TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF POLYMER MATERIALS
CHAIR OF WOODWORKING

Design of Solid Wood Interior Panel with Increased Moisture Buffering Properties

Master´s thesis

Alaa Al Barazi

Supervisor: Jaan Kers,

Head of the Chair of Woodworking, Professor

Technology of Wood and Plastic, KVEM 12/13

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TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY
POLÜMEERMATERJALIDE INSTITUUT
PUIDUTÖÖTLEMISE ÕPPETOOL

Puidust siseviimistluspaneeli disaini välja töötamine saavutamaks paremaid niiskussalvestusomadusi

Magistritöö

Alaa Al Barazi

Juhendaja: Jaan Kers,

Puidutöötlemise õppetooli juhataja, professor

Puidu- ja plastitehnoloogia, KVEM 12/13
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Declaration

Hereby I declare that this master's thesis, my original investigation and achievement, submitted for the master degree at Tallinn University of Technology has not been previously submitted for any degree of examination.

All the work of the authors, important aspects from literature and data from elsewhere used in this thesis are cited or (in case of unpublished work) authorship is shown in text.

Alaa Al Barazi

MASTER’S THESIS ASSIGNMENT

Student data:

Name of the student: Alaa Al Barazi Student Code: 132129KVEM

Master’s thesis topic:

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Supervisor:

Forename and surname: Jaan Kers

Employment: Chair of Woodworking

Profession: professor

Aim and tasks of the master’s thesis:

Studying the potential of using wood to improve Indoor Air Quality passively and suggest a suitable design for indoor panels. Finding computational simulation methods to measure and predict the performance of moisture absorption of wood panels.

FOREWORD

I would like to extend my thanks to Tallinn University of Technology and to everyone participated in teaching or inspiration. To Aalto University and to everyone supervised and participated in this work.

ABSTRACT

This thesis studies the criteria that maximize the moisture buffering in a wooden panel for indoor usage. Using such panel will help to achieve better indoor air quality (IAQ) and will increase dwellers comfort by the passive regulation of relative humidity.

The aim of this thesis is to analyze the design factors that are related to the hygroscopic properties of wood to develop indoor wooden panel that has high moisture buffering capabilities to achieve better indoor environment.

There are many factors that increase the moisture buffering capacity and speed of a panel. The guidelines for making the panel are - to use sapwood of softwood across the grain having rough surface without coating and with a proper geometry and dimensions that maximize specific surface area in (SSA) air exposure. The "Moisture Buffer Value" MBV is used to determine the best wood species for this task. Spruce (Picea abies) may have the highest MBV value documented in literature today for solid wood.

Practical tests were performed at Aalto University to direct the work and inspire proper panel design. These panels were compared with Stora Enso's panel EffexTM prototype. The practical tests showed that the final designs improved the moisture buffering capabilities of wooden panel between 2-4 times compared to the reference with same dimensions. Overall for the same dimensions (excluding thickness), EffexTM panel absorbed around 60% less moisture than the ones presented here.

The MBV for pine (Pinus sylvesteris) was determined and it was found to be lower than the MBV for spruce (Picea abies). For the estimation of moisture buffering through the panel, a new method, which relies on computational simulation, was introduced. The method use HAMOPY Python library that model the flow of the moisture in the cross section of the material. It was found that the theoretical model deviate by around 5 % to max of 50% from the practical tests. It was found that this method is more accurate than using the MBV of the material surfaces to estimate the total moisture buffering of a shaped panel that is designed from this material. The suggested theoretical method is used to compare the impact of changing some dimensions of the panel MBV.

LIST OF SYMBOLS AND ABBREVIATIONS

A - Area in cm^2

ACTG - Across the Grain

ALTG - Along the Grain

ASHRAE - American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

b_{m} - Moisture diffusivity

℃ - Celsius degree

DTU - Technical University of Denmark

EMC - Equilibrium Moisture Content

FSP - Fiber Saturation Point

g - gram

$G(\mathrm{t})$ - The amount of absorbed moisture

h - Hour

I - Indoor Air Quality

HAM - Heat, Air and Moisture transfer.

HVAC - Heating, Ventilation and Air Conditioning

IAQ - Indoor Air Quality

RH - Relative Humidity

MBV - Moisture Buffer Value

NBI - Norwegian Building Research Institute

m_{dry} - Dry mass of wood sample (kg)

m_{wet} - Wet mass of wood sample (kg)

SSA - Specific Surface Area

VTT - Technical Research Centre of Finland

t_{p} - Time period

Δp - The difference in pressure

α - Fraction of time where the humidity level is high

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INTRODUCTION

Many humans are spending most of their time inside buildings. Health problems like building sickness syndrome are gaining more attention in the last years, especially in the countries that rely continuously on active HVAC systems (Burge 2004). Preventing or minimizing these problems sustainably require in depth study for many aspects of the building like the materials, the processes and the systems (Rostron 2008). The usage of indoor wooden panels inside living spaces could make the indoor air quality better by regulating the relative humidity.

Wood is a renewable material that has properties, which make it one of the best options for many applications. This magical connection between humans with wood has been reviving recently, as the world is prioritizing the sustainable materials over others.

The aim of this thesis is to analyze the design factors that are related to the hygroscopic properties of wood to develop indoor wooden panel that has high moisture buffering capabilities to achieve better indoor environment. As the result of using such panel in the space to condition it passively, the relative humidity (RH) becomes closer to the recommended levels and the fluctuations in RH levels reduce. This panel could be used in bedrooms or living rooms. Using such panels may minimize the need for using an active ventilation system and save energy. Also it helps in achieving better indoors condition and thermal comfort for occupants passively (vary based on the application of the space).

1. LITERATURE REVIEW

This chapter includes an overview of the relationship between the moisture and the physical properties of wood. The effect of the levels of the relative humidity on health is discussed. The potential of using coating over the panel surfaces is evaluated. Wood properties are explained to set suitable criteria for wood selections in relation to species and surfaces. The methodology of the test that is used to determine the MBV and the formulas that were used in the test are explained. Introduction to the main principles of computation simulation is presented.

1.1 The Relationship Between Moisture and Physical Properties of Wood

Wood is a hygroscopic material that adsorbs and desorbs water when air humidity arises or decreases until it reaches its equilibrium moisture content (EMC). The diagram that represents this change is called sorption isotherm, Figure 1 (Conservationphysics.org).

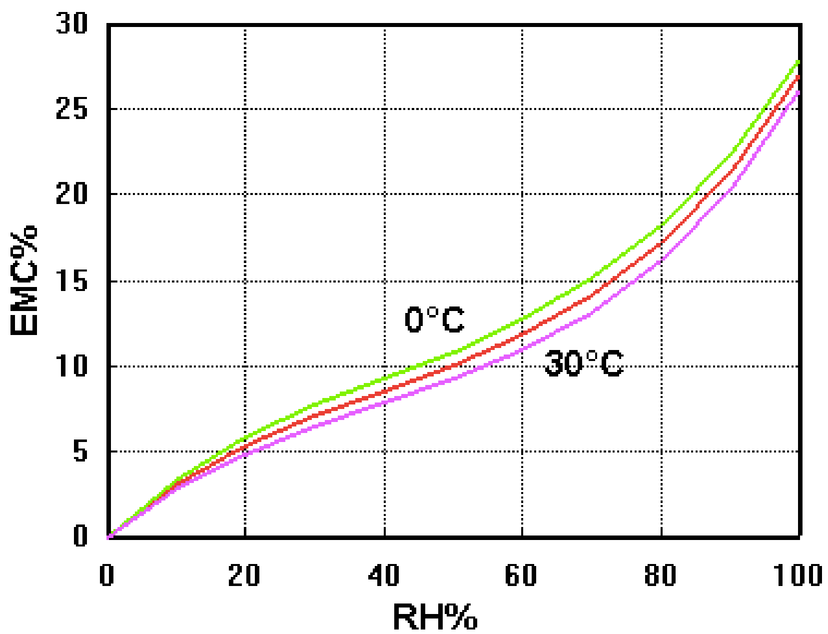


Figure 1. Sorption isotherm diagram (Conservationphysics.org).

Moisture exchange between wood and air depend on humidity and temperature. The physical properties of the wood influence its moisture content at particular relative humidity and temperature. The equilibrium represents the amount of the Moisture Content (MC) that the hygroscopic material is able to hold at specific temperature and at specific RH (Glass et al. 2010). MC formula can be seen in formula 1:

$$MC = \frac{m_{wet} - m_{dry}}{m_{dry}} \% \qquad (1)$$

where,

MC − Moisture Content (%)

m_{dry} − Dry mass of wood sample (kg)

m_{wet} − Wet mass of wood sample (kg)

Green wood, freshly sawn wood, has its cells walls completely saturated with water. Wood adsorbs bound water vapor through its cells walls until the fiber saturation pressure (FSP) reaches around 30%. This is the moisture content level at which the physical and mechanical properties of the wood do not change as function to moisture content increase. Then it starts to absorb water vapor in the lumina and cavities of the wood. This thesis deals with the moisture that is absorbed by the cell wall. Moisture can also exist in wood as free water. The moisture content in green wood can range from 30% to more than 200%. The moisture content varies between wood species and between sapwood and heartwood of the same species. The maximum possible moisture content is reached when the cell lumina and cell walls get completely saturated with water. (Glass et al. 2010)

Water vapor transport in wood by diffusion where the movement of molecule is driven by the differences in concentrations. It occurs from the high concentration to the lower concentration. (Wadsö 1993). There are many attempts that were made to mathematically model the diffusion of water and water vapor inside the wood or more precisely the moisture transport in wood. (Berit 1998).

Water vapour permeability is the rate of moisture, which moves through particular material as a function to water vapour pressure gradient that can exist between two surfaces (Performancepanels.com).

1.2 The Link Between Indoor Relative Humidity and Health

Thermal sensation of human body is related to temperature and humidity, in high relative humidity, the humidity of the skin is an important reason for discomfort (Toftum et al. 1998). Also the thermal discomfort could occur to the respiratory system because of the lack of cooling. Actually, the respiratory system is stricter for the requirement of proper humidity than the skin (Toftum et al. 1998). High indoor relative humidity increases the threat of molds and fungus. Fungus can affect health by two means. Direct contact could cause eye irritation, respiratory irritation and toxicity. Mold, as a form of fungus, may cause particular threats for people who have high sensitivity to it. The symptoms include sinus irritation, nasal irritation, wheezing, forming more liquid in the eyes, redness in the eyes, rashes and burning on the skin. Moreover, people who have high sensitivity to molds might have worse symptoms like shortness in breath. Also people with other specific illnesses like immune system deficiency might be more likely to get infections from molds, viruses and bacteria. For persons with asthma, molds can result in asthma attack. In addition to all the aforementioned, symptoms like headaches, memory problems, mood swings, nosebleeds and body aches and pains are sometimes reported in mold complaints. (Zhong et al. 2008)

Low moisture levels are also a cause for other kind of annoyance and make the occupants uncomfortable. Infections in respiratory system can be resulted from very low humidity. Also electrostatic which causes electrical shocks is the result of low humidity. (Zhong et al. 2008)

It has been found that keeping the relative humidity level between 40 and 60 % would minimize the majority of health problems. To reach this level it is required to humidify the air during winter if the air outside is too cold. (Arundel 1986). It was found that people are more able to tolerate low relative humidity of warm houses during cold climate (Andersen et al. 1974). Thus, it is expected that high relative humidity is more problematic than low relative humidity.

ASHRAE gives recommendation about the RH in living spaces (ASHRAE TC-04-03-FAQ-12. 2014). There are many ASHRAE standards, which could be used to determine the recommended RH. ASHRAE 62.1-2013, state that the RH should be 65% or less for mechanical systems with dehumidification capability.

ASHRAE 55-2013, state that the humidity control system must be able to maintain a dew point temperature of 16.8 °C and 2011 ASHRAE Handbook – HVAC Applications recommends specific relative humidity for specific applications. Water dew point is the temperature at which the air can no longer hold all of the water vapor, which is mixed with it, and some of the water vapor must condense into liquid water (Jörg P. Müller et al. 2015).

In general, ASHRAE recommended indoor humidity level for homes between 30% and 60% (ASHRAE Standard 62-2001). A wider range of humidity levels from 25% to about 80% can be acceptable in terms of thermal comfort (your comfort level) depending on the type of clothing worn and the level of physical activity (ASHRAE 55). See Table 1 for the recommended RH levels.

Table 1. Recommended temperatures and RH based on the space application for commercial buildings (ASHRAE Handbook 1999).

General Category	**Specific Category**	**Inside Design Condition**		**Air Movement**	**Circulation, Air changes per hour**
		Winter	**Summer**		
Dining and Entertainment Center	**Cafeterias**	21 to 23°C 20 to 30% RH	26° C 50% RH	0.25 m/s at 1.8 m above floor	12 to 15
	Restaurants	21 to 23°C 20 to 30% RH	23 to 26° C 55 to 60% RH	0.13 to 0.15 m/s	8 to 12
	Bars	21 to 23°C 20 to 30% RH	23 to 26 ° C 50 to 60% RH	0.15 m/s at 1.8 m above floor	15 to 20
	Nightclubs and Casinos	21 to 23°C 20 to 30% RH	23 to 26°C 50 to 60% RH	Below 0.13 m /s at 1.5 m above floor	20 to 30
	Kitchens	21 to 23°C	29 to 31°C	0.15 to 0.25 m/s	12 to 15
Office Buildings		21 to 23°C 20 to 30% RH	23 to 26°C 50 to 60% RH	0.13 to 0.23 m/s 4 to 10 L/(s*m2)	4 to 10

Using the hygroscopic feature of wood may help achieving the recommended RH level passively. In bedrooms, using the wood to buffer the moisture reduced the maximum RH by 35%. This makes it possible to increase the minimum recommendation for humidity by 15% (Simonson 2002).

1.3 The Link Between Material Properties and Moisture Buffering Performance

The exchange of moisture between wood and air is dependent on the temperature and relative humidity of the air and on the moisture content of the wood. (Berit 1998). Softwood absorbs more moisture than hardwood. It reacts better to moisture changes than hardwoods (Moore 2013). Moisture absorption is also dependent on the density of the wood. The denser the wood is, the lower its sorption become. Heartwood and sapwood absorption is related to the level of extractives and to porosity. Heartwood has more extractives than sapwood with higher density; yet lower buffering properties because of the higher extractives level. Extractives are less hydrophobic than wood thus it reduces the sorption properties. The level of extractives and all other factors differ in the same wood specie. (Rode et al. 2008) Figure 2 shows the surfaces of the wood and the macroscopic structure.

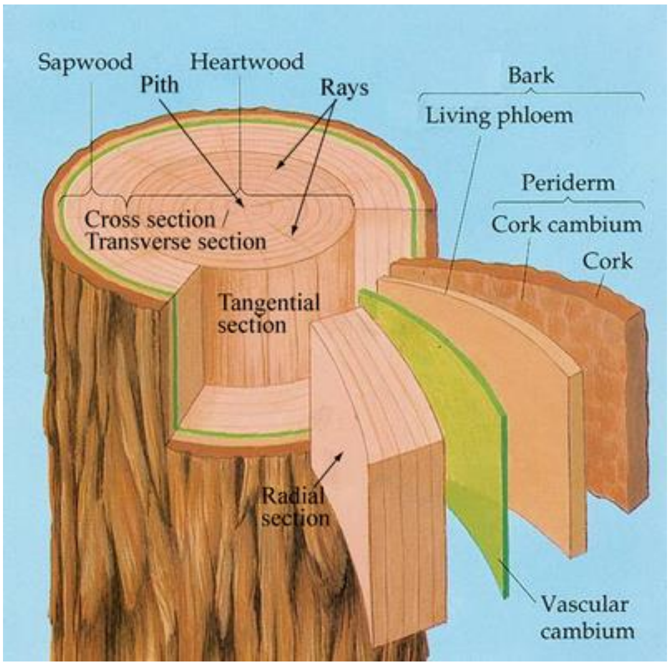


Figure 2. Different sections and directions of wood.

The content of lignin, hemicelluloses and cellulose affect adsorption. Hemicelluloses properties have the best water adsorption while lignin has the lowest vapor adsorption. (Lewin 1998). Thus, as hemicellulose percentage increase in wood, the adsorption also increases.
The absorption from the cross section surface is higher than other surfaces as the water is able to move along the lumens of wood cells replacing the air that escape out (Glass et al. 2010). Adsorption involves the attraction of water molecules to wood cell wall hydrogen bonding sites present in cellulose, hemicelluloses and lignin until the fiber saturation point is reached (30%). Absorption results from surface tension and capillary forces and it results in bulk accumulation of water in the porous wood. (Shmulsky, 2011) The surface area increases the sorption. Surfaces with high roughness have higher sorption because the roughness increases the surface area that is in contact with the humid air.

1.4 The Role of Coatings

Wood is biodegradable material that requires protection against external factors such as fungus and insects. Surface coating is used for protections and also to change the appearance to match the preference of some designers or customers. The thickness of coating layer varies from thin oil treatment to thick enamel paints (Svennberg 2004). This topic was researched in order to study the potential to use the paint to create varied aesthetics, like color, texture and reflection, and at the same time to reserve or even increase the absorption capability.

Surface coating provides protection for the wood by hindering the moisture from entering it. Thus, all the articles that examined showed that coating reduce the buffering ability (De Meijer et al 2000; James et al. 2010; Mortensen et al. 2005; Ramos et al. 2010). Ramos et al. (2010) found that coating reduce the MBV by around half. Coating affects not only the absorption, but also the desorption (Svennberg et al. 2007*)*
The impact of coating on moisture buffering is dependent on the type of coating that is used and also on the thickness of the film (Meijer & Militz 2000). Meijer & Militz (2001) found that waterborne acrylic coating to be the best option for coating and solvent borne alkyd as the worst. The impact of coating on moisture buffering varies among species (Van Meel et al. 2011).

As there is so many researches show that coating reduce moisture buffering, coating is not considered as an option for such applications.

1.5 Estimation for Buffering Performance - Moisture Buffer Value

To appraise the ability to adsorb/desorb moisture for different materials, a value called Moisture Buffer Value (MBV) is used for this purpose. There are two types of moisture buffer value, ideal and practical. The definition of MBV is mentioned in Rode et al. (2005) as "the amount of water that is transported in or out of a material per open surface area, during a certain period of time, when it is subjected to variations in relative humidity of the surrounding air".(Rode et al. 2005)

The ideal MBV is found based on the heat transport theory, which handles the transport of heat through a surface when the temperature varies according to sine function. The changes in RH level from high to low could be represented by a signal function which changing from high level of RH for a certain period of time and low level for another period of time to mimic the heat formula. Using Fourier transform analysis it is possible to predict the moisture uptake of a surface by time by integrating the moisture flux over the surface g(t) (Rode 2005). This can be seen from formula 2.

$$G(t) = \int_0^t g(t)dt = b_m * \Delta p * h(\propto)\sqrt{\frac{t_p}{\pi}} \quad (2)$$

where:

$$h(\propto) = \frac{2}{\pi}\sum_{n=1}^{\infty}\frac{\sin^2(n\propto\pi)}{n^{3/2}} \approx 2.252[\propto (1-\propto]^{0.535}$$

where:

b_m- is the moisture diffusivity

t_p - is the time period

α - is the fraction of time where the humidity level is high

For 8/16 period (8 hours high humidity and 16 hours low humidity) α= ⅓ . Thus the amount of absorbed moisture through surface for this particular cycle set is:

$$G(t) = 0.568 * b_m * \Delta p * t_p \quad (3)$$

The practical MBV is determined by experiment. The experiment requires the sample to be exposed to cyclic step-changes in RH between high, RH = 75%, for 8 hours and low values RH = 33% for 16 hours. The difference in RH in this case is 42%. (Rode 2007).

To assess the performance of different materials, the absorption capability of material is classified based on its MBV. The classification of MBV is shown in Table 2. The material, which has low absorption capabilities, has moisture buffer value between 0.0 and 0.2. A material with excellent MBV has and absorption capability from 2 and above. (Rode 2005)

Table 2. MBV classification. (Rode et al. 2005)

MBV practical Class	**Minimum MBV level**	Maximum MBV level
	[g/(m2%RH)@8/16h]	
Negligible	0	0.2
Limited	0.2	0.5
Moderate	0.5	1
Good	1	2
Excellent	2	…

The MBV of materials differ in relation to the equipment and the methods that are used to apply the test conditions on the samples and also based on the differences between same materials. Thus, determining the MBV for the same material in different institutions resulted in different MBV. The differences however were not huge. Table 3 show the approximate results of MBV for different materials tested in different institutions.(Rode 2007)

Table 3. Moisture buffer value for different buildings materials. (Rode et al. 2005)

Materials/ Appoximate mean	**Instituation/University**		
	DTU	**NBI**	**VTT**
Spruce Board	1.2	1.1	1.15
Concrete	0.4	0.35	0.37
Gypsum	0.7	0.58	0.67
Laminated Wood with Varnish	0.5	0.4	0.55
LW Aggregated Concrete with Stucco	0.7	0.8	0.7
Cellular Concrete	1.07	0.87	1.1
Brick	0.4	0.35	0.7
Birch Panel	0.9	0.6	1.03

Most of the tested materials have moderate MBV. Spruce has the highest MBV among all the materials. The mean of Spruce MBV ranged between 1.1 and 1.2 depending on the testing institution. Based on these results Spruce is considered to have good MBV.

The practical test should be done at $23°C$ degrees for all specimens. The specimens should be sealed from all surfaces except one or two. The exposed surface area should not be less than $100cm^2$. The thickness of the specimen should be more than the daily moisture penetration depth that happen due to RH variation. And also three specimens at least should be used. (Rode & Grau 2007)

The weight of the specimens should be measured continuously or intermittently throughout the test. Five measurements at least should be carried out during the 8 hours high humidity part of the last cycle. A minimum of three cycles has to be carried out, and the weight range must not vary by more than 5% from day to day. (Rode & Grau 2007)

1.6 The Principle of Computational Estimation for Buffering Performance

The estimation of moisture buffering for complex panels shapes that are made for indoor use require performing many practical tests for different designs to assess their performance under different relative humidity and temperatures. This also involves performing so many measurements for water vapor penetration, weights, and temperatures manually to analyze the results and evaluate the buffering performance throughout the time of the practical test. Finding a mathematical model and performing computational simulation to predict and estimate the buffering across the layers of the wood could minimize the number of required practical experiments, measurements and the time that is required to find the best design. The wooden panel might not necessarily have a smooth surface and one thickness. Computational simulation could be used to estimate the buffering in the smaller parts that compose the final shape. As a simple example the absorption of the wooden piece that is shown in Figure 3, which is a wooden rectangle 10*10*2cm that has holes could be divided in three main parts (red, green and blue).

Figure 3.Dividing the panels into parts with different thickness 1,2 and 3.

The simulation could be run on these parts. The first part (red) consist of four pieces between the holes is similar to the first one with a thickness of 2 cm and volume of 0.5*10*2cm3. The second ones are the holes (green), ten pieces with a volume of around 0.5*1*10 cm3 each. The third part consist of two pieces is the solid edges with a thickness of 2 cm and volume of 1*10*2cm3. Simulating two part of thickness 1cm and 2cm will give approximation of the moisture absorption in the whole piece.

Building engineering has studied the transfer of moisture inside the layers of envelope materials. Temperature, air and humidity (HAM) inside building envelope layers are modeled and computationally simulated. The model predicts the hygro-thermal behavior of the building components (Hagentoft et al. 2004). This computational model is used in this thesis to predict the approximate humidity inside the wood panel that is made for indoor use. Building physics approach consider the difference of water vapor pressure as the driving potential for moisture transfer in materials. This is different from the approach that is widely used in wood science consider the water concentration as the driving potential.(Time 1998)

The mathematical formulation for HAM relies on four main principles. Heat and mass balance, the transfer of HAM and the boundary and climate conditions. There are many mathematical formulations to this problem that rely on the same principle. The numerical solution for the resulted mathematical formulas varies but all of them give accurate results. (Hagentoft et al. 2004)

Open source software called Hamopy is one of the softwares that could be used to solve these equations. It performs numerical simulation for one-dimensional humidity, air and moisture transfer inside a material. The practically performed test is used as a benchmark to estimate the accuracy of this method. (Srouchier.github.io)

1.7 The Role of Surface Area

Taking in consideration the requirements and function lists and building on the theoretical knowledge that have presented in the literature review section, the ways to maximize the absorption and determining the factors that affect it were searched. The moisture buffer value formula is (Rode et al. 2005):

$$MBV = m/(RH\%*A) \tag{4}$$

where:

m- is the average of the water masses that are absorbed and desorbed in all test cycles

RH - is the relative humidity of the space

A - is the area that is exposed to humid air

Formula 4 shows that the surface area A is the main variable that could be utilized to increase the moisture absorption. Given a constant volume, there are many ways to increase the surface area. Surface to volume ratio could be used to understand the relationship between the shape, volume and surface area. Figure 4 shows this ratio for some shapes.

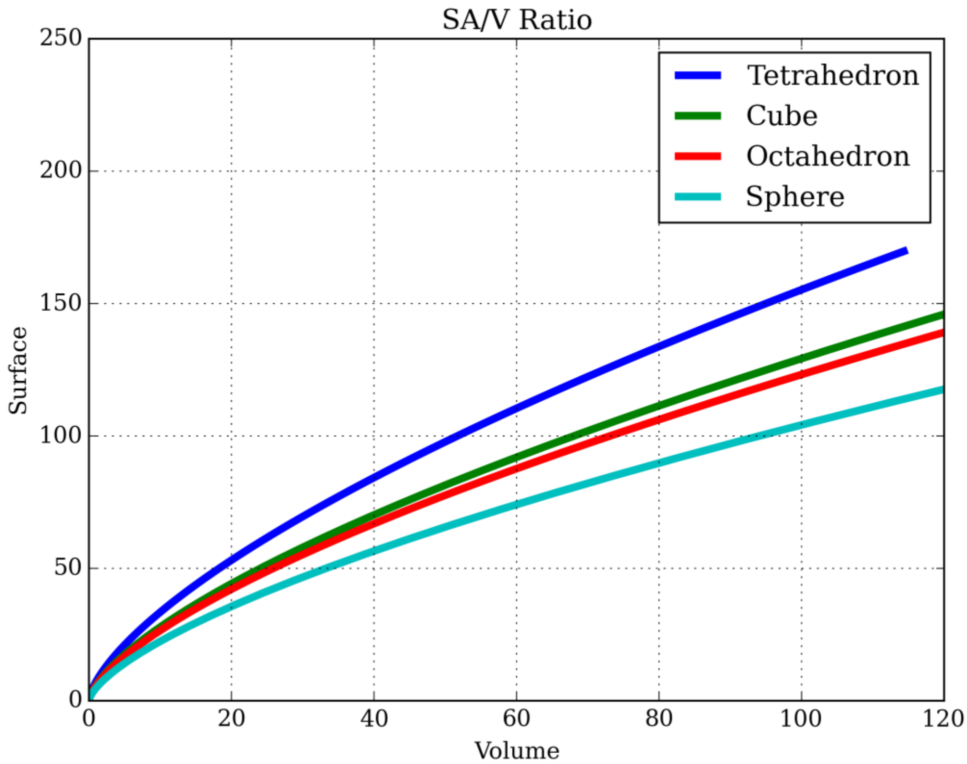
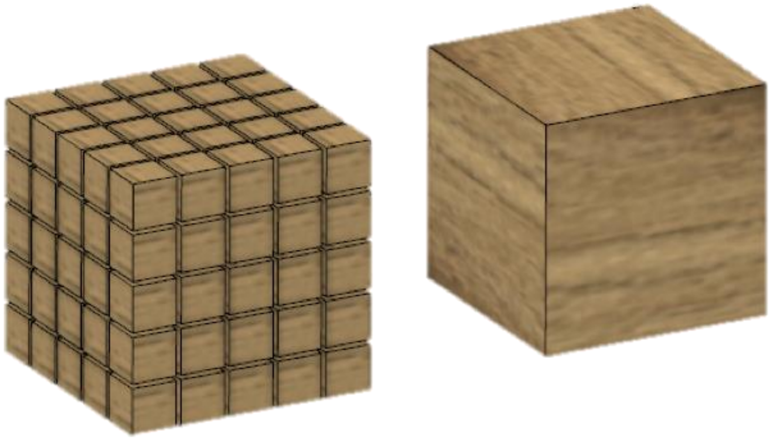


Figure 4. Surface areas for different shapes.

Figure 4 shows that making a tetrahedron shape out of particular volume of wood will result in obtaining higher amount of surface space (and adsorption) in comparison with other shapes. But in practice, things are not as they seem to be in theory. The common way of selling wood is boards, rectangular boards in particular. Using CNC and laser cutting technology could be utilized to produce sophisticated surface shapes.

The surface area for an assumed cube with 5-unit side is 150 and its volume is 125 units and the surface area to volume ratio is 1.2. If this cube is divided into small cubes with 1 unite sides, then the surface area will be six times more with the same volume. Figure 5 explains the reason for this increment.



Total Surface Area	750	150
Total Volume	125	125
Surface To Volume Ratio	6	1.2

Figure 5. Increasing the surface area from particular volume.

Also changing the shape increases the surface area. For any shape changing the thicknesses/dimensions for specific volume also increases the surface area, Figure 6.

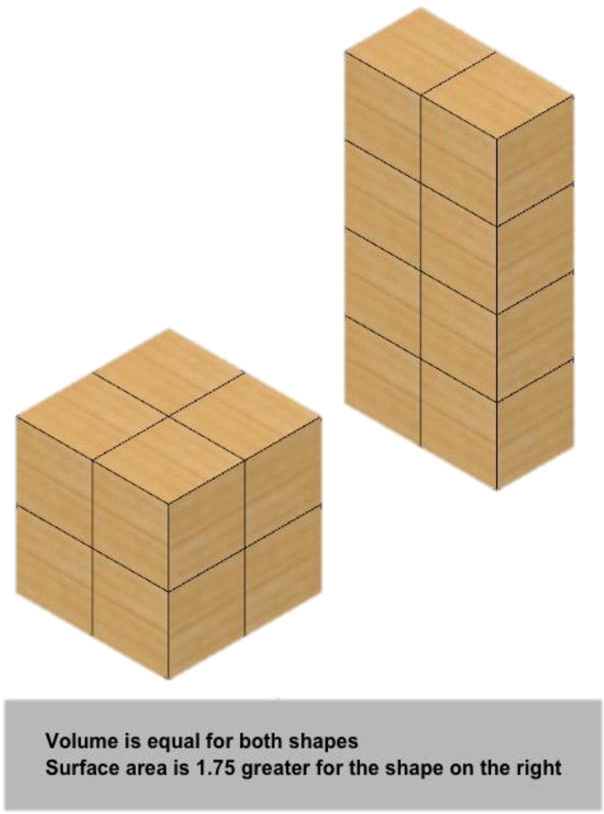


Figure 6 .Changing shape for particular volume increase the surface area.

The same concept could be expressed using Specific Surface Area (SSA) which is the surface area in a unit of mass.

Python modules were written to calculate the approximate required surface area for a given rectangular panel that has a known MBV for it's wood species, to achieve particular RH level inside a space. See Appendix A for more information.

1.8 Stora Enso Effex^{TM} Panel

As this topic is new, it was hard to find wooden panels that are designed for moisture buffering purposes. Stora Enso makes the only panel that was found. The panel is called Effex^{TM} and it is still in development stage (Cronhjort et al. 2012).

There was not much information about this panel. The information that was found that the panel is made from pine and pieces that are glued together to form one piece of panel. (Rema 2015)

Grooves were made in the backside of the panel to increase the buffering. The grooves are shown in Figure 7. A small sample of this panel was obtained and was tested against the other designs.

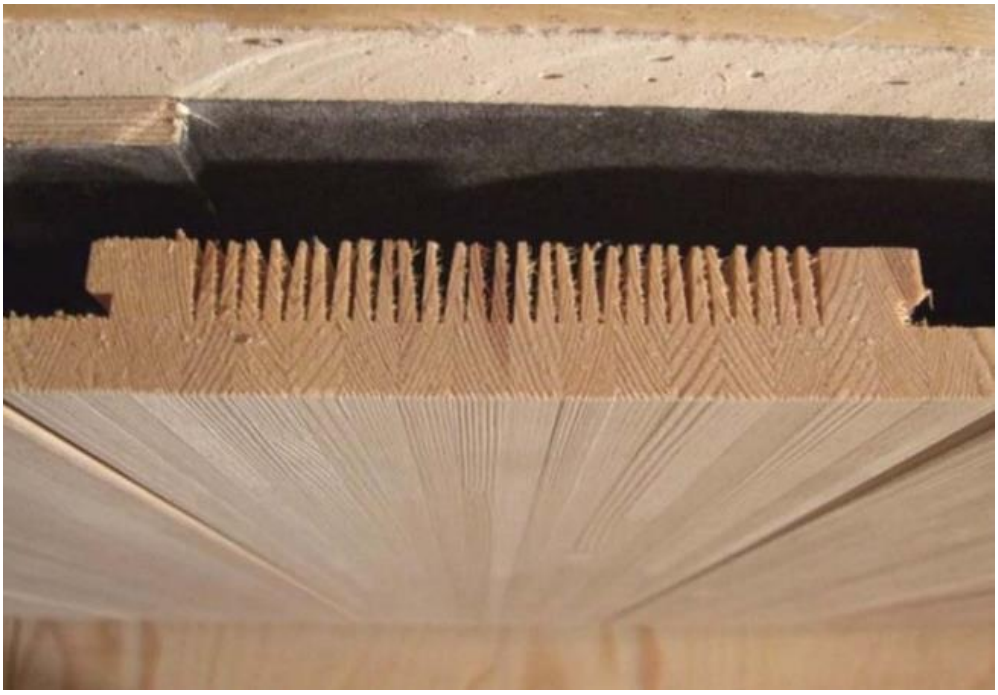


Figure 7. Design of Stora Enso Effex^{TM} panel. (Cronhjort 2012)

2. MATERIALS AND METHODS

This chapter introduces the materials and methods that were used in practical test at Aalto. The panels were made out of pinewood species (*Pinus Sylvesteris*). Also information about the simulation tool and the settings that was used is presented here.

2.1 Materials

The pine wooden boards were provided from Stora Enso to make the final panels. The moisture content of the boards was very high around 20% and the dimensions thickness and width was 50x150mm. The height/length was not determined. The boards were in their raw state so they required machining using circular saw, planners and sander. Also they were required to be glued together. Requirements list, which reflect the main criteria's of the design that has to be considered, were made (Appendix C). This in addition to numerical evaluation helped in the design stage and was used to assist the selection of the most suitable design.

2.2 The Preliminary Designs

In this chapter two designs[1] that could be mixed together in one room are presented. These designs are relatively easy to manufacture. Figure 8 shows the designs.

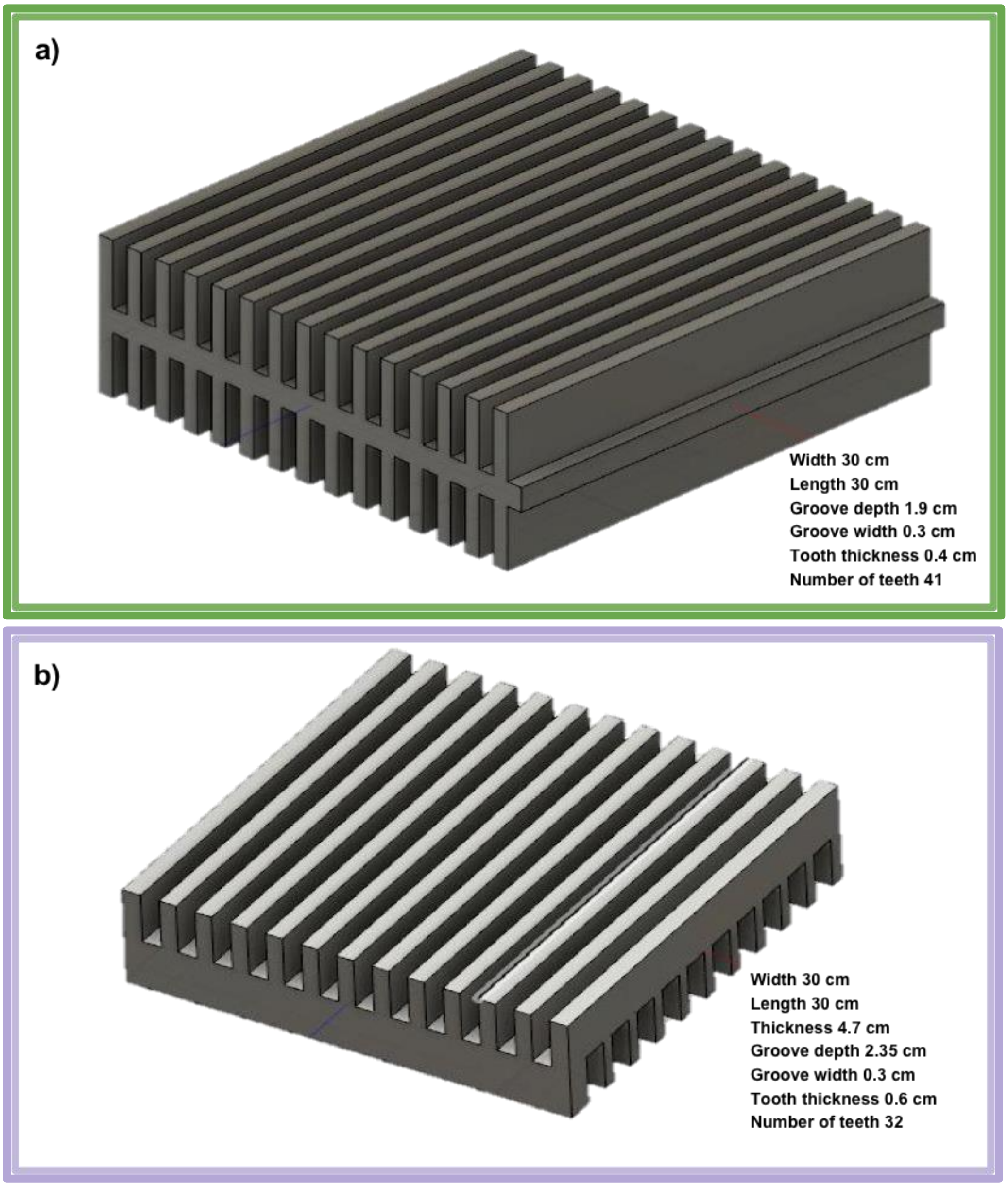


Figure 8. Two designs a) made of double grooves and b) made of cross grooves

Design a) on Figure 6 (Design 1) is made of double grooves that are cut across the grain. Design b) on Figure 6 (Design 2) is made of cross grooves, across the grain from one side and along the grain from the other side. The depth of the grooves for each side is half of the panel thickness. The grooves from both sides meet in the middle of the depth to allow for the light penetration as shown in Figure 9. The choice to have the depth of the grooves equal is not necessarily the optimal one. It is also possible to alter this design to have deeper across the grain grooves.

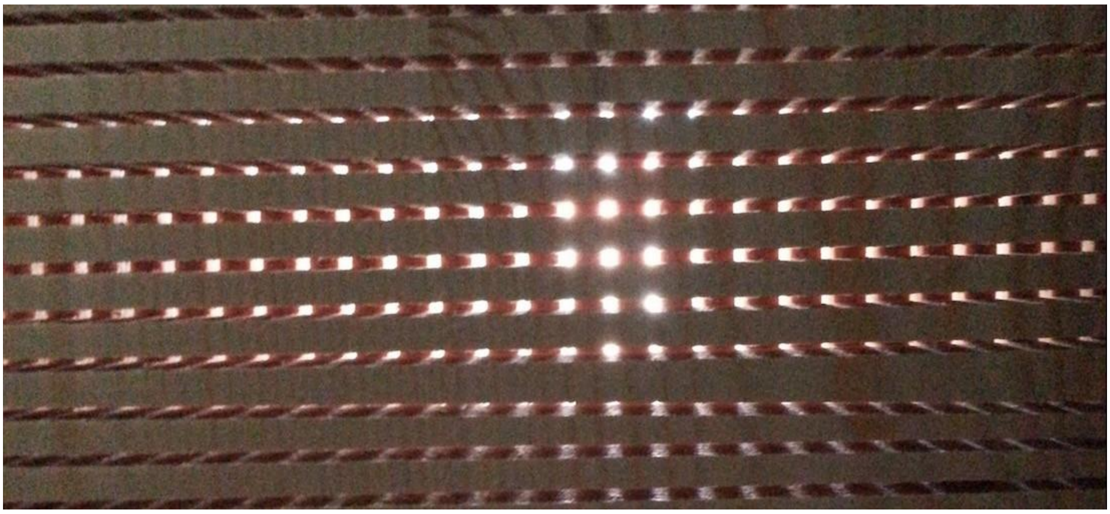


Figure 9. Design 2 and light example.

Numerical evaluation for the designs was made. The purpose of this is to show the importance for each property separately and as part of a function. The installation of the panel should allow for the flow of the air to occur in the back side of the panel some information about the installation that explain this thought is presented in appendix D.

3. TESTS AND RESULTS

Two practical tests were made. The first test was done for two goals. The first was to determine the MBV. The second was to evaluate the absorption speed for reference board and compare it with other identical board (same shape, volume and dimension) but with the modification done on it.

The second test was performed by placing the samples and panels for 8 hours in a chamber with high RH. The difference of absorption by time in relation to surface and thickness is evaluated. A theoretical method was used to estimate the buffering of a panel by knowing the MBV. Two other theoretical methods, one use computational simulation, for moisture buffering estimation are presented.

3.1 Practical Tests

Six samples were made to determine the MBV for the given wood (pine). The whole surfaces of all samples were wrapped with aluminum foil except of one surface[2]. The test samples were as follow:

- Three samples had across the grain exposed surface (ACTG 1, 2 & 3) with dimensions of ~18x16x4.5 cm.
- Three had along the grain exposed surface (ALTG 1, 2 & 3) with dimensions of ~16x16x4.5 cm.
- Two panels that have the designs that are shown previously in this section and one reference panel, Figure 6. Their dimensions are 30x30x4.7 cm.

The densities of the samples varied between around 403 to 494 kg/m³ as shown in Table 4.

[2] The dimension of the exposed surface is 18x16cm for ACTG samples and 16x16cm for ALTG samples.

Table 4. Sample densities in Rh 50%.

No.	Sample	Water	Wood	Wood
	g @ 50% RH	g	g	kg/m3
ACTG 1	550.21	27.51	522.70	403.32
ACTG 2	554.92	27.75	527.17	406.77
ACTG 3	596.74	29.84	566.90	437.43
ALTG 1	599.91	30.00	569.91	494.72
ALTG 2	502.14	25.11	477.03	414.09
ALTG 3	508.61	25.43	483.18	419.43
Average				429.29

Panel Design 1 is made by 41 grooves from both sides that are cut in transverse direction with the width of 3 mm for each groove and depth of 1.9 cm. Design 2 and is made of 32 grooves. Design 2 grooves have a depth of 2.4 cm from both sides. In one side they are cut in transverse directions and from the other side in tangential direction. Table 5 shows the dimensions and the calculated surface areas for two panels (Design 1 and Design 2).

Table 5. Panels dimensions and the gain in surface area against the reference panel.

Description	Unit	Design 1	Design 2
Length	**cm**	30	30
Width	**cm**	30	30
Depth	**cm**	4.8	4.8
Number of grooves	**No.**	41	32
Groove width	**cm**	0.3	0.3
Groove depth	**cm**	1.9	2.4
Tooth thickness	**cm**	~0.4	~0.6
Total transverse surface area	**m^2**	0.95	0.65
Total tangential/radial surface area	**m^2**	0.21	0.48
Total surface areas	**m^2**	1.16	1.13
Transverse total area to reference panel area ratio	**None (ratio)**	49	24.9
Tangential total area to reference panel area ratio	**None (ratio)**	1	2.32
Total surface areas ratio to reference panel	**None (ratio)**	~5	~4.9

Table 5 shows that the modification reference panel, to form Design 1 Design 1 Design 1 and Design 2, added 49 more transverse surfaces for Design 1 and 24.9 times for Design 2 in comparison with the reference unmodified panel. Overall, the increasing in the surface area, transverse/tangential/radial, is 5 times in Design 1 and 4.9 for Design 2.

The test was performed based on NORDTEST standard that was explained in literature review. NORDTEST require having two levels of RH, which are 75% and 33%. As there was no conditioned room with RH 75% available, a conditioned room with RH 65% is used instead. As required by the standard, the test pieces and the panels were placed in a humid room with RH 50% before the test. The weights were measured after 3 days then after 7 days. The negligent changes in weight reflect that the pieces have reached the equilibrium. (Rode et al. 2005)

The pieces were weighed at the beginning of the test and then placed at 9 am in the conditioned rooms with RH equal to 63% (less than the set RH of 65%, for 8 hours. The pieces were then taken out of this chamber and weighed again and then placed in the conditioned room for desorption test with lower RH (33%) for 16 hours. These procedures continued for three days. As per NORDTEST, it is required to calculate the average mass of absorption and desorption for each cycle of at least three cycles. Then the average mass for these three cycles is calculated (Rode et al. 2005). This is the mass that is then used to calculate the moisture buffer values

The same criteria of the aforementioned test were performed on Effex™ sample with dimensions of 13x13.9x2.7 cm. The sample got sanded to remove the paint from its surface. The aim of this second test (will be referred to as Test 2) was to firstly compare the performance of Design 1 with the performance of Effex™ sample and secondly to determine how the absorption differs by time and by grain direction. The test did not extend for 4 cycles like the previous one. It lasted for 8 hours in conditioned room with temperature around 22 ℃ and RH around 60% (it was unstable) and the weights for all panels were taken every hour.

3.2 Results

This chapter presents the results from the practical tests and calculations based on the results. Detailed evaluation can be found from the next chapter "Discussion".

Table 6 shows the results of the last test, which is used to determine the MBV and compare the performance of the final panels.

Table 6. Final test results.

Time	RH	ACTG 1 mass	ACTG 2 mass	ACTG 3 mass	ALTG 1 mass	ALTG 2 mass	ALTG 3 mass	Design 1 mass	Design 2 mass	Ref mass
h	**%**	**g**	**g**	**g**	**g**	**g**	**g**	**g**	**g**	**g**
0	**50**	550.21	554.92	596.74	599.91	502.14	508.61	1712.9	1775.26	2319.97
8	**62**	552.1	556.6	598.7	600	502.4	508.7	1722.8	1787.4	2323.7
24	**33**	547.4	552.3	594.1	599.2	501.6	508	1691.8	1752.1	2311.8
32	**62**	550	554.8	596.5	600	502.1	508.7	1710.8	1772	2319.5
48	**33**	545.6	551.4	592.5	598.9	501.6	507.8	1689.2	1750.6	2308.3
56	**62**	549.3	554.5	595.8	599.6	502.7	508.5	1708	1773.6	2315.5
72	**33**	545.4	551.6	591.7	598.7	501.8	507.7	1687.4	1749.5	2305.5
80	**62**	548.7	554.7	595.1	599.4	502.5	508.3	1706.5	1767.2	2313.4
96	**33**	545.3	551.5	591.7	598.6	501.7	507.5	1687.7	1748.7	2303.7
104	**62**	548.5	554.6	595.1	599.2	502.3	508.6	1707.7	1772.7	2311.2

Figure 10 shows that all the samples that have exposed transverse surfaces (ACTG 1 to 3) absorbed more moisture in desorption and absorption phases than the samples with along the grain surfaces.

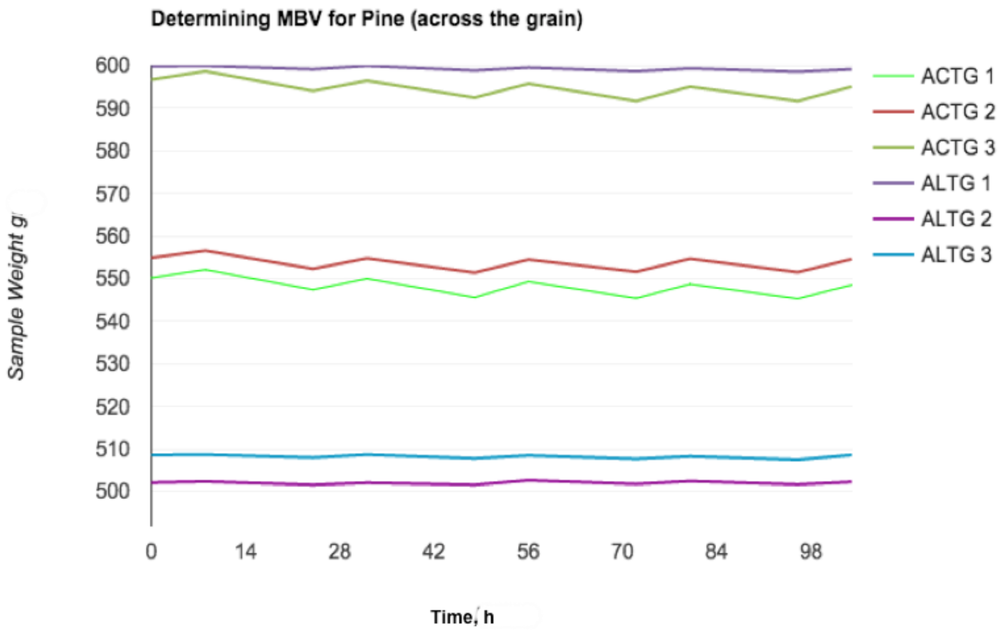


Figure 10. Changes in the sample weights.

The amount of absorbed moisture for (ACTG 1, 2 & 3) ranged from 4.3 grams to 4.7 grams. The desorbed moisture mass during desorption phases was higher than the absorbed mass during the absorption phases. The higher weight in ACTG samples did not result in more moisture absorption. ACTG 1 was the lightest yet its performance was better than other heavier samples. Comparison can be seen from Table 7.

Table 7. The amount of moisture absorbed/desorbed for the test pieces.

Time	RH	ACTG 1 mass	ACTG 2 mass	ACTG 3 mass	ALTG 1 mass	ALTG 2 mass	ALTG 3 mass	Design 1 mass	Design 2 mass	Ref
h	**%**	**g**	**g**	**g**	**g**	**g**	**g**	**g**	**g**	**g**
16h desorption	**33**	4.7	4.3	4.6	0.8	0.8	0.7	31	35.3	11.9
8h absorption	**62**	2.6	2.5	2.4	0.8	0.5	0.7	19	19.9	7.7
16h desorption	**33**	4.4	3.4	4	1.1	0.5	0.9	21.6	21.4	11.2
8h absorption	**62**	3.7	3.1	3.3	0.7	1.1	0.7	18.8	23	7.2
16h desorption	**33**	3.9	2.9	4.1	0.9	0.9	0.8	20.6	24.1	10

The samples that have exposed tangential surfaces (ALTG 1, 2 & 3) were steadier in their buffering. The differences between the adsorbed and desorbed water masses were less than what is seen in ACTG samples. Also, contrary to ACTG samples which desorbed more mass than absorbed in each cycle, some absorption cycles buffered more moistures than the desorbed amount in the followed desorption cycles. For example, ALTG 1 absorbed 1.1 grams in the last cycle and desorbed 0.9 grams of water.

Overall, ACTG samples buffered around 3 times more than ALTG samples. But they had more differences in the adsorbed and desorbed masses during the cycles. All the pieces desorbed more moisture in the first cycle than all the other cycles. For example, Design 2 desorbed 35.3 grams in the first cycle and 21.4 grams in the second cycle.

The results also show continuous increment in samples weights during the 8 hours test, test 2 (Table 8). The absorbed amount of moisture by time was not constant. In general, the amount is reduced by time for all samples. The reduction in absorption capability was the highest in the Design 1 and Design 2 panels and the lowest in the ALTG samples. Graphs in Appendix D show how the weight changes by time for all samples.

Table 8. Results of the test 2.

Time	ACTG 1 mass	ACTG 2 mass	ACTG 3 mass	ALTG 1 mass	ALTG 2 mass	ALTG 3 mass	Design 1 mass	Design 2 mass	Effex™ mass	Ref mass
h	**g**	**g**	**g**	**g**	**g**	**g**	**g**	**g**	**g**	**g**
0	557.25	563.16	603.3	599.38	503.39	509.11	1720.08	1788.16	195.4	2320
1	557.47	563.36	603.56	599.45	503.48	509.22	1721.94	1789.92	195.55	2320.76
2	557.56	563.48	603.64	599.45	503.48	509.24	1722.94	1790.64	195.63	2321.11
3	557.65	563.54	603.69	599.5	503.51	509.28	1723.8	1791.11	195.76	2321.4
4	557.82	563.66	603.8	599.52	503.55	509.33	1724.36	1791.93	195.89	2321.66
5	557.84	563.71	603.92	599.55	503.58	509.36	1724.81	1792.11	195.94	2321.77
6	557.91	563.82	604.04	599.57	503.62	509.4	1725.59	1793.16	196.04	2322
7	558.01	563.91	604.15	599.62	503.66	509.44	1725.92	1793.41	196.09	2322.19
8	558.12	563.97	604.24	599.64	503.69	509.48	1726.19	1793.57	196.15	2322.27

These graphs show that in ACTG samples the relationship between weight increments with time is not as linear as ALTG samples. Effex™ panel graph is very close to the ALTG samples. Design 1 and Design 2 graph shows big reduction in absorption by time. This applies to reference panel with less severity. The graph shows some irrational sudden jumps or declines in absorption and desorption which might be resulted from the conditioned room that did not have stable RH. Also it could be a result of the diffusers blowing air with differing flow from time to time.

Table 9 shows how the relationship between the absorbed moisture with time for each sample/panel numerically.

Table 9. Relationship between absorption and time.

Time	~RH	ACTG 1	ACTG 2	ACTG 3	ALTG 1	ALTG 2	ALTG 3	Design 1	Design 2	Effex^{TM}	Ref
after	**%**	**g**	**g**	**g**	**g**	**g**	**g**	**g**	**g**	**g**	**g**
1 h	60	0.22	0.2	0.26	0.07	0.09	0.11	1.86	1.76	0.15	0.76
2 h	60	0.09	0.12	0.08	0	0	0.02	1	0.72	0.08	0.35
3 h	60	0.09	0.06	0.05	0.05	0.03	0.04	0.86	0.47	0.13	0.29
4 h	60	0.17	0.12	0.11	0.02	0.04	0.05	0.56	0.82	0.13	0.26
5 h	60	0.02	0.05	0.12	0.03	0.03	0.03	0.45	0.18	0.05	0.11
6 h	60	0.07	0.11	0.12	0.02	0.04	0.04	0.78	1.05	0.1	0.23
7 h	60	0.1	0.09	0.11	0.05	0.04	0.04	0.33	0.25	0.05	0.19
8 h	60	0.11	0.06	0.09	0.02	0.03	0.04	0.27	0.16	0.06	0.08
Absorption at 1h divided by absorption at 8h ratio		2.00	3.33	2.89	3.50	3.00	2.75	6.89	11.00	2.50	9.50

The red numbers in Table 9 shows the reduction in absorption after 8 hours. Design 2, which has the largest across the grain surface area, has the maximum reduction in absorptions. Also the reference showed the second largest reduction. The changes in absorption by time for Design 1 and Design 2 is shown in Figure 11.

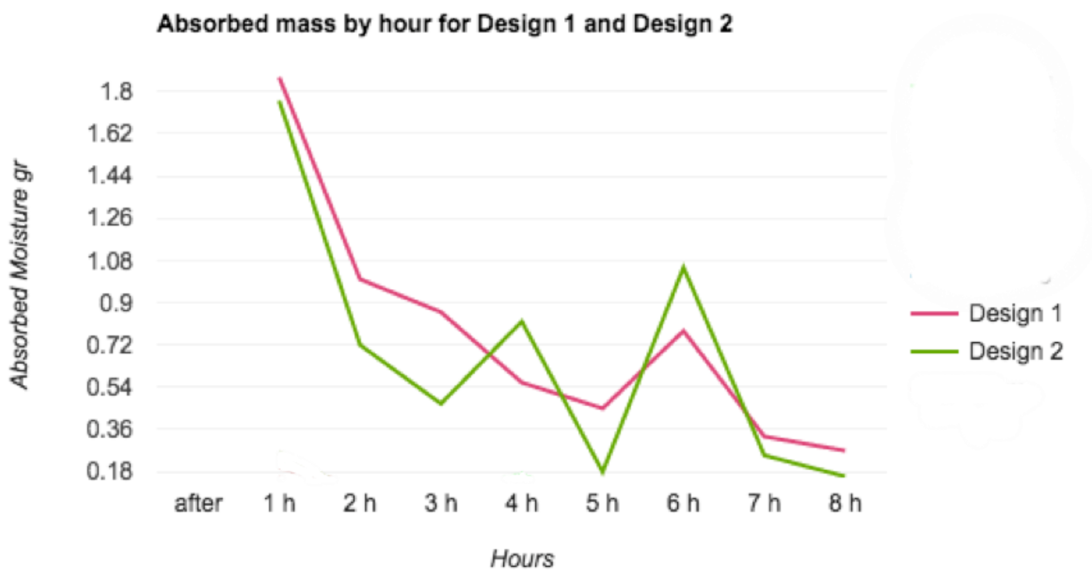


Figure 11. Reduction in moisture absorption for designs.

As concluded previously the absorption reduces severely by time in Design 2 and Design 1. For Design 2, the reduction is around 11 times and for Design 1 it is 6.8.

3.2.1 Determining the MBV

Based on the previous results on Table 6, the practical MBV on the basis of formula 4 is calculated as shown in Table 10.

Table 10. Calculated MBV values.

Sample name	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Average mass	Delta RH	Area	MBV
	Average mass	Average mass	Average mass	Average mass	Average mass		%	One Face	Practical
	g	g	g	g	g	g		m²	
ACTG 1	3.295	3.5	3.8	3.35	3.2	3.55	30	0.03	3.92
ACTG 2	2.99	2.95	3	3.15	3.1	3.03	30	0.03	3.35
ACTG 3	3.28	3.2	3.7	3.4	3.4	3.43	30	0.03	3.77
ALTG 1	0.445	0.95	0.8	0.75	0.6	0.83	30	0.027	1.00
ALTG 2	0.53	0.5	1	0.75	0.6	0.75	30	0.027	0.90
ALTG 2	0.395	0.8	0.75	0.7	1.1	0.75	30	0.027	0.90

3.2.2 Comparing Effex™ Panel with Other Designs

To compare the performance of the design with Effex™, two parameters are used. The first is absorption by square meter. This evaluates the absorption performance for two panels that have the same surface area. In other words, this parameter does not take in consideration the amount of the used material. The other parameter (surrounded with green box) is the absorption by volume (g/m³). This take into consideration the amount of material used to achieve the absorption of water vapor. Comparison of the results can be seen in Table 11.

Table 11. Comparison of Effex™ vs Design 1 and Design 2.

8 hours	Total Absorbed Mass	Thickness	Area	Absorption by Unit Area	Ratio	Absorption by Volume	Ratio
	g	cm	cm²	g/cm²	-	g/cm³	-
Design 1	6.11	4.7	900	0.00679	1.64	0.00144	0.94
Design 2	5.41	4.7	900	0.00601	1.45	0.00128	0.83
Effex™	0.75	2.7	180.7	0.00415	1.00	0.00154	1.00

Design 1 and 2 outperforms the Effex™ panel for absorption by unit area by 1.64 and 1.45 times subsequently. For absorption by volume the results of Design 2 and Design 1 were very close to Effex™. Design 1 achieved 0.94 the performance of Effex™ sample.

However, if the same values assessed after 1 hour then the results are different. Design 1 and Design 2 outperform Effex™ in performance as shown in Table 12.

The absorption by unit area was 2.36 times better than Effex™ for Design 1 and 2.49 times better than Effex™ for Design 2. The same apply for Absorption by Volume. Design 1 and 2 performed better by 1.43 and 1.35 respectively.

Table 12. Comparison Effex™ vs Design 1 and Design 2 (after 1 h)

1h	Total Absor bed Mass	Thickness	Area	Absorption by Unit Area	Ratio	Absorption by Volume	Ratio
	g	**cm**	**cm^2**	**g/cm^2**	**-**	**g/cm^3**	**-**
Design 1	1.86	4.7	900	0.00207	2.49	0.000440	1.43
Design 2	1.76	4.7	900	0.00196	2.36	0.000416	1.35
Effex™	0.15	2.7	180.7	0.000830	1.00	0.000307	1.00

3.2.3 Estimating Panels Absorptions Using MBV

By knowing the MBV for the wood, an attempt to predict the absorption for the designed panels theoretically was performed. The theoretical results then compared with the practical ones. See Table 13 for the results.

Table 13. Practical vs theoretical estimation for panel buffering.

Desc.	MBV Along the Grain	MBV Across the Grain	Practically Absorbed Moisture	Total Absorption Along the Grain	Total Absorption Across the Grain	Theoretically Absorbed Moisture	Differences ratio
Mass, g							
Design 1	0.94	3.68	31	5.86	105.37	111.22	3.59
Design 1	0.94	3.68	19	5.86	105.37	111.22	5.85
Design 1	0.94	3.68	21.6	5.86	105.37	111.22	5.15
Design 1	0.94	3.68	18.8	5.86	105.37	111.22	5.92
Design 1	0.94	3.68	20.6	5.86	105.37	111.22	5.40
Design 2	0.94	3.68	35.3	18.14	53.55	71.69	2.03
Design 2	0.94	3.68	19.9	18.14	53.55	71.69	3.60
Design 2	0.94	3.68	21.4	18.14	53.55	71.69	3.35
Design 2	0.94	3.68	23	18.14	53.55	71.69	3.12
Design 2	0.94	3.68	24.1	18.14	53.55	71.69	2.97

Table 13 shows that the practically absorbed moisture content is less than the theoretically measured one by around 5 times for Design 1 and 3.55 times for Design 2. The main reason for this is that the MBV does not take in consideration how the speed of moisture buffering reduces based on the design. The graph that was presented in Figure 9 shows that the reduction in absorption is around 11 times after 8 h for Design 1 but it is only around 3 times for ACTG samples. This lead to the conclusion that for the calculation to be more accurate, the thickness of teeth should be closer to ACTG samples thickness, this would have led to more realistic results. Based on all of this, it is expected that the MBV, which is used to estimate the buffering for the Design 1 panel, is 3 times more than the real MBV. Dividing the reduction in absorption of the Design 1 panel by the average reduction in absorption of ACTG samples, approximately 11/3=3.66, could derived this same conclusion. Which gives a sense of the expected divergence from the real absorption value.

3.2.4 Estimating Panels Absorptions Using Samples Absorptions

The same method was used to estimate the absorption of the panels in 8 hours by knowing the absorption of the surfaces along the grain and across the grain relying on information provided in Table 8. The average absorption for the samples in g and in g/m2 is presented in Table 14.

Table 14. Calculations of average absorption for the samples.

Time	~RH	ACTG 1	ACTG 2	ACTG 3	ACTG Moisture Buffering Average Each Hour	ACTG Moisture Buffering Average Each Hour	ALTG 1	ALTG 2	ALTG 3	ALTG Average	ALTC Average	ACTG / ALTG
After	**%**	**g**	**g**	**g**	**g**	**g/m2**	**g**	**g**	**g**	**g**	**g/m2**	**Ratio**
1 h	**60**	0.22	0.2	0.26	0.23	7.87	0.07	0.09	0.11	0.09	3.13	2.52
2 h	**60**	0.09	0.12	0.08	0.10	3.36	0	0	0.02	0.01	0.23	14.50
3 h	**60**	0.09	0.06	0.05	0.07	2.31	0.05	0.03	0.04	0.04	1.39	1.67
4 h	**60**	0.17	0.12	0.11	0.13	4.63	0.02	0.04	0.05	0.04	1.27	3.64
5 h	**60**	0.02	0.05	0.12	0.06	2.20	0.03	0.03	0.03	0.03	1.04	2.11
6 h	**60**	0.07	0.11	0.12	0.10	3.47	0.02	0.04	0.04	0.03	1.16	3.00
7 h	**60**	0.1	0.09	0.11	0.10	3.47	0.05	0.04	0.04	0.04	1.50	2.31
8 h	**60**	0.11	0.06	0.09	0.09	3.01	0.02	0.03	0.04	0.03	1.04	2.89
					For 8h (g)	**For 8h (g/m2)**				**For 8h (g)**	**For 8h (g/m2)**	**For 8h**
					0.87	**3.79**				**0.31**	**1.35**	**4.08**

The result shows that the absorptions vary by time in ACTG and ALTG samples. The average of total absorptions for ACTG samples in 8 hours is 0.87 gram. The average absorption varied between 0.07 and 0.23 gram. The highest absorption average was in the first hour 0.23 gram. The average absorption in each hour per area ranged between 2.31 g/m2 to 7.87 g/m2. The average of absorptions is 3.79 g/m2. The average of total absorptions for ALTG samples in 8 hours is 0.31 gram. The average absorption per hour varied between 0.01 and 0.09 gram. The highest absorption average was in the first hour 0.09 gram. The average absorption in each hour per surface area ranged between 0.23 g/m2 to 3.13 g/m2. The average of absorptions is 1.35 g/m2. The table also shows the differences in absorptions for the samples averages, which ranged between 2.11 to 14.5 times. The average of ACTG / ALTG absorption ratio is 4 times.

These results were used to predict the absorptions for the panels in each hour and the total absorption in 8 hours by multiplying the average absorption for each type of surface in g/m2 by the surface area. The results are shown in Table 15.

Table 15. Calculations of the panels moisture absorption practically and theoretically in 8h (Method2)

Time	~RH	Design 1 Practical	Estimated ACTG (0.95 m2)	Estimated ALTG (0.21m2)	Total	Difference	Design 2 Practical	Estimated ACTG (0.45 m2)	Estimated ALTG (0.65m2)	Total	Difference	Reference Practical	Estimated ACTG (0.027 m2)	Estimated ALTG (0.207m2)	Total	Difference
after	**%**	**g**	**g**	**g**	**g**	**Ratio**	**g**	**g**	**g**	**g**	**Ratio**	**g**	**g**	**g**	**g**	**Ratio**
1 h	**60**	1.86	7.48	0.66	8.13	4.37	1.76	3.54	2.03	5.57	3.17	0.76	0.21	0.65	0.86	1.13
2 h	**60**	1.00	3.19	0.05	3.24	3.24	0.72	1.51	0.15	1.66	2.31	0.35	0.09	0.05	0.14	0.40
3 h	**60**	0.86	2.20	0.29	2.49	2.90	0.47	1.04	0.90	1.94	4.14	0.29	0.06	0.29	0.35	1.21
4 h	**60**	0.56	4.40	0.27	4.67	8.33	0.82	2.08	0.83	2.91	3.55	0.26	0.13	0.26	0.39	1.49
5 h	**60**	0.45	2.09	0.22	2.31	5.13	0.18	0.99	0.68	1.67	9.26	0.11	0.06	0.22	0.28	2.50
6 h	**60**	0.78	3.30	0.24	3.54	4.54	1.05	1.56	0.75	2.31	2.20	0.23	0.09	0.24	0.33	1.45
7 h	**60**	0.33	3.30	0.32	3.61	10.95	0.25	1.56	0.98	2.54	10.16	0.19	0.09	0.31	0.41	2.13
8 h	**60**	0.27	2.86	0.22	3.08	11.40	0.16	1.35	0.68	2.03	12.70	0.08	0.08	0.22	0.30	3.71
Total Buffering in 8h																
		6.11	28.81	2.26	31.07	6.36	5.41	13.65	7.00	20.64	5.94	2.27	0.82	2.23	3.05	1.75

The differences between the practically measured absorption and the theoretically calculated one in each hour ranged between 2.9 and 11.4 times for Design 1, between 2.3 and 12.7 for Design 2 and between 0.4 to 3.7 times for the reference. The average of sample differences between the practical and theoretical calculation of total absorption in 8 hours for Design 1, Design 2 and the Reference was 6.36, 5.94 and 1.75 respectively.

The method in Table 15 relied on calculating the average of absorptions for samples in each hour and then finding the average absorption for the panel for each hour. This is a logical assumption that did not result in logical outcome. Thus, another theoretical calculation was made. So instead of multiplying the average of absorption in each hour by the relevant panel surface area, the average of absorptions in during 8 hours is calculated for ACTG surface and ALTG surface and the results are multiplied by the relevant surface areas (method 3), Table 16.

Table 16. Calculations of the panels moisture absorptions practically and theoretically in 8h (Method 3)

After 8h	~RH	ACTG Average	ALTC Average	Design 1 Practical	Estimated ACTG (0.95 m2)	Estimated ALTG (0.21 m2)	Total	Difference		Design 2 Practical	Estimated ACTG (0.45 m2)	Estimated ALTG (0.65 m2)	Total	Difference		Reference Practical	Estimated ACTG (0.027 m2)	Estimated ALTG (0.207m2)	Total	Difference
	%	g/m2	g/m2	g	g	g	g	Ratio		g	g	g	g	Ratio		g	g	g	g	Ratio
	60	3.79	1.35	6.11	3.60	0.28	3.88	1.57		5.41	1.71	0.87	2.58	2.10		2.27	0.10	0.28	0.38	5.98

The differences between the practically measured absorption and the calculated one ranged between 1.57, 2.10 and 5.98 times for Design 1, Design 2 and the reference respectively.

3.2.5 Theoretical Estimation Using Computational Simulation

The simulation of the practical test using Hamopy requires entering the changes in conditions throughout the time. The parameters of the initial condition and the climates (climate 1 and climate 2) on the two sides of the wooden (cross section) were entered. The program allows for the input of different parameters (Temperature, RH, Pressure) at different times and simulates the changes of the condition, which is defined by these parameters during time. The entered information mimic the conditions that have their results presented in Table 8. The benchmark samples are ACTG1, ACTG2, ACTG3, Design 1, Design 2 and the reference. The code of the program is presented in Appendix E.

During the simulation, the program can read input information and their changes in time from a text file. In this test, the information that was entered includes the temperature and the relative humidity during the test time, which is 8 hours. Table 17 shows the configuration input.

Table 17. HAMOPY settings

Description	**Time (seconds)**	**Temperature (K)**	**RH%**
Initial	0	295	50 (0.5)
Climate 1 (clim1)	28800	295	60 (0.60)
Climate 2 (clim2)	28800	295	60 (0.60)

As it is shown in the above table, the entered data match the condition of the testing room/chamber where the practical test took place in test 2 (Table 8). Figure 12 illustrates the concept of the simulation.

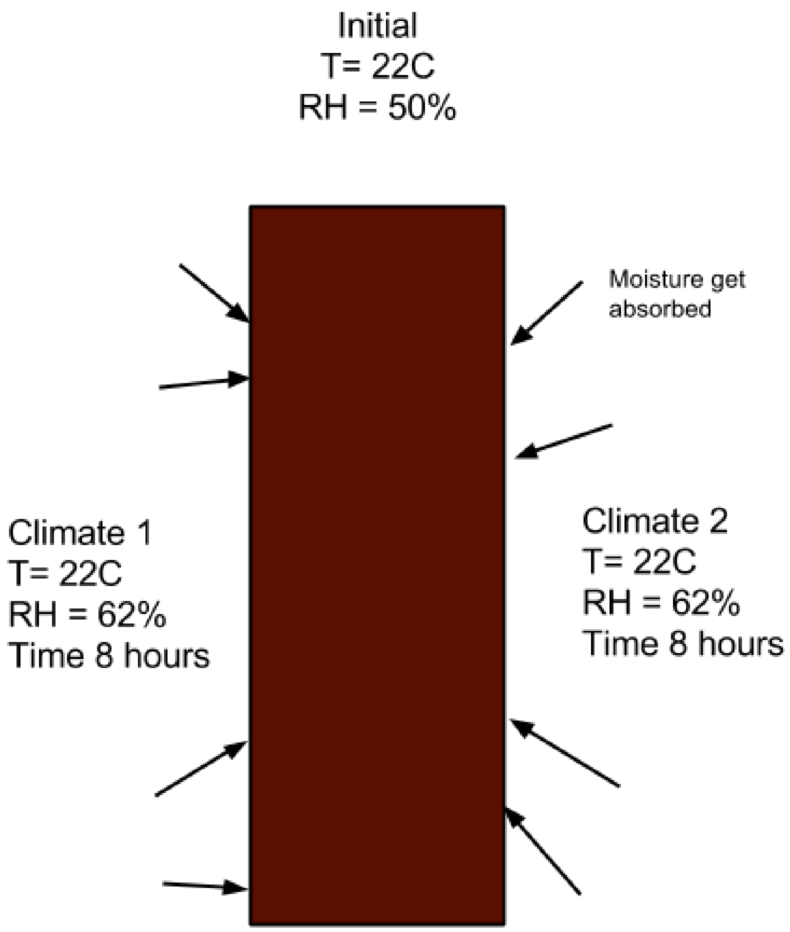


Figure 12. Software configuration

The cross section of the wooden sample (the brown rectangle) which has the initial conditions of T =295 °K and RH = 0.5 is placed in the virtual conditioned room where the condition is same from the two side of the cross sections. The temperature of the room is T=295 °K, RH = 0.60 and the duration of the test is 8 hours (28800 s). The arrows show that the water vapor is getting absorbed from both sides of the sample.

The program requires entering the sorption isotherms for used material, which is pine in this case. The program offers two ways to enter the adsorption isotherm of material. The one that is used is the 3rd degree polynomial interpolation, for a list of measurement points. The program requires four points to perform the interpolation. Table 18 shows the data that were used.

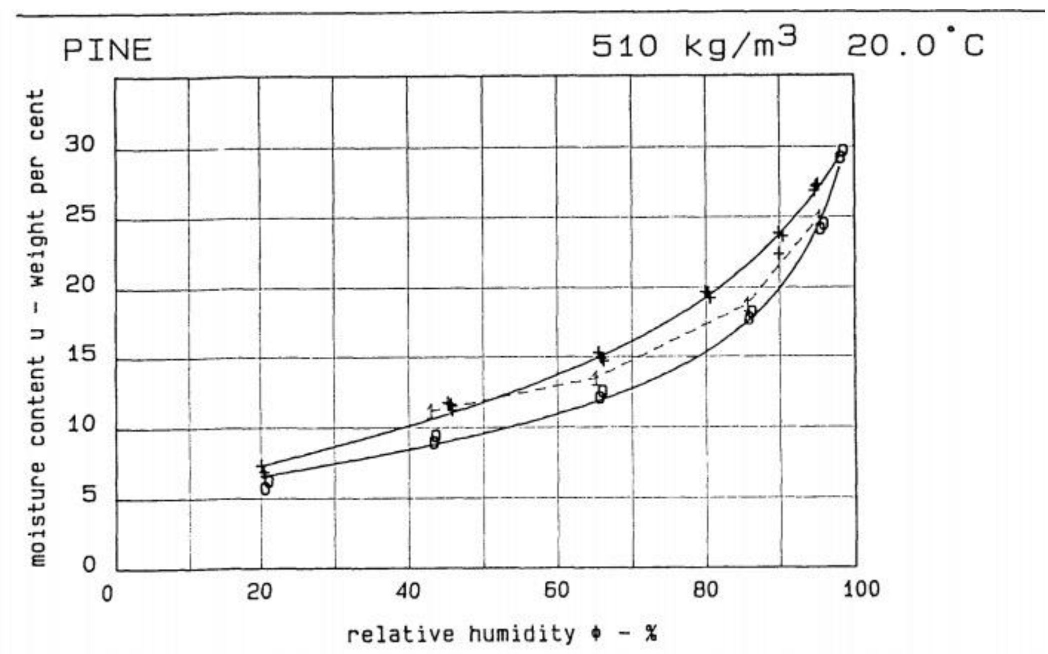


Figure 13. Sorption isotherm for pine.(Hansen 1986)

Figure 13 shows the moisture content at different RH for pinewood. As the software require the units in kg/m3, conversion for units was made considering the average density for the samples in test 2 is around 429 kg/m3. The selected points that were entered in the program were shown in Table 19. (Hansen 1986)

Table 18. Sorption isotherm for pine (kg/kg)

RH	**kg/kg**	**kg/m3**
%	**water/wood**	**water/wood**
20.5	0.057	24.453
43.5	0.094	40.326
65.6	0.12	51.48
85.8	0.177	75.933
95.9	0.244	104.676

Based on the points in Table 20, the program is able to calculate approximation for the moisture content of wood fiber at other RHs.

Table 19 shows the permeability value, which is used in the software. The density that was used in the software is 429 kg/m3, this resemble the average density of the samples.

Table 19. Pine permeability.(Salonvaara et al. 2004)

Material	**Water Vapor Permeability**	
Pine	**(10e-12*kg/(m*pa*s))**	
	RH : 20%	**63%**
	1.25	5

The program offers more than one ways to enter the permeability. The interpolation method using two points is used for this application as shown in Table 22

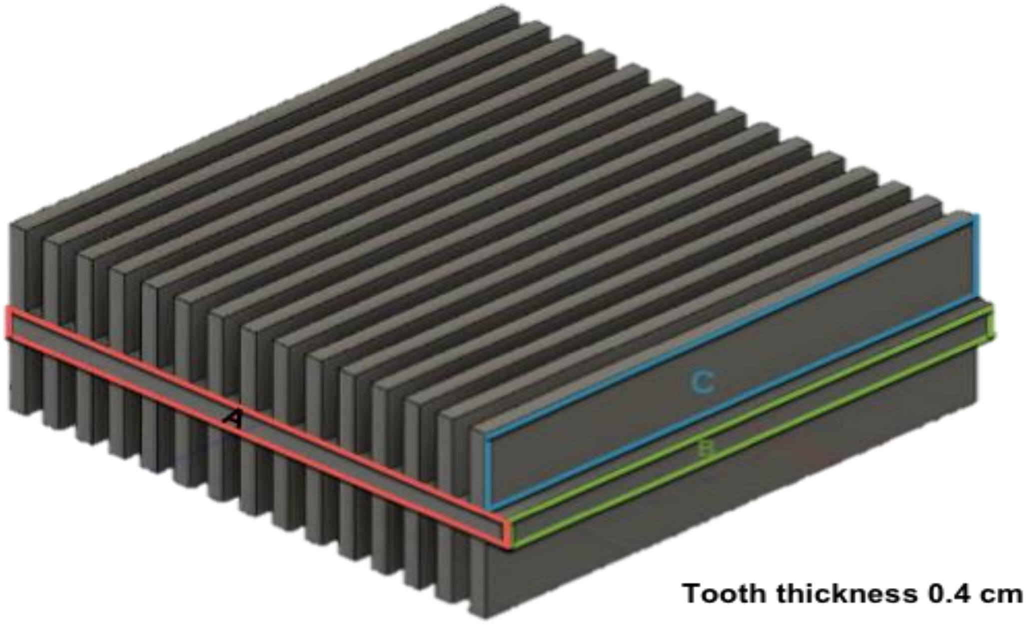
Table 20. Sorption isotherm for pine sapwood

Point Number	**RH%**	**Permeability (kg/m*pa*s)**
Point 1	20	1.25e-12
Point 2	63	5e-12

It is clear from Table 22 that vapor permeability of wood cell wall is not constant but rather varies in a small range and it is also relevant to the density of the wood.

The components of the panels were categorized by their thicknesses and the simulation (one dimensional simulation) was run to estimate the moisture content value throughout the cross section of each thickness. Figure 14 shows the surfaces that were considered in the simulation.

a)



b)

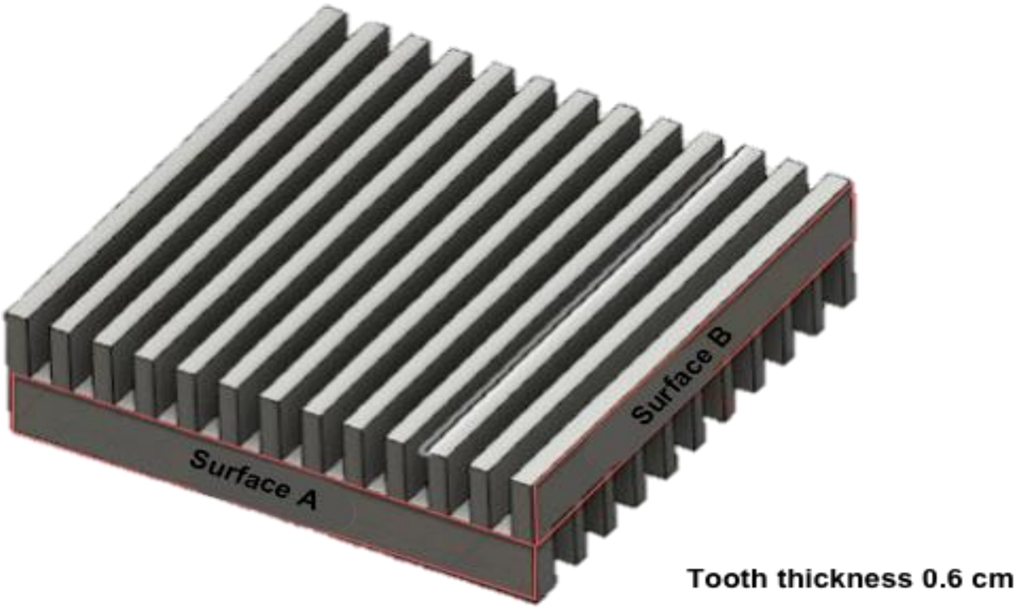


Figure 14. Dividing the panel into parts for simulation. a) Design 1 with teeth thickness of 0.4 cm. b) Design 2 with teeth thickness of 0.6 cm. Surfaces B and C are transverse. Surface A is tangential

Design 1; consist of 4 main parts with different thicknesses. Part C for example resembles the teeth with thickness of 0.4 cm. Part D is not shown. It is the surfaces between the teeth looking from top and bottom of the panel. The thickness of this part is 2.9 cm.

The layers throughout the thickness were divided into 0.5 mm, Figure 15, and the water content is then estimated in each layer by kg/m^3 at beginning and after 8 hours.

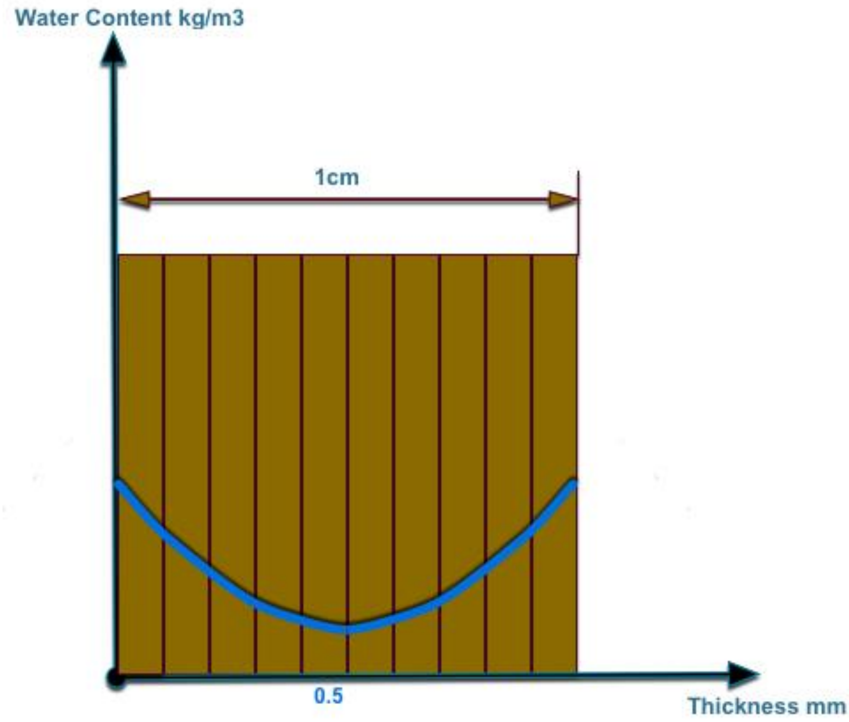


Figure 15. Illustrating the concept of calculation.

As Figure 15 shows, the value of moisture content reduces throughout the thickness. By time, the external wood layers become saturated and reach equilibrium and their ability to absorb moisture diminish. By subtracting the moisture in each layer after 8 hours from the moisture at the beginning, the increment of moisture in each layer (the buffered moisture) is found. The mean of the absorptions in the layers, Figure 16, is then calculated only for the main external layers that have significant moisture increment in kg/m3.

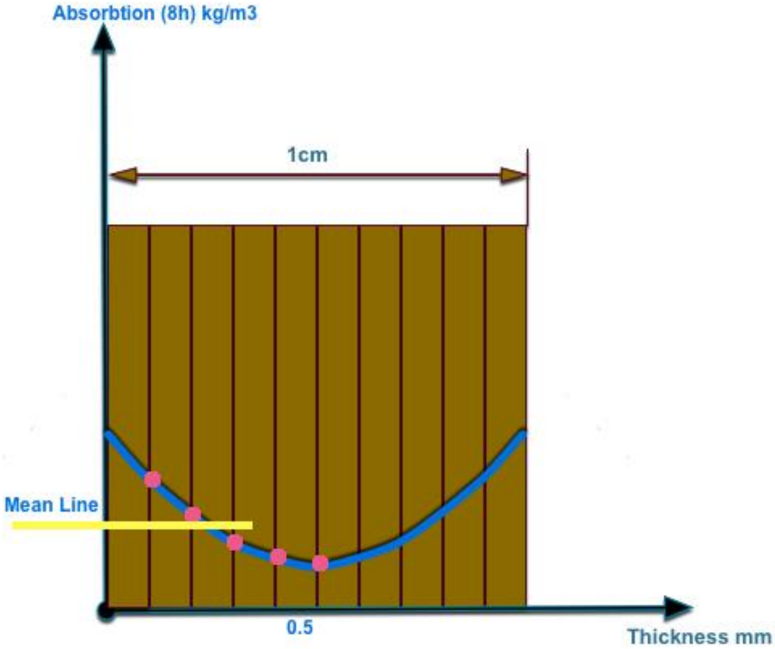


Figure 16. Calculating the mean of absorption in the layers

Figure 16 is used for illustration and the value in it does not reflect the reality. The red dots represent the found absorption after 8 hours in each 0.5 mm layer. The mean of absorptions for these is then considered the approximate absorption for the whole thickness. By multiplying the mean by the active thickness (the layers that absorbed moisture) the absorption in kg/m^2 is obtained.

This assumption is made to speed up the calculations by ignoring the internal layers that barely affect the overall results. The deep internal layer of wood that does not involve much in absorption was ignored. This consideration is made because the moisture uptake requires very long time to penetrate all the layers throughout the thickness. For 8 hours, it is expected that only the external layers participate in moisture absorption. For the internal layers, there is only minor increment in absorption gained through these layers. This method gave good estimation but does not take into consideration the non-linearity of the absorption graph. Thus another method is suggested which rely on integration throughout the thickness, Figure 17, to obtain the absorbed moisture for the thickness in kg/m2. Multiplying this value by the surface area gives and estimation of total moisture absorption through the surface of particular thickness. This method is used in the calculations.

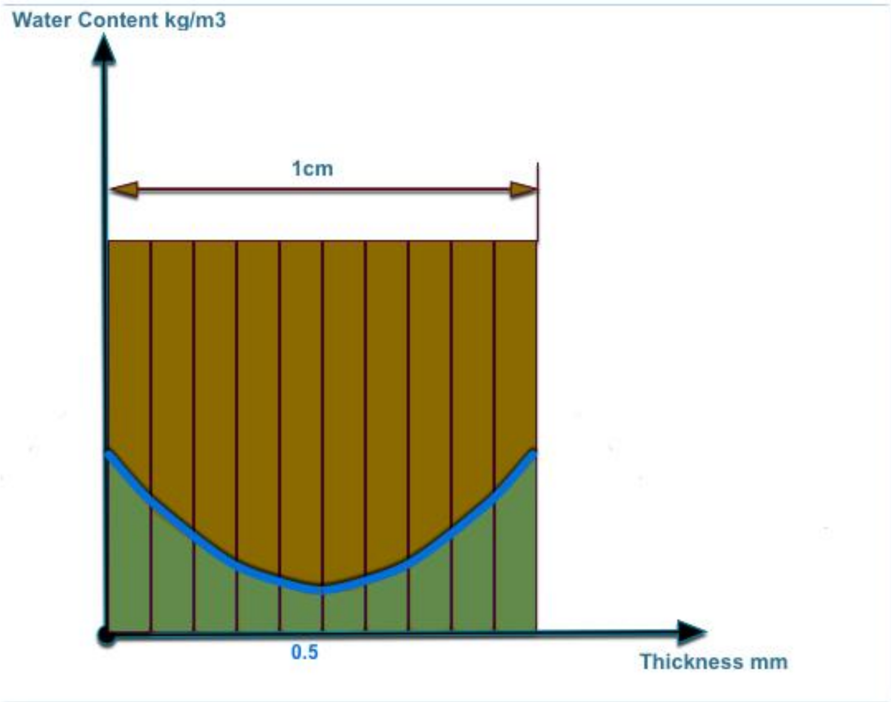


Figure 17. Calculate the absorption using integration.

The green area beneath the graph shows the absorbed moisture in kg/m2. The differences in absorption across the grain and along the grain within 8 hours decrease rapidly. This was illustrated in the graphs in Appendix E and in Table 9.

The differences between absorption across the grain and along the grain could be expressed in HAMOPY by changing the water vapor permeability for each case. However, since it was not feasible to get these values, the practically calculated differences in the averages of the absorptions between surfaces type ACTG/ALTG (2.8 times) for the samples along the grain and across the grain in 8h is used instead.

In general, as thickens increases the moisture content in all wood layer in kg/m3 decrease (considering constant x step). The simulation generates results that were visualized in Figure 18, which shows the relationship between the moisture content through out the thickness.

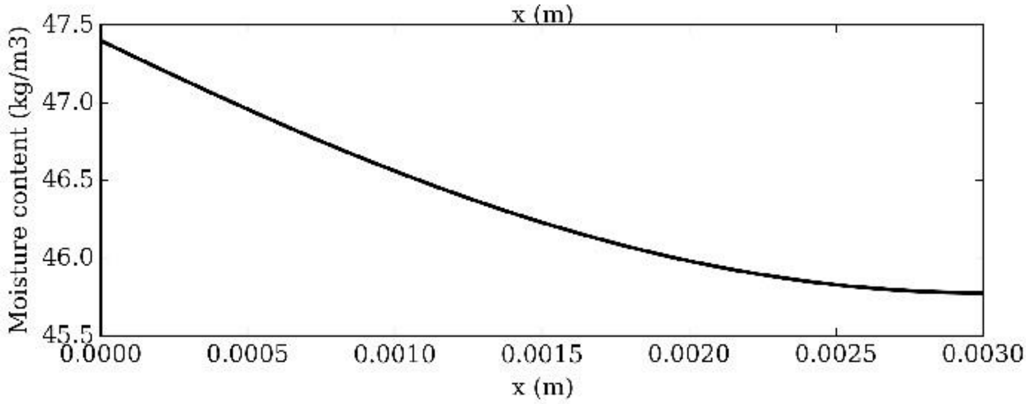


Figure 18. Reduction in moisture content for sample layers with thickness of 0.6cm in relation to depth (m).

It is clear that the moisture decreases in deeper layers as x move inside the wood. Figure 19 shows the changes of moisture content at different layers by time for the same sample (0.4 cm thickness).

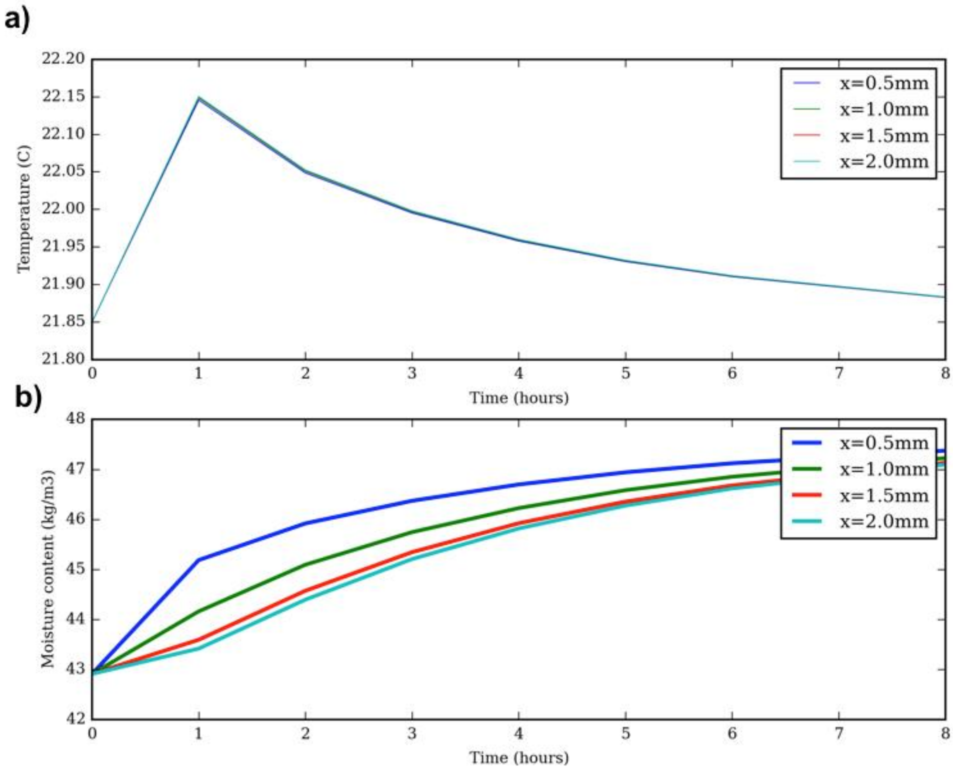


Figure 19. Moisture content and temperature change by time at different thickness/layers. (sample thickness 0.4cm). a)Temperature change in wood layers by time b)Moisture content change in wood layer by time.

The outer layer (0.5 mm) absorbs the highest amount of moisture throughout the exposure time. Considering the aforementioned, these findings could be applied on the panels to estimate their absorption. For example, Design 1 has 42 teeth from both sides with each tooth thickness of around 0.4 cm. Simulating the transfer of moisture into one tooth and multiplying the result by the number of the teeth gives an estimation of the expected moisture absorption during 8 hours. Table 21 compares the results of simulation with the results of the practical test.

Table 21. Absorption estimation using computational simulation

After 8h	Surface Name	Total Absorbed Mass	Thickness	Surface Area (R/T)	Surface Area (AC)	Estimated Absorption by Surface for The Given Thickness	Estimated Absorption by Surface for The Given Thickness	Differences
		g	cm	cm2	cm2	kg/m2	g	%
ACTG1		0.26	4.50		256.00	0.00865	0.22	-14.83
ACTG2		0.30	4.50		256.00	0.00865	0.22	-26.19
ACTG3		0.37	4.50		256.00	0.00865	0.22	-40.15
Design 1	C	unknown	30.00		174.00	0.0196	0.34	
Design 1	B	unknown	0.40		9,576.00	0.0064	6.13	
Design 1	A	unknown	30.00	174.00		0.0196	0.12	
Design 1	D	unknown	2.90	792.00		0.00846	0.24	
Moisture Buffered in 8h		6.11					6.83	11.8%
Design 2	B	unknown	0.60		4,608.00	0.00818	3.77	
Design 2	A	unknown	0.60	4,608.00		0.00818	1.35	
Moisture Buffered in 8h		5.41					5.11	-6%
Reference	A		30.00	270.00		0.0196	0.19	
Reference	B		30.00		270.00	0.0196	0.53	
Reference	C		4.50	1,800.00		0.00866	0.56	
Moisture Buffered in 8h		2.27				0.00865	1.27	-43.84%

The difference between the practical and the suggested theoretical approach ranges from 6% to around 44% for all samples. Taking in consideration that the results in practical tests of absorption between samples that has the same dimensions and which are cut from the same wood species and brought from the same supplier varied by around **30%** (from 0.26 gram ACTG1 to 0.37 gram ACTG3), these results seems to be very promising. Also, it is expected that better results could have been obtained if the exact properties of wood are known and if the practical tests were made in ideally conditioned room. Overall, It is extremely hard to render perfectly precise results as the samples differ in the same cross section and also they probably were cut from different trees. But overall, reducing the inaccuracy in estimation that was made using the other methods by at least 200%, could be seen as a leading step for advancement in such complex and challenging topic.

3.3 Estimating the Best Thickness for the Teeth

The thickness of the teeth is an important factor for the design of the panel in two contradictory ways. Making more teeth with small thickness requires more machining time and effort. In addition to this, more wood that could be utilized in absorption is wasted as saw dust. However, this does not guarantee more absorption during the occupancy time of the space (considered 8 hours). The results of the practical tests suggest that the teeth with smaller thickness get saturated faster than the teeth with bigger thickness. Thus a panel with teeth with small thickness has very large surface area but low overall absorption capacity. Thus most of the absorption happens in the first exposure hours and then it slow down exponentially. In contrast to this, if the teeth thickness is reduced then the surface area decreases thus the potential absorption and at the same time the capacity of absorption for each teeth increases. Finding the best teeth thickness requires solving this problem.

A code was written to estimate the water absorption for different teeth thicknesses. The range of thicknesses that were tested for virtual panels with same dimensions varies from 0.2 cm to 2 cm. In reality, exposed teeth that have a width of 0.2 cm or less are not suitable for reasons related to rigidity and durability. Also teeth with a thickness more than 2 cm are way too thick. Figure 20, shows the relationship between teeth thickness and teeth absorption capability.

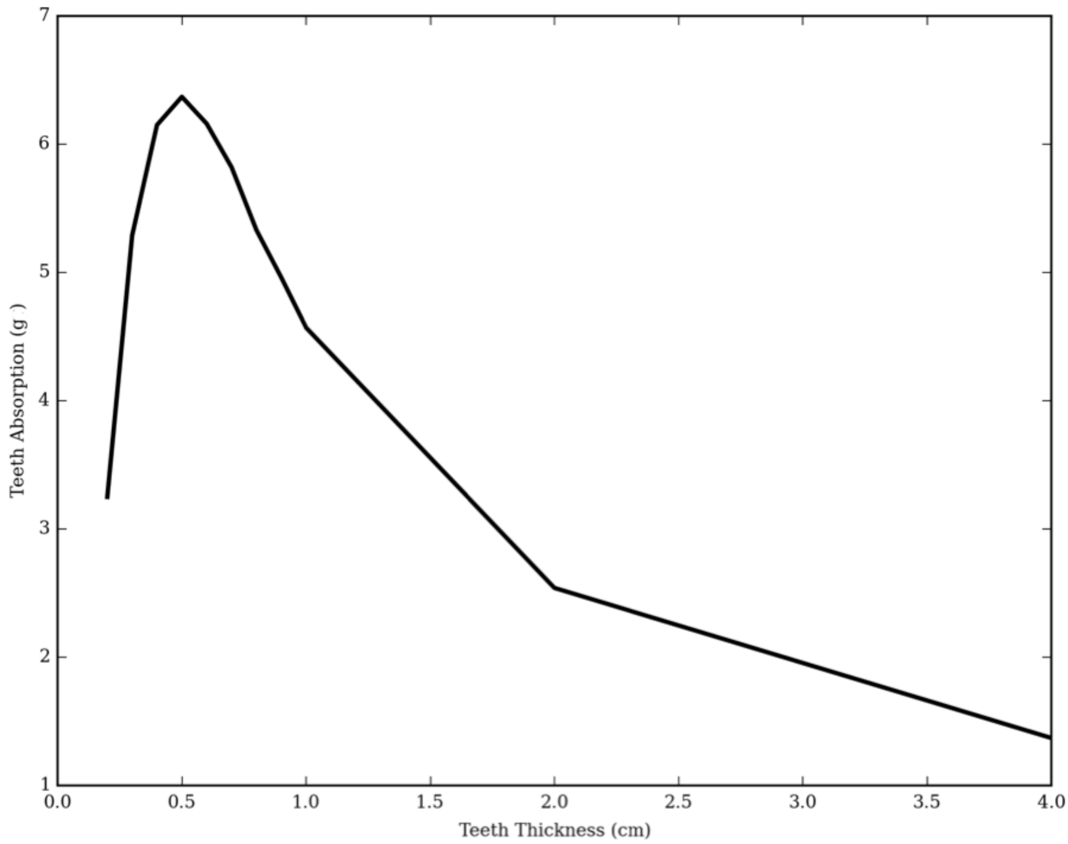


Figure 20. Finding the best teeth thickness

The total water absorption increase as the thickness of teeth increase from 0.2 cm to 0.5 cm and then it decreases again. Table 22 shows the estimated capacity of absorption at each thickness.

Table 22. Sorption isotherms for pine boards from teeth

Teeth Thickness Board (30x30x4.8)	Number of Teeth	Total Surface Area for Teeth	Absorption	Total Absorption
cm	**-**	**cm2**	**kg / m2**	**g in 8h**
0.2	60	13680	0.002379	6.43
0.3	50	11400	0.004638	7.18
0.4	42	9576	0.0064275	6.70
0.5	37	8436	0.00755	5.59
0.6	33	7524	0.008189	4.73
0.7	30	6840	0.0085098	3.86
0.8	27	6156	0.0086573	3.16
0.9	25	5700	0.008707379	2.68
1	23	5244	0.00872169	2.25
2	13	2964	0.00855445	0.73
4	7	1596	0.00859848	0.21

Based on the results, the optimum thickness for panels' teeth is 0.5 cm. These results suggest that the thickness of the wooden layers that account for the absorption is around 2.5 mm from each side of the teeth (the absorption is happening from both side of each tooth). Adding more wooden layers thus, increase the thickness and the wasted material and reduce the exposure to air surface area for the given volume. Whereas reducing the layers thickness below this increase the exposed surface area in the panel that loss its absorption capabilities fast. This size reflects the optimum usage of the wood for this particular purpose. Taking these results into consideration, it is suggested that Design 1 with the 42 teeth and with thickness of 0.4 cm would have performed better if the thickness were 0.5 mm. In addition to this, the small teeth size meant more time spent on machining. The thickness of Design 2 teeth of 0.6 cm was selected by coincidence to save time in machining. It turned out, based on the graph in Figure 18, that this thickness performance matches the performance of the thickness of 0.4 cm thickness and that this dimension is close to the optimum thickness, which is recommended by this study.

4. DISCUSSION

The received wood boards were in their raw state without machining. The boards arrived with very high moisture content and required drying. They also contained so many knots in them. They were machined in the university workshop with just acceptable results. As there was no possibility to leave them to dry for long time, the boards were machined before drying. This caused some curving and distortion in them.

The conditioned rooms did not have stable conditions. The RH and the temperatures were changing in their values. The diffusers were blowing the air in the room causing the flow of the air to be different in the room. The room was used not only for this test but also as storage and for other application. Opening and closing the door might have also caused changes in the room climate parameters. The output of the sensors also supports this. The measurements of the weights performed out of the room as the airflow inside the room affected the accuracy of the readings.

HAMOPY configurations that are related to the used wood are selected based on the articles from the Internet. These properties do not necessarily reflect exactly the properties of the wood that have been used. The program did not simulate the unstable state of the conditioning room. Also, there were barely any available attempts to utilize HAMOPY documented in the same application before that could have helped for comparison. The software use approximation method to find the graph of the absorption isotherm and the water vapor permeability of the materials, which could reduce the accuracy of the result. However, practical tests could help finding the optimum setting for particular wood species.

These limitations are all notable, but not critical. The results were logical and consistent, which proved that the process was successful.

The MBV in transverse direction is between (3.35 and 3.92) and in tangential direction is between (0.9 and 1.0) g/RH%*m². Based on this number, which is close to spruce MBV (1.2) (Rode & Grau 2007), pine is considered to have moderate (if MBV = 0.9) or good (if MBV = 1.0) MBV.

The panels did not differ much in their buffering ability. Even though, Design 1 has the highest numbers of grooves (41) its performance was comparable with the performance of other panels, which have 32 grooves. The thickness of each tooth is larger in Design 2, which could have played a role in the absorption from the transverses surfaces. Overall, Design 1 and Design 2 have very close total surface areas (with different transverse/tangential/radial surface areas) to each other but their performance were very close to each other. This probably due to the thicker teeth (0.6mm) that Design 2 has.

The results showed that the moisture buffering in transverse surface is better than the buffering in tangential surface. This conforms to the findings from Glass & Zelinka (2010). Also this is in accordance with the tests results for ACTG samples in comparison with ALTG samples.

It is expected that the ACTG moisture buffering decline faster than ALTG by time especially in low thicknesses. A possible reason is that the transverse surfaces reach equilibrium faster than tangential/radial surfaces. Probably, the thickness of ACTG samples had more roles in increasing the absorption than in ALTG samples. Also these findings support the findings by Glass & Zelinka (2010).

The theoretical estimation for the buffering of the panels which performed using the obtained MBV (along and across the grain), the surface areas of the panels (along and across the grain) and RH difference to estimate the buffering ability for the panels gave inaccurate results. For the panel Design 1 the theoretical estimation was around 3 times more than the number obtained practically.
The methods, which were used to predict the absorptions for the panels in 8 hours, deviated from the practically measured values from around 60% to 500%. It is expected that this is happening because the speed of absorption vary by time on relation to the thicknesses.

Using Hamopy simulation, the results were very promising. The practically measured absorption varied among the samples from the same wood, but with different density, by approximately 15%. There are many reasons that make the simulation results very acceptable. Among them that the samples were not glued perfectly due to the curve that was formed in the glues surfaces as the machining was not perfect and as the wood, which had high moisture content, was left to dry only for two days before machining. This could have increased the surfaces that are in contact with the air. The chamber humidity was not stable and it seem, based on the graphs, that it increased above 60% for sometime mainly around the fourth and sixth hour. But overall, setting the properties of the material, which probably not precise, the initial temperatures, the conditions around the wood, and the changes in these conditions resulted in very close results from the practical tests.

It is expected that in any space with different applications the speed of buffering is more important than the amount of buffering and this is what make the presented panel in this project unique compared with Effex^{TM} panel.

Effex^{TM} sample has smaller dimensions and thicknesses that make the surface area to volume higher than Design 1 and Design 2 and this could be also the reason for the good buffering performance for Effex^{TM} panels in unit volume of material after 8 hours.

Imagining that such panels find their way to the market, it is expected that the user need to know how many panels are required, or at least what is the required surface area needed based on particular humidity, sweating rate, ventilation, the amount of plants and the number of persons. For this it is possible to provide an online tool that could assist in the selection process. Appendix A show a code that could be altered further for such tasks.

As this field is considered new, it has big potential for future researches. The asymmetrical shapes of the design could cause the generation of internal stresses in the panel, especially when used in this application, which could cause deformation or even cracks and breaks. This topic should be researched thoroughly to assure the durability of the panel and that it is not going to deform by time. The panel should have an acceptable life span. This might require the usage of coating and protection. Finding a treatment that keep or maximize the hygroscopic ability of the wood could be researched. The goal of maximizing the surface area could result in making unsmooth surfaces that could accumulate dirt. Researching ways to minimize the dirt could be performed in the future.

CONCLUSIONS

In this thesis studies the criteria that maximize the moisture buffering in a wooden panel for indoor usage were studied.

Practical test to measure wooden panel moisture buffering value were performed in Aalto University.

Six samples are used to determine the MBV for pinewood. Three samples were used to determine the MBV for transverse surfaces and the other three are used to determine MBV for radial surfaces. MBV for pinewood transverse surface ranged between (3.35 and 3.92). MBV for pinewood radial surface ranged between (0.9 and 1.1).

Two panels were designed using the same wood (pine) and practically tested for their potential to provide better indoor air quality that benefits the dwellers. They approved their ability to give better moisture buffering than the reference panels by two to four times (depending on temperature and RH level and the time).

Three theoretical methods to estimate the MBV of the panels using the practical test results of ACTG and ALTG samples were performed. None of these methods render precise estimation. The calculation error ranged between 350% to more than 500%. Using

Computational HAMOPY simulation was made and resulted in more accurate estimation than other methods. The calculation error was reduced to maximum of around 50%.

Using HAMOPY simulation, the recommended thickness of teeth in wood panel was found to be around 5mm. It was demonstrated that the major penetration of moisture during 8 hours is mainly occurs in the depth of around 2.5mm.

The HAMOPY simulation worked out in current thesis can be utilized to evaluate the MBV of different solid wood interior panel designs.

KOKKUVÕTE

Käesolevas magistritöös uuritakse puidust siseviimistluspaneeli niiskussalvestusomaduste maksimeerimise võimalusi. Sellise paneeli kasutamine võimaldab saavutada paremat toaõhukvaliteeti suurendades elanike mugavust läbi suhtelise õhuniiskuse passiivse reguleerimise.

Magistritöö eesmärgiks on analüüsida puidu hügroskoopsete omadustega seotud disainitegureid kõrgete niiskussalvestusomadustega puitpaneeli väljatöötamiseks ja saavutamaks paremat siseõhukvaliteeti.

Puitpaneeli niiskussalvestusomadused ja protsessi kiirust mõjutavad mitmed faktorid. Vastavalt juhtnööridele tuleks paneeli valmistamisel kasutada okaspuidu maltspuitu, mis on ristikiudu lõigatud ja kareda viimistlemata välispinnaga, mille geomeetria ja mõõtmed võimaldavad maksimeerida eripinna pindala õhukäes eksponeerimiseks. Niiskussalvestusomaduste (NSO) põhjal selgitatakse välja parimad puiduliigid selle ülesande täitmiseks. Hariliku kuuse (*Picea abies*) niiskussalvestusomadused on dokumenteeritud puiduliikidest parimad.

Paneelile sobiva disaini välja töötamiseks viidi eksperimentaalsed katsed läbi Aalto Ülikoolis. Katsepaneele võrreldi Stora Enso Effex^{TM} paneeli prototüübiga. Katsete tulemusena selgus, et väljatöötatud disainilahendustel olid 2-4 korda paremad niiskussalvestusomadused kui samade mõõtmetega referentspaneelil. Sarnaste mõõtmete juures (v.a. paksus) absorbeeris Effex^{TM} paneel ligi 60% vähem niiskust kui töös esitletud paneelid. Töös Määrati hariliku männi (*Pinus sylvesteris*) niiskussalvestusomadused, mis võrrelduna hariliku kuuse (*Picea abies*) NSO-ga olid madalamad. Paneeli NSO omaduste hindamiseks esitleti töös uut arvutisimulatsioonil põhinevat meetodit. Niiskusvoo modelleerimiseks läbi materjali ristlõike kasutati *HAMOPY Python* tarkvara.

Modelleerimise tulemusena selgus, et mudeli arvutustulemused erinevad vahemikus 5% kuni 50% praktiliste katsete resultaatidest. Töö tulemusena selgus, et modelleerimisel rakendatud arvutusmeetod annab täpsemaid tulemusi paneeli NSO-te hindamiseks kui paneeli materjali ja väliskuju eripinna pindala arvutamine. Soovitatud teoreetilist arvutusmudelit kasutati töös võrdlemaks paneeli välismõõtme muutmisest tingitud mõju paneeli niiskussalvestusomadustele.

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APPENDIXES

Appendix A. Estimating the Required Surface Area

Using Python programing language, a formula that estimates the required surface area of wood based on:

- Room/space volume in m^3
- Temperature at start
- RH% at beginning
- RH% target
- Number of persons
- Sweat rate in liter/day
- MBV: moisture buffer value in $g/RH*m^2$

Using this code the needed surface area can be calculated. The surface area that are required to absorb the moisture which is generated by two person in a bedroom with dimension 4x3x2.5 m is $11.3m^2$. Conditions are stated in the next Table.

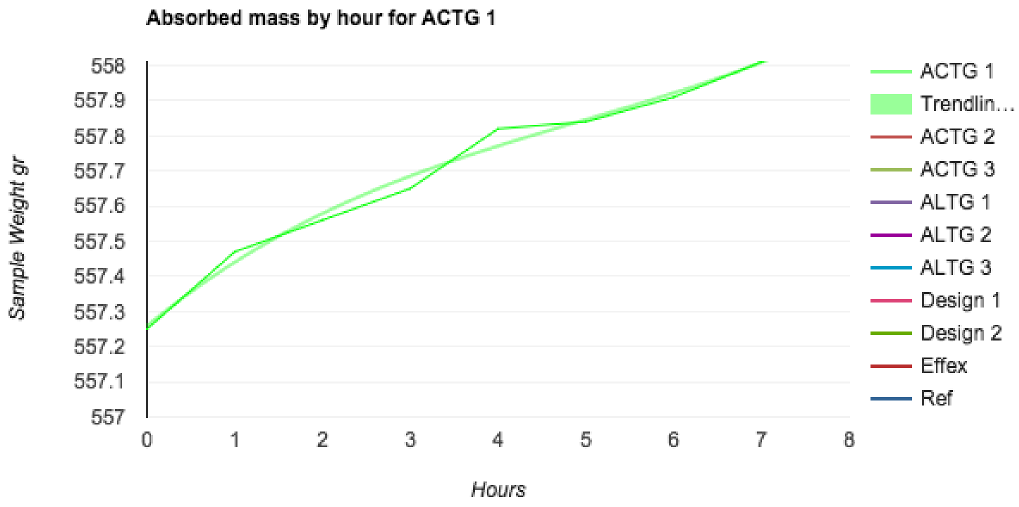
Table 23. The Program Estimate the Required Surface Area

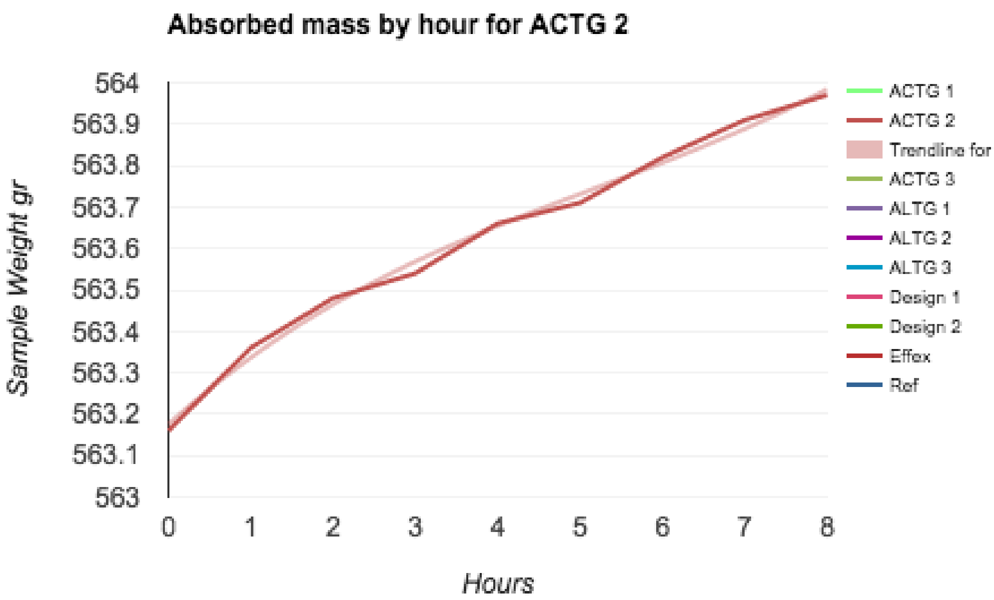
Scenario of a Bedroom for Two	
Room Volume m³	30
One modified panel surface area	0.77
MBV	1.2
Tst C	23
RHst%	36.4
RHtrg %	60
Persons	2
Sweat g/h	60
Ventilation g/h	60
MBV (g/(m²*RH%)	1.2
Surface Area Needed m² (program output)	11.3

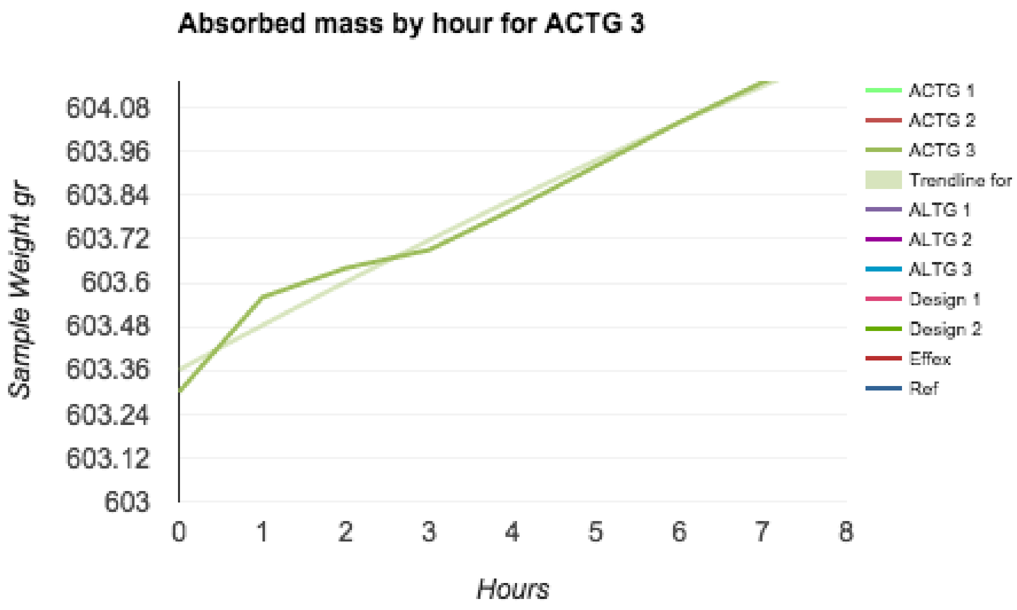
These results are very close to the result that was obtained for the same conditions by (Rode et al. 2005) Based on this, it is possible to estimate how many panels are required for such a room.

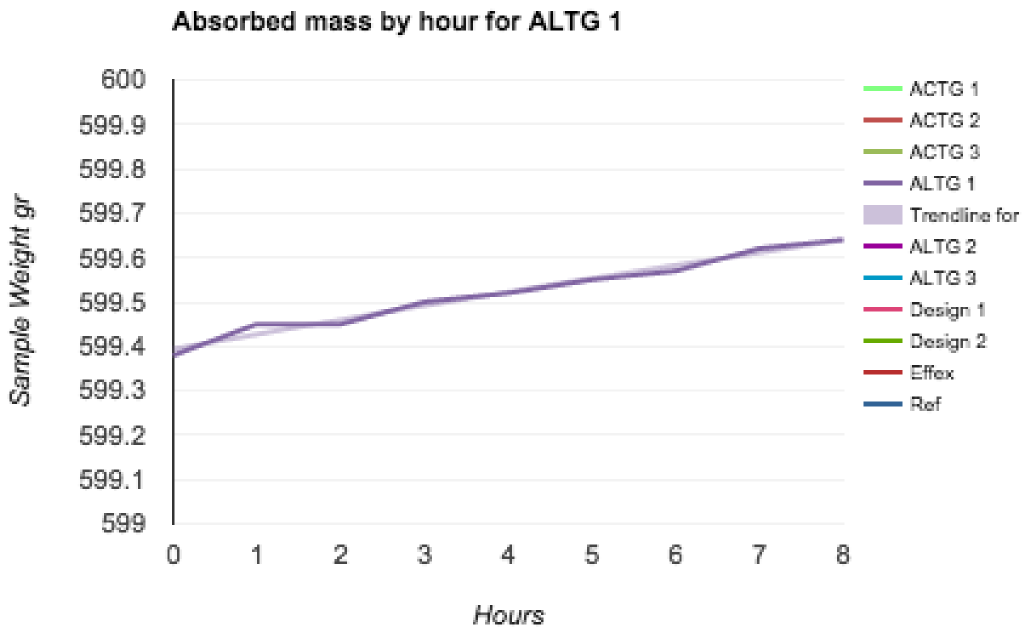
Appendix B. Absorption Graphs (8h test)

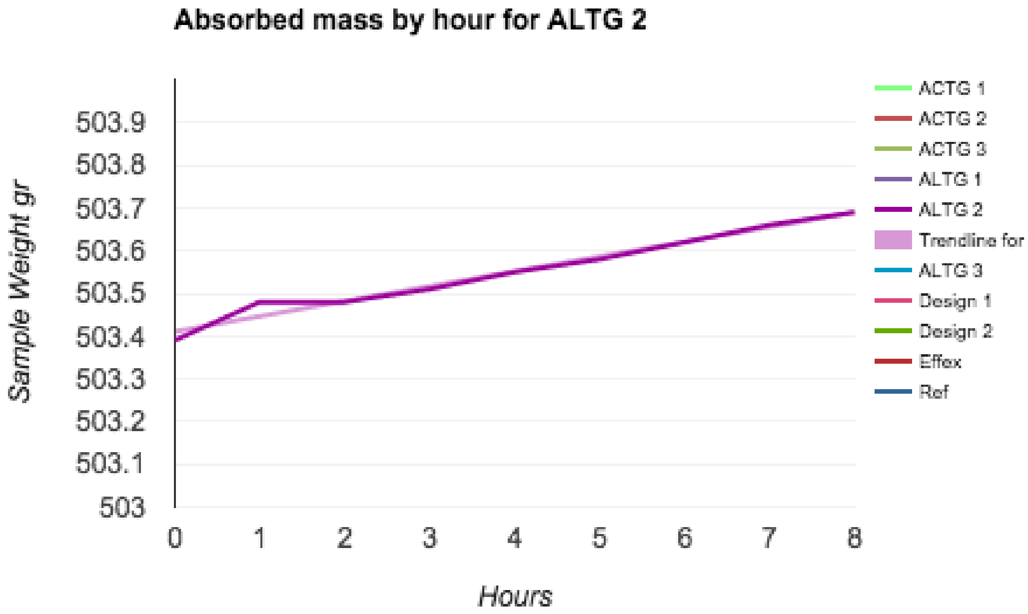
In the section, the graph of the relationship between buffering by time for each sample/panel in presented. Figures as follows show the graphs.

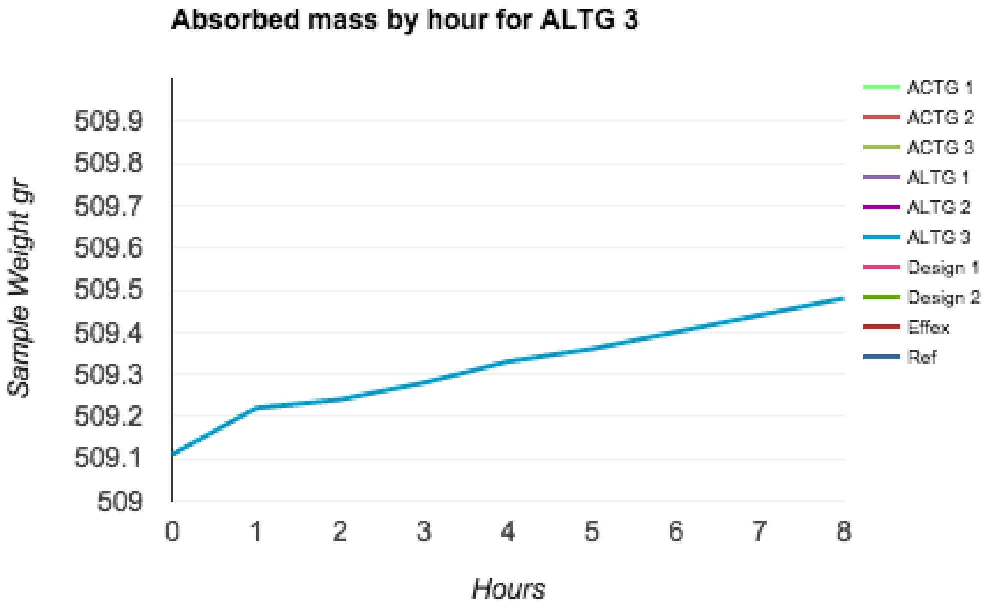


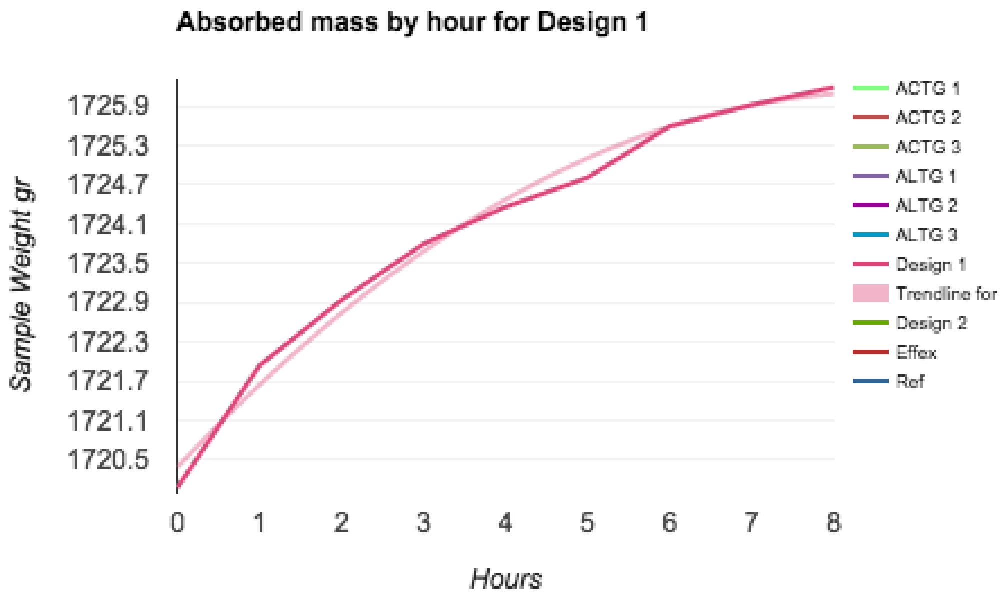


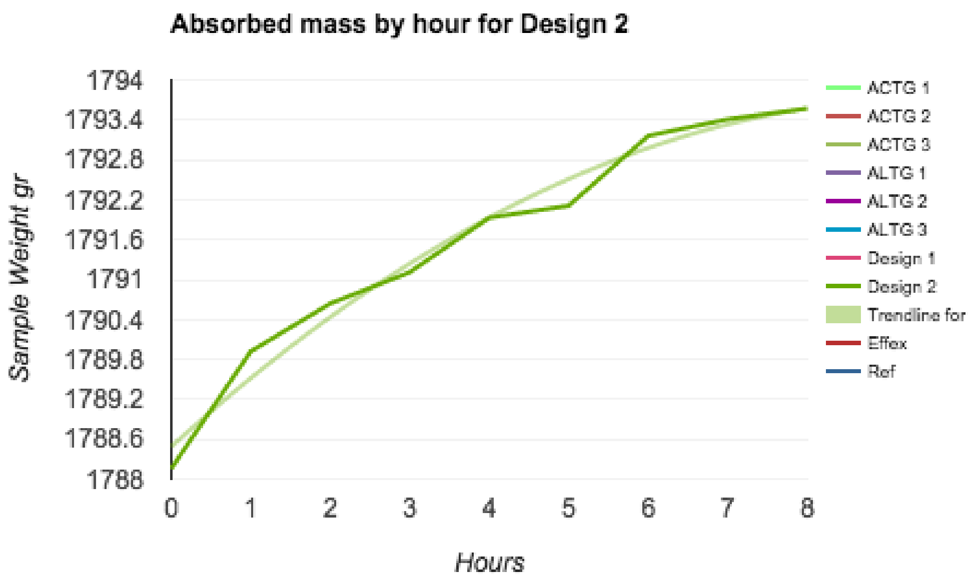

Absorbed mass by hour for ACTG 3
Sample Weight gr
604.08
603.96
603.84
603.72
603.6
603.48
603.36
603.24
603.12
603
0
1
2
3
4
5
6
7
8
Hours
ACTG 1
ACTG 2
ACTG 3
Trendline for
ALTG 1
ALTG 2
ALTG 3
Design 1
Design 2
Effex
Ref

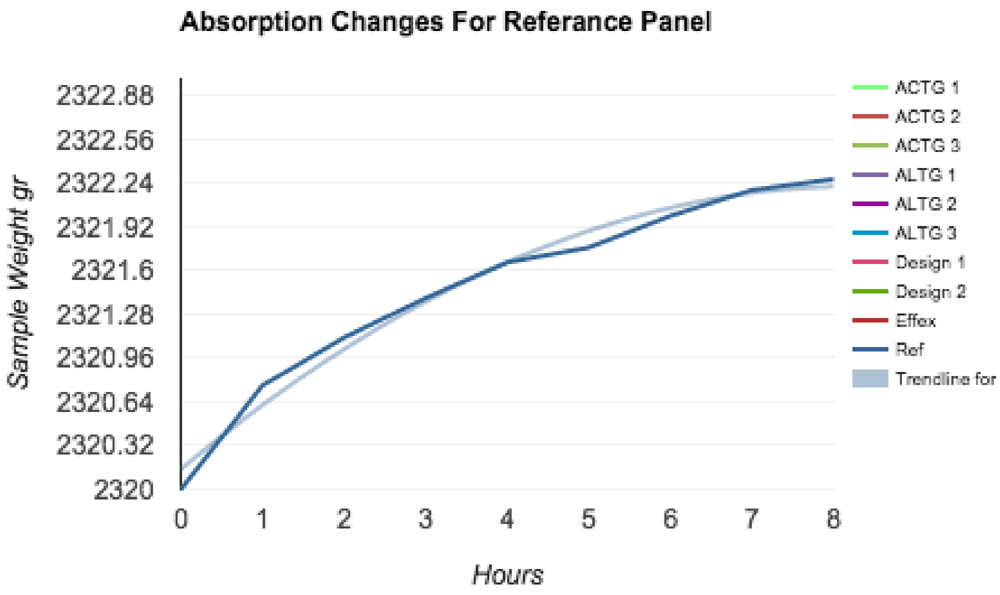

Absorbed mass by hour for ALTG 1
Sample Weight gr
600
599.9
599.8
599.7
599.6
599.5
599.4
599.3
599.2
599.1
599
0
1
2
3
4
5
6
7
8
Hours
ACTG 1
ACTG 2
ACTG 3
ALTG 1
Trendline for
ALTG 2
ALTG 3
Design 1
Design 2
Effex
Ref

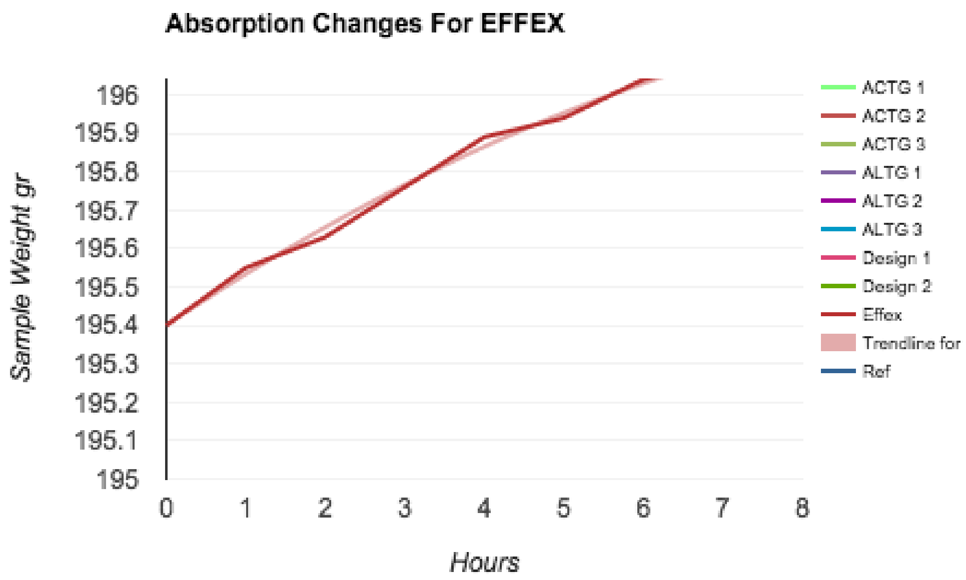

Absorbed mass by hour for ALTG 2
Sample Weight gr
503.9
503.8
503.7
503.6
503.5
503.4
503.3
503.2
503.1
503
0
1
2
3
4
5
6
7
8
Hours
ACTG 1
ACTG 2
ACTG 3
ALTG 1
ALTG 2
Trendline for
ALTG 3
Design 1
Design 2
Effex
Ref


Absorbed mass by hour for ALTG 3
Sample Weight gr
509.9
509.8
509.7
509.6
509.5
509.4
509.3
509.2
509.1
509
0
1
2
3
4
5
6
7
8
Hours
ACTG 1
ACTG 2
ACTG 3
ALTG 1
ALTG 2
ALTG 3
Design 1
Design 2
Effex
Ref


Absorbed mass by hour for Design 1
Sample Weight gr
1725.9
1725.3
1724.7
1724.1
1723.5
1722.9
1722.3
1721.7
1721.1
1720.5
0
1
2
3
4
5
6
7
8
Hours
ACTG 1
ACTG 2
ACTG 3
ALTG 1
ALTG 2
ALTG 3
Design 1
Trendline for
Design 2
Effex
Ref


Absorbed mass by hour for Design 2
Sample Weight gr
1794
1793.4
1792.8
1792.2
1791.6
1791
1790.4
1789.8
1789.2
1788.6
1788
0
1
2
3
4
5
6
7
8
Hours
ACTG 1
ACTG 2
ACTG 3
ALTG 1
ALTG 2
ALTG 3
Design 1
Design 2
Trendline for
Effex
Ref


Absorption Changes For Referance Panel
2322.88
2322.56
2322.24
2321.92
2321.6
2321.28
2320.96
2320.64
2320.32
2320
Sample Weight gr
0
1
2
3
4
5
6
7
8
Hours
ACTG 1
ACTG 2
ACTG 3
ALTG 1
ALTG 2
ALTG 3
Design 1
Design 2
Effex
Ref
Trendline for


Absorption Changes For EFFEX
196
195.9
195.8
195.7
195.6
195.5
195.4
195.3
195.2
195.1
195
Sample Weight gr
0
1
2
3
4
5
6
7
8
Hours
ACTG 1
ACTG 2
ACTG 3
ALTG 1
ALTG 2
ALTG 3
Design 1
Design 2
Effex
Trendline for
Ref

Appendix C. The Requirements List

The early stage of product development included making a requirement list then categorizing this list under functions (the outcome that these requirements serve) and finally evaluating different designs numerically to choose the best one. The requirements list resembles the philosophy of the required design and act as the base to build the final product. Even though, the requirements for such task might seem obvious, listing them into demands and wishes and connecting them with the design requirements and functional requirements make evaluating the different outcomes possible to meet the most important design criterions.

Table 24. Requirement list.

Requirements	**Demand / Wish**
1. Geometry:	
Width = 15-70 cm	D
Depth = 2-5 cm	D
Height = 120 - 200 cm	D
2. Material:	
Hygroscopic	D
Working temperature range 15 - 35 ℃	D
Has to handle RH range = 20 - 70 %	D
Biobased	D
3. Cost:	
Retail price 15/m² €	D
4. Forces:	
Has to handle the internal stresses	D
Rigid enough to handle external forces	W
5. Assembly:	
Easy to assemble	W
Doesn't require special tools	W
Modular	W
Shapeable	W
6. Safety:	
Contains only non-toxic materials	D
Stable installation	D
8. Production:	
Industrial scale production (Low labor)	W
Environmentally friendly production	W
Low usage of material	W
Low waste of material	W

Design that consider the shape of raw materials (Boards)	W
<u>9. Characteristics:</u>	
Visually attractive	D
low collection of dirt	W
Easy to clean	W
Different surface color and texture	W
<u>10. Performance</u>	
Has high surface area	D
<u>11. Installation</u>	
On ceiling or wall (both)	W

The geometry of the panel should have widths that facilitate maneuvering the panel with both hands. The thickness is decided so that the panel should not reserve much space from the room and also to reduce material so that the price and weight fall under an acceptable range. The height could vary as presented in the Table 23.

Since the panel is going to be used indoor, it should not have toxic components. The price should not exceed 15 Euro/m². The material is going to be used in areas with different temperatures, thus it has to handle temperatures ranging from 15 ℃ to 35 ℃. The material should withstand a RH range between 20% to 70%. It is uncommon for the RH to exceed these limits indoor. Expectation is that the material needs to handle these ranges for a long period.

The panel should withstand the internal forces, which are generated by the shrinkage and expansion, and also the external forces that resulted from someone leaning on the panel.

The panel should be easy to assemble, as saving the installation time mean more productivity and this make the panel more attractive. Also the installation should be strong enough to ensure safety. The panel, preferably, should not require any special tool and should be assembled by the tools that are readily available in the market. From production perspective, having a modular pieces, those are identical in their shape, is recommended as it save time in production. Also having a modular pieces that can be shaped in more than one way may be an attractive option for designer and customers.

The design of the panel should be made of shapes that are possible to manufacture using the current technology and that increase the surface area and it should not be labor intensive or time demanding. It is recommended that the outcome is approached with minimal material consumption and that the design consider the raw material shapes. The production facility should comply with the regulation of harmful emission and should meet or better exceed the environmental policy that is set by the government. Also the production should consider producing minimal waste by optimizing the usage of the material.

The panel should be visually attractive. It is expected that not all customers will like the exact same shape and texture of the panel, thus the panel shape or color is better to be customizable or made from pieces with different patterns. It is expected that the panel required cleaning from time to time thus the shape should consider this. The design, preferably, should consider accumulating minimal amount of dirt, for example making vertical grooves instead of horizontal. And preferably, the panel should have the style and the features that make it installable on a wall or on a ceiling.

Appendix D. Installation Concept

The dimensions of the panels can be easily adjusted to suite the standard sizes which are available in the markets. It is possible to make the same panels using longer boards. Figure 20 show the suggested installation, a section and front view. The plan is to perform the installation using cheap and readily available hardware that does not require special tools. The fixtures consist of two screws and two washer to keep the back face exposed to air and to maximize the buffering performance. The number could be increased to four screws in the corners or reduced to one screw in the center of the panel if the test proof the feasibility of such solutions. This simple installation option works for the other designs also.

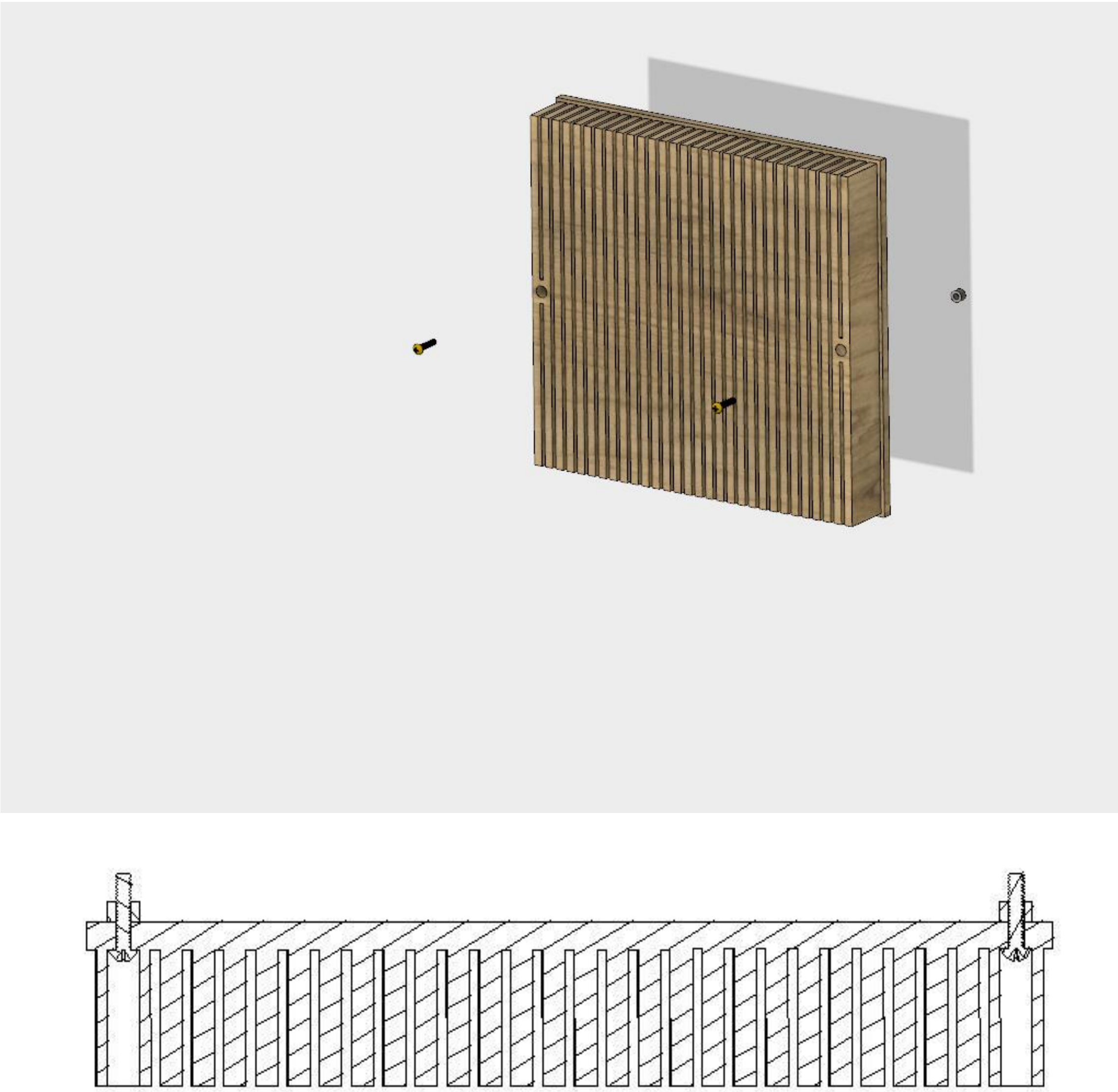


Figure 21. Attachment example of the panels.

The panel installation and attachment proposal is open for recommendations from manufacturers to meet the standards of the wooden wall panels.

Appendix E. HAMOPY Code Algorithm

The illustrative algorithm that was used in HAMOPY is presented hereunder.