ, ρ, c, μ. Only the moisture storage function was added because the WUFI software needs the dependence of the moisture content on RH for the calculations of moisture content in each layer. Also, the boundary conditions were put identically to the TEPLO 2010 software. In other words, the values of the surface transfer coefficients remained unchanged, as well as the mean values and the humidity class of the indoor environment. Concerning the outdoor conditions, meteorological data (only RH and temperature) from the same station (Hradec Kralove; 50,18° N; 15,83° E) were gathered from Meteonorm in hourly steps. This hourly data format is required by WUFI Pro, in order to run the non-stationary analysis.

5.1.2.2. WUFI 02

Then, to get closer to the real moisture behaviour of the structure, hygrothermal functions available in WUFI® Pro 6.1 for separate materials were considered. Moreover, the rain and the solar radiation were taken into account, thus realistic climatic conditions were created.

Material characteristics

Hygrothermal functions

Unlike TEPLO 2010 software, WUFI® Pro 6.1 enables to calculate with those characteristics which are temperature- or moisture-dependent. This is applied only for those materials, which properties vary with different T and RH (*e.g.* liquid transport coefficients are considered only for capillary-active materials).

Moreover, certain functions, such as moisture- or temperature-dependent thermal conductivity or temperature-dependent enthalpy, do not have an impact on the resulting moisture content within the structure. For that reason, only the necessary functions were considered.

Moisture storage function

This feature closely relates to the sorption isotherm. While the sorption isotherm normally shows the relationship between mass MC and RH, the moisture storage in the WUFI software is interpreted by volumetric MC. The link between the mass MC and the volumetric MC is discussed in Theory chapter.

The moisture storage function was taken from the WUFI database for most of the analysed materials. Only in the case of wood, the sorption isotherm was measured by myself and it was exported in the form of the volumetric MC to the software.

Liquid transport coefficients

As mentioned above, liquid transport coefficients depending on the moisture content describe liquid water migration in the capillary-active materials. In the content of building physics, it is sufficiently accurate to consider this transport as diffusion. Thus, WUFI Pro introduces two coefficients: the first one is for suction (*Dws*) and describes water uptake when it is raining and the surface of material sucks the water. The second one relates to the redistribution (*Dww*). This corresponds to the water migration throughout the material when no more new water is coming into the structure and the present water is redistributing.

Those functions (if applicable) were taken from the Fraunhofer-IBP database.

Water vapour diffusion resistance factor, moisture-dependent

This dependence is shortly discussed in the Theory chapter. Although most of the materials do not possess this relation, spruce and OSB board show significant decrease of μ-value with increasing RH. The approximation created from several measurements of μ of wood was applied to WUFI (see Fig. 8). For OSB board, the dependence was derived from the Fig. 8 by increasing all μ values of 10. This is based on an internal approximation of faculty of Civil Enginnering in CTU, as there are no other available sources for this dependence.

Boundary conditions

Surface transfer coefficients

In the detailed analysis, heat resistance for exterior surface remained 0,059 $m^2 \cdot K/W$ as in TEPLO software. Solar radiation was expressed by short-wave radiation absorptivity equal to 0,4. Long wave radiation emissivity remained empty because this factor is already included in heat resistance value. No special environment around the structure such as weathered concrete or desert sand was considered, hence, ground short-wave reflectivity was given by standard value 0,2. To incorporate the rain aspect, normal value (0,7) of adhering fraction of rain for vertical structures was calculated. (see Figure 22)

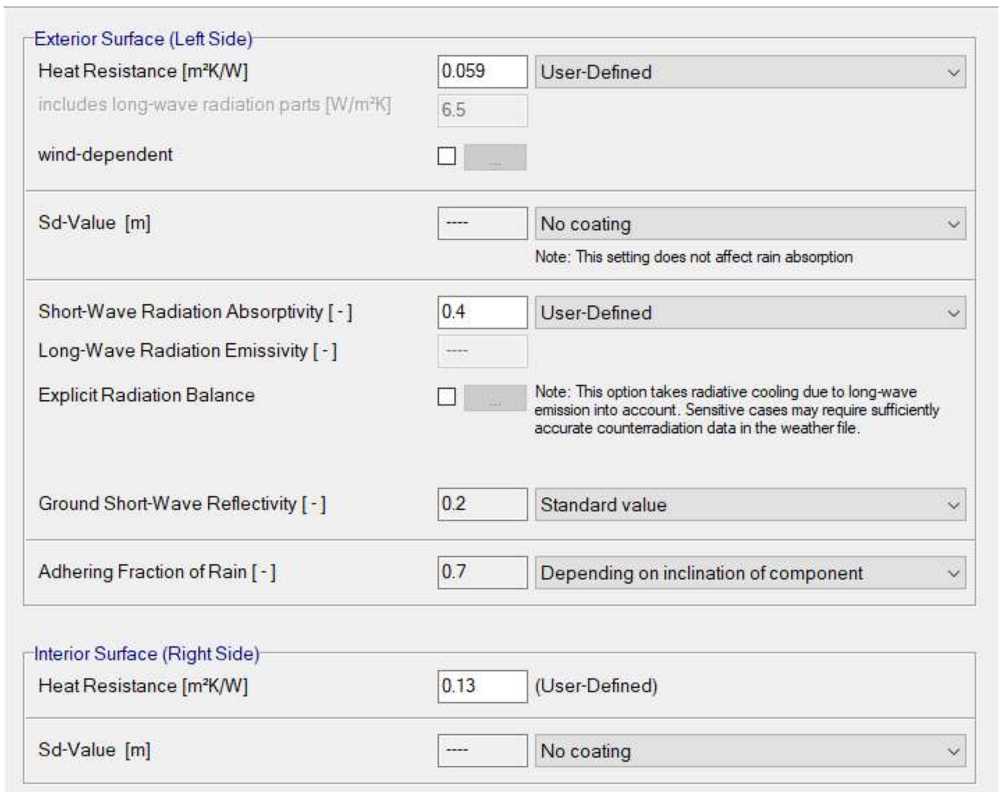

Figure 22: Surface transfer coefficients for the detailed hygric analysis

Climatic data

Indoor climate

Indoor climate was set according to ČSN EN ISO 13788 with temperature 21°C. Humidity class no.3 was considered.

Figure 23: Indoor climate conditions for the detailed hygric analysis

Outdoor climate

A meteorological data file was exported from Meteonorm. It includes temperature, RH, solar radiation and precipitation data from Hradec Kralove ground station (50,18° N; 15,83° E, 285 m a.s.l.). Temperature and RH curves are seen in the Figure 24.

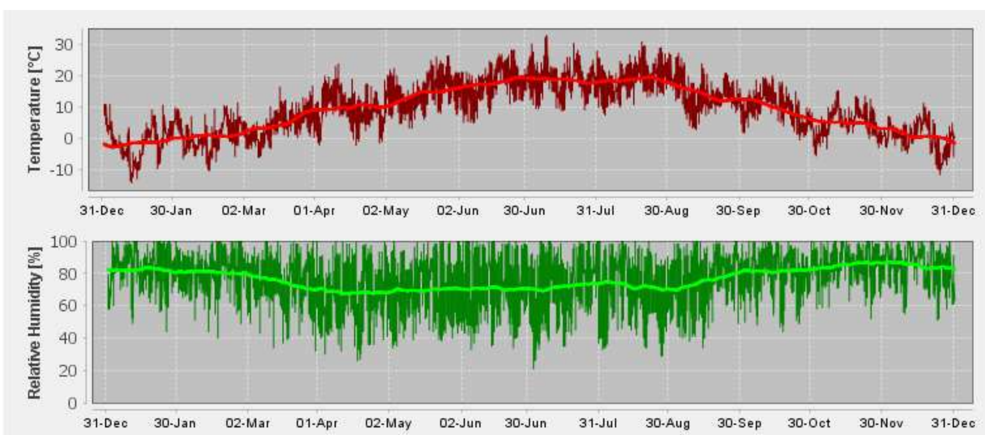

Figure 24: Outdoor climate conditions for the detailed hygric analysis

Solar radiation and rain was automatically made by WUFI software (see Fig. 25). Sun has the most unfavourable effect on north side of the construction, whereas, rain comes from the west most often. In the method WUFI 02, north orientation was considered.

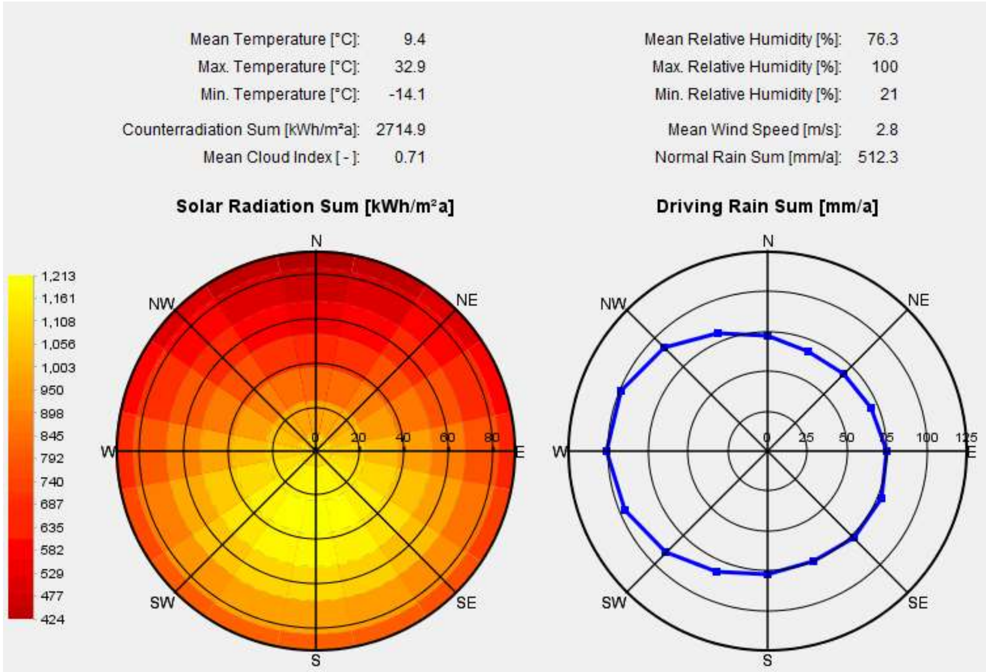

Figure 25: Climate analysis of solar radiation and rain effect on the construction [WUFI® Pro 6.1]

Additional steps in the analysis of structure 01

The most common assembly of external walls in the modern wooden houses, i.e. Structure 01 - vapour permeable structure in the frame/panel construction, was analysed by several additional steps described below.

WUFI 02A

All materials were described with basic characteristics (i.e. no hygrothermal functions considered) + solar radiation was taken into account.

WUFI 02B

Liquid transport coefficients were added to the basic characteristics, however, μ value of OSB remained as a constant + solar radiation was taken into account.

WUFI 02C

Liquid transport with basic characteristics was considered, however, μ value of OSB still remained as a constant + solar radiation and rain were taken into account.

WUFI 02W

All detailed characteristics were considered + solar radiation and rain effect was taken into account + the construction was oriented to the west.

5.1.3 Summary of the methods

In the following table, all methods are summarized (see Table 6).

Table 6: Summary of the methods used in the hygric analysis

<table>
<tr><th rowspan="2"></th><th colspan="3">MATERIALS</th><th colspan="3">CLIMATIC DATA</th><th colspan="2">ORIENTATION</th></tr>
<tr><th>Basic char.</th><th>Liquid trans.</th><th>μ of OSB</th><th>T+RH</th><th>SUN</th><th>RAIN</th><th>NORTH</th><th>WEST</th></tr>
<tr><td>TEPLO</td><td bgcolor="yellow"></td><td></td><td></td><td bgcolor="yellow"></td><td></td><td></td><td colspan="2">unspecified</td></tr>
<tr><td>WUFI 01</td><td bgcolor="yellow"></td><td></td><td></td><td bgcolor="yellow"></td><td></td><td></td><td bgcolor="yellow"></td><td></td></tr>
<tr><td>WUFI 02A</td><td bgcolor="yellow"></td><td></td><td></td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td></td><td bgcolor="yellow"></td><td></td></tr>
<tr><td>WUFI 02B</td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td></td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td></td><td bgcolor="yellow"></td><td></td></tr>
<tr><td>WUFI 02C</td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td></td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td></td></tr>
<tr><td>WUFI 02</td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td></td></tr>
<tr><td>WUFI 02W</td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td bgcolor="yellow"></td><td></td><td bgcolor="yellow"></td></tr>
</table>

Note: yellow fields in the column "μ of OSB" indicate considering of μ as dependent on RH; white fields indicate μ as a constant. In other columns, yellow fields always state that the particular function is considered.

5.2 Results and discussion

In this chapter, all results are presented and possible causes are discussed. It is divided into two major parts, each debating one fundamental method of the analysis: TEPLO and WUFI. Furthermore, each structure was discussed separately as it was analysed in WUFI Pro software.

5.2.1 TEPLO

In TEPLO, Amount of condensated and evaporable water vapour within the entire structure was calculated for all present assemblies.

Table 7: Results of TEPLO Assessment

TEPLO ASSESSMENT		STRUCTURE					
		01	**02**	**03**	**04**	**05**	**06**
ČSN 730540	Amount of **condensed** water vapour per annum $M_{c,a}$ [kg.m^{-2}.a^{-1}]	0.021	0	0	0.001	0.010	0
	Amount of **evaporable** water vapour per annum $M_{ev,a}$ [kg.m^{-2}.a^{-1}]	10.736	-	-	0.294	0.190	-
	$M_{c,a} < M_{ev,a}$ and $M_{c,a} < 0.10$ kg.m^{-2}.a^{-1}	OK	OK	OK	OK	OK	OK
ČSN EN ISO 13788	Maximal amount of **condensed** water vapour within one month M_c [kg.m^{-2}]	0	0	0	0	0	0
	$M_c < M_{ev}$	OK	OK	OK	OK	OK	OK

The resulting data were compared with ČSN 730540 and ČSN EN ISO 13788. All structures easily met both standard requirements.

5.2.2 WUFI

Structure 01

The structure 01 was simulated in WUFI for four years.

Wood fibreboard was observed as a crucial layer in terms of the potentially large amount of water. Thus, moisture content (MC) in this layer was exported and compared with the Standard value of MC in the wood-based materials 18%. All WUFI methods were calculated.

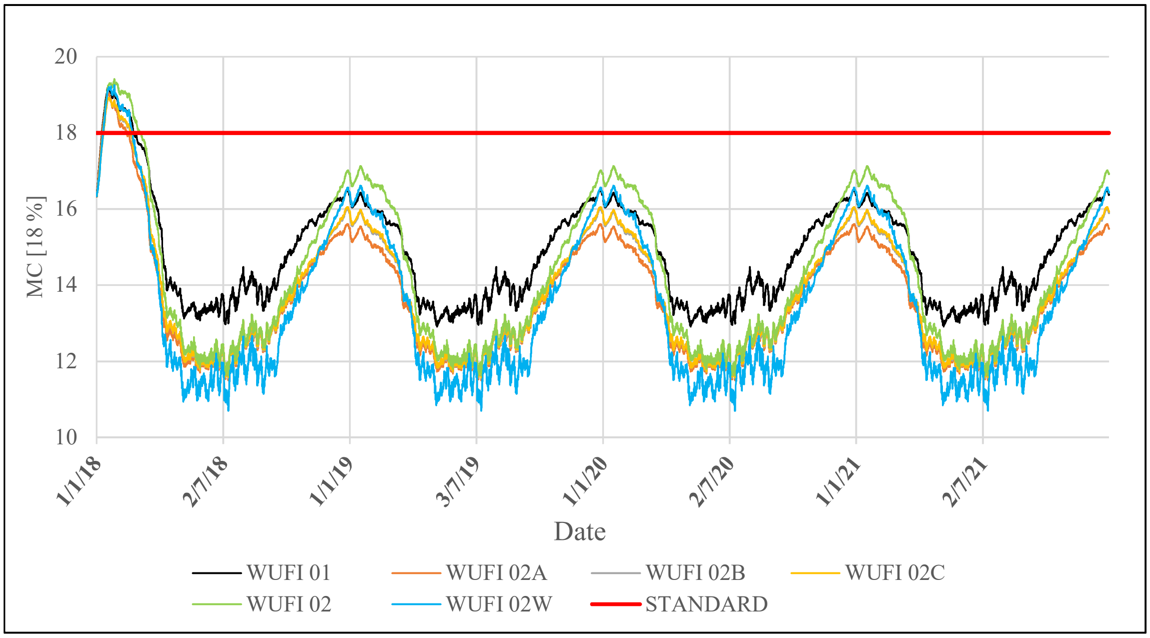

Figure 26: MC in the external wood fibreboard_STRUCTURE 01

First, it is seen that all the methods report the MC value below 18%. Consequently, the structure meets the Standard requirement and the design is safe in the context of the excessive moisture. The incipient increased values of MC are given by initial conditions (RH, temperature, built-in moisture) set in WUFI and it is not needed to concern about them because they are above the 18 % limit only for first two months. The important deduction is that MC does not increase every year, thus, the amount of condensed water does not exceed the amount of evaporable water. As a result, the moisture is not going to affect the structure negatively.

Second, there are obvious differences among presented methods. The maximal values of MC during winter were further investigated.

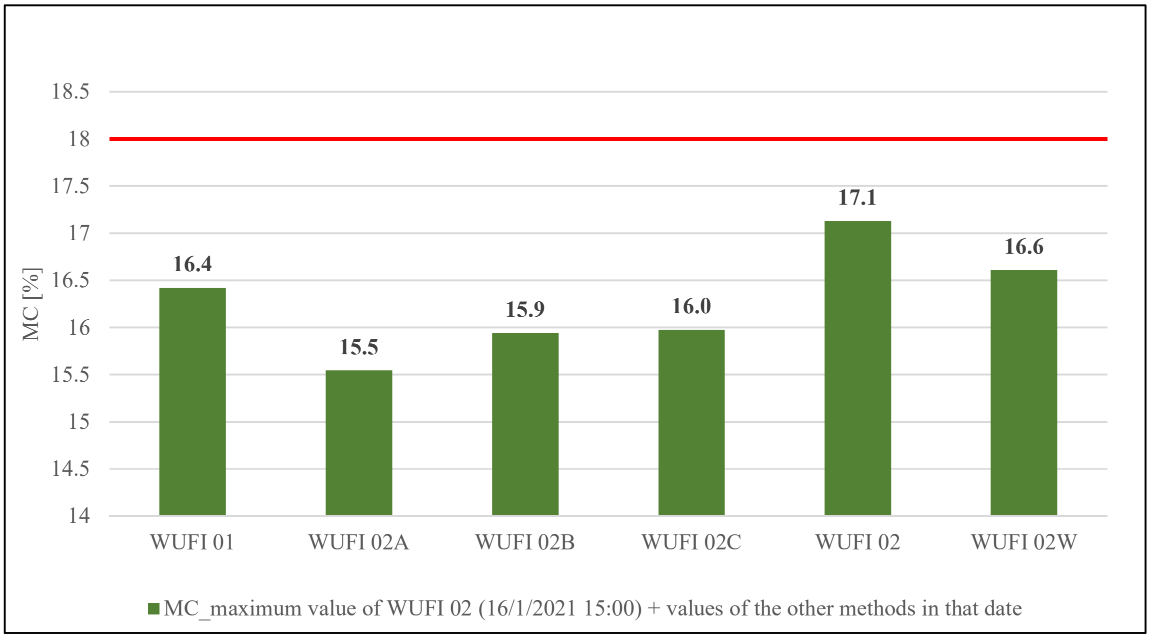

Figure 27: Comparison of maximum values of MC in the wood fibreboard_STRUCTURE 01

The method WUFI 01 shows that the maximal value of MC which appears in the structure within a year is 16,4 %. Then, the second method WUFI 02A varying from WUFI 01 only by adding a solar radiation reports a considerable decrease by 0,9 %. Obviously, the sun helps to dry out the structure and thus, acts as a favourable factor. Thereafter, the liquid transport coefficients of applied materials are added (WUFI 02B). This causes an increase of maximal value of MC by 0,4 % even though the rain influence is not involved. When switching on the rain effect (WUFI 02C), the maximal MC increases only by 0,1%. It says that consideration of water redistribution through the structure has larger effect on the MC then the suction of the water during the rain.

However, the most rapid growth of MC (by 1,1 %) is seen between WUFI 02C and WUFI 02. In that case, only μ-value of OSB board changed from the constant to the dependent on the RH as in reality. Hence, it is obvious that μ-value of OSB significantly influences this structure. When the constant value μ = 200, as it is stated in the data sheet of the product, is replaced by the variable value according to the RH, the maximal MC raises by 1,1 %. Even though this construction stays unharmed, it is not negligible difference.

Finally, difference between southern and western façade is observed. As seen, the structure oriented to the west behaves more favourably. It is caused by proportion of solar and rain effect. Accordingly, a lot of rain on the west (see Fig. 25) do not influence the structure as negatively as low solar radiation on the north.

Structure 02

As there is no wood-based material in the assessed cross section, total moisture content within the Structure 02 is evaluated.

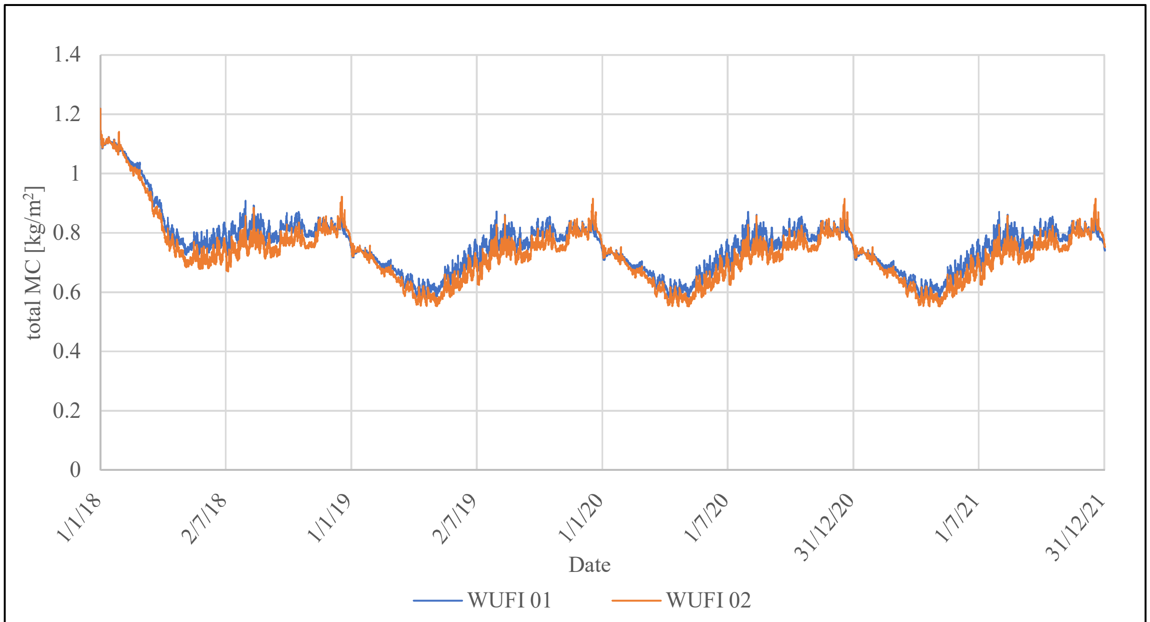

Figure 28: total MC within STRUCTURE 02

There are two inferences from the result. First, after the attainment of steadiness (after 4 months), the total MC does not report any annual increment. As a consequence, the amount of condensed water is not larger than the amount of evaporable water in the annual cycle; which fulfils the Standard requirement. Consequently, there is no threat that the moisture would cause damage in the structure on condition that, there are no leakages in the vapour barrier.

Second, the differences between two methods are insignificant. To explain that, the μ-value of the vapour barrier made of PE does not vary according to the surrounding environment. Hence, unlike the Structure 01, the μ value is the constant in both methods and the nuances between those two methods are given by considering solar radiation, rain and liquid transport.

Structure 03

The structure 03 was also simulated for four years. Similarly, in the Structure 01, MC in the external wood fibreboard was observed.

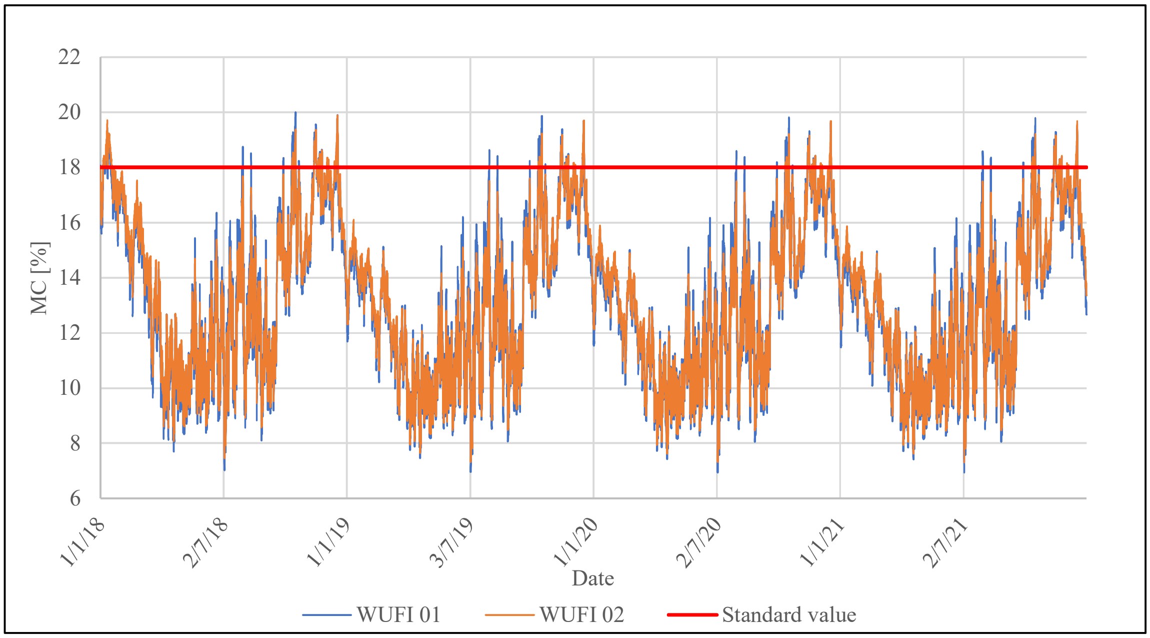

Figure 29: MC in the external wood fibreboard_STRUCTURE 03

First of all, compared to the Structure 01, there is a noticeable change in the shape of the curve expressing MC. The possible clarification of this is that the Structure 03 consists of ventilated wooden cladding at the external surface. Consequently, the wood fibreboard covered only by breather membrane reacts faster on the variances of the outdoor conditions than if it is covered by plaster. Therefore, the change of MC is more rapid, and the curve more "fluctuates".

As in the previously examined structures, the amount of moisture does not annually grow, which fulfils one of the Standard presuppositions for safe design.

Considering WUFI 02 method, MC in the wood fibreboard is above the Standard limit of 18% in 3,9% of the total time, which is equal to 14 days a year. It can be assumed that it does not endanger the wall´s function; however, it does not meet the Standard requirements.

Comprising the WUFI 01 and WUFI 02 methods, the difference in the results is inconsequential. (The total averages of MCs differ by 0,05 %). It determinates, that even though all additional factors summed together are considered, they do not have any significant effect on the moisture behaviour of the Structure 03. Probably, the detailed climate conditions cause a decrease of MC, however, the consideration of liquid transport and variable μ-value of the solid wood cause a reappearance on the same values as in WUFI 01. Possibly, one of the reason, why the values do not go higher, as in Structure 01, is, that μ-value of wood (μ = 157) is differently set than the μ-value of OSB board (μ = 200). To sum up, it can be said, that in the case of Structure 03, the basic simulation reports the same results as the detailed analysis.

Structure 04

The structure 04, with its only one layer (massive spruce wood), is much simpler than other assemblies. The MC was observed in the wood for twenty years.

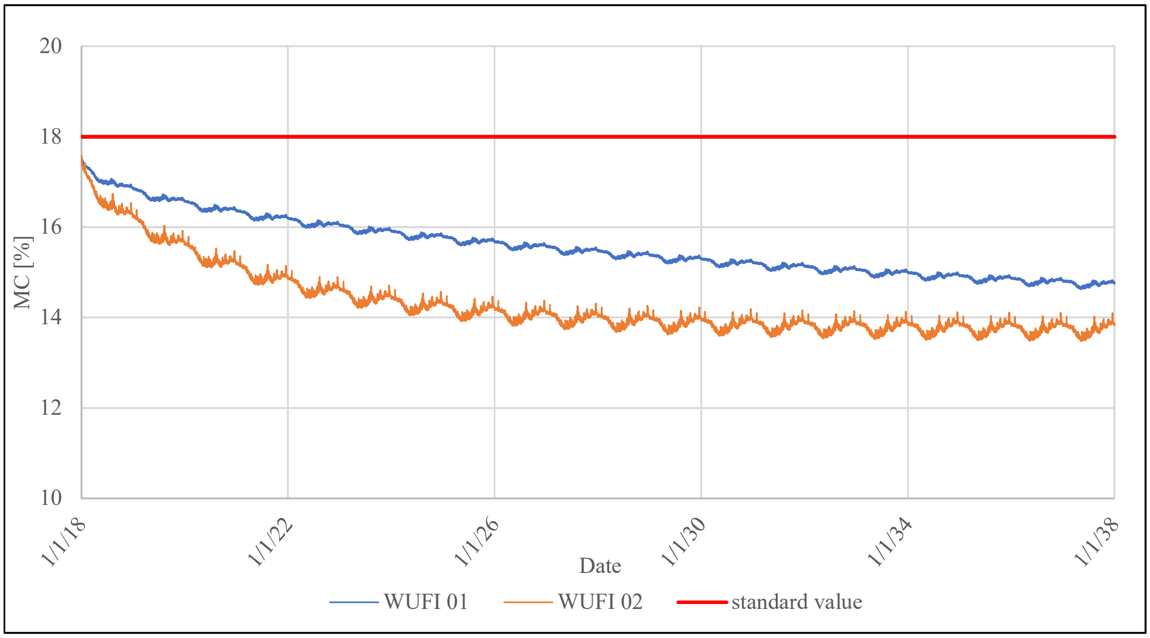

Figure 30: MC of wood_STRUCTURE 04

First, it is important to mention that the initial RH set at 80 % is related to the 17,5 % of MC in the wood. It can be seen from the Fig. 30 that if the wood is built into the structure with this built-in moisture, it takes a lot of time to equilibrate the MC in the wood. However, nor in one case (WUFI 01, WUFI 02), the MC exceeds the limit value of 18 %. Therefore, the moisture should not cause any troubles. Among other things, this can be one of the reasons, why construction of log houses has a long tradition.

Second, there is a visible difference between two presented methods. Whereas the basic method WUFI 01 shows very long time of drying (even after 20 years the MC annually decreases), WUFI 02 model displays a shorter time of reaching annual equilibrium, and also, a smaller amount of MC. Thus, in this case, factors in the detailed WUFI 02 method contribute to the more favourable behaviour. The structure could be further investigated to find out, which aspect play a key role in the difference as it was in the instance of Structure 01. My assumption is that variable μ-value of wood influences the change the moisture behaviour the most. As it is seen from the Fig. 31, RH within the structure moves between 65 – 80 %. According to the considered dependence of μ-value on RH, μ-value moves between 53 – 22. The basic method WUFI 01 calculates with μ = 157. The lower the μ-value is, the more moisture goes through and less moisture remains in the structure. Therefore, WUFI 02 reports faster stabilization and lower values of MC than WUFI 01.

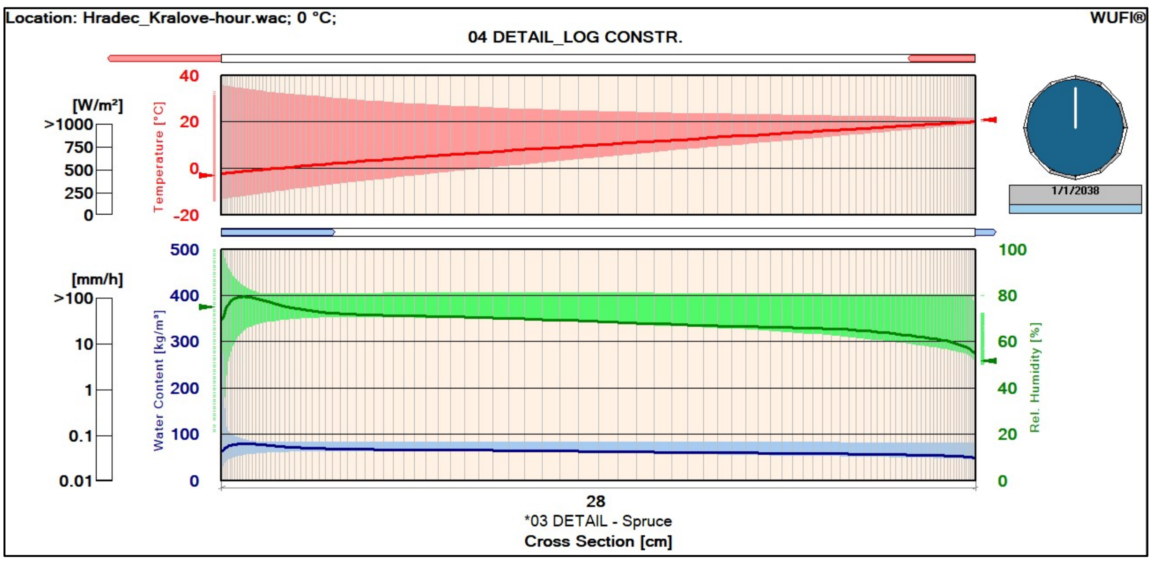

Figure 31: RH and T values in the STRUCTURE 04

Structure 05

External wooden layer was selected for observation of MC as it is prone to moisture problems.

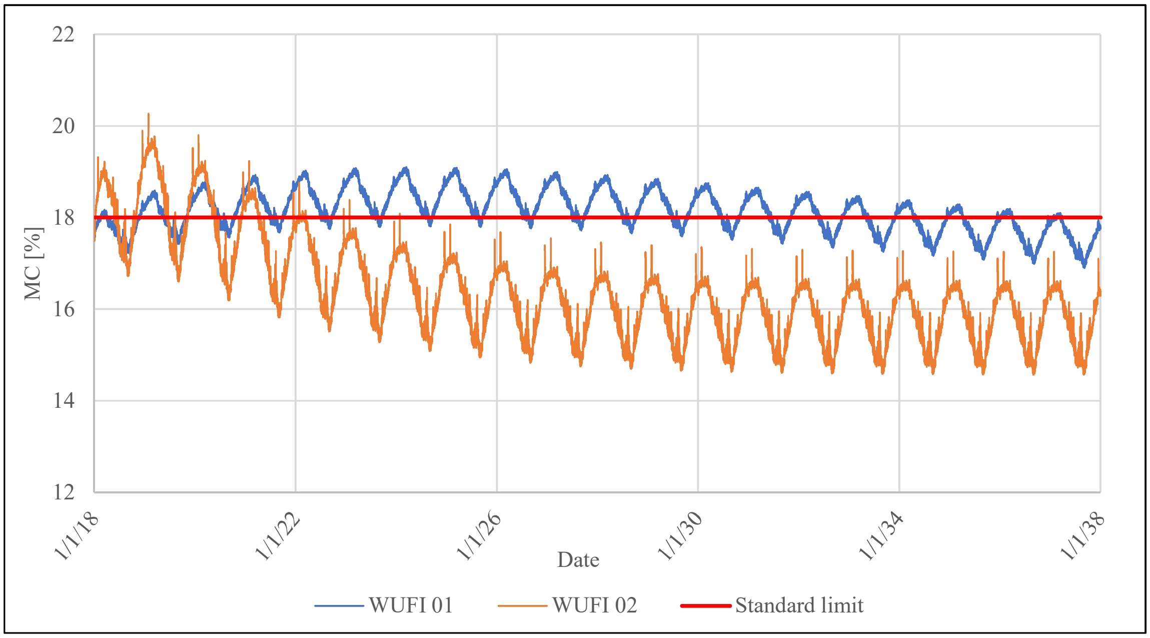

Figure 32: MC in the external wooden layer_STRUCTURE 05

It is seen, that both methods report an increase of MC in the beginning of the simulation. While the WUFI 02 curve reaches its peak in the second year, the WUFI 01 records annual growth of MC until the seventh year. The explanation of this growth occurring in both methods, derives from the fact that inner wood layer dries out from the beginning of the simulation (see Fig. 33).

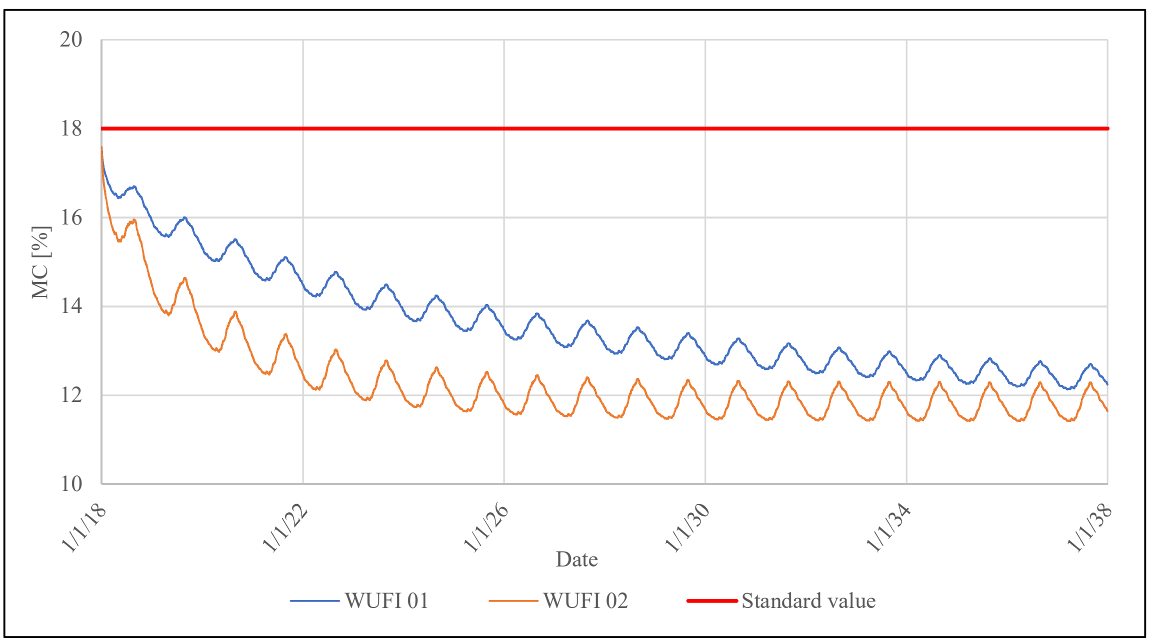

Figure 33: MC in the internal wood layer_STRUCTURE 05

In winter, when outdoor temperature is lower than in the interior, the moisture goes from the inner wood through the insulation to the external wood thanks to diffusion. The external layer is exposed to low temperatures, which relate to high RH. The high values of RH cause high rate of adsorption. Thus, external wood takes a lot of water and MC increases.

In the WUFI 02 model, μ-value of spruce reacts on high RH and causes that wood becomes more permeable. Therefore, more moisture can leave the construction, and MC decreases. This does not apply to the WUFI 01, where constant μ = 157 "keeps" the moisture in the structure for a long time.

In this simulation, the initial conditions had been set relevantly to 17,5 % of MC in the wood. As it is mentioned in the ČSN 73 0540-2, wood should be dried under 16 % when it is built into the structure. Our results confirmed that this recommendation should be followed in order not to exceed 18 % of MC.

Structure 06

Finally, MC in the external wood fibreboard of Structure 06 is examined.

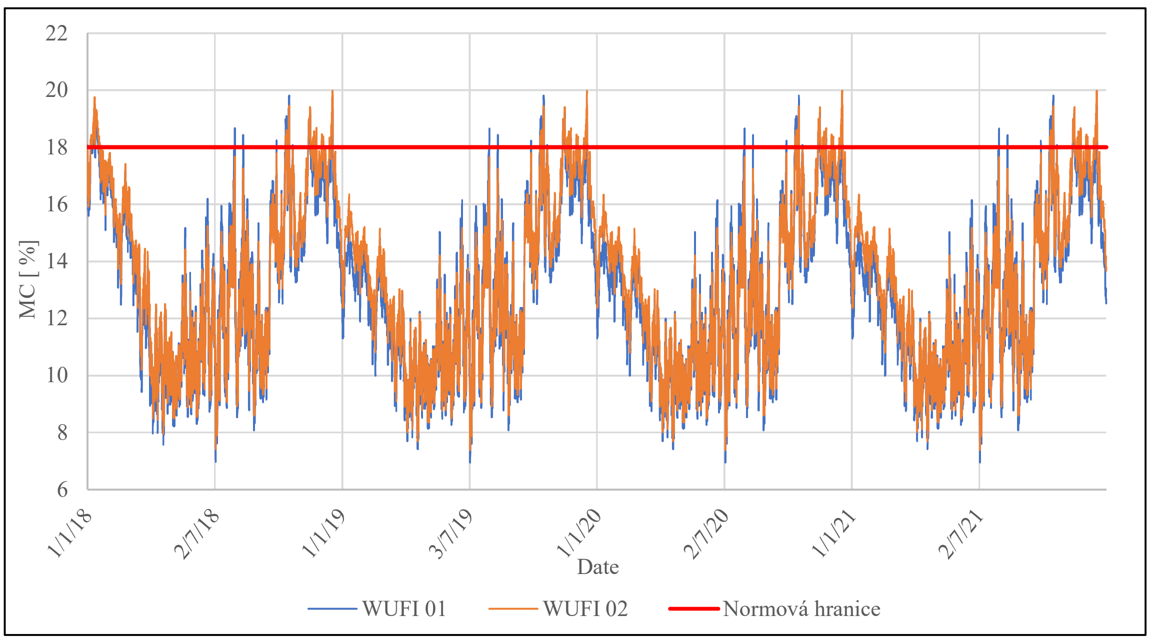

Figure 34: MC in the external wood fibreboard_STRUCTURE 06

First, both curves have similar shapes to those in the Structure 03. It proves that ventilated gap at the external surface contributes to the rapid fluctuation of MC in the wood fibreboard.

A slight difference between WUFI 01 and WUFI 02 can be detected. Even though averages of hour data of those two methods differ only by 0,25 %, it is apparent that the additional factors have a certain role. WUFI 02 reports a little higher values of moisture content.

Considering WUFI 02 method, MC in the wood fibreboard is above 18 % in 5,0 % of the total time, which is equal to 18 days a year. It does not follow the Standard presuppositions; however, likely does not cause any large damage in the structure. Moreover, there is no annual increase of moisture within the structure.

5.3 Conclusion of the hygric analysis

5.3.1 TEPLO

According to the stationary assessment in TEPLO 2010 software, all common external walls of modern timber buildings meet Standard requirements of ČSN 730540-2 and EN ISO 13788.

5.3.2 WUFI

Structure 01

a) All the sub-methods show results which meet Standard requirements of ČSN 730540-2 related to the maximal moisture content of wood-based materials 18 %. Also, the moisture content does not annually increase. Thus, the structure is safely designed in terms of the excessive moisture.
b) The step-by-step analysis pointed out that the aspect of μ value of OSB dependent on the RH plays an important role in the moisture transport.
c) Detailed analysis considering dependence of μ value of OSB on RH leads to more unfavourable results than the basic simulation calculating with the constant μ value 200. Hence, the simplified simulation is not on the side of safety.
d) Orientation of the facade to the north is the most unfavourable variant for the considered climatic conditions.

Structure 02

a) Both of the methods result in low total moisture content (MC) which does not annually increase. This is analogical to one of the Standard requirement (see Eq. 1). Thus, the structure is safely designed.
b) In those particular climatic conditions, the basic simulation of this structure is on the security side in terms of the moisture behaviour.

Structure 03

a) Moisture content in the external wood fibreboard does not annually increase. However, the moisture content value is above the limit in 14 days a year in total. Even though, the structure does not meet the Standard requirement of ČSN 73 0540, it can be assumed that the wall is not going to be microbiologically attacked, and its functioning will not to be threatened.
b) The basic simulation of this structure corresponds to the realistic model.
c) Most likely, the amount of moisture content in external wood fibreboard changes more rapidly in assemblies with ventilated gap and wooden cladding at the external surface than in the structures with an external plaster.

Structure 04

a) Both methods show that external walls of traditional log houses do not suffer from excessive moisture content.
b) Basic simulation is on the side of safety.

Structure 05

a) If the massive wood is built into the structure during winter, the moisture content of the external wood layer annually increases in the following two years. Therefore, the Standard recommendation (that wood should be built into the structure with its MC under 16 %) should be respected in order not to exceed the limited MC value of 18 %.
b) The difference between the results of the detailed and simplified analysis is significant. Despite the fact that the basic simulation is on the safety side, it shows an unrealistic behaviour. The dependent μ value of wood on RH plays an important role in this case.

Structure 06

a) The moisture content in the external wood fibreboard does not annually increase. However, in 18 days a year in total, the moisture content value is above the limit. Even though, the structure does not meet the Standard requirement of ČSN 73 0540, it can be assumed that the wall is not going to be microbiologically attacked, and its functioning will not be threatened.
b) The detailed and basic method give only a little difference in the outcome. Nevertheless, it was shown that simplified model considering constant μ value of OSB board 200 results in slightly lower values of moisture content than the detailed simulation with dependent μ value on RH. Thus, the basic simulation is not on the side of safety.
c) The assumption, that wooden cladding with ventilated air gap at the external surface contributes to faster fluctuation of moisture content in the external wood fibreboard, was confirmed.

6 Conclusion

During this work, the research of common external walls in modern timber buildings was performed, upon which five specific structures were chosen and one additional structure was designed. All the structures were subjected to the regular assessment in TEPLO 2010. Then, a sorption isotherm of spruce wood was measured, plus the dependence of the diffusion resistance factor on the RH was drawn from the available sources. These data were exported into the WUFI® Pro 6.1, in which a simplified model relevant to TEPLO 2010 was created. Finally, a comprehensive analysis was performed in order to approach to the realistic behaviour.

All the six structures successfully passed the basic hygric assessment in TEPLO 2010 software. The results of the measured sorption isotherm were sufficiently accurate. Thus, the data were applied in further analysis. Then, a detailed hygric analysis in WUFI® Pro 6.1 has confirmed that all the assessed structures are safely designed in the context of moisture behaviour. For the solid timber construction and the vapour permeable structure in the frame construction, consisting mainly of wood-based materials, the moisture content of wood fibreboard exceeded the critical value (18 %) in 14 and 18 days in a year, respectively. For this reasons, those two structures do not meet Standard requirements. However, from a practical point of view, this will probably cause neither microbiological problems nor the worsening of the material´s function.

When focusing on the different results of the simplified and detailed analysis, it was shown that for the structures without OSB boards, the basic simulation either corresponds to the realistic behaviour or is even on the safety side. Nevertheless, this does not apply for the structures where the OSB board is used as a semipermeable layer. The hygric analysis pointed out that when the diffusion resistance factor of OSB board is considered as a constant value of 200, the situation is not on the side of safety.

Future experiments could contribute to the clarification of this issue by providing more precise material characteristics of wood and wood-based materials. Especially, further measurements of the μ value of OSB board and other wood-based boards would be beneficial for better understanding of moisture transport through envelope structures in timber buildings.

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List of figures

List of tables

List of appendices