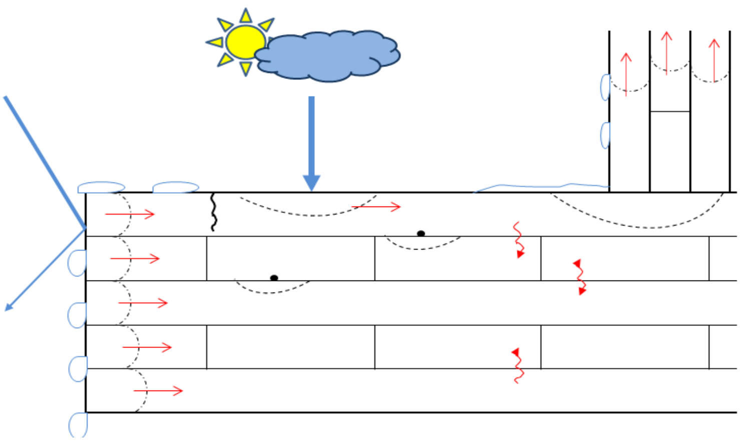
Moisture risks with CLT-panels subjected to outdoor climate during construction

-focus on mould and wetting processes

Fuktrisker på KL-trä som utsätts för yttre klimat under produktion

-fokus på mögel och uppfuktning



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Abstract

When going through relevant research, moisture safety guidelines and talking to builders, moisture experts and architects it is clear - and not surprising - that water and wood make no easy combination. The experiences from building with cross laminated timber (CLT) differ from building sites and there are good and bad examples building without weather protection.

In this study the moisture influence on CLT is analyzed. CLT is a type of massive wood with glued lamellas, increasing usage worldwide as structural elements in buildings. The bulk of the work is performed in the hygrothermal calculation tool WUFI(™). Focus is on the wetting process and the evaluation of mould risk from rain loads during production in Nordic climates. Subsequent drying after built into walls and floors is also evaluated.

A vast literature survey is performed in order to compare and select material data for modelling CLT. Following the simulation work, moisture content, mould growth and volumetric distortion are judged both with and without weather protection. Results are also compared to measurement data from field tests.

It is found that short building times are crucial, some weather protection is required all year around and early planning and constructing for moisture safety are crucial. The benefits of prefabrication and short building times using CLT should be exploited. If there is a risk of rainfall exceeding 10-20 mm, arrangements to divert rain loads should be undertaken. If the expected rain loads are above 40 mm or if the building time exceeds 2 weeks, a roof cover will be required. At air humidities averaging 80% and yearly rain exceeding 1200 mm, a complete building cover is recommended. A controlled environment may be expensive, but it speeds up production and shortens drying time.

key words: *moisture, CLT, massive wood, mould, WUFI, drying, construction, weather protection. best practice*.

Sammanfattning

När man går igenom relevant forskning, riktlinjer för fuktsäkerhet och pratar med byggare, fuktexperter och arkitekter är det tydligt - och inte överraskande - att vatten och trä inte är någon enkel kombination. Erfarenheterna från att bygga med korslimmat trä (KL-trä) skiljer sig från byggarbetsplatser och det finns bra och dåliga exempel från byggande utan väderskydd.

I denna studie analyseras fuktpåverkan på KL-trä. KL-trä är en typ av massivt trä med limmade lameller, som ökar i användningen över hela världen som strukturella element i byggnader. Huvuddelen av arbetet utförs i det hygrotermiska beräkningsverktyget WUFI (™). Fokus ligger på uppfuktning och utvärdering av mögelrisker från regnbelastning under produktion i nordiskt klimat. Efterföljande torkning efter inbyggnad i väggar och golv utvärderas också.

En omfattande litteraturstudie utförs för att jämföra och välja materialdata för modellering av KL-trä. Efter simuleringsarbetet bedöms fuktinnehåll, mögeltillväxt och fuktrörelser både med och utan väderskydd. Resultaten jämförs också med mätdata från fältförsök.

Det konstateras att korta byggtider är avgörande, någon form av väderskydd krävs året runt och tidig planering och konstruktion för fuktsäkerhet är avgörande. Fördelarna med prefabricering och korta byggtider med KL-trä bör utnyttjas. Om det finns risk för nederbörd över 10-20 mm bör åtgärder vidtas för att avleda regn. Om de förväntade regnbelastningarna är över 40 mm eller om byggtiden överstiger 2 veckor krävs ett regnskydd. Vid luftfuktigheter på i medeltal 80 % och årligt regn över 1200 mm rekommenderas ett väderskydd runt hela byggnaden. En kontrollerad miljö kan vara dyr, men det påskyndar produktionen och förkortar torkningstiden.

Nyckelord: *fukt, KL-trä, massivt trä, mögel, WUFI, torkning, konstruktion, väderskydd, best practice*.

Preface

This study has been carried out within the Bachelor degree of Building Technology at the Department of Building **Technology** at the Royal Institute of Technology (KTH), Stockholm, in cooperation with PolygonAK (Polygon Sverige AB).

We would like to express our gratitude to our supervisor Anders Joelsson at PolygonAK for the opportunity provided for this work to be possible. Also our advisor Anders Kumlin is greatly acknowledged for his support and guidance, never failing to impress. By his competence, pedagogics and professionalism he is truly excellent in his field.

During our work different obstacles have been cleared and insights given by several persons:
S. Olof for education on the software WUFI and modelling issues,
A. Kumlin for helping us see the “bigger picture”,
F. Herrmann for arranging a visit to a CLT building site,
among others within and outside the company.
Important contacts were also established after attending the information day at FuktCentrum (The Moisture Research Centre), held in Stockholm on April 24.

Following persons have been kind enough to give comments on various parts of the initial versions of the report and are greatly acknowledged: J. Winther, A. Joelsson, A. Kumlin, P. Brander and M. Eriksson. We would also like to thank several fellow students for proofreading. Last but not least we are thankful to the persons and organizations allowing us to reuse certain informative figures in our report.

We hope our work becomes useful and important to whoever is involved in issues regarding the topic of this study. In a larger perspective it would be even more satisfying to convince readers - not necessarily working with moisture related issues - of the importance of understanding and dealing with its mechanisms and consequences, as well as of the need for further work in this field.

Johan and Erik,
Stockholm, summer 2018

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Nomenclature

Definitions and abbreviations

CLT	Cross laminated timber.
dMC90	Moisture content difference with and without weather protection, evaluated as the 90%-percentile.
KFX	Hygrothermal simulation tool that calculates time invariant moisture transport. Swedish origin.
MC	Moisture content.
MI	Mould index according to some specific model.
RH	Relative humidity.
RHC or RHcrit	Critical relative humidity.
VBA	Visual Basic Programming (within MS Excel(™)).
WUFI	Advanced hygrothermal simulation tool, developed in Germany.
Digitizing	In this report this refers to the extraction of values from a published chart by manual measuring and scaling.
End grain	Is the grain of wood seen when it is cut across the growth rings.
Fiber saturation	Cell walls are saturated. Occurs around RH 100%.
Free saturation	The pores in the material are filled with liquid water.
Hygroscopic	Materials have the ability to accumulate and release moisture due to change in the surrounding humidity.
Hygrothermal	Combination of moisture and heat.
Isothermal	Constant temperature.
Lumen	Major wood cell voids in the tracheids.
Pits	Orthogonal pathways between the parallel lumens
Tracheid	Elongated hollow wood cells. Provides strength and serve in water transport.
Transient	Rapid change of state. RH and temp changes for example quickly on an
Vapour concentration	Absolute humidity. The mass of water vapour in a given volume of air.
Building cover	A ‘tent’ or scaffolding cover which completely covers a building during production.
Rain diversion	Activities that hinders rain from reaching a surface. The rain is ‘shut-off’.
Roof cover	A roof over the building during production. This is without wall.
Weather protection	General definition of temporarily protection against the outdoor climate of a building. This could be achieved by a roof or cover construction.

Symbols

°C	Degrees Celsius. Conversion to Fahrenheit is made by 1F= 9/5·C+32.
D, sometimes with subscript w, ws or ww	Diffusivity or capillary transport, driven by moisture concentration (m^2/s).
g	Moisture flux (kg/m^2,s)
G	Moisture transport (kg/m^2)
sd	Vapor diffusion resistance expressed in equal air resistance (m)
v	Vapor concentration (g/m^3)
w	Moisture content (kg/m^3)
x	Distance (m)
Z	Moisture resistance factor, x/d (s/m)
δ or d	Moisture transport coefficient, driven by vapor concentration (m^2/s)
λ	Heat conductivity (W/m, K)
μ	Vapor diffusion resistance factor (-)
ρ	Bulk density (kg/m^3)

Other symbols are defined in conjunction with equations presented in Section 4.3.

1. Introduction

1.1 Background

Cross laminated timber (or "CLT") is an engineered wood product that consists of several layers of timber. The layers are odd and often in 3, 5 or 7 layers orientated by varying the grain direction in each layer (Xu, 2013). The individual parts of wood are planed to specific dimensions and then dovetailed together in the longitudinal direction if needed. Internal layers of CLT may be of thinner material and of other quality than exterior parts (Stora Enso, 2017).
The laminated wood make up larger elements (or "panels") that may be used directly as load bearing components in walls, roofs, balconies, supporting floors etc.

Since the varying grain direction together with the bonding adhesive between each layer counteract internal movement, the product becomes fairly stable against moisture induced movements. Moreover, CLT may buffer moisture and act as a moisture variable vapour barrier in a wall or floor assembly (Stora Enso, 2017).

Although the moisture behaviour of CLT can not be fully described in the same way as for pure wood, the building physics of wood clearly applies. Several studies have focused on the modelling of CLT in terms of hygrothermal behaviour and material properties, see for example Alsayegh & Mukhopadhyaya (2013), Alsayegh (2012) and Lepage (2012). Additional studies also relies on field measurements of hygrothermal data, collected from CLT building samples and by means of built-in sensors in buildings, see for example Mundt Petersen (2013a); McClung & Ge (2013); Srisgantharajah & Ullah (2015); Serrano, Enquist & Vessby (2014); and Fedorik & Haapala (2017). The consequences of moisture affected CLT structures have been evaluated with focus on moisture exposure, risk of mold and deformations respectively by Alsayegh; Alsayegh & Mukhopadhyaya (2012; 2013); Lepage (2012); Sortland, (2016); Thiis, Burud, Kraniotis & Gobakken (2015); Katavic, Nore & Aurlien (2014), among others.

A simple search for "CLT wood" on Google (google.com, 180403) gives about 6,800 hits, so there are seemingly a lot of general information around this topic.
In a recent study by Espinoza, Trujillo, Mallo & Buehlmann (2016) it was concluded that the second most relevant research topic on CLT is moisture behavior (besides structural issues). Although Espinozas study is based on a large - yet limited - amount of interviews and do not claim to be exhaustive, it clearly indicates a need for further research in this field.

Most studies about CLT were all done outside Scandinavia and thus focused on CLT subjected to the climate of the countries in which the studies were performed (Alsayegh & Mukhopadhyaya, 2013; Lepage, 2012). Within the Nordic and Baltic countries the interest in CLT is growing, as found by several references (Vatanen, Sirkka, Pirttinen & Ahoranta, 2016; Kukk & Kers, 2018; Section 6.1). However, no study have focused on the amount of wetting a CLT panel can withstand during production and use in the Swedish climate. Also is a need for a comprehensible compilation of CLT moisture related data. To compile, evaluate and finally create a table of the various existing material data on CLT would provide a valuable asset to engineers.

1.2 Sustainable buildings

The current issue is strongly linked to sustainable buildings since the risk of mould and built-in moisture affects the indoor environment (Norbäck, 2015) as well as the accelerated demand to replace parts of the building prior to its designed lifespan. Moisture may also affect the heat transfer and losses and thus energy usage. Moisture management is therefore regarded as crucial for sustainability both health-wise and economically (Kumlin & Norberg, 2016).

Moreover the use of wood as building material reduces the climatic impact compared to the use of concrete and steel among others (Tycho, 2018; Espinoza et.al, 2016). Especially the development of CLT as a material is claimed to be driven by the green building movement (Xu, 2013).

1.3 Aim

The current study focuses on evaluating the risk of mold on exterior surfaces on CLT panels located in Nordic climate, especially when subjected to outdoor environment during construction.

The primary aim is to evaluate the amount of wetting, primarily caused by rain, which an unprotected CLT panel subjected to a Nordic climate is able to withstand and dry out without an accelerated risk of mould growth. In a larger perspective this also relates to the need and design of weather protection during the construction phase.

1.4 Objectives

This aim is achieved and motivated by the following research objectives:

1. Investigate and present a general overview of 'the state of the art' for CLT moisture behaviour and its modelling. This requires a literature survey and forms an important basis for model development and moisture management.
2. Compare and evaluate hygrothermal data relevant for describing CLT from various references. In doing so, influences by varying grain direction, adhesives etc. must be considered.
3. Evaluate the moisture influence and risk of mould on CLT panels by means of computer simulation using a simplified structural model. To some extent the results are checked against measurements performed over time.
4. Describe and formulate some moisture management principles and guidance, based on findings from the literature survey. Results should be given as a "check list".

The first objective forms the basis of the study and the second objective stipulates input data for simulations to be performed in WUFI (Section 2). The third objective deals with combining simulation results and measurements in order to further establish a relationship between moisture exposure, damage and the drying process. The results should be of practical use rather than theoretically formulated.

Lastly, the fourth objective is somewhat minor in the current study - although by all means probably the most important issue for further work. Several references were found that is believed to contribute to existing in-house experience on moisture management during design and construction of CLT buildings.

1.5 Scope

Nordic climate

This study only accounts for CLT material intended to be used in the Scandinavian climate with the emphasis on Sweden.

Sweden is a long stretching country covering about 13 longitudes which separates the climate in the north from the south greatly. The study accounts for this varying climate factor by examining CLT placed in four Scandinavian cities located at geographically significant positions (Figure 1.5-1).
Sweden is a Nordic country synonymous with cold and wet climate. Because of the warm Gulf Stream, which goes by Norway, the climate in Sweden can be much milder than one might expect.
The four seasons are very pronounced. Spring runs from March/April to May, summer from June to August, fall from September to October/November and winter from November/December to February/March.

The Norwegian city of Bergen is included due to its relatively extreme rain amounts (Figure 1.5-1).
The climate in Stockholm is used in the initial comparative simulations but is not included in the main study.

Figure 1.5-1 Part of Scandinavia and selected main cities. (Google Earth)

Simulation and weather data

- Simulations consider 1-dimensional heat and moisture transfer. The principle of relative comparisons is emphasized.
- The calculations do not include potential water intrusion in end grain and joints, but the qualitative discussions do.
- Weather data is collected from the Swedish Meteorology Institute (SMHI) and the simulation software WUFI (See further Section 5.4.6).

1.6 Outline of the current study

Chapter 2 describes the method used to achieve the aims of the current study. In Chapter 3, the current state is given. Chapter 4 provides the theoretical framework and the basics of moisture physics are described. The implementation is described in Chapter 5. Results of the literature survey are found in Chapter 6, where the findings are summarized under different sections.

Within the limited time frame and scope of the thesis work, there are by nature tasks and findings left unanswered, simplified or excluded. An analysis of the results is given in Chapter 7 and future work is prioritized in Chapter 9, following conclusions in Chapter 8.

2 Method

The work is mainly based on a comparative simulation study. Firstly a literature survey is performed in order to establish material and moisture properties, modelling principles and best practice for CLT. Based on the findings from literature (articles, hand books, papers and other) material data and properties of CLT are compared, evaluated and selected for further use in simulations. Finally, moisture safety criteria are derived and a limited amount of measurement data is analyzed.

A literature survey could easily grow extensively and within the current study and time frame it is not possible to do a complete scanning of all publications related to moisture and CLT. Instead the study relies on a selection of some 70 of the most relevant references found by searching for articles, publications and handbooks. In doing so, several additional references are also found. Especially cross-references that are repeating indicate the most cited references to follow up. The literature survey is mainly performed within different databases as well as on academic publications sites. Some material is found in handbooks and similar, but the most relevant research is reported by articles in various scientific journals.

The calculations are primarily done with the commonly used hygrothermal computer simulation software WUFI (Fraunhofer IBP, 2018), but also with other computer tools (Chapter 4). Based on these results for a simplified CLT-panel, some comparisons with measurements are also done. The measurements originates from real samples of CLT put in an outdoor environment with instrumentation (F. Herrmann, personal communication, April 4, 2018). There are also limited measurement results available from an ongoing building construction (see section 5.7) that are evaluated.

Once the simulation model is believed to produce reasonable results, further analysis are done with varying climate, constructions with CLT as well as initial moisture conditions in order to judge the risk of mould growth, increased moisture content and other quantities. As with all simulation work there are always limitations in the model framework, simplifications made and the risk of misinterpreting the results. Measurements have by nature a lot of built-in uncertainties and the post processing of data heavily influence how it may be used. By using established software and by limiting the complexity of the model, possible errors are more likely avoided. Several sources of data are also used in order to compare results and input data. By cautiously choosing input data and boundary conditions on the basis of relevant material and climate behaviour (influenced by several other studies), comparisons of basic output results to other known results and new measurements will make our conclusions more reliable.

Still there are - and must be - allowance for ideas and proposals on for example evaluation quantities, their limit values and measuring principles, building methods etc. to be brought forward as novel opinions by the authors. Such ideas are indeed presented in Chapter 7 based on the knowledge and results from the study and forms a natural base for further research.

Even if no organized interviews have been used as a stand-alone research method, a lot of valuable insight in moisture mechanics, measuring techniques and building solutions have been gained by talking to experts - within and outside of the company - and from visiting a building site. This information is referenced and added to the literature survey.

3 The current state

Cross Laminated Timber seems to gain attention in Sweden and the rest of the world. Although the building industry is curious about CLT and it's more environmentally friendly aspects, it has not yet gained substantial usage. Today the Swedish market is dominated by concrete. 88 % of all new buildings in 2014 where built in concrete. All type of wood buildings took a 9 % market share and steel took less than a 3 % share (Farads, 2016, Jan).

This study is conducted in collaboration with the Swedish water/moisture damage restoration company PolygonAK, part of global Polygon group which leads the European market in property damage restoration. It has 3300 employees in 13 countries. PolygonAK is an engineering division where moisture and environmental experts can be hired as consultants by construction companies in all phases of the building process. During the course of this study, the physical working place has been in Stockholm at the PolygonAK office.

Following an initial literature search and discussions with the supervisor and advisor, it was concluded that the knowledge on CLT and moisture management is limited in Sweden. It is a need for collecting knowledge and best practice from within and outside Europe in order to formulate a common base for further research and use in daily work. Also on the practical side different entrepreneurs and manufacturers have different experience and valuable insight in building with CLT; but there are no common understanding on how, when and possibly why it could be a need for protecting CLT from the weather during production.

Without protection to the elements, the risks of mould, distortion and weakening could be accelerated. Thus evaluating CLT material data, its modelling and moisture behaviour in Swedish climate and possibly establish general principles for moisture management during construction, constitutes the basis of the aim for this thesis. The focus will mainly be on the wetting and mould development. Refer to Chapter 4 for the theoretical framework.

4 Theoretical framework

4.1 General

This chapter describes the theoretical background and calculation tools which are used within the current study. This includes a selection of the gathered theoretical knowledge about the physics, relations and equations which are used to describe and predict the behaviour of moisture.

4.2 Anatomy and structure of wood

Wood is a highly anisotropic material. The load resistance properties as well as the moisture behaviour and effects varies with the direction of the loads and moisture uptake direction (see Figure 4.2-1). The load resistance varies with the angle from the load to the longitudinal direction. Longitudinally wood can resist higher stresses from tension-, compression- and shear forces (Svenskt Trä, 2018).

Woods resistance to moisture also varies but in opposite from its stress resistance. Moisture resistance in the tangential direction is more effective than in the radial direction. Longitudinal moisture resistance is the least effective due to the size of the lumens (tracheid pores) which reduces the friction losses of the transported liquid water (Lepage, 2012).

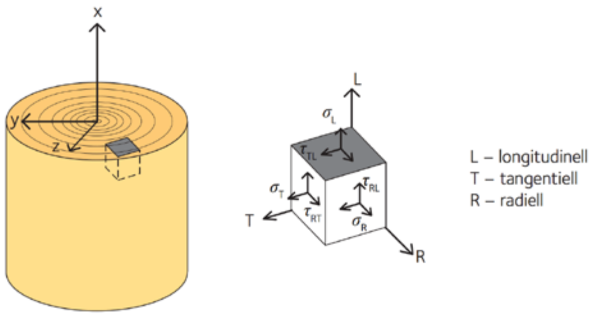

Figure 4.2-1. Illustration showing the anisotropic directions longitudinal, tangential and radial. This orthogonal symmetry puts wood in the orthotropic sub-category of anisotropic materials. Potential stresses is also shown. (Träguiden, 2018 with permission).

The reason for the anisotropy of wood lays its cell structure. CLT panels are mostly constructed with softwood. The majority of softwoods consists of so called tracheid. Tracheids are long, hollow cells that makes up about 90-95% of the material, see Figure 4.2-2. It gives the tree strength and serve as water pathways (Time, 1998). Small openings called pits connects the tracheids forming a network of pathways.

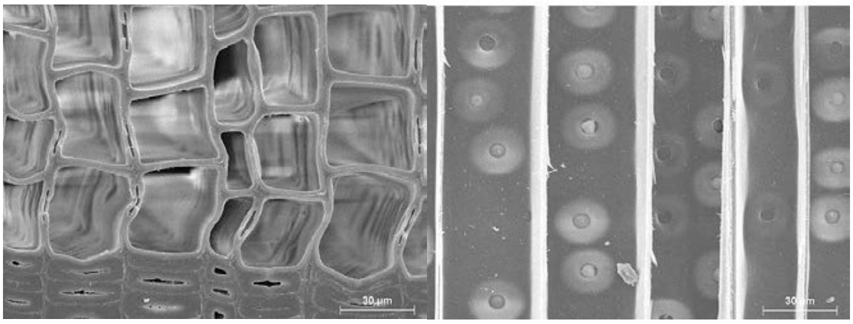

Figure 4.2-2 *Norway spruce through a scanning electron microscope The rectangular shaped tracheids and the adjacent pits can be seen creating pathways through the lumen walls. Bottom picture shows a radial view of the same system. The front side of the pits can now be seen as circular pathways. (Wikipedia -Pit botany- by Dr. Michael Rosenthal, Technische Universität Dresden). Allowed usage.*

4.3 Moisture physics

4.3.1 Moisture in air

Relative humidity (RH) is the relationship between vapour concentration in a cubic meter of air and the value of the saturated vapour concentration in a cubic meter of air at a given temperature. RH of 100% equals condensation (Arfvidsson et.al., 2017).

$$\mathrm{RH} = \frac{\mathrm{v}}{\mathrm{v_s(T)}} \qquad [4{:}1]$$

RH relative humidity [-]
v vapour concentration [g/m^3]
vs saturated vapour concentration [g/m^3]

Saturated vapour concentration of air is strictly temperature dependent.
This equation gives a value below 30 degrees Celsius.

$$\mathrm{v_s(T)} = \mathrm{e}^{\mathrm{a} - \frac{\mathrm{b}}{\mathrm{T}+273.16}} \qquad [4{:}2]$$

T temperature ℃

a,*b* are coefficients according to Table 4.3-1.

Table 4.3-1 *Parameters for calculating the saturated vapour concentration (vs) with equation [4:2]. Accurate below 30 degrees celsius.*

	< 0˚ C	*≥ 0˚ C*
a	23.077	20.11
b	5872	5061

4.3.2 Moisture in materials

Moisture content (MC) - Moisture binds in a materials inner pores. The moisture binds in both vapour- and in liquid form, how much depends on the materials porosity.
MC is determined by comparing the weight of a wet sample to the same sample in a dry state (Arfvidsson et.al., 2017).

$$u = \frac{m_w - m_0}{m_0} \qquad [4:3]$$

u moisture content [-]
m_w mass of wet sample [kg]
m_0 mass of dry sample [kg]

Sorption isotherm functions

The relationship between a specific materials moisture and the relative humidity of the surrounding air can be described with a sorption isotherm curve (see Figure 4.3-1).

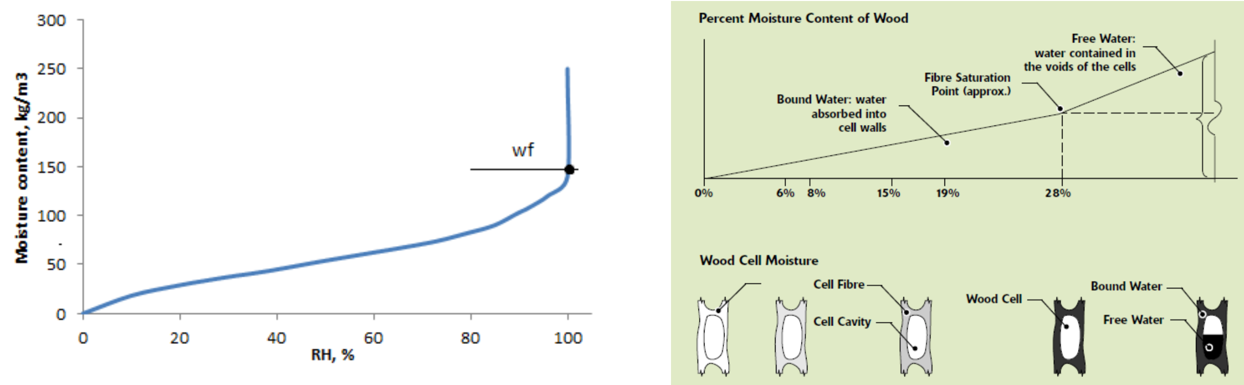

Figure 4.3-1 To the left a principal sorption curve and to the right the relation between moisture content and wood cell structure (Canada Wood, with permission).

When a wooden material is exposed to air it will eventually reach equilibrium with the relative humidity of the surrounding air. This is done by the way of moisture diffusion from the outside air into the material pores. Water molecules in the pore air can thus become bound to the pore walls by adsorption. The bound water molecules gather up and increases in mass as the humidity rises. Eventually a multimolecular film forms on the cell walls. This partly explains the roughly proportional relationship between equilibrium moisture content in relation to the surrounding relative humidity in the hygroscopic region (Fraunhofer IBP, 2018).

When RH reaches close to 100 % and around a 30 % MC, some effects of the adsorbed water film reduces the saturation vapour concentration at such a degree in which it causes condensation. This is called the fibre saturation point (wf). After this point is reached the condensation in the pores leaves more room and allows for more moisture to flow in. Now the pore structure contains unbound, free water as well as adsorbed moisture. This phenomenon rapidly changes the slope of the sorption curve (Fraunhofer IBP, 2018). Wood is a capillary-active material. A capillary-active material which has the potential to take up liquid water through its capillaries will, if sufficiently supplied, continue to do so until it reaches the free saturation point. Due to air pockets in the pore structure, this does not mean that all of the pores are filled with water. Reaching the maximum water content, i.e. filling all the pores, demands a high pressure difference which do not usually happen naturally, although material specific values has been shown experimentally (Fraunhofer IBP, 2018).

4.3.2 Moisture transport through porous material

General

The moisture transport through a porous material describes the flow of moisture through one or more layers of material. This process is complex and seems to not be fully understood. The information in this subchapter is generally accepted, although errors and simplifications may be present due to the complexity of the subject.

Moisture flow can occur simultaneously in gaseous-, adsorbed- and in a liquid state.
The total moisture flow is due to five different mechanisms (see Table 4.3-2), although the contribution of diffusion, surface diffusion and capillary transport seems to be dominating. (Lepage 2012). Different mechanisms are active during different states of relative humidity. The progression of raising the relative humidity is illustrated in Figure 4.3-2.

Table 4.3-2 Known moisture transport mechanisms in porous materials . Recreated from Straube & Burnett (2005).

Mechanism	*Water Phase*	*Driving Potential*
Vapour Diffusion	Gaseous	Water Vapour Concentration
Vapour Effusion	Gaseous	Water Vapour Concentration
Surface Diffusion	Adsorbed	Relative Humidity
Capillary Transport	Liquid	Capillary Suction Pressure
Osmosis	Liquid	Solute Concentration

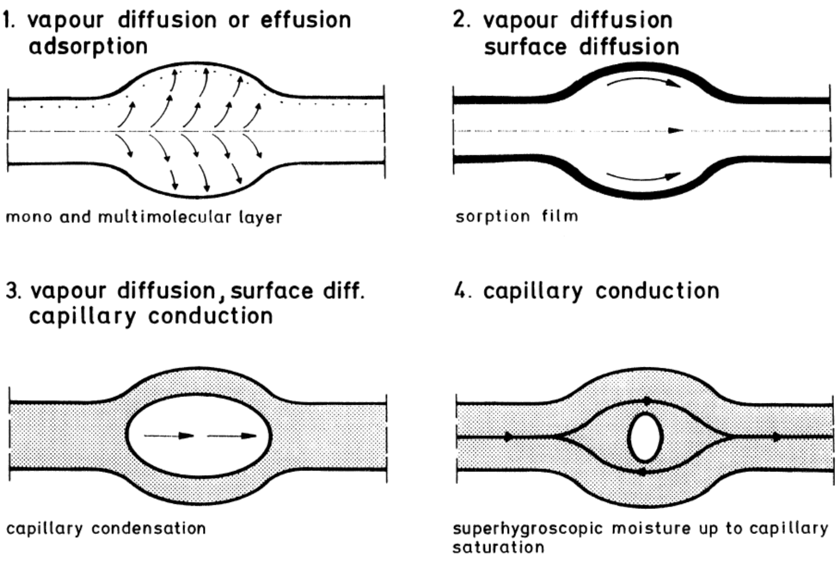

Figure 4.3-2 Transport mechanisms in a pore varying from low to high RH. (Krus, 1996 with permission).

Vapour diffusion

According to the most preferred Swedish description the vapour diffusion part of the moisture transport is described with the Absolute humidity gradient (dv) as the driving potential (Arfvidsson, et.al., 2017).

$$g = -\delta_v \cdot \frac{dv}{dx} \qquad [4{:}4]$$

g moisture flux [kg/m^{2}s]
δ_v vapour diffusion coefficient [m^2/s]
v vapour concentration [kg/m^3]
x distance [m]

However, internationally the transport is often described with the vapour pressure gradient as the potential (Arfvidsson et.al., 2017).

$$g = -\delta_p \cdot \frac{dp}{dx} \qquad [4{:}5]$$

g moisture flux [kg/m^{2}s]
δ_p vapour diffusion coefficient (driven by vapour pressure) [kg/(m·s·Pa)]
p pressure [Pa]
x distance [m]

Conversion between the two methods can be achieved with the ideal gas law (Arfvidsson et.al., 2017).

$$\delta_v = \frac{R}{M_w} \cdot T \cdot \delta_p \qquad [4{:}6]$$

with
R The ideal gas constant $= 8.314\ [J \cdot K^{-1} \cdot mol^{-1}]$
M_w The molar mass of water $= 18.015 \cdot 10^{-3}\ [kg \cdot mol^{-1}]$
T temperature [K]

Surface diffusion

When the relative humidity reaches above ca. 60 % a film of adsorbed moisture on the pore walls starts spreading. The moisture film travels from parts with thicker film to parts with thinner films. The potential of this mechanism is relative humidity. This is explained by how the thickness of the film is increases with relative humidity (Fraunhofer IBP, 2018).

Capillary transport

The most effective mechanism for moisture transport in porous materials is the capillary liquid transport. The real potential of capillary transport is the capillary suction pressure gradient. In the context of building physics it is sufficient to treat it as a diffusion phenomenon (Fraunhofer IBP, 2018). The liquid transport coefficient for wood is greatly dependent of the moisture content.

$$g_w = -D_w(w) \cdot dw/dx \qquad [4{:}7]$$

g_w liquid transport flux density [kg/m^{2}s]
w moisture content [kg/m^3]
D_w liquid transport coefficient [m^2/s]

To more accurately model the liquid transport the coefficient can be separated, describing different parts of the wetting process.

Liquid transport coefficient for suction (Dws) - Describes the uptake of water when a surface is fully imbibed in water.

Liquid transport coefficient for redistribution (Dww) - Describes the liquid water behaviour when the wetting is finished and the moisture spreads throughout the material.
This is a slower process than Dws making the values of Dww considerably lower than Dws.

Because of the limited amount of measured material property data, sometimes an estimation of Dws has to be made. This exponential function was derived for estimations of Dws of mineral materials.

$$D_{ws}(w) = 3.8 \cdot \left(\frac{A}{w_f}\right)^2 \cdot 1000^{\left(\frac{w}{w_f}-1\right)} \qquad [4{:}8]$$

D_{ws}	liquid transport coefficient for suction [m^2/s]
A	water absorption coefficient [$kg/m^2 \cdot \sqrt{s}$]
w	moisture content [kg/m^3]
w_f	free water saturation [kg/m^3]

A-value - The absorption coefficient can be determined experimentally with a simple test by placing the material specimen in water and measuring the weight gain. The A-value can be calculated by plotting the mass gained against the square root of time and then determining the slope of the curve (Arfvidsson et.al., 2017).

$$G = A \cdot \sqrt{t} \qquad [4{:}9]$$

G	mass of water absorbed per unit area [kg/m^2]
A	absorption coefficient [$kg/m^2 \cdot \sqrt{s}$]
t	time [s]

Total moisture transport

When modelling the total moisture transport it can be useful to separate the transport in parts.
In a moisture condition below the fiber saturation point the moisture flow inside the pore structure only active transport mechanism consists of vapour diffusion and adsorbed vapour diffusion. (L.O. Nilsson, personal communication, April 16, 2018). Although in most cases the adsorbed moisture comprises the larger part of the total weight of transported water, it can be important to separate the mechanisms in a model. The reason for this lies in the difference in driving potentials of the transport mechanisms. The driving potential of vapour diffusion is the water vapour concentration and the potential of surface diffusion is RH or moisture content [kg/m^2].
Under isothermal conditions these to potentials go in the same direction (see Figure 4.3-3 left).

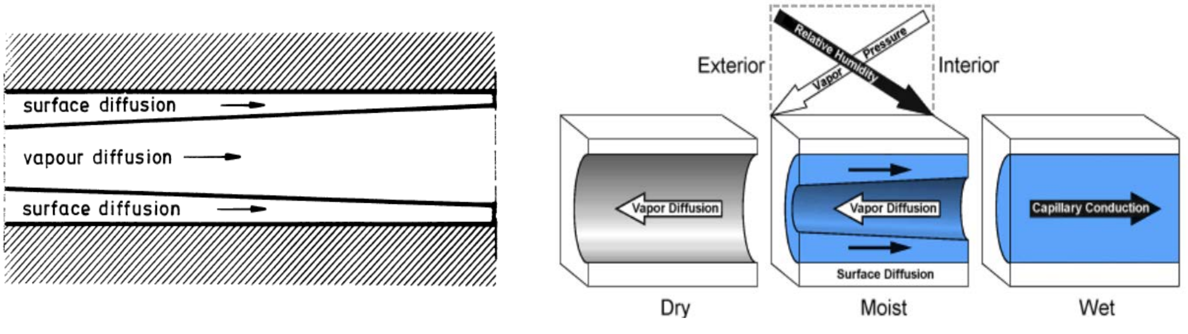

Figure 4.3-3 *Left- Isothermal conditions causes both mechanism to travel in the same directions. Right- Temperature gradient causes the flow to go in opposite directions. (Krus 1996, with permission.)*

However, in a material exposed to a temperature gradient, the mechanisms can force the moisture to travel in different directions, partially canceling each other out (see Figure 4.3-3 right).
To account for this phenomena one way is to separate the vapour diffusion in one function and regard surface diffusion as a type of liquid transport, i.e. including it in the capillary function.

This can be written mathematically as:

$$g = \delta_v \cdot \frac{dv}{dx} + D_w \cdot \frac{dw}{dx} \qquad [4:10]$$

g moisture flow [kg/m²s]
δ_v vapour diffusivity [m²/s]
v vapour concentration [kg/m³]
D_w liquid diffusivity [m²/s]
w moisture content [kg/m³]
x distance [m]

Moisture resistance
Another useful quantity is derived by flipping the concept of moisture diffusivity and instead describing the moisture resistance of a material.

$$Z = \frac{x}{\delta} \qquad [4:11]$$

Z moisture resistance [s/m]
x distance [m]
δ moisture transport coefficient [m²/s]

4.3.4 Moisture content change in relation to time

Contrary to stationary moisture flow, where the flow is constant through the whole depth of the material, non-stationary moisture transport is when the flow of moisture is varied in different depths of the material.

With knowledge of the distribution of RH and temperature in different depths of a material or an assembly of materials you can determine the moisture concentration, the saturated vapour concentration and the vapour concentration in different points. The vapour concentration distribution can then be used to calculate the moisture flow (*g*).

Finally the moisture content over time is calculated with the following equation.

$$\Delta w = \frac{g_1 - g_2}{\Delta x} \cdot \Delta t \qquad [4:12]$$

w moisture content (kg/m³)
g moisture flow [kg/m²,s]
Δx examined depth in which moisture travels
Δt change in time

4.4 Calculation softwares

WUFI PRO 5.3
WUFI, **W**ärme- **U**nd **F**euchtetransport **I**nstationär (Transient Heat and Moisture Transport) is a German computer simulation program developed to model the hygrothermal transport phenomena and its effects on building materials and assemblies (Fraunhofer IBP, 2018).

When calculation **heat transport** WUFI accounts for:
thermal conduction, enthalpy flows through moisture movement with phase change, shortwave solar radiation and longwave night time radiation.

When calculation **moisture transport** WUFI accounts for:
vapour diffusion, solution diffusion, capillary conduction and surface diffusion. After a simulation is done the possible output results are heat flux densities, temperature and relative humidities at user determined monitoring positions and the mean moisture content of each layer or the total MC of the entire assembly. Also Profiles for the temperature, RH and MC at a specific time (Fraunhofer IBP, 2018).

Rain load equation
WUFI accounts for the wind velocity when calculation rain loads in the following way:

$$\text{Driving rain load} = \text{rain} \cdot (R1 + R2 \cdot \text{wind velocity}) \qquad [4{:}13]$$

rain [mm/m^{2}h]
wind velocity [m/s]
R1 & R2 [s/m] depends on the inclination

KFX
KFX is an Excel based in-house calculation tool developed by the Chalmers university of technology. It is based on the glasser-model. Modifications have been made to allow for transient hygrothermal calculations, but without consideration of rain and liquid transport.

4.5 Mould modelling

4.5.1 General

To predict and compare the growth risk and extent of mould on building materials various mathematical models have been developed. Modelling such a complex biological process is hard and none of the models claims that they can give a detailed realistic simulation of the growth process. At this current state the models can only be used for the assessment of possible growth risks on materials and assemblies (WUFI-BIO, 2018).

4.5.2 VTT model

Developed in Finland in cooperation between Technical research center (VTT) and the Tampere University of technology (Moisture Handbook; Arfvidsson, Harderup, Samuelsson, 2017). The VTT model is an empirical model based on laboratory experiments. The results of the experiments was then modeled with differential equations. The first version, developed in 1990s, considered only northern wood species. The newer model also consider other materials such as gypsum boards, cement screed on concrete, porous wood fibreboard and spruce plywood. (Gradeci, Labonnote, Time & Köhler, 2018).

This model separates itself in the way that it accounts for unfavourable growth conditions and thereby delays the growth (Krus, 2010). This delay goes into effect after a dry or cold period of 6 hours with a limit of under 80% RH or when the temperature drops to 0 celsius or lower (Moisture Handbook; Arfvidsson, et.al., 2017).

The mould growth is expressed by the mould index (MGI) varying from 0 to 6 where mould index 1 indicates germination (Gradeci et.al., 2018), 2 represents several local mould growth colonies on the surface (visible with microscope), 3 represents both microscopic and visual findings of mould on the surface, 4-5 represents an escalation of the previous and finally index 6 represents a 100% coverage of mould growth on a surface (WUFI-VTT, 2018).

4.5.3 Bio Hygrothermal model (WUFI bio)

Developed by the Fraunhofer institute of building physics in Holzkirchen. Unlike the VTT model WUFI bio is a fully theoretical model (Krus, Seidler, Sedlbauer, 2010). The model can be downloaded and implemented as an add-on for the computer simulation program WUFI.

The basis of the model is the fact that mould spores have an osmotic potential that allows it to absorb water from the environment through the spore walls by the way of diffusion. When a certain critical water content is reached, varying with temperature and RH, biological activity begins and the spore germinates (WUFI-BIO, 2018).

Input needed is climate conditions (temperature and relative humidity) and material data of the spore in which the user desires to model. Which includes its moisture storage function and diffusion resistance. The output consists of plots of information on critical water content and computed water content in the spore over time. The second plot shows millimeter spore growth over time. As mentioned before, the process of mould growth is complicated and therefore simplifications are made. These simplifications cause certain limitations of the model. For example some influence factors such as pH value, salt content, light, oxygen content, surface quality and biogenic factors are not considered (WUFI-BIO, 2018).

5 Implementation

5.1 Chapter outline

This Chapter describes the working process and progress throughout the study. For convenience this section gives an orientation of the study. The implementation phase is subdivided into a number of chronological steps, referenced in table 5.1-1.

Table 5.1-1 Implementation steps. The implementation is divided into chronological steps. Refer to specified Sections for further details.

Phase	*Outcome*	*Section*
Literature survey	Material data (wood and CLT) Methods and models for calculation Mould physics and modeling Best Practice moisture safety	5.2
Compare material data	Primary sources of data, massive or layered wood. Conversions of quantities to comparable units etc.	5.3
Initial simulations	Revised material data and model forms a Base case	5.4 & 5.5
Main study	Moisture influence on floor and wall elements (bulk of the study)	5.6
Analysis of measurement data	Some basic comparisons and conclusions on available measurements of moisture quantities.	5.7

5.2 Literature survey

Information on CLT is searched on Internet and in special databases relevant for material and building science. Several articles and conference papers were also found on university publication portals and branch organisation websites. Additional information from building related magazines, news publications and personal communication with moisture experts also belongs to the literature survey.

All relevant references were summarized in a separate Excel sheet with a scoring system which made it easy to sort relevant information at hand throughout the work progress. Besides material data on CLT, also modelling and simulation principles, mould theory and best practice in moisture safety were searched for. CLT have acronyms such as ‘massive wood’, ‘X-lam’ and ‘BSP’ among others, which have to be alternated in the search criteria. The most relevant articles, proceedings and theses were scrutinized and references within the references were checked. In doing so the quality of the limitation of the literature survey was further enhanced.

The literature survey constitutes a major part of the study. Especially material data was difficult both to find and to assess (refer to the next section). In the process of gathering information about CLT it became obvious to also study wood and moisture transport in wood. The transport mechanisms are driven by both vapour and capillary moisture, which requires a theoretical understanding of the the material itself as well as the moisture physics.

The results of the literature survey are broken down on sub topics and presented in Section 6.1.

5.3 Material data

The bulk of the literature survey deals with material data on CLT and wood. Although various data is easily found, a collective and comprehensive overview and comparison was not found.
In order to formulate a base case for further evaluation, the selection of relevant quantities and their values and possible range of variance is important.

An apparent choice of material quantities is derived by the required parameters for hygrothermal calculation (EN 15026). Thus the primary interest is basic material data such as density, heat capacity, thermal resistance, etc.; and moisture related data such as diffusion resistance, water uptake and sorption isotherms. All relevant quantities are listed in a comparative table in Section 6.1.3.

Since different sources of data are derived for various usage and during various conditions, the variations among quantities become naturally big. A large variety of units is expressed in the moisture transport coefficients and sometimes it is difficult to establish for which moisture phenomena a certain coefficient apply. Some of the differences could even be caused by the test methods or the assembly and thicknesses of the CLT in question. In addition, experimental data are difficult to compare. This part of the implementation is therefore by far the most challenging within the study.

Initially all relevant material data are collected in a table and compared. The comparisons make little sense if units and ranges are not converted to the same base. Moreover, the different moisture transport coefficients and functions are not straight forward to convert, since they may reflect different potentials (moisture content, moisture concentration, vapour difference etc.). It is necessary to compare the *moisture transport*, rather than the moisture *transport coefficients*. This method is further outlined in Section 5.4.2. The choice of values on a certain quantity is further discussed in Section 7, but could be based on a general trend, a typical or 'mean' value, or from a single reference.

Justified decisions are based on the nature of the quantity and its variation. For some parameters like the adhesives and capillary suction, simulation were required in order to establish the influence. The simulation software and its material database, as well as other studies form a benchmark when comparing and choosing material data. It is a conscious choice not to simply use provided data on CLT in the simulation software or from a certain manufacturer, simply because some parameters may be missing or simplified. Data that is common for both CLT and ordinary wood are partly inferred.

A natural risk in selecting data from various sources is the difficulty to justify its validity and possible variation. In this study the aim is to investigate certain moisture behaviour of CLT, primarily in a comparative simulation study also including ordinary wood. Therefore the specific manufacturer or experimental setup is not of primary importance. This is also further detailed in the next sections. Results are given in Section 6 and further analyzed in Section 7.

Besides wood, the material data on adhesives is also of interest. Here the most relevant adhesive types for CLT were chosen. The adhesive was first believed to be significantly more vapour resistant compared to wood, which was however later revised. This made the first calculation results too conservative with respect to the moisture profile development in CLT.

Also other material data had to be revised after initial calculation, simply because they resulted in moisture behaviour too far from ordinary wood and compared to other studies on CLT. This iterative process is part of the hygrothermal calculation step (5.4.).

5.4 Initial hygrothermal calculations

5.4.1 Material properties and assembly

In principle there are two different modelling approaches available for a CLT panel, see Figure 5.4-1. Either adopt an massive wood element to equivalent material properties to that of CLT, or to consider each material layer and adhesives and their thicknesses respectively in the model. Both approaches have been tested and compared in this study.

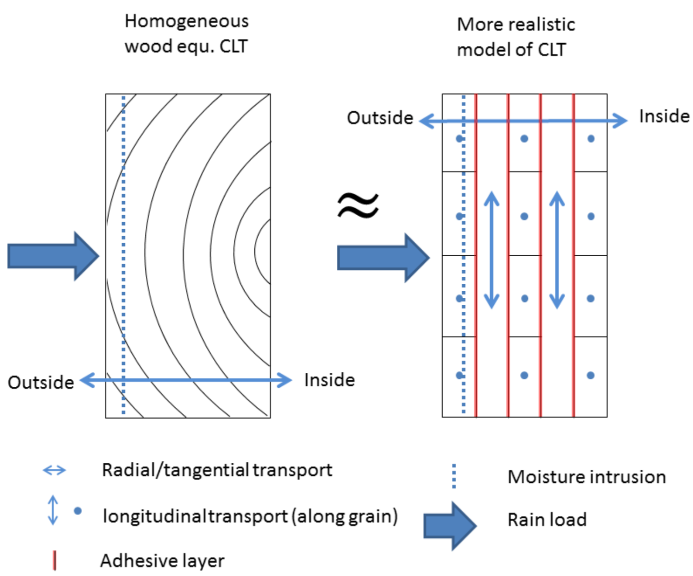

Figure 5.4-1 Theoretical models of CLT. To the left a homogeneous approach and to the right a layered model, subjected to surrounding moisture loads. Both models are evaluated.

Initial material properties for calculations were roughly approximated based on material data for wood and adhesives. Adhesive layers were treated as moisture barriers. By performing calculations with the in-house hygrothermal tool 'KFX', different properties and behaviour were assessed to gain a better understanding of the behaviour of the CLT-models and the influencing parameters.
As a result of this step, some adjustments of material data were made primarily to reflect the similarities between massive wood and CLT.

The initial calculations revealed that a massive wood model is possible to use, but do not reflect moisture behaviour during drying as well as during wetting compared to CLT. This step also aims at understanding the influence and codependence of material parameters on the overall moisture behaviour. The input data used in the pre study are defined in Appendix I.

Also WUFI was used in the pre-simulation study. Results are given in Section 6.2.

It was found that the solar radiation had a significant impact on the results, in terms of calculated moisture content and mould risk. The option “explicit radiation balance” (also refer to Section 6.2.2) was at first switched off for all calculations, but lead to suspicious results when comparing surface temperatures with cover and no cover cases. Since night overcooling reduces the surface temperatures and thus increases the relative humidity, it may otherwise be an underestimate of the mould growing criteria. The explicit radiation balance was therefore switched on for all cases using real climates.

5.4.2 Moisture transport and distribution

As mentioned earlier the moisture transport coefficients are often not straightforward to compare, since they may describe different transport mechanisms. In order to compare them it is therefore necessary to compare the resulting moisture transport at given conditions. The theory is described in Section 4 and the results of the recalculation of moisture parameters are presented in Section 6.

In Sweden the tradition is to describe moisture transport as a total transport expressed by e.g. vapour concentration as driving potential. In other countries the moisture transport is often divided in vapour and liquid stages (such as in the simulation software used here). In particular the division of moisture transport on different driving potentials is complicated and not even possible without explicit test results (L.O. Nilsson, personal communication, April 16, 2018). A very limited amount of data is available on pure liquid transport versus pure vapour transport and the transition in between is difficult to establish.

Within this study the separation between moisture transport mechanisms are important as input data to simulations and have been selected based on available reference data. By choosing liquid transport ‘L’ and vapour transport ‘V’, the sum ‘V+L’ should roughly correspond to the total moisture transport. The result of such simplified calculations and comparisons are given in Section 6 and 7.
At first, data on capillary suction for an equivalent homogeneous CLT material was chosen based on values proposed by Lepage (2012), as a result of experiments on CLT.

The primary simplification made is that the moisture transport mechanisms may be combined as independent quantities, although they are in reality interrelated (Nilsson, 1988; Tong, 1986). These assumptions are further discussed in the analysis section. The initial assumption of adhesives was that their moisture diffusivity is significantly larger than that of wood, thus dominating the moisture transport resistance through CLT panels. Calculations were performed using the in-house simulation tool ‘KFX’ with adhesive layers modelled as vapour barriers. Initial evaluations focused on simplified material properties and only vapour diffusion, aiming at describing the moisture distribution over time.

5.4.3 Post processing

Simulation work produce significant amounts of data, often visualized in charts and integrated post processors. Still some data need to be further processed and compared and in this work Microsoft (™) Excel(™) is used.

A simple ‘post-processor’ is built within Excel using visual basic programming (VBA). The post processor does the following:

- read ascii data result file from selected calculation set in WUFI and import results by 24-hour intervals in an Excel sheet.
- Extract data from various structure elements and present them in charts.
- Calculate some main quantities, such as moisture content, max, mean and median values.

Another 'processor' takes care of the mould index presentation. Besides the actual calculation of the mould index which is done in WUFI, the processor extracts data and calculates the accumulated time when the relative humidity limit is exceeded. These results are presented in a 'MIRHT'-chart, refer to the next section.

5.4.4 Mould risk evaluation

Using software additions WUFI Bio and WUFI VTT (Section 4.5), the risk of mould is evaluated. Initially the Bio model is used but later the VTT mould index is used instead, primarily because of its possibility to reflect different preset materials and conditions.

The mould index is evaluated at the surface of the CLT panel. This surface could be inside or outside depending on the case evaluation (in this study on the outside). All available mould models have limitations in their applicability to transient climate and fluctuating moisture conditions, as found in the literature survey (see 6.1.2). However, the risk of mould growth is still indicative and should be relevant for relative comparisons.

Mould growth is derived from the critical RH depending on temperature, which are output from the simulations. By evaluating the accumulated time for exceeding the critical RH by a certain amount, the 'MIRHT'-chart is produced. The composition of the chart is inspired by the Folos-chart (Mundt Petersen, 2013b) also described below.

An example of the MIRHT-chart and Folos chart respectively is given in Figure 5.4-2.

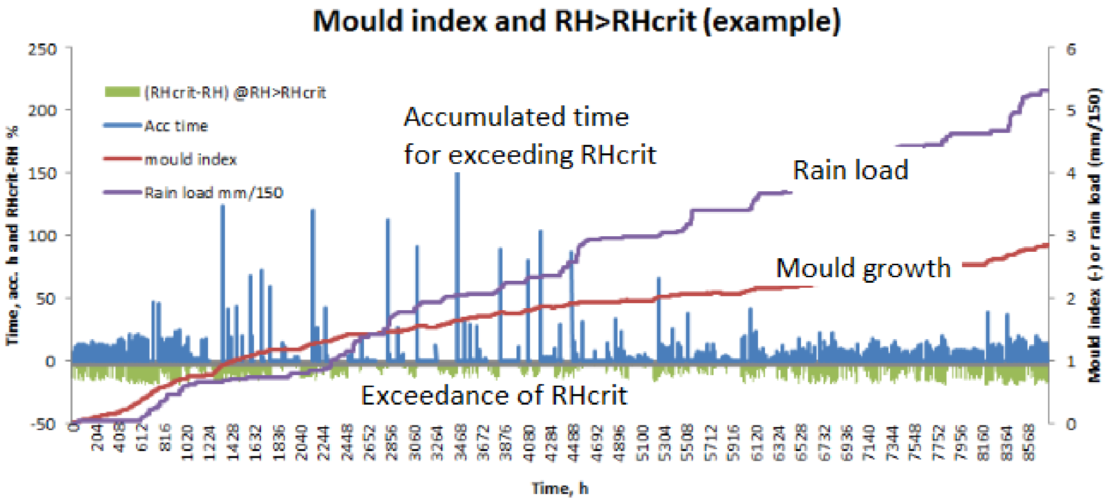

Figure 5.4-2 Example of the MIRHT chart. This chart is used as part of the result evaluation.

The MIRHT-chart stands for "mould index, critical relative humidity and time". It shows the development of the mould index over time, together with the accumulated collected time for exceeding the critical humidity level by at least 1%-unit. It also presents the amount of the exceedance of the critical humidity. Initially, and as presented in the Figure above, also the rain load (divided by 50 x maximum mould index) is included. The rain load was later removed from the charts for simplicity.

The bars define the accumulated time of a collected sequence of exceedances of the critical RH. For example, 10 hours should be interpreted as during a certain period, the critical RH is exceeded by at minimum 1%-unit for 10 hours straight. The mould index depends on material, critical RH etc. and threshold values indicated whether mould is likely to develop. Refer to Section 5.4.4 for additional information on how the mold index is used as part of the result evaluation.

The Folos-chart visualizes the temperature, RH and critical RH as well as the exceedance of the critical RH (‘signatures’). Refer to the example in Figure 5.4-3. It is helpful in comparing different designs or conditions, quickly revealing the critical relative humidity and thereby risk. However, the chart does not involve any mould modelling.

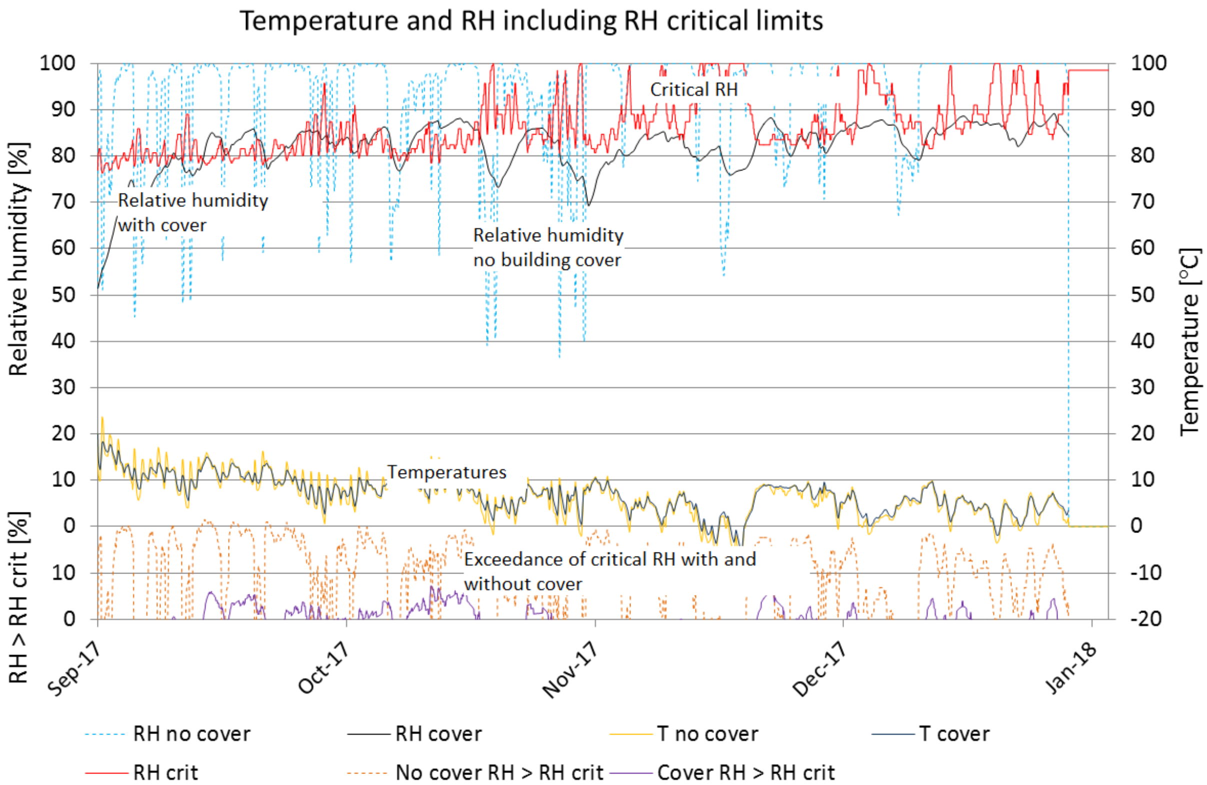

Figure 5.4-3 *Example of generated Folos chart. This chart is used as part of the result evaluation. Hygrothermal signatures are compared.*

It is important for the mould model to consider the type of material used in the evaluation of the mould risk. The influence on mould development is significantly affected by the surface quality and material type (Fedorik et.al., 2017). In this study, mostly a planed surface of untreated pine or spruce softwood/heartwood is used.

5.4.5 Simulation strategy and modelling

Parameter influences and variances

A strategy for the main simulation work was set out prior to any simulation work began. The strategy includes a flow chart and a table of relevant input quantities and how these are to be sorted and prioritized. Table 5.4-1 was subsequently detailed. By starting with a set of limited simulations on various cases, the influence of various parameters is better understood. This approach also helps in the search for envelope cases and thus impose a better selection of illustrative and realistic cases.

Table 5.4-1 and -2 list the possible variations of various parameters and topics, as well as the chosen solution for the current simulation study.

Table 5.4-1 Simulation parameter strategy. The table is self explaining.

Simulation strategy	*Possible variations*	*Suggested solution*	*Comment*
Rain/ water model	1) Rain load depending on wind speed and orientation (climate data) 2) Specific moisture source, e.g. rain intrusion [1].	1) is the major approach used. 2) is used as an indicator of along the grain and internal moisture uptake.	A point source of moisture cannot easily represent rain variations and changes in intensity and wind speeds.
Climate model	1) Climate database in WUFI at various locations. 2)Extreme climate /future climate.	1) Yearly average climate in Sweden. 2) Use rain intense climate, e.g. Bergen as a comparison.	Vary the start of simulation (the build) for a typical autumn and spring case respectively.
CLT model	1) Massive wood with adopted parameters. 2) layered wood and adhesives separately	Both are compared and 2) used for further analysis.	Transport direction is in reality 3D, but here 1D. Layers may impose quasidimensional aspects. See further analysis.
Moisture risk assessment	Several individual and combined quantities may be used.	Focus on moisture content and mould index.	End grain and other water uptake areas are possibly simplified to consider an increase in calculated moisture content.
Documentation	-	Name conversion on files, cases and result data for traceability.	Material data are read as separate input files for convenience.

[1] Could also be a moisture source reflecting rain left on surface after a rainfall.

Table 5.4-2 Cont. Table 5.4-1 Simulation parameter strategy.

Simulation strategy cont.	*Possible variations*	*Suggested solution*	*Comment*
Measurement data	1)Calibration 2)Comparisons	2) used in this study for indicative purposes.	A strategy for measurement analysis was derived prior to knowing the quality and accuracy of available measurement data.
Mould model	1)The m-modell 2)WUFI BIO/ Sedlbauer 3) VTT/ Viitanen 4) Other…	Primarily 3) is used, based on findings in the literature and given justifications (Section 6)	Difficulty to evaluate the validity of any results.
Building cover/ water protection	Size, type, controlled climate, paint etc. etc.	With and without cover, some tests with treated surfaces (floor). Ex. of moisture profile development in controlled climate.	A cover is essentially a roof over the construction, with an arbitrary air volume inclusion. Water protection refers to diversion of rain load.
CLT built into constructions	Different built-in times with respect to prior moisture loads (cover/no cover).	Parametric simulation using different MC start values. Consider “type wall” and “type floor” at various locations. Moisture in outer layers, or all layers, may be varied.	Number of cases are reduced and simplified if the initial values are set as independent variables. These should be compared to the estimated change in MC with/ without cover. Also includes cases where cover is used after initial periods without cover.
Additional influence	End grain, water damage, 3D-transport, cracks etc.	Not part of the scope, but addressed qualitatively.	Some increase of moisture content could be justified.

The layers and thicknesses of the CLT panels are chosen based on existing types and the type used for measurements (Section 5.7). Refer to Table 5.4-3 below.

Table 5.4-3 CLT assemblies.

CLT product	*Thickness and layers*	*No. of layers*	*Comment*
Floor element	230; 40+30+..+40	7	Same as for the measurement instrumentation
Wall element	120; 20+20+40+20+20	5	Ordinary wall element

It is also a justified significant difference in thickness and the number of layers between the floor and wall element respectively. It is also realistic that the floor element is thicker than the wall element for most applications.

Limitations

Within the simulations it is assumed that all water that reaches a horizontal surface is either repelled or adhered to the surface. For an vertical element, 70% water is adhered. This means that no water is assumed to be left on the surface after the rain has ended. There is no direct method of handling remaining water on surfaces within WUFI, other than defining additional material layers with moisture capacity, working as a moisture source. Results are therefore a best case when all free water is removed after a rain load. The building cover is limited to a roof and walls which protects against both downward falling and driving rain. The cover is well ventilated and also protects against direct solar radiation.

Modelling

As mentioned earlier, both massive and layered wood are modelled for comparisons.
During production it is assumed that the external climate is acting on both sides of a floor or wall element. This is reasonable in the case of no weather protection or a simple protection against rain. If an outside climate is defined on both sides of a structure within WUFI, rain can still only reach the external side. This is true for a floor element, but may be an underestimation for a standing wall element that is not protected. However, the water uptake would be the same on either side, considering the same wind conditions. Since the outer layer of the CLT behaves the same on either side, it is reasonable to assume that the CLT wall panel would be at worst case equally wet on both sides. Such case does not change the outcome of the results, merely adding to the risk of wetting of erected walls.

For a weather cover, there are additional boundaries to the inside climate, which is heated or cooled by the surrounding environment through heat radiation, ventilation etc. Even here, the outside climate is adopted to both sides of the cover, shielded by an enclosed and ventilated air volume. The influences of heat and moisture transfer from surrounding building elements in all three dimensions are not included. Besides the difficulties to define boundary and input data to such a model, it is not possible in the chosen simulation software. Other work also justifies an external climate on both sides for non-controlled building environment and enclosures (Lepage, 2012).

A water repelling surface is modelled as a surface with no rain load intrusion, whereas a building cover is modelled as an external roof and over an enclosed air volume having a certain air exchange rate with the outside climate. A completely “sealed” cover with controlled humidity is not modelled, since it gives lowest variation in moisture content. However, a controlled environment could be relevant as a measure after initial building has taken place without cover. This case is however omitted from evaluation due to limitation in the scope. Ventilated air gaps are physically complex to model and in WUFI the convection flow is for example not handled (Fraunhofer IBP, 2018.

The case of water repelling surfaces was actually not included in the original scope and more of a “mistake” than an expanded investigation. At first the rain intrusion was set to zero to roughly simulate a protected surface (i.e. rain is diverted). However, long wave radiation, air volume and ventilation has significant influence on the climate inside a building cover so the cover cannot simply be expressed by setting surface parameters. Moreover, a protective coat on the surface should be modelled as a thin layer and not by simply omitting the rain intrusion (WUFI, 2014).

However, initial simulations with the rain load shut of had already been carried out. It was therefore decided to present these results as an simplified, yet indicative measure of the possibility to protect surfaces by paint, oil or similar. It is emphasized that future work should refine these assumptions on protective coatings.

The building cover was modelled in two different ways; model A with an enclosed but ventilated air volume beneath an exterior roof and model B as a vapour shield without longwave radiation. Model A is more similar to reality, whereas model B is a simplification not to include the ventilated space above the protected CLT, but still represent some air tight cover. The latter model is based on flat roof modelling (WUFI, 2014). Type A is based on modelling of cold attics (Mundt Petersen, 2015).

After comparing the behaviour of the models, model A was chosen and is presented in Appendix II. The roof is modelled with solar properties close to a polyester cover. Note that the climate inside the cover is close to outside climate due to ventilation. However, the cover protects the surface from the solar radiation and thus reduces the maximum surface temperature somewhat. It can be discussed how to set the moisture resistance of the roof top layer. For the current study several different membranes/values were tried, but the final selection is an weather resistive barrier (sd=0,1m) which impose some vapour resistance, although very limited. An underlying wood sheet is used merely to give some additional moisture capacity and small insulation properties to the roof cover.

The cover tent is considered almost fully ventilated with the outside air and the ventilation rate was first set to 100/h. Above 300/h no changes could be observed. The final rate was chosen to 200/h to speed up calculations. Theoretically the ventilation rate should be in the range 50 - 1500/h depending on the size of tent and ventilation rate. These figures correspond to the rate in a thin layer as a function of volume enclosure according to authors' calculations. However, a rate above 200 produces hardly noticeable changes in moisture response.

Still it is believed that the modelling of the roof cover overestimates the effect of a simple roof, since it encloses an air volume that is not fully exchanged with the outside climate. Using a vapour resistive roof membrane and a lower ventilation rate may even produce lower relative humidities under the building cover than calculated here. Such a case would represent a closed cover, probably more resembling a controlled climate. Even if the cover could be modelled in more detail, it still reflects the importance of reduced relative humidity and the influence of rain loads respectively. This helps in the conclusions on whether a full cover with controlled climate or simply a "roof" is required.

5.4.6 Climate data and approximations

Within WUFI, climate data can be selected from various regions and cities by a map service. Climate data is also available from other sources, both by national and international services. Within the current study only climate data already part of WUFI has been used (Fraunhofer IBP, 2018). This comes with a number of limitations, at least for the climate files of Sweden. These limitations are discussed further in Chapter 7.

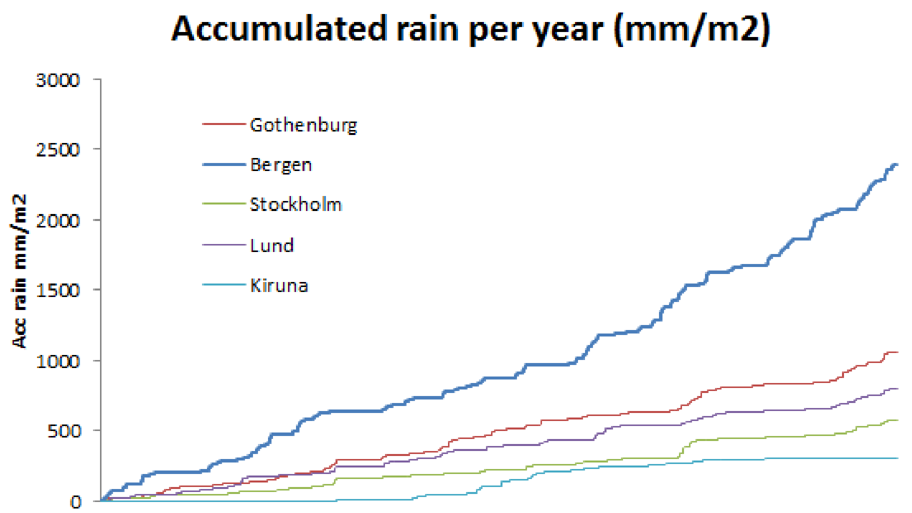

Figure 5.4-4 *Accumulated rain loads derived from simulation climate files and checked by other sources. Bergen is at the top, followed by Gothenburg, Lund, Stockholm and Kiruna.*

Rain data is not directly exportable from simulations, due to what is believed to be proprietary meteorological data. Since the accumulated rain exposure is of interest, this was extracted by using a fictive material setup with high capillary suction performance and a very high vapour resistance. The moisture flux density becomes a measure of rain (or at least with very high correlation to it).

The accumulated annual rain loads for some major cities are illustrated in Figure 5.4-4. It is easy to extract the outside temperature and relative humidity over a certain period for a specific location. A 'climate analysis tool' is also available within WUFI. The rain loads, RF and temperatures were also checked against climate statistics to conclude that it is reasonable (Arfvidsson et.al., 2017; CantyMedia, 2018).

It is a drawback that the rain loads can not simply be varied for a certain location (also true for RH etc.), without constructing new climate files. Moreover, the climate files do not include extreme cases or future prognosis which are perhaps the most interesting. It is not possible to use a year-by-year variation of climate, but instead a yearly climate is repeated. Due to scope and time limitations however, available climate data is used in the current study. The effects of extreme climate is instead crudely considered by using rain loads from Bergen, for example.

Wind loads affect the driving rain load against a surface. For a horizontal floor element, the rain is assumed to be normal against the surface. This is not an extreme case, but the focus in on one dimensional moisture transport and the effect of rain hitting edges, joints or end grains is not part of the simulation itself. It is also questionable what the rain load coefficients would be at any horizontal surface. A wall element is assumed to be hit by 70% of the rain load (proposed value within WUFI). It is emphasized that the influence of rain loads is relatively compared. Any more detailing of the approach would require not only a thorough justification of the transient and very local wind loads, but probably also some fluid dynamics simulation to establish the rain load patterns around a certain building envelope. Besides the Nordic countries, also Vancouver (cold year) is used to verify some of the boundary conditions for the analysis of critical rain loads.

5.5 Base case hypothesis for further calculations

A base case is derived based on pre-simulation runs and parametric studies. This ensures that the selection of material properties and range of variations triggers the effects that are of interest. Results are given in Section 6.2 and the initial base case is included in Appendix II. The base case is both the material assembly and its properties, as well as the simulation strategy defined in Section 5.4.5. This means that there are separate base cases for a typical wall and floor element respectively. As a base case, CLT is modelled as a set of discrete wood layers with adhesive layers in-between. The impact of rain is believed to be limited to the outermost layers of the material.

Several calculations on an 7-layer floor element subjected to outdoor climate (Gothenburg, November-February) were initially performed in order to establish a reasonable approach to model the behaviour of i) a massive CLT equivalent panel and ii) a layered panel. This is a check of the base case used for further simulations. The period and climate is not of most importance, but the water content and moisture flux is more relevant to compare.

Comparisons of the resulting moisture profile from varying suction and redistribution curves were made in order to quantify the influence of the parameters. The results are significantly influenced by the values set on suction and a qualitative selection was made based on these results. The revised base case and main results are presented in Section 6.3 and Appendix III.

5.6 Simulations and parametric studies (bulk study)

The main study consists of the simulation work performed with the base case and variation of model parameters. Location, time at year, period and assemblies with and without external rain loads were evaluated. Table 5.6-1 summarizes the base cases used for evaluation of building cover and rain protection.

Table 5.6-1 Simulation cases. y- yes; n-no rain; c- cover
MC- moisture content; MI- mould index; RHC- critical RH.

	Period	*Rain load*	*Element*	*Evaluation*
BER Bergen	sep-dec mar-may	y/n/c y/c	Floor	MC, MI, RHC MC (MI, RHC)
GBG Gothenburg	oct-dec apr-jun	y/n/c y/n/c	Floor	MC, MI, RHC MC, MI, RHC
LUN Lund	sep-sep mar-may	y/n/c y/c	Floor	MC, MI, RHC MC (MI, RHC)
KRA Kiruna	apr-jun	y/n/c	Floor	MC, MI, RHC

The choice of cities for simulation reflect a wide range of average relative humidities, temperatures and rain loads. Still there are no worst case climates available and therefore Bergen in Norway is used as a worst case in Sweden. This approach is crude but yields a climate close to what would be a very rainy Lund.

In addition to the simulations on floor elements, walls and built-in walls and and floors are also included. A set of cases also evaluates the influence from an controlled environment during production. These cases are not as extensive as the floor elements, since the aim is to indicate how a (wet) wall or floor behave over longer time. Obviously the outside and inside climate is most relevant, but the principle outcome is the same within Sweden at least. The Canadian climate is more extreme in terms of temperatures and relative humidities compared to Sweden and therefore simulation on built-in moisture in walls in such climate by Lepage (2012) for CLT and Alsayegh (2012) for wood frames complement our results.

After each simulation run, the calculated RH, temperature, moisture content etc. are extracted at one hour intervals and processed by the post processor (Section 5.4.3). At the outer surface of the wall or floor element the mould development risk is evaluated using WUFI Bio and WUFI VTT. Refer to Section 5.4.4 for a discussion on the choice of WUFI VTT as selected model. Mould model theory is found both in Sections 4 and 6. The mould index depends on the surface conditions, material etc. and works as a threshold value over which it is indicated a certain mould growth. All these models should be used with great care as they are very simplified, yet state of the art (Wadsö, 2018).

Initially the moisture content and mould index were of most concern. However, due to the often short time periods (months) the mould index did not always rise above the critical levels; although it is assumed that it would have shortly afterwards. For fluctuating climate, the mould index is often underestimated in the models which should be kept in mind (Vereecken, Vanoirbeek & Roels, 2015).

It could be both the time period and the external conditions that determine the final mould index. In order to consider not only a ‘go or no go’ criteria, additional parameters were added to the evaluation of the results. Based on the result of the literature survey and the driving mechanisms of moisture loads, the following set of quantities were selected as a novel approach. Note that the results from this evaluation often are indicative rather than absolute. Interpretations of the result must be based on a multitude of parameters and circumstances. A ranking of influences and boundary conditions is also necessary in an comparative study.

- Change in moisture content, dMC. Not more than 3-4 %-units based on an initial 13 % MC.
- Mould index and the rate of mould index growth. If the mould index is not above limits, but close and/or having a continuously increasing growing rate that is ‘worse’ than the opposite.
- Exceedance of the critical relative humidity, RHC. This is also input to the mould model and the accumulated time and exceedance of the RHC is taken as a complementary indicator.

The moisture content is an indicator of increased risk of mould (and finally rot) as well as related to volumetric distortion (Sortland, 2016). Also risks of cracking is addressed by e.g. Kukk et.al. (2017). The mould index is calculated within the simulation software and also plotted in a MIRHT-chart explained earlier. The exceedance of the RHC is also plotted in the previous chart and in a Folos-chart. Besides calculated accumulative time for exceeding the critical RH, the charts also give an quick overview of when and where the exceedances take place.

In general the determining case is the maximum of either one criteria above. The mould index, its growth and exceedance of the critical relative humidity may even be more important than the moisture content. However, an increasing moisture content needs to be controlled and is also an indicator of the rain loads at site. The critical RH is a function of temperature and not a constant value. It is discussed in the section on mould modelling.

Throughout the report different values on initial and target values of moisture contents are used. These values could for example be 13% and 16% respectively. In principle whatever value could be used as long as it is reasonable and used in the same relative comparisons. However, it should be noted that these values are based on the allowed variance of target moisture contents according to regulation (EN 14298). The set of criterias has been used in the analysis of simulation cases, results and discussion are presented in Sections 6 and 7.

5.7 Analysis of measurement data

No measurements have been performed as part of the current study, but other available measurement data have kindly been shared and utilised. A moisture uptake test with CLT samples placed outside in Gothenburg was conducted in November-December 2017 (F. Herrmann, personal communication, April 4, 2018), Figure 5.7-1. During the test, moisture content was both manually and automatically logged together with temperature. From these tests also the influence of edge and surface treatments were tried. The measurement results are presented and analysed in the next sections. Some of the measurements were also compared against simulations with internal water uptake.

Figure 5.7-1 Test setup for outdoor floor elements. Tests performed by Herrmann. To the left is the exposed samples and to the right the automatic measurement devices installed at different depths (Herrmann, with permission).

A big commercial building with CLT as floor elements supported by glulam columns and a steel beam structure is erected in Gothenburg. The building is built without weather protection and a careful follow up on moisture levels. Part of the building is instrumented and logged for moisture content. At the time of this thesis work a lot of the structure was built and in practice only one logger in a floor element was available (several more to be placed). The data is evaluated and compared against simulations in Section 6.

In the preparatory work for the current study, analysis of measurements was pointed out as possible strengthening of any simulation work or at least a check of its reasonableness. A strategy for how to use measurement data depending on its quality was worked out prior to accessing the data. The strategy is not included here, but is part of the working material. Simplified it says that if the quality or extent of the measurement are limiting, any other supporting measurement should also be considered.

However the limitation in the available measurements makes it impossible to claim that they in any way are a validation of simulations. The measurement analysis merely serves as an indicator of the moisture behaviour during various conditions. Validity of the simulation software is not addressed here, but covered in other benchmarks (EN 15026). It is also important to remember that any measurement is associated with a lot of uncertainties. Other work with comparative simulation and measurements could be found in literature, but within the current study the focus is more on the relative influence of different parameters. Obviously the use of tested software and collected material data should come with a high degree of reliability.

In summary the following measurements have been evaluated:

- Test case and logging of outdoor CLT elements subjected to rain. Within simulation the moisture content of a non-treated panel is compared to measurements, assuming a water intrusion profile.
- Logging of moisture content in a floor element from an ongoing build with CLT in Gothenburg is compared to a short sequence of simulation.

The building site in Gothenburg was also visited during the study, with experience reported in Section 6.1.4. PolygonAK is gratefully acknowledged for giving access to these measurements.

Comparisons of the measurements to simulations are presented in section 6.4.

6 Results

6.1 Literature survey and other experience

6.1.1 Moisture behaviour of wood and CLT

Wood has a moisture capacity in the higher range of relative humidity that is about 60% of that of concrete and about three times higher than brick. In fact the sorption curves for wood and concrete are very similar in shape and size. This means that a massive wood structure with a lot of volume will have the ability to absorb substantial amounts of moisture, potentially comparable to that of a concrete structure. For a traditional framed structure this is not true since the ratio of wooden volume between a massive and framed structure is calculated to 10:1.

Cross laminated timber (CLT) is also referred to as ‘massive timber’, ‘X-lam’ (Grasser, 2015), BSP in Germany (Brandner, et.al., 2016) or sometimes ‘laminated wood’. Although it is an engineered product, CLT is very similar to massive wood that has been used as a building material for centuries back. Nevertheless, its physical behaviour is still not fully known and research is very much ongoing (Espinoza et.al, 2016).

CLT consists generally of an odd number of layers, in which the grain direction is alternated 90 degrees between layers. There is research going on for variations by 45 degrees (Buck et.al., 2016). Each layer is glued to the next one and sides between boards in each layer may also be glued together. Moreover, joints in the longitudinal direction may be finger jointed or dovetailed (Stora Enso, 2017). Besides adhesive there exist other means of fastening the lamellas together using mechanical fasteners, although less common (Grasser, 2015).

CLT is used as a core building material which can sustain heavy loads with a limited dead weight. Since the material is wood it is meant to be covered with other building materials, at least on the side closest to the surrounding outside environment. The outermost layers may however be produced with a different quality, such as a certain wood species if the surface shall be exposed (Stora Enso, 2017). Usually soft lumber are used in the products, although hardwood may also be used. Internal layers could be of lower grade than outer layer, although dimensional construction timber is the base material (Xu, 2013).

The result of the literature survey revealed that most (relevant) references on the topic of CLT and moisture can be found in scientific articles and conference proceedings. This was evident from the distribution of source material found in the literature survey and also later found to be in agreement with findings made by Mundt Petersen et.al (2013a). Since the 1990:s CLT has developed continuously and Europe has become the leading producer (Xu 2013). Production exists in countries such as Germany, Sweden, Norway, Austria, Canada, UK, Italy and the US.

The ability to build tall wood buildings using CLT has also increased the production and driven the product development (Grasser, 2015). Research on CLT started already in the 1970s but has increased since the early 2000s. Also building code revisions have allowed the usage of wood in tall buildings (Grasser, 2015). Grasser provides a thorough and condensed overview of CLT, its history and description of details from the production steps. For a comparison of production volumes of CLT worldwide refer to Espinoza et.al (2016) and Grasser (2015).

Interestingly, Tong (1986) performed an early and extensive literature survey on moisture behaviour of wood and laminated panels at the former Swedish Institute for Wood Technology Research. Moisture mechanisms are thoroughly described and a lot of material data are presented.

6.1.2 Mould growth and decay

CLT is made up of wood which is a biodegradable building material. Under certain conditions wood can provide excellent nourishment for various microorganisms. With the use of oxygen and water these organisms can break down the polymers of the wood and cause damages of different sorts. With the exclusion of pest organisms the fungi organisms can be split into different categories: moulds, stainers and decay fungi (Canada Wood).

Mould develops spores in order to reproduce. The spores are released into the air and some types can cause health risks if emitted to the indoor climate. Stainers discolour wood which is aesthetically damaging. Moulds and stainers only grow on the outer layers of a material and do not cause any structural damage. When spores on a wood specimen have access to oxygen and nourishment the critical RH for mould growth depends on temperature as shown in Figure 6.1-1.

Decay fungi can however cause rot which can have a significant structural weakening effect. Large quantities of moisture are required for fungal colonization and proliferation. This means a MC above the fibre saturation point for extensive periods of time. Unlike mould fungi, decay fungi have no known correlation to human health problems and there seems to be no link between the two types of organisms. Mould growth does not serve as an indicator of future decay fungi growth (Canada Wood).

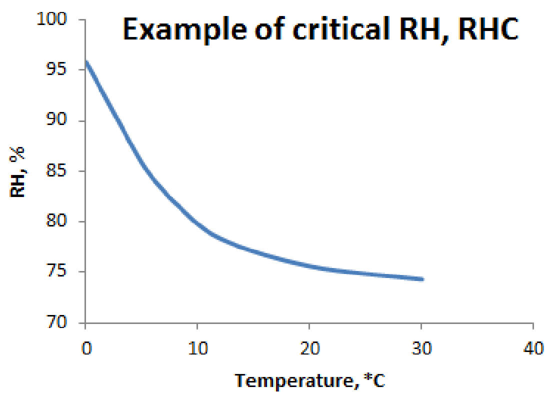

Figure 6.1-1 Critical RH for mould. The probability for mould growth on wood varies with temperature. Example based on typical behaviour of wood, with RHC 75% at 20 ºC. There is also a time dependence which is not shown here.

Mathematical mould models

Various mathematical models have been developed to predict and compare the growth risk and extent of mould on building materials. Modelling such a complex biological process is hard and none of the models claims that they can give a detailed realistic simulation of the growth process. At this current state the models can only be used for the assessment of possible growth risks on materials and assemblies (WUFI-BIO, 2018).

VTT model

Developed in Finland from a cooperation between Technical research center (VTT) and the Tampere University of technology (Arfvidsson, et.al., 2017). The VTT model is an empirical model based on laboratory experiments and then modeled with differential equations. The first version, developed in 1990s, only considered northern wood species. The newer model also considers other materials such as gypsum boards, cement screed on concrete, porous wood fibreboard and spruce plywood. (Gradeci et.al., 2018).

This model separates itself in the way that it accounts for unfavourable growth conditions and thereby delays the growth. (Krus, 2010). This delay goes into effect after a dry or cold period of 6 hours with a limit of under 80% RH or when the temperature drops to 0 °C or lower (Arfvidsson et.al., 2017).

The mould growth is expressed by the mould index (MGI) varying from zero to six where mould index 1 indicates germination (Gradeci et.al., 2018).

In present work, ‘untreated planed spruce’ is selected as substrate for mould evaluation, although there are cases where ‘outdoor wood’ was selected by mistake. The differences are however mostly small and not dimensioning for the results. A mould index above 1 is considered as initiation of mould and between 2 and 3 a transition takes place towards the extensive growth above.

Bio Hygrothermal model (WUFI bio)

Developed by the Fraunhofer institute of building physics in Holzkirchen. Unlike the VTT model WUFI bio is a fully theoretical model (Krus, 2010). The model can be downloaded and implemented as an add-on for the computer simulation program WUFI.

The basis of the model is the fact that mould spores have an osmotic potential that allows it to absorb water from the environment through the spore walls by the way of diffusion. When a certain critical water content is reached, varying with temperature and RH, biological activity begins and the spore germinates (WUFI-BIO, 2018). Input needed is climate conditions (temperature and relative humidity) and material data of the spore in which the user desires to model. This includes its moisture storage function and diffusion resistance. The output consists of plots of information on critical water content and computed water content in the spore over time. The second plot shows millimeter spore growth over time.

As mentioned before, the process of mould growth is complicated and therefore simplifications are made. These simplifications cause certain limitations of the model. For example some influence factors such as pH value, salt content, light, oxygen content, surface quality and biogenic factors are not considered.

MRD model

The Moisture Resistance Design model was developed by Lund University. The model is based on experimental data and can be used to predict the onset of mould growth (Gradeci et.al., 2018). The models definition of onset of mould growth is a sparse but well established growth which can be observed with a microscope. For a given area of material the potential for mould growth depends on RH, temperature and the exposure time. In order to account for the diurnal climate variations the RH and temperature from the climate data is converted into a 12 hour average value. The model transforms these inputs into a dose of growth (D (t)). D increases in periods when the given material area is exposed to a climate suitable for growth. In the case of non-growth suitable climates the dose subsequently decreases. To avoid the models limit for the onset of mould growth, the dose can not exceed a material specific critical dose.

m-model
The m-model is a Microsoft Excel based mould growth risk evaluation model. It was developed by the Swedish building company Skanska. The m-model uses a modified version of the VTT mould index where 1 is set as the maximal allowed value (Flink, 2012). Input needed is temperature and RH over time. The three parameters (Temp, RH and duration) are condensed into two parameters: m and duration.

$$m = \frac{RH_{act}(t)}{RH_{crit}(T(t)) \cdot \gamma} \qquad [6{:}1]$$

$RH_{act}(t)$	Actual RH in a material at the time t [h]
$RH_{crit}(T(t))$	Critical RH at the temp. T [°C] and the time t [h]
γ	Safety factor, normally set to 0.98

The critical RH functions are based on data from the VTT model and are used for six different durations: 1 day, 1 week, 2 weeks, 4 weeks, 8 weeks and 12 weeks.

Duration greatly affect the value of the critical RH. RHcrit is lowered (to a certain point) the longer the duration is. For example, at constant 20 degrees Celsius in the 24 hour duration RHcrit is about 100 % and for the 12 week duration the RHcrit is ca 80 %. Six different calculations (one for each duration) are run simultaneously and adds every time step where the critical RH or over is reached i.e. m ≥ 1. The model also accounts for periods of unfavourable mould growth climate. Where a reduction factor is multiplied in to calculate the reduction of the total accumulated time of growth.

6.1.3 Hygrothermal properties of CLT

It is evident from the various data available on hygrothermal quantities that there are large discrepancies and uncertainties related to them. This has also been concluded by others (Alsayegh, et.al., 2013). It is our opinion that uncertainties in data and quantities are larger than the uncertainties and simplifications made within related simulation tools and even within the current study. However, two major reasons for discrepancies are the methods and ranges used and attributed to each quantity determined by e.g. laboratory experiments.

When gathering moisture transport data a range of possible ways to describe the process of transporting moisture was discovered. Coefficients for the total moisture transport as well as coefficients that describe just the vapour or fluid part of the transport are all used. When comparing the various moisture transport coefficients a conversion to a total moisture flow plotted to moisture content was made in order to see a comprehensible and comparable pattern. In relation to each quantity used for hygrothermal evaluation of CLT, the relevant findings are further analyzed and discussed in Section 6.2.

Vapour resistance for CLT is similar to that of massive wood, however the glued joints and layers increase the resistance. This is reasonable from the fact that an adhesive acts as a vapour barrier inside the wooden structure, although they comprise a minor part of the structure.
In various literature the vapour resistance from the adhesives is judged to have a very limited influence on the overall behaviour (Alsayegh, et.al., 2013). Other literature indicates that the influence may be relevant consider (Stora Enso, 2017).

Since CLT is made of massive wood it also has the moisture buffering capability as wood. Since the thickness and bulk material of CLT often are large, the moisture capacity quickly becomes significantly higher than that of an ordinary wooden stud structure. Considering a small building of about 100 square metres, height 3 m and a circumference of 40 m, the ratio of wood volume for a CLT versus an ordinary structure is calculated to about 10.

Kukk & Kers (2018) reports of instrumentation of a CLT building in Tallinn, which focus on deriving hygroscopic data. Fedorik & Haapala (2017) emphasizes the protection of CLT against water and the importance of air layers in the constructions. They have investigated a wall-to-floor part of a commercial building using WUFI simulations and its bio-module. The article provides some physical properties used for CLT. Results should be verified against measurements but are at the moment delayed due to technical issues (F. Fedorik, personal communication, March 22, 2018).

In (Alsayegh, et.al., 2013) the history and knowledge of CLT are discussed. The purpose of the study is to document material properties. Based on tests with different qualities, several physical properties are evaluated. Direct water should be avoided due to the large capillary suction of wood grains. The study concludes that CLT behaves very much like pure wood in hygrothermal aspects. Alsayegh (2012) describes a relationship between shrinkage and moisture content of CLT. The study further compares different hygrothermal simulation tools, although calculations are done on a conventional wooden frame structure. The anisotropy of wood and CLT is further addressed and it is concluded that the vapour diffusion slows down by additional adhesion joints. The results are based on standardized tests and provide several relevant material data and comparative sorption curves for hygrothermal analysis.

Building moisture and CLT are discussed in (Lepage 2012). Furthermore, parametric simulations are performed. Mould criteria are briefly mentioned. Cracks in the surface of CLT influence the absorption of water, which is addressed by Lepage. By instrumenting CLT at various depths, wetting and drying are investigated by (Lepage 2012). The influence of the adhesives on material properties is also discussed. By hygrothermal simulation various wall types are analysed and the importance of allowing diffusion through open vapour barriers in CLT walls are emphasized. Possible mould growth is not part of the performed simulations.

WUFI is used for comparison against test results and the procedure and lessons learned from this calibration process is described in detail by Lepage (2012). The focus is on water uptake and drying above the hygroscopic range. One important conclusion is that WUFI is suitable for hygrothermal simulation of CLT material. Moisture content profiles from measurements inside CLT is presented.

In (McClung et.al., 2013) field measurements of CLT are compared to hygrothermal simulations using WUFI. Different wood types and both with and without vapour barriers are tested. McClung concludes that there are certain drawbacks with WUFI, although results show relatively good agreement with measurements. Material properties of CLT are given.

An article written by Kukk et.al (2017) reports of tests performed in a climate chamber in order to evaluate CLT in between in- and outdoor environment. The shape, size and development of cracks are monitored. The risk of crack formation is greatly enlarged if the moisture content is more than 2% above expected value in current surrounding. The importance of cracks and air barrier for CLT are mentioned. Although the material can be considered airtight it is important to use an air barrier in practice.

A master thesis presented by Srisgantharajah & Ullah (2015) suggests that WUFI 2D does not produce the time-dependent moisture content of massive timber constructions. Test samples of CLT are wetted and consequently dried for various time. The idea is to represent free water intrusion on a floor to wall element. This is the only reference found that considered two-dimensional flow in a connection of wall and floor element of CLT. The wall and floor are also instrumented and moisture content is compared to simulations in WUFI.

There is no apparent calibration process involved in the simulation work and spruce is used to represent the 5 layers of CLT. The measured moisture profile was not reproduced in the simulations, but the total moisture content showed better agreement. By wetting the CLT sample it is concluded that the moisture content quickly increases, but the drying process takes much longer (Srisgantharajah & Ullah, 2015; Nore, 2014). This is also in accordance with tests performed by e.g. Lepage (2012).

It is also concluded that WUFI in general underestimates the drying sequence compared to real measurements. Finally it can be said that the results show that the adhesive layers in CLT slows down the drying process (Srisgantharajah & Ullah, 2015). The experience from a study performed by Krus & Vik (1999) where WUFI simulations was compared with real measurements showed that WUFI is relevant for wood calculations. However, wetting is easier to model than drying. The moisture transport coefficient is dependent on the pore swelling and shrinking and this influence the moisture redistribution function. A faster wetting and drying sequence in real tests compared to simulations using WUFI was also found by Lepage (2012).

Adhesives used in CLT products and other engineered wood have been examined by for example Belleville et.al (2008), Sonderegger et.al. (2010), Kläusler, et.al. (2013), Hassani (2015) and Messmer (2015). A common type of glue is polyurethane, which reacts with moisture during curing.
From the literature survey about 20 references on relevant material data was found and compared. The Table 6.1-1 and Table 6.1-2 are presented below and further analyzed in chapter 7. In order to compare material properties some recalculations are required in order to express quantities with the same units and ranges. This recalculation is clearly indicated in the table comments below.

*Table 6.1-1 Selected material properties for CLT, part 1. *) authors' rough recalculation. Underlied references: Data on sorption and permeability are separately analyzed by the authors.*

Source and notes	Theoretical framwork	Density, p (kg/m3)	Porosity (m3/m3)	Specific heat capacity – dry (J/kgK)	Thermal conductivity (W/mK)	Water vapour diffusion resistance factor my	Water Absorption Coefficient (kg/m2s^1/2)	Sorption (EMC, %@%RH)	Moisture transport coeff. (diffusivity vapor and liquid)			Capillary absorption (kg/m3)
a) Mundt Petersen et.al. (2013) Ch. 9.1.	Simulation	455	0,73	1500	0,09	130						
b) Alsayegh et.al. (2013)	Experiments	401			0,103	20-264 *)	0,00168	7,95@50% 11.05@70% 19.8@90% 22.35@95%	Permeance ranging from 0.3e-12 to 16 e-12 kg/sm,Pa for RH25-90%			
c) Alsayegh (2012)	Experiments	340+/-12,7			0.103 & 0.104	73/176/244 @50/70/90%RH *)	0,00163	8@50% 11.3@70% 20.3@90% 21@95%	7.59*10^-13 (dry test)@50% 60.3*10^-13 (wet test)@50% kg/msPa	12.7*10^-13 (dry test)@70% 83.4*10^-13 (wet test)@70% kg/msPa	25.2*10^-13 (dry test)@90% 110*10^-13 (wet test)@90% kg/msPa	
d) Gradeci et al (2018)	Simulation	410	0,74	1300	0,098	500						
e) Stora Enso, 2017	Experiments	470/490/500			0,13	105@ MC8% (interpolated) 52@ MC11,3% 33@ MC14,7%						
f) Arfvidsson et.al. (2017)	Experiments	450, 500	0,65		0,14	100-700 (author's rough recalculation)*	Parallell (den. 450 kg/m3)=0,016 Orto (den. 450 kg/m3)=0,004	Refer to original figure 8.2.2 in source	Refer to table 8.2.3 in source			400 (sat)
g) Fedorik&Haapala (2017)	Simulation	410	0,74	1300	0,1	500, 33 (std-dev)						
h) McClung et.al. (2013)	Experiments/ simulation					469 (25% RH), 208 (35% RH), 187 (45% RH), 46,9 (75% RH), 28,8 (85% RH), 18,76 (95% RH)						
i) Lepage (2012)	Experiments/ simulation	335.9 @ 6.5% surface MC at 40% RH (average of samples)	0,73		0.1-0.14	130	0,011	Refer to table 5.2 in source, originating from WUFI database for spruce wood, radial	liquid values m2/s @norm water content (w/wmax) 0@ 0 7.6e-12@ 0.09 2e-10@ 0.18 1e-4@ 0.68 100@ 0.7			@norm water content (w/wmax) 0@ 0 53@ 0.09 100@ 0.18 383@ 0.68 393@ 0.7
j) Kukk & Hortaa (2017)	Experiments					185 (single lamella) 269 (glued lamella) 259 (glued lamella, small "crack"= 2 mm hole) 198 (glued lamella, larger "crack"=6 mm hole)						

Table 6.1-2 *Selected material properties for CLT, part 2. *) authors' rough recalculation. Underlied references: Data on sorption and permeability are separately analyzed by the authors.*

Source and notes	Theoretical framwork	Density, p (kg/m3)	Porosity (m3/m3)	Specific heat capacity – dry (J/kgK)	Thermal conductivity (W/mK)	Water vapour diffusion resistance factor my	Water Absorption Coefficient (kg/m2s^1/2)	Sorption (EMC, %@%RH)	Moisture transport coeff. (diffusivity vapor and liquid)	Capillary absorption (kg/m3)
k) Ferk, et.al. (2006)	Simulation	500			As a function of density = 0.1954*p + 0,0256					
l) KLH technical data	Technical data			1600	0.1-0.13					
m) Glass et.al. (2013)	Technical data	300-600			0,11	20-1800 *)		Refer to figure 3 in source, originating from the Wood handbook for pure wood	Refer to figure 4 in source, originating from NRC tests on CLT	
n) Brandner (2016)	Experiments	385								
o) Wang& Ge (2016)	Experiments/ simulation	536	0,73	2500	0,12	1876 (std-dev 156,3) (dry extrapolated data)		Refer to fig 6 in source, based on other data e.g. the NRC report	100 (std-dev 8,4) (sat) m2/s. Distribution function based on the study by NRC and Lepage. Refer to fig 6 in source.	630 (std-dev 42) (sat)
p) Sonderegger et.al. (2010)	Experiments	402 (radial)							Refer to table 1 in source for data on wood, glue and dependence on no. Of layers	
q) Hassani (2015)	Experiments/ simulation							Refer to figure 2.8 in source for data on glue sorption isoterms. Table 3.7 for spruce radial.	Refer to Appendix B in source for data on glue.	
r) Srisgantharajah et.al. (2015)	Experiments	420	0,75	1600	0,13	50				
s) WUFI data base StoraEnso	Experiments	410	0,74	1300	0,098@0 0,452@740 kg/m3 moisture content & 0,092@ -20*C 0,112@80*	Max 500 or varying with moisture content according to material data table in WUFI.		Defined in table within WUFI database.	A general equation for capillary transport defined for mineral materials. Based on capillary suction and moisture content. May serve as an approximation.	678 (free sat)
t) WUFI data base KLH	Experiments	423	0,7	1500	0,12@0 0,378@700 kg/m3 moisture content 0,114@-20* 0,134@80*	Max 300 or varying with moisture content according to material data table in WUFI.		Defined in table within WUFI database.	A general equation for capillary transport defined for mineral materials. Based on capillary suction and moisture content. May serve as an approximation.	550 (free sat)

a) Fraunhofer IBP – Holzkirchen; Germany, References: Vik 1996 Massive wood; spruce, radial. Adhesives not considered. Thermal conductivity: 10 °C reference; density as bulk-density.

b) Experiments in laboratory 4 types considered; here selected: finger-jointed Norwegian Spruce (Euro), 3 lamellas, thickness 90 mm Glued edges. Adhesives are not included when measuring EMC in this study. Adhesive joint is part of samples when determining the vapour resistance. Thermal conductivity and density: 5% initial MC during measurement. Water absorption reduced due o glued edges. Measurements of EMC on pure wood without glue.

c) Experimental, master thesis 4 types considered; here selected: finger-jointed Norwegian Spruce (Euro), 3 lamellas, thickness 90 mm polyurethane glue. Adhesive joint is part of samples when determining the vapour resistance. Dry-density. EMC sorption values selected from set 1. Model parameters for sorption curve is also given.

d) Input as defined in the study 100 mm 5 layers (according to figure 4) - Authors comment: probably the CLT data defined within WUFI.

e) Academic research at University of Hamburg and Thünen Institute (Holzforschung) CLT 3 or more layers. Citation:"In a dry climate (23 °C and 26.5% mean RH), the CLT adhesive joint has the same transmission-equivalent air film thickness as a spruce lamella with a thickness of 6 mm± 4 mm. In a humid climate (23 °C and 71.5% mean RH), the adhesive joint has the same transmission-equivalent air film thickness as a spruce lamella with a thickness of 13 mm ± 6 mm"". Joints 1-3 mm"

f) Several other sources for spruce and "wood". Not CLT. Regular massive spruce parallel, orthogonal *Water vapour diffusion: delta (vapor) values (from 35-70% RH) converted to water vapour diffusion factor using D (air 20 degrees) = 25*10^-6.

g) CLT wall and floor, 120/140 mm .

h) NRC (2012) FPInnovation "Characterisation of Hygrothermal properties of CLT" reported in Lepage, 2012. 4 types considered; here selected: finger-jointed Norwegian Spruce (Euro), 3 lamellas, thickness 90 mm - Wall assembly and measurements of MC during drying of samples of CLT. Simulations over-estimate MC in the centre of the panels by 5-10 %.

i) Experiments and simulation. WUFI database and additional references. Several types; here selected: CLT European 3 layers (other types also tested) Tests on face glued panels with a polyisocyanurate adhesive. The glue is apparently not defined as separate layers within simulation, but included inherently by adjusting material properties to achieve agreement between simulation and measurements. Basis for material data and model is WUFI CLT, calibrated to experiments. Set the saturated liquid diffusivity for redistribution to 100 m^2/s and calibrate the slope at a value at 10 kg/m^3 less than saturated. Set the saturated liquid diffusivity for redistribution to 2E-10 m/s@ MC 30%. Many material data where inferred from softwood lumber properties.

j) Experiments CLT spruce, 5 layers 95 mm - 4 type samples tested S1: no occurred cracks; S2: six occurred cracks of a mean length of 143 mm and a mean maximum width of 0.2 mm; S3: nine occurred cracks of a mean length of 221.44 mm and mean maximum width about 0.89 mm; S4: three occurred cracks of mean length of 468 mm and mean maximum width about 2 mm.

k) Experiments and data from TU Graz General CLT - Primarily density and conductivity are reported material hydrothermal properties.

l) KLH Bauphysik 2012. v1. CLT 3-9 layers - Gap width 2-4 mm.

m, o) CLT 3 or more layers. The technical source from NRC is cited among other studies. National Research Council (NRC), Characterization of Hydrothermal Properties of CLT, Report to FPInnovation.Ottawa, ON, Canada, 2012. Same data as McClung 90-130 mm. Material data for simulation N/A Data used in simulation tool Delphin are derived from statistical distributions based on material data from various sources.

n) EN 14080 CLT 3 or more layers.

p) Experiments Up to 5 adhesive layers Diffusions curves are defined. Considers PUR, UREA, Epoxy and PVAc.

q) Experiments Glue data Diffusion and sorption curves are defined. Considers PUR, PRF and MUF. diffusivity in liquid phase

r) Experiments and simulation 5 layer CLT wall on floor PUR defined similar to plastic. Density 1200 kg/m^3, porosity 0, lambda 0.25; heat cap. 1800 J/kgK, vapour resistance 6000 WUFI 2D on connection between wall and floor.

The diversity of source data on material properties could be taken as a sign of the complexity when modelling moisture behaviour. One available database on wood properties is the ASRAHE database (Kumaran, 2006). This data was not included in the literature survey due to time limitations.

6.1.4 Weather protection and CLT buildings

This section begins with an short introduction to weather protection and continuous with a presentation of a variety of selected CLT buildings in Sweden. It is by no means the result of an complete search, nor based on any specific selection basis such as representative building types.

Weather protections

From a moisture safety perspective a building cover is always preferable to no building cover. Although economic and or practical reasons may sometimes stand in the way. Some manufacturers claim that building without a cover is possible, although it requires thorough planning. When CLT buildings are raised without a cover protective tarpaulin and moisture resistant tape is recommended . It is also recommended that you let the wood sufficiently dry out before applying any further assembly layers (Svenskt trä, 2018).

Figure 6.1-2 Scaffolding cover- (Axelsson, 2004).

The range of different building cover solutions has increased rapidly since the 1990s (Axelsson, 2004). Now there are multiple types of building covers on the Swedish market with various advantages and disadvantages. In a thesis conducted by Ehrnström & Selvarajah (2011) an historic overview of CLT buildings in Sweden is presented. Weather protection is addressed by several references. A building covers must be custom designed depending on the object. Loads to design for are wind, snow and personnel.

There are three main types of weather protections:

- **Scaffolding cover -** A building cover attached to the scaffolding. Includes challenges especially with wind loads. The scaffolding must be attached securely to the building frame and can there by follow the height of the building as it being built. A scaffolding cover can be combined with a roof cover or temporary floor element covers. See Figure 6.1-2.
- **Stationary or wheel movable roof cover -** This type will stand still and carry the loads on its own. It is typically built with aluminum trusses which is stabilized with orthogonal struts. To make this solution more flexible, retractable for example, the trusses can be placed on rails.
- **Climbable cover -** A climbable cover which is built on poles and can rise as the building grows taller. Can be combined with hanging platforms and movable crane rail beams which replaces a conventional crane.
  (Svenskt trä, 2018)

CLT buildings

The following examples are from real projects built with CLT. The results considering moisture security are with varying success. The observations are partly made from the authors and partly from people involved in the projects.
Due to the sensitivity of the issue, we have decided to keep some information regarding one the projects disclosed.

*Building 1***,** Johanneberg Science Park (JSP), Gothenburg, see Figure 6.1-3.
A multi story building built with glulam pillars and steel beams, with CLT floor elements without weather protection.

 

Figure 6.1-3 Constructions site of the JSP project in Gothenburg. Half of the building is enclosed (left). Protective tarpaulin and water diversion covers gives protection the end grain of the panels. (Photographs taken by the authors)

The following points are observations from the authors visit to the active JCP construction site, as well as points of the predetermed demands from the developers and the moisture safety goals set by the contractor.

Demand from the developer:

- Microbial growth, abnormal smells or discoloration from ophiostomatoid fungi are unacceptable.
- Goal MC on delivery was 12 % and max 16 % before the additional organic building materials are to be applied.

From the contractor:

- Glulam beams and CLT floor elements are to be adequately sealed by the material supplier.
- Inspection and MC measurement upon delivery. Procedure are implemented to make sure MC never exceeds 16 %
- Procedure of Lumi-tests are routinely carried out in order to quickly assess the potential biomass on the materials. A Lumi test is done with a device that transforms the ATP molecule into light with the help from a firefly enzyme. The light can then be detected and quantified, which gives an indication of the size of the biomass.
- If the MC measures critical levels, samples are gathered and tested for microbial growth.
- Reserve CLT floor elements is available on the building site if needed.
- Routines are in place to ensure that tarpaulin covers are intact.
- Dirt and sawdust are routinely cleaned from the floor elements.
- Decontamination procedures are established. Mechanical sanding of the potentially mould contaminated surfaces will be performed.

Authors' observations:

- Workers seemed to had been trained in moisture management.
- Some wide cracks up to circa 7 mm were observed.
- Water resistant tape had been meticulously applied. In wet conditions the surfaces was heated and dried in order to apply the tape correctly. Gaps were however observed and tape on joints at low points did not seem to be watertight.
- Gaps between lamellas were observed on the surface of the floor elements.
- Stains were observed, although tests had been done which showed no mould indications. The stains were caused by pollution particles from melting snow.

When reviewing measurement data and according to moisture manager Fredrik Herrmann, no critical RH nor any microbial growth have been demonstrated throughout the building process so far (Fredrik Herrmann, personal communication, May 18, 2018).

*Building 2***,** Undisclosed location

Multi story CLT building built without weather protection nor with sufficient tarpaulins nor water resistant tape.

Observations from an undisclosed source with insight of the project:

- Slow building process. The first floor was raised in about a week. The contractor team then proceeded to take a 3 week vacation leaving the floor elements fully exposed to rain without tape sealed joints nor protected end grains.
- Doors and windows were installed later than what was possible. Water puddles were left without consideration until they dried out on their own.
- The first story floor element took the worst damage with microbial growth down into the inner lamellas. Tests showed mould growth down 35-40 mm
- Solutions before remaining layers were applied: Blasting to remove mould on the outer layers, install a surface emission trap. A surface emission trap is an absorbent sheet which is claimed to hindre harmful molecules from being emitted to the indoor environment.

Other
Examples of a CLT building with a relatively short building time is the Stadthaus in London, 9 stories high with 29 apartments. It was erected in only 27 days by a crew of 4 men working a 3 day work week (Lepage, 2012).

Norwegian architects and building engineers Oslotre AS have a lot of experience with CLT buildings. Their opinion and experience is that weather protection is not necessary. Any wetting dries fast since the brunt of the moisture load is taken by the surface. Free standing water is although dangerous and should always be avoided (Jörgen Tycho, personal communication, May 24, 2018).

6.1.5 Guidelines for moisture management of CLT builds

Moisture management are all activities that are undertaken both in order to prevent moisture from entering a structure where it may cause damage as well as designing a structure to withstand unwanted moisture. Since moisture originates from various sources; such as built-in moisture from manufacturing, transport and storage of building materials; moisture loads from occupants and the surrounding air; outdoor climat, rain, snow, etc. it consequently affects all stages of building and maintenance.

Depending on quality, the moisture content at delivery from the factory is around 12 +/-2 % (Stora Enso, 2007; Xu, 2013; Grasser, 2015). Being made of wood, the ability to handle hygroscopic moisture is often brought forward as an advantage of CLT. Guidelines for sound and fire proofing of CLT are given in Matzinger & Teibinger (2013). Also moisture management is addressed and details on construction of edge connections, windows, joints, balconies among other are given.

The CLT Handbook (Glass et.al., 2013) provides guidance for moisture protection of CLT. During construction all CLT panels must be protected from rain and wetting by adding the protective layers as soon as possible. Special care should be taken to allow the CLT to dry over time once it is included in the structure.

Canada Woods gives examples of moisture management. For ordinary framed buildings it is important to allow shrinkage and swelling by allowing appropriate joints between e.g. facade material. It is pointed out that there are two main philosophies in moisture management; one being to prevent moisture from entering the structure and the other is to use materials and constructions with high moisture endurance margins. Furthermore, a principle named “4D” - Deflection, Drainage, Drying and Durable materials. These principles are somewhat self-explaining and can be used both in the planning and production stages. Moisture management may consequently influence architecture, the order in which the building is constructed and the materials used in combination. Several examples are given on deflection strategies, such as roof overhang; drainage in terms of water barriers, air barriers; drying by the use of permeable materials and self drying constructions; and finally durability which deals with either moisture insensitive materials or treatment of sensitive materials.

Cracks and splitting of joints and lamellas could occur due to fast drying, alternating climate and other reasons. Such cracks will undoubtedly enter water into the material. Kukk & Kers (2018) discusses the impact of cracks to the hygrothermal properties of CLT. From the literature found on moisture management and guidance, a summary is provided in Table 6.1-3. More details are selected by the authors and presented below as a list. In Section 7.5 this is further discussed.

Table 6.1-3 Moisture management and guidelines found in literature. An ‘x’ means a covered aspect of moisture safety.

Source	*Planning*	*Construction details*	*Production*	*Comment*
Matzinger & Teibinger (2013)		x		Details on building physics.
Glass (2013) *CLT Handbook*	x	x	x	Moisture management and properties.
CanadaWood *Moisture and Wood-Frame Buildings*	x	x	x	Moisture management.
Nore et.al. (2014)		x		Drying slots are built in in advance in order to dry moisture intrusion.
Karnehed (2017)	x		x	Roof as soon as possible. Leave areas open to dry, do not cover with plastic or cover at least 1 m up from surface. Tape on surface and diversion of water in joints.
Mundt Petersen et.al (2013c)			x	Literature survey; dry building is essential.
Mjörnell & Ohlsson (2017)	x	x	x	Several recommendations
Olsson & Nilsson (2016)		x	x	Swedish CLT buildings

Source	*Planning*	*Construction details*	*Production*	*Comment*
Mayo (2015)		x	x	A lot of world-wide experience from massive timber buildings
Thivierge (2011)	x	x	x	Moisture management

The following selection of principles are found (see further Section 7.5):

- Remove snow so that it does not melt and becomes a moisture source.
- Use wax or sealants on areas where covering is difficult or delayed.
- Tape on joints and edges have been used in several projects, but it does not always work properly.
- Building cover is preferred over other type of temporary weather protection.
- Arrange water diversion by rubber gutters at joints.
- Around windows use boxes of plywood to protect from moisture intrusion and simplify mounting.
- Use temporary weather protection with drainage around staircases and larger holes.
- Possibly arrange sloping floors to drain water.
- Short building times are important.
- Plan and predict moisture damage both qualitative and quantitative.
- Moisture content should be kept low at delivery and storage.
- Do not store CLT outside more than a month, and keep emballage and clearance of ground.
- Moisture safety plan (swedish ByggaF).
- Mounting on rain free days.
- Follow up with measurements at least weekly.
- If water leaks in, be prepared with equipment to remove it quickly and istruct everyone at site.
- Apply controlled and drying climate as soon as possible, preferably sectioning large buildings.
- Use weather protection.
- Preassembled moisture barriers. Peel and stick weather barrier.
- Reduze exposed openings.
- Apply weather vapor resistive barriers on walls as soon as possible.
- Minimize gaps between boards in the panels.
- Prevent moisture condensation beneath weather barriers.

6.2 Hygrothermal calculations - pre study

6.2.1 Modelling CLT panels

A number of pre simulations were performed both in KFX and WUFI (Section 4.4) to gain a better understanding of the behaviour of the CLT-models and the influencing parameters. In this section a selection of those results are presented. Often a CLT panel is modelled as a modified massive wood panel without specific adhesive layers. This study will evaluate the plausibility of such a simplified model without the influence of adhesive layers. The hypothesis is that CLT will behave similar to wood, but that adhesives in theory will influence the moisture behaviour. Results are further discussed in Chapter 7.

Since the adhesive layers impose a moisture transport barrier, it is interesting to study the effect of internal moisture and drying-out sequences of a simple CLT model. KFX is used for the first trials and it should be noted that this program do not handle free water, like rain loads. Instead an initial moisture profile was assumed, reflecting a high moisture content in the centre of the CLT panel and consequently decreasing towards the sides. The total thickness is 150 mm. Refer to Figure 6.2-1.

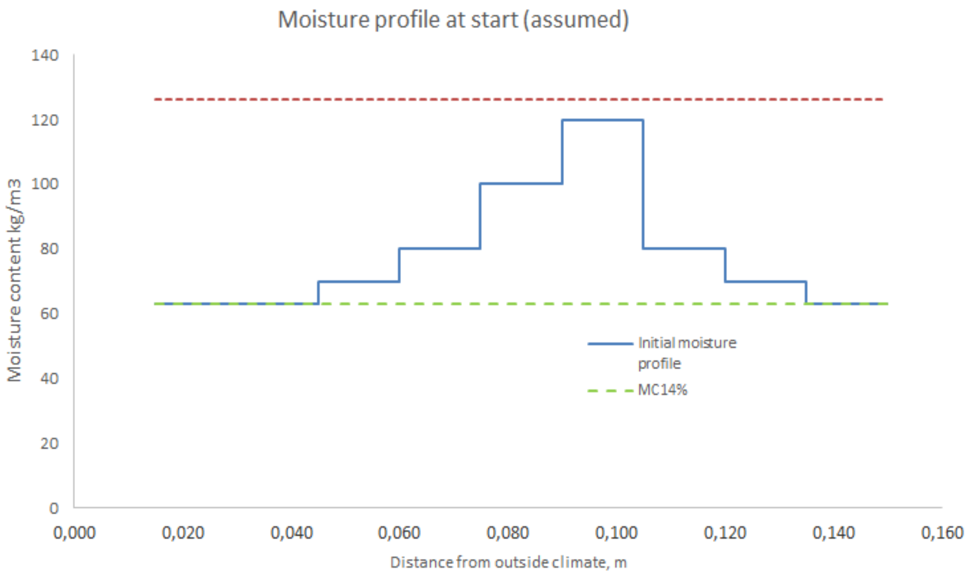

Figure 6.2-1 *Initial moisture profile in a CLT model. The upper dashed line represents the fibre saturation point and the lower line is equal to an MC of 14%.*

This moisture profile is deliberately exaggerated and the middle part almost reaches the fibre saturation point. The CLT panel is then subjected to a climate of 90% RH on the outside and 40% RH on the inside at 20 degrees Celsius. This is of course not a realistic climate, but it shows the principle behaviour. The resulting moisture profile after 100 days is given for various CLT properties in Figure 6.2-2. The complete definition of input data and properties used for the various cases are presented in Appendix I.

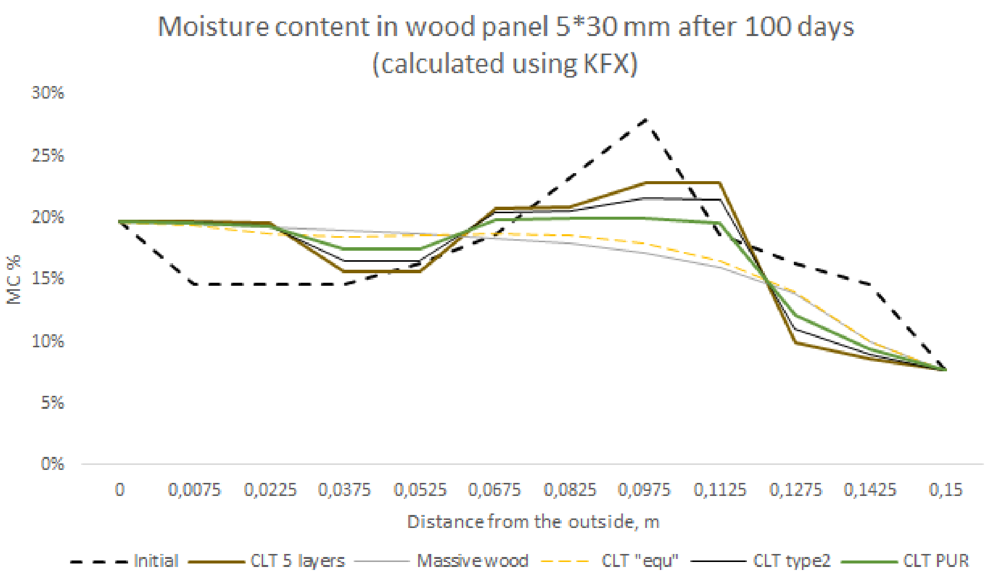

Figure 6.2-2 *Calculated moisture profile for different CLT properties using the KFX tool. The legend is described below.*

Legend:

Initial	*Moisture profile at start*
CLT 5 layers	*5*30 mm wood with adhesive layer*
Massive wood	*massive wood, no glue*
CLT "equ"	*CLT as massive wood with modified properties**
CLT type2	*same as CLT5 but with different adhesive properties**
CLT PUR	*Polyurethane adhesive (base case)*

*) refer to Appendix I.

Evidently the adhesive layers play an important role in the drying process, rather than in the wetting process. The moisture profile in equivalent CLT and massive wood are more or less the same when compared after 100 days (not at the first weeks of drying).

It should be noted that material properties used in the initial calculations are not the final ones, or even not all the ones used for the base case. Still it is all about relative comparisons and thus not decisive not to use final input data. Input data to the simulations in KFX are described further in Appendix I.

Secondly WUFI was used for initial simulations with rain loads and with both massive and laminated wood panels. A massive wood model with several layers of 15 mm wood was created and adhesives were added in-between for the CLT case. Resulting moisture profile in the outermost layers are given in Figure 6.2-3.

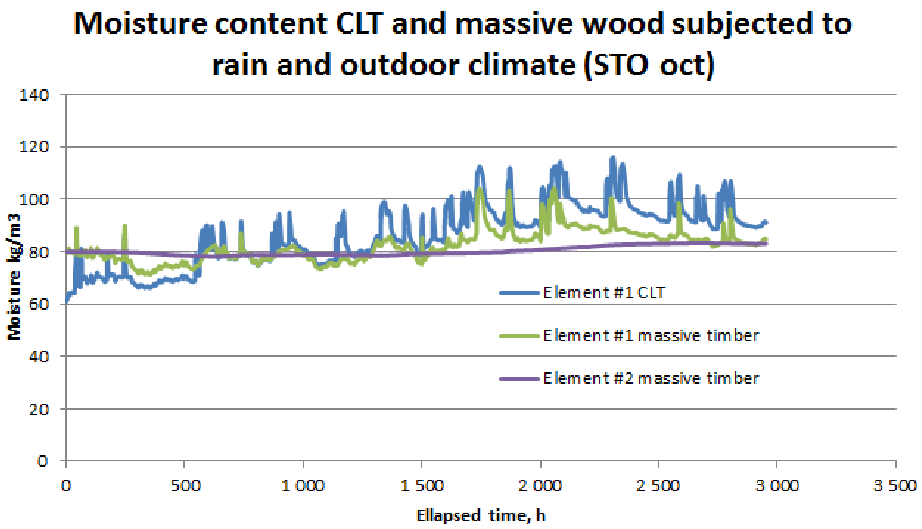

Figure 6.2-3 *Calculated moisture profile for CLT and massive wood using WUFI. The elements are 15 mm thick. Climate is Stockholm starting in october. The curves are sorted in order top down according to the label.*

Figure 6.2-3 shows that the intrusion of water only affects the outermost layers and that the adhesive in practice have a very limited role in the hindrance of external wetting (at least if there are no cracks). This is also found by Nore et.al. (2014). The base case and input data to the simulations in WUFI are described further in Appendix II.

Numerous simulation runs were conducted with both Stockholm and Gothenburg climates, varying the parameters and assembly of the CLT model based on the selected material data (Section 6.1.3).

The aim is to define an appropriate set of input parameters to the base case for further simulation. These runs produce a substantial amount of output data, such as moisture profiles development over time. These 'signatures' were compared and the hypothesis is that massive wood and CLT would behave much similar during wetting from rain and surrounding air humidity (at least for the outer layers). The main parameter to judge is the capillary suction and redistribution of liquid water.

A comparison of some calculated and referenced liquid water transport coefficients are given in Figure 6.2-4. A more detailed discussion on transport coefficients are found in Section 7.3.

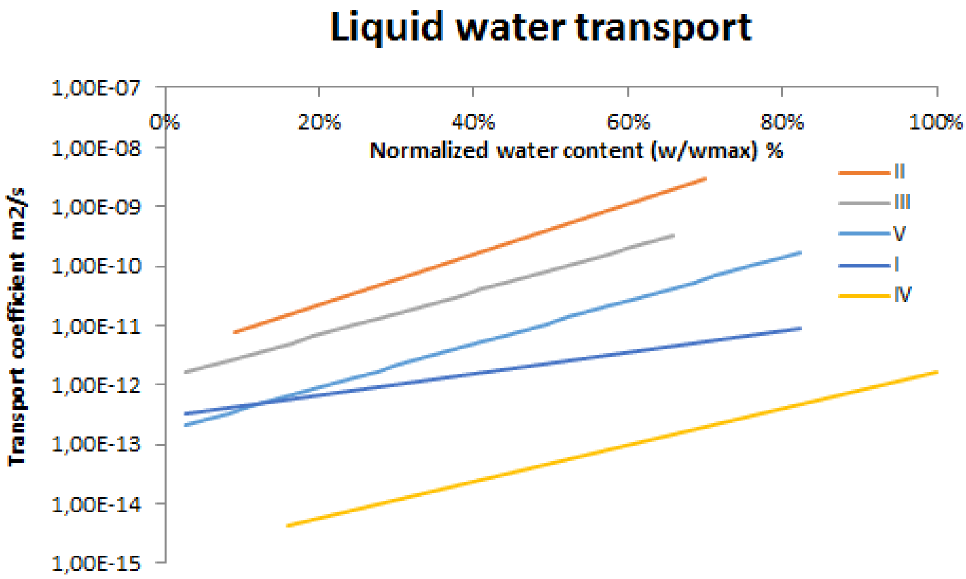

Figure 6.2-4 *Comparison of liquid water transport coefficients. The legend is defined below. Curves are sorted in the same order as the legend, starting with 'II' at the top.*

Legend:

I	*WUFI Spruce radial - database values.*
II	*Lepage (2012) - experiments.*
III	*WUFI general equation [4:8] (A- value 0.011 kg/m^2,√s according to long. direction (Lepage, 2012).*
IV	*WUFI generated suction curve - defined from general data in the base case (Appendix III)*
V	*WUFI general equation [4:8] (lower A- value of 0.007 kg/m^2,√s).*

Following initial simulations in WUFI, the following modifications to the base case for CLT are done:

- Capillary suction and redistribution of liquid water according to spruce data within the WUFI database. Redistribution is set equal to suction according to the comment on swelling influence made in WUFI.
- The sorption curves reach 100 % RH and have values corresponding to free saturation. The free saturation is set to 500 kg/m^3, which is somewhat lower than several material data found. However it is believed that a limitation of this value is more realistic in terms of how water is taken up by the material.

The outermost layers of CLT and massive wood should behave similar during wetting (both from liquid water and hygroscopic moisture). This is supported by various simulation runs using different material data on wood with and without glue layers. The water intrusion is very similar in those cases (refer to the result chapter and also to non-included working material).

A simulation run with a 7-layer element subjected to outdoor climate in Gothenburg (starting in November) show very similar behaviour to massive wood in the outer layers. Refer to Figure 6.2-5.

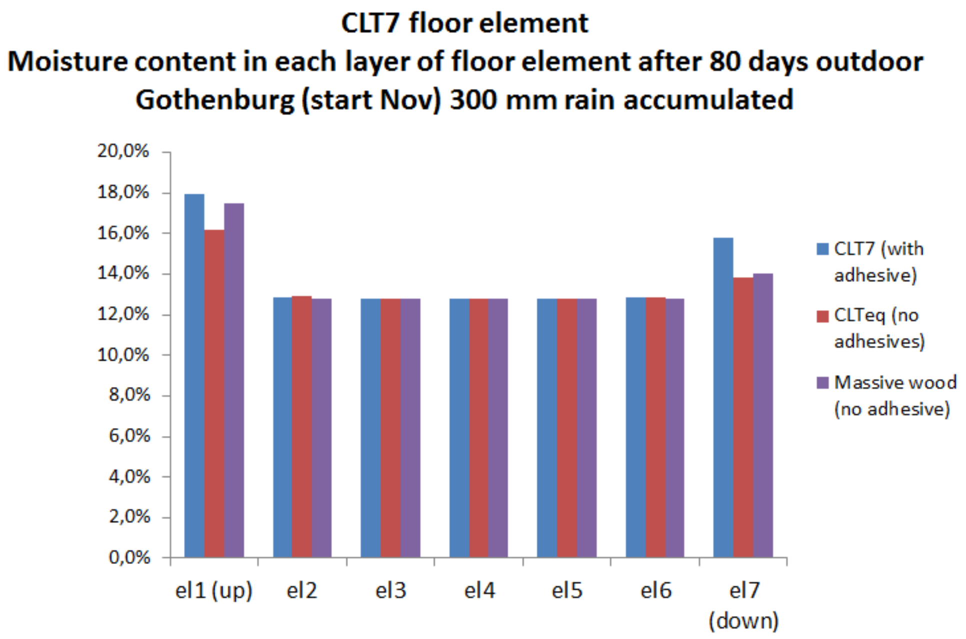

Figure 6.2-5 Moisture content in each layer (e1-e7) of a 7-layer floor element subjected to outdoor climate. Note the similarities between massive wood and CLT with adhesive layers.

The results show that after 300 mm rain (November -January) in Gothenburg, the floor element has increased its moisture content from 13 % to 18 %. The outermost layers have the highest moisture content and the inner layers are only changed minor due to the adhesive layers.
An equivalent CLT model underestimates the moisture content since it uses a reduced diffusion function. It is noticeable that massive wood also resembles the moisture profile to that of laminated CLT, although it shows lower values on the underside (el 7) of the panel (where no raining occurs). Note that no adhesive layers are included in the massive and CLT equivalent models respectively. The CLT7 model is used as a base case for further evaluations, i.e. adhesives are included in the model.

6.2.2 Boundary conditions

It is found that the radiation balance is important for the simulations in WUFI. Generally this has big influence on the surface temperatures, as the long wave radiation deals with the cooling of surfaces through atmospheric radiation. Since mould risk is driven by both temperature and RH, this effect must be included. In WUFI the option “explicit radiation balance” takes into account long-wave radiation exchange with the surroundings. If it is switched off, simply the heat transfer coefficient of the surface is increased. The only situation when it should be switched off, is if internal or sinusoidal climates are used on both in- and outsides.

The implementation (Section 5.4.5) discussed the basics and treatment of the radiation balance. Figure 6.2-6 illustrates the influence of radiation with an example.

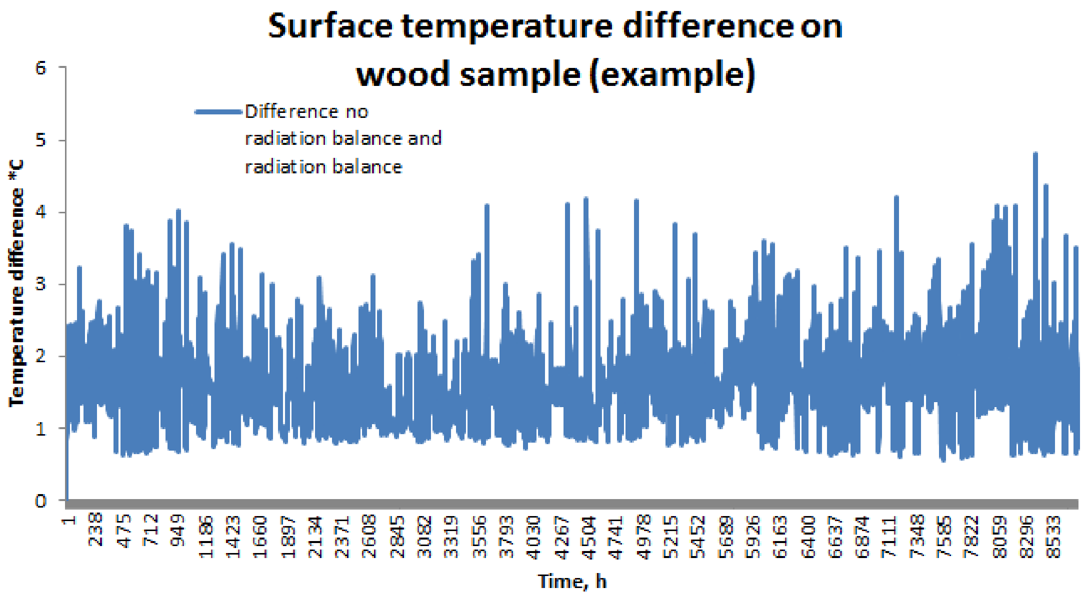

Figure 6.2-6 Example from 1-year simulation in Lund. The radiation balance reduces the surface temperatures by several degrees and thus increases the relative humidity. It is thus more conservative to consider long-wave radiation.

Air layers are 'materials' within the WUFI database with very special properties. Initially they were developed only to be used as heat resistances and in thin layers. The moisture capacity for air is defined by a general function relevant for mineral wool in WUFI. Since air cannot store more than tenths of grams of moisture per volume unit, the mineral wool approximation is an considerable overestimation. Therefore there are both air layers with and without additional moisture storage capacity available in WUFI. If the interest is mainly in RH and not in exact moisture storage the simplification to use air layers with additional capacity of moisture storage is reasonable and will speed up calculations significantly. In the building cover design, both types of air layers are used in order to both consider condensation and ventilation of humid air.

6.3 Hygrothermal calculations - main study

6.3.1 Wetting

The main study constitutes the bulk of the simulation work. It uses the base case refined in the previous section and evaluates wetting by different climate and periodicity. Evaluation of moisture content and mould risk is done according to the principles in Section 5.4.4. Both the cases of rain diversion (rain 'shut off') and building covers are simulated. There are a lot of underlying parameter input to the simulation cases, please refer to Appendix III for an definition of those values used. Table 6.3-1 summarizes the simulation cases.

*Table 6.3-1 Simulation cases for floor elements. y- yes; n-no rain; c- cover MC- moisture content; MI- mould index; RHC- critical RH. *) The number corresponds to number of months.*

Location	*Period*	*In charts**	*Rain load*	*Evaluation*
BER Bergen	Sep-Dec Mar-May	aut 4 spr 3	y/n/c y/c	MC, MI, RHC MC (MI, RHC)
GBG Gothenburg	Oct-Dec Apr-Jun	aut 3 spr 3	y/n/c y/n/c	MC, MI, RHC MC, MI, RHC
LUN Lund	Sep-Sep Mar-May	aut 12 spr 3	y/n/c y/c	MC, MI, RHC MC (MI, RHC)
KRA Kiruna	Apr-Jun	spr 3	y/n/c	MC, MI, RHC

The simulation cases cover various time periods and varying climate conditions. It is somewhat arbitrary time periods only to indicate the moisture behaviour at different times during the year. Note that all months in any ranges are included, e.g. Mar-May means March, April and May. Figure 6.3-1 gives an example of the moisture content development for a floor element subjected to rain and protected from rain respectively.

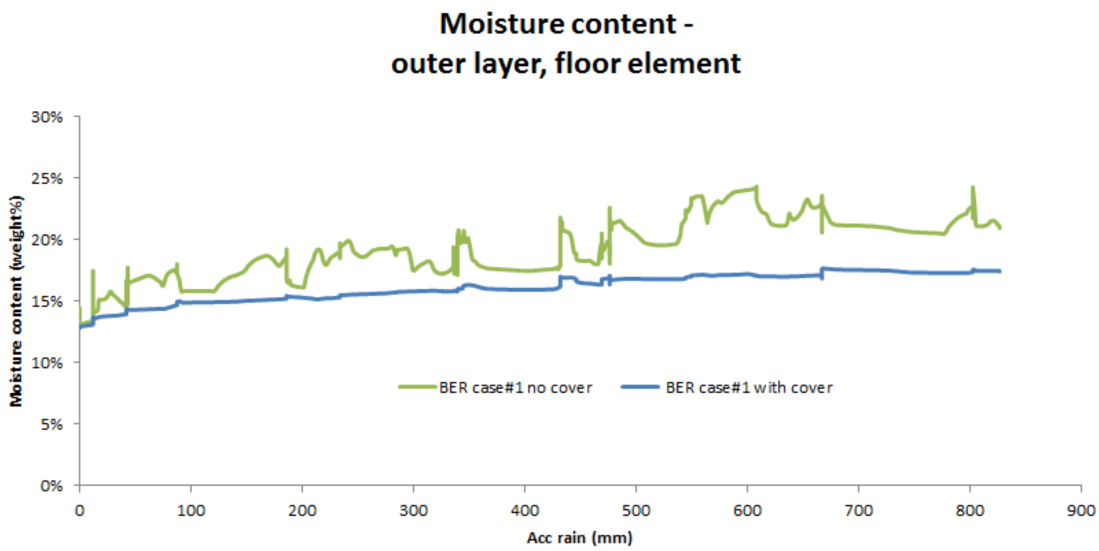

Figure 6.3-1 Moisture content development from outdoor floor element of CLT in Bergen during 3 months in the autumn. It is a clear difference in the moisture profile determined by the rain load.

From Figure 6.3-1 it is clear that the outer layer of wood could reach moisture content values in the range of 18-20% within a very short time, eventually reaching above 20%. Other locations show similar behaviour.

Within the scope and time frame of the current study it was not possible to establish any possible deterministic relations between moisture quantities and rain load. However, several attempts were made in order to express such dependencies. Instead a probabilistic approach was used, expressing the change in quantities in terms of a distribution function related to those selected random variables. There is a strong correlation between mould index and moisture content and rain load respectively. It is also noted that there is a time shift in-between accumulated rain load and moisture content respectively. The correlation between rain load and moisture content is high, although any relationship requires some pattern analysis, since rain intensity (not only accumulated rain) plays an important role.

Figure 6.3-2 shows the cumulative distribution of the the change (increase) in moisture content (MC) for the case with and without rain load, for a floor element in different climates. It should be interpreted as the additional moisture taken up by a horizontal element if it is not protected against rain. A value of 100% on the vertical axis corresponds to the respectively maximum increase in average MC on the horizontal axis. Note that the results are influenced by the length of the time period for the different locations and should be compared cautiously. Refer to Section 7 for a more thorough analysis.

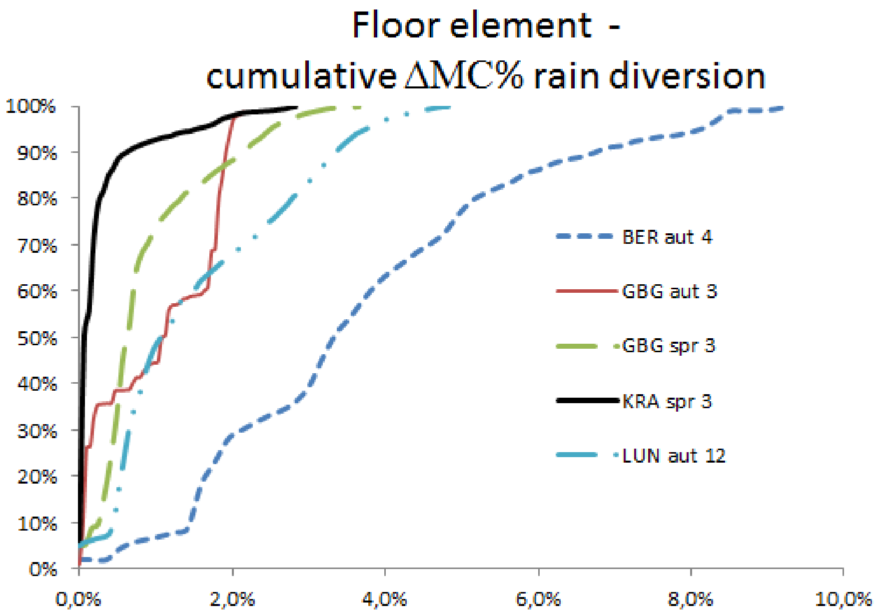

Figure 6.3-2 *Cumulative distribution of the the increase in moisture content (MC) for the case with rain load. Note that time periods vary in length.*

Figure 6.3-3 shows the cumulative distribution of the the change (increase) in moisture content (MC) for the case with and without cover, i.e. a roof and side cover which is ventilated by outside air.

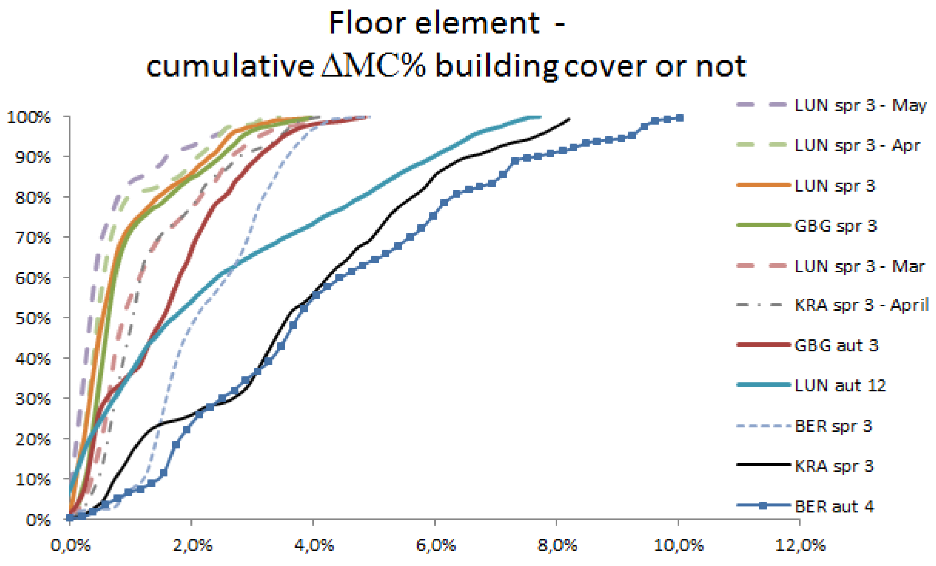

Figure 6.3-3 *Cumulative distribution of the the increase in moisture content (MC) for the case with weather protection. Note that time periods vary in length and some are broken down on months.*

By deciding what increase in moisture content that could be allowed, the above Figures serve as a guideline for evaluating the risk at different time periods and locations. These results are further discussed in Chapter 7.

The mould index and growth have been evaluated using both the indicator in WUFI (a green, yellow or red 'light'), the MIRHT-chart and the Folos-chart. The latter two shows graphically how much the critical RH is exceeded during the simulated time period. Part of the MIRHT-chart routine also calculates the accumulated time of exceedance. Both the Folos and MIRHT charts uses the critical relative humidity (RHC) which is an isoplete function derived from the WUFI BIO and VTT models. The mould index is evaluated based on the RHC.

An example of MIRHT-chart is given below in Figure 6.3-4 for a long time exposure of a CLT floor element in Lund, starting in September. Rain is diverted from the surface so it does not intrude in the panel. Regardless, there is an continuously increasing risk of mould development over time, due to preferable moisture and temperature conditions. There are not so many stagnation periods in the growth over the same time. A mould index above 1 is considered initiated growing and above 3 means clear visual findings on the surface.

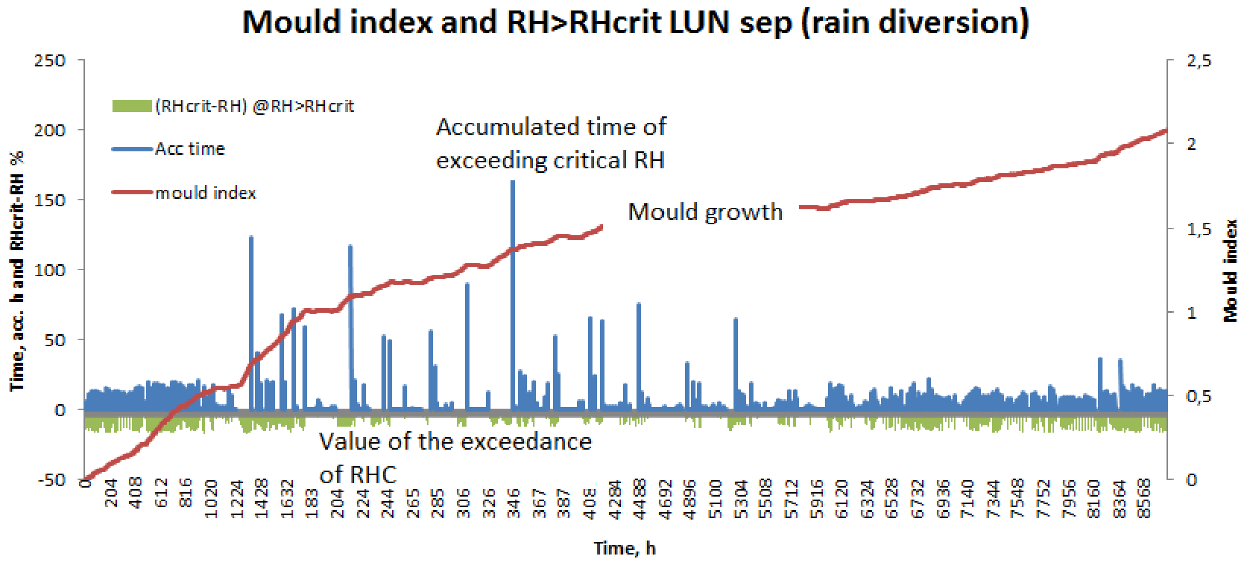

Figure 6.3-4 MIRHT-chart representing Lund over a one year period starting in September. The mould risk is continuously increasing.

The critical RH is at most exceeded by at least 1%-unit for about 200 h straight. Appendix III contains several MIRHT-charts for the various simulation cases.

The corresponding Folos-chart constitutes Figure 6.3-5.

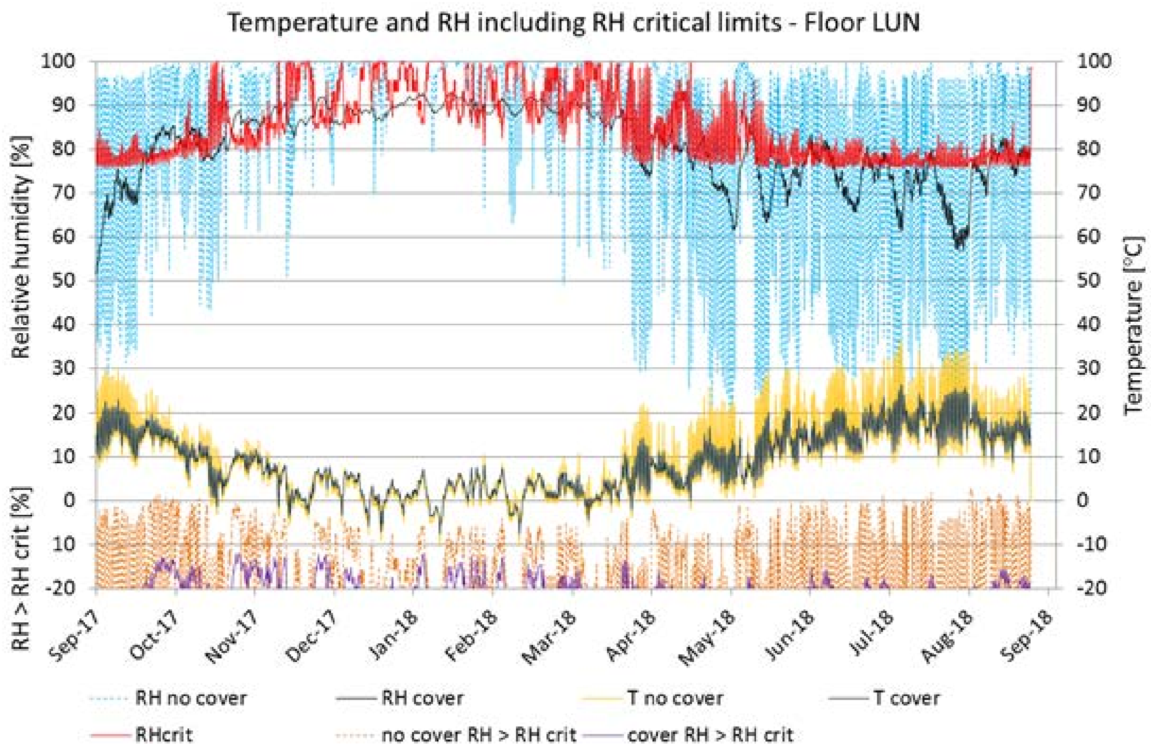

Figure 6.3-5 Folos-chart representing Lund over a one year period starting in September. The critical relative humidity exceeded for long periods of time due to the high RH and/or temperature.

Appendix III contains several Folos-charts for the various simulation cases. Results are discussed in Chapter 7.

Wall elements of CLT have also been simulated in outdoor and protected climates respectively. The number of cases for walls are more limited than for floor elements and the most illustrative examples and principles are included here. The rain load on a vertical surface is influenced by the wind speed and direction. A building with exposed outside walls of CLT and an indoor climate (EN 15026) is illustrated in Figure 6.3-6. In this particular case the adhesive layers are removed from the model in order to represent a local area with no adhesives (the adhesive coverage is in reality at least 80%). However, the effect of rain and external mould risk is the main interest here.

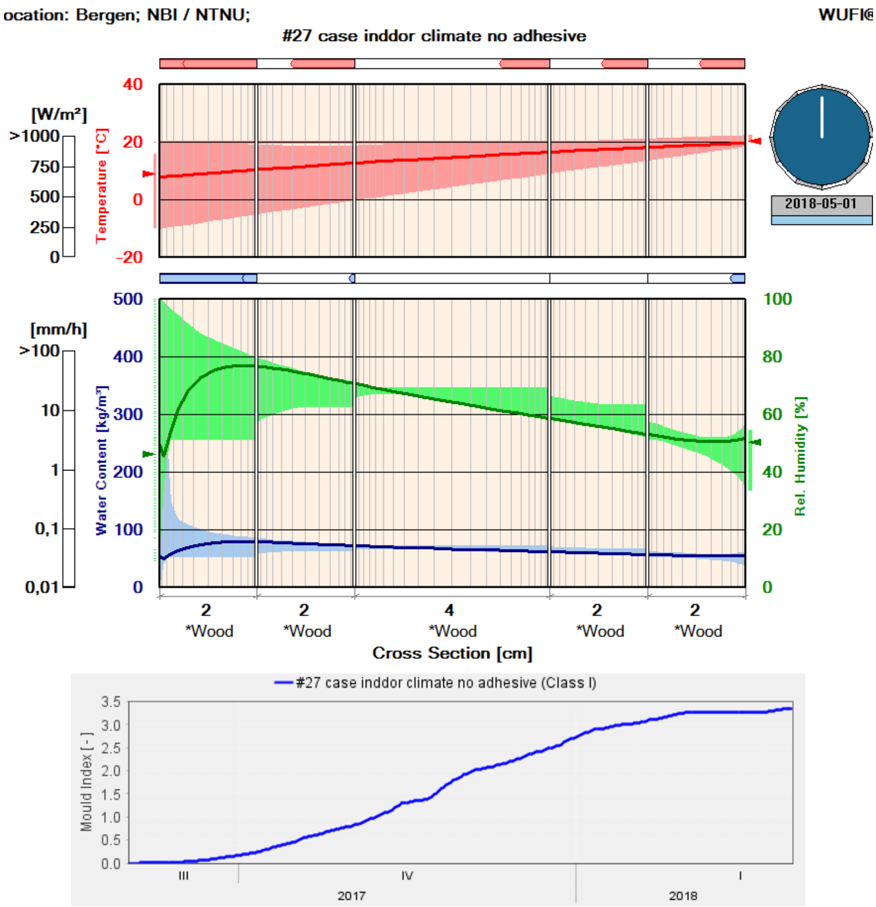

Figure 6.3-6 *Moisture and mould profiles for a wall element in Bergen (evaluated using WUFI BIO). Time period Sep.-Mar.*

The mould index exceeds 1 after about the third of the period and 2 after about the half the period (Sep.-Mar.). Generally there is a strong correlation between the moisture development in floor and wall elements. This has been illustrated by plotting the wall and floor moisture for the same surrounding conditions. Figure Figure 6.3-7 represents Lund in spring and autumn (Mar-May and Sep-Dec). Different locations show similar dependencies.

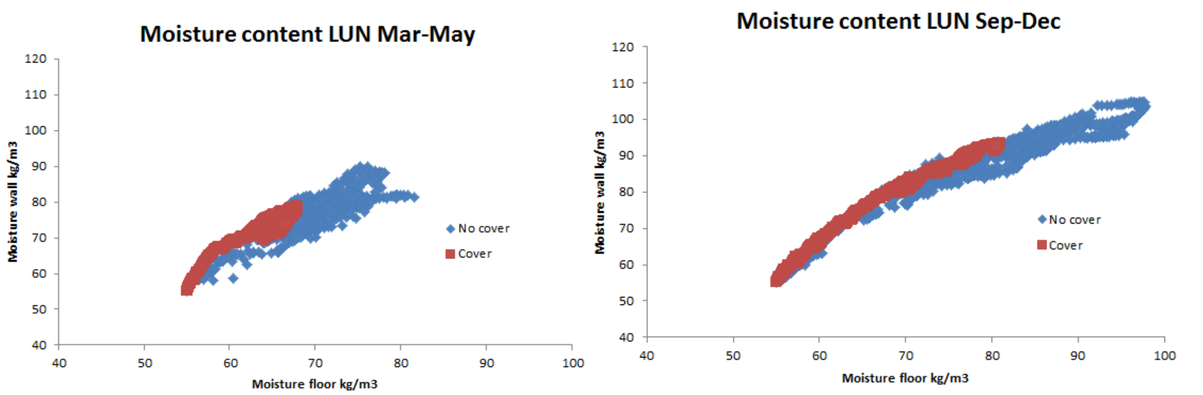

Figure 6.3-7 *Moisture content in a wall (y-axis) and floor (x-axis) with and without cover, in Lund during spring and autumn.*

Both the influence of building cover, time of year and correlation between moisture loads on wall and floor elements are showed in the Figure. Results are discussed in Chapter 7.

6.3.2 Drying and inclusion of CLT panels

CLT panels that have been wetted must dry either naturally or during a controlled climate. Drying and redistribution of moisture is a complex process with different transport mechanisms. Diffusion and/or liquid transport may occur at the same time and even in different directions during temperature gradients. The possibility of drying is also influenced by the construction in which the CLT panels are built-in.

One of the aims of the current study is to evaluate the drying process in terms of moisture redistribution and change in moisture profiles over time. In doing so, different floor and wall elements have been built in to a ‘typical’ wall or floor construction and subjected to in- and outdoor climates.

Note that the following drying situations are generally of principle interest:

- drying in natural surrounding environment without specific control or inference,
- controlled surrounding climate, combined with an outside weather protection.

Primarily the first situation may also include cases with built-in panels and internal moisture loads from activities within the building. Different cases with increased moisture content and varying climate and construction boundaries are evaluated. A ‘dry’ reference case is considered to have a MC of 13% (balanced moisture content at 50% RH of air and also close to the upper limit of 14% on MC for average wood species in the class 12%, EN 14298).

Table 6.3-2 summarizes the simulation cases. Refer to Appendix III for additional information on the cases.

Table 6.3-2 Simulation of ‘built-in’ cases. MC- moisture content; MI- mould index.

Location	*Period*	*Wall*	*Roof/ floor*	*Evaluation of CLT*
LUN Lund	Jan-	Wall with or without external insulation.		Controlled climate Natural climate MC 15-20 %
LUN Lund	2 years (May-)		Compact roof with outside insulation and 2 moisture barriers.	MC 14-18% outer layer and 13-16% other layers.
Internal moisture load EN 15026	4 years (May-)		Floor with gypsum+carpet and insulated ceiling	MC 14+17+17+...14+15% MC 14% at top layer before gypsum board is laid.

Only selected results are presented here.
Figure 6.3-7 corresponds to the moisture profile development in a compact roof in Lund. The outer CLT layer closest to the external insulation has a moisture content of 18% when the roof is built. Such a high initial moisture content would of course not be allowed in reality, but it illustrates the principle of moisture redistribution and drying. The other layers have MC 13%. After a period of 2 years with normal indoor activity (moisture loads from EN 15026), the outer wood layer has dried and the second outer layer has taken up moisture. The inner layers fluctuates with internal climate.

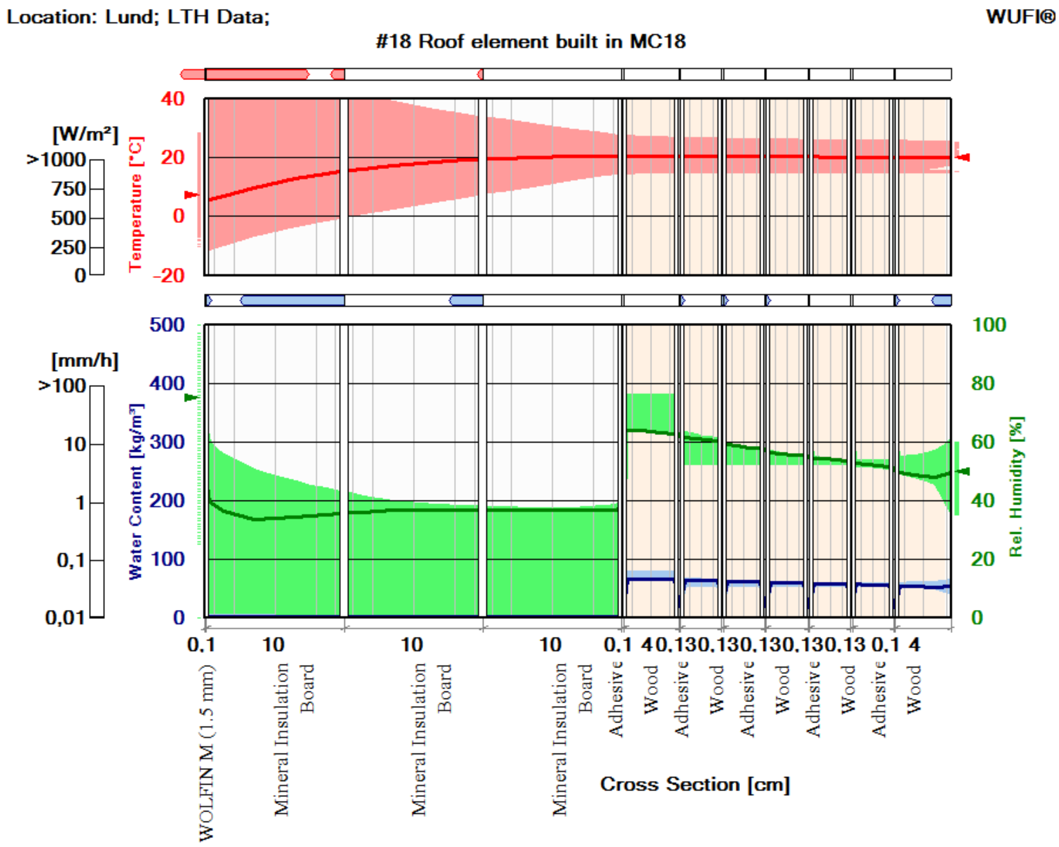

Figure 6.3-7 *Moisture profile of a compact roof in Lund. At the top is the temperature profile and the bottom part shows the water content and RH respectively. The simulation period covers 2 years.*

The moisture content in the outer wood layer (closest to the insulation) will reach below 15 % after about 1.5 years. The other layers have MC between 13 to 14%. Figure 6.3-8 corresponds to the moisture profile development of a floor between two internal climates (EN 15026). The outer CLT layer closest to the gypsum board has a moisture content of 14% when the floor is laid, whereas the internal layers have MC of 17%. The layers closest to the underside have MC of 14-15%. The case reflects an internally wet CLT panel.

After a period of almost 4 years with normal indoor activity (moisture loads from EN 15026), the outer wood layer has taken up moisture from the inner layers and the inner layers starting at MC 17% have dried to about 15%. The inner layers fluctuates with internal climate.

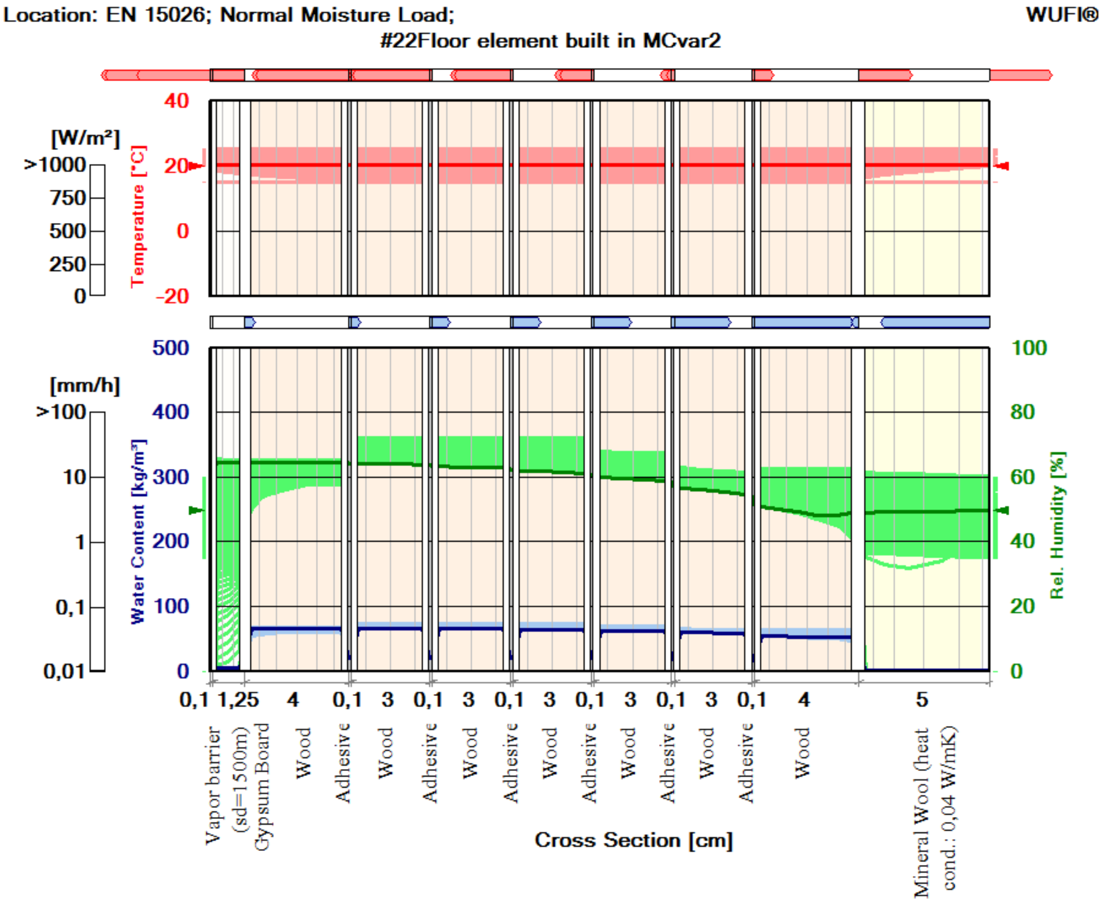

Figure 6.3-8 Moisture profile of a floor. At the top is the temperature profile and the bottom part shows the water content and RH respectively. The simulation period covers 4 years.

The drying is forced to go through the CLT element since the floor carpet works as an efficient moisture inhibitor (sd=1500 m). Therefore drying takes long time and will continue beyond the simulation period. Using an controlled climate on both sides of a CLT wall is also evaluated. Several moisture profiles are defined for a wall. The time until the target moisture content of 16% is reach is then evaluated from simulations. Figure 6.3-9 defines the initial moisture profiles for 4 cases. These are simply examples and case 1 is probably the most probable in a real situation. Cases 2 and 3 represent an internally wet wall.

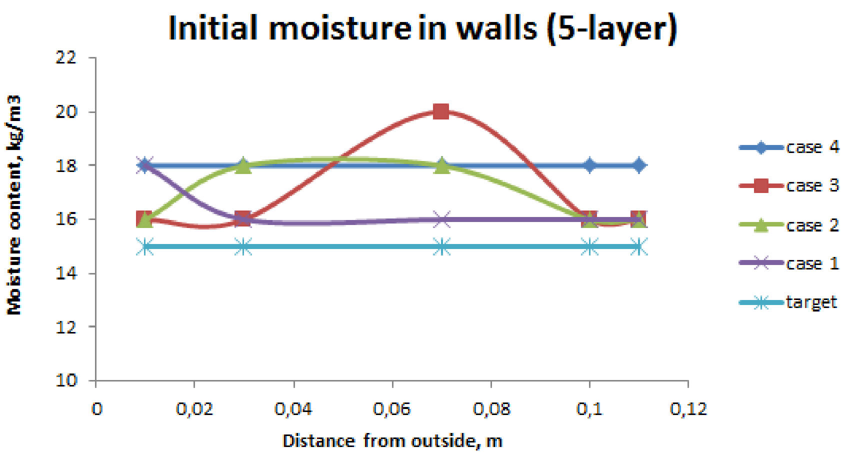

Figure 6.3-9 Initial moisture profiles for a 120 mm thick wall in Lund.

The moisture content, MC, is evaluated for both the controlled and non-controlled climates. A controlled climate is set on both sides of the wall using sinusoidal variations of temperature (20 +/-2 ºC) and humidity (40% +/-10%). The controlled climate is referred to as "dry". For some cases also an external layer of 280 mm mineral insulation is added and indoor climate according to EN 15026. Outdoor climate is Lund. Results after 45 days of drying are presented in Figure 6.3-10.

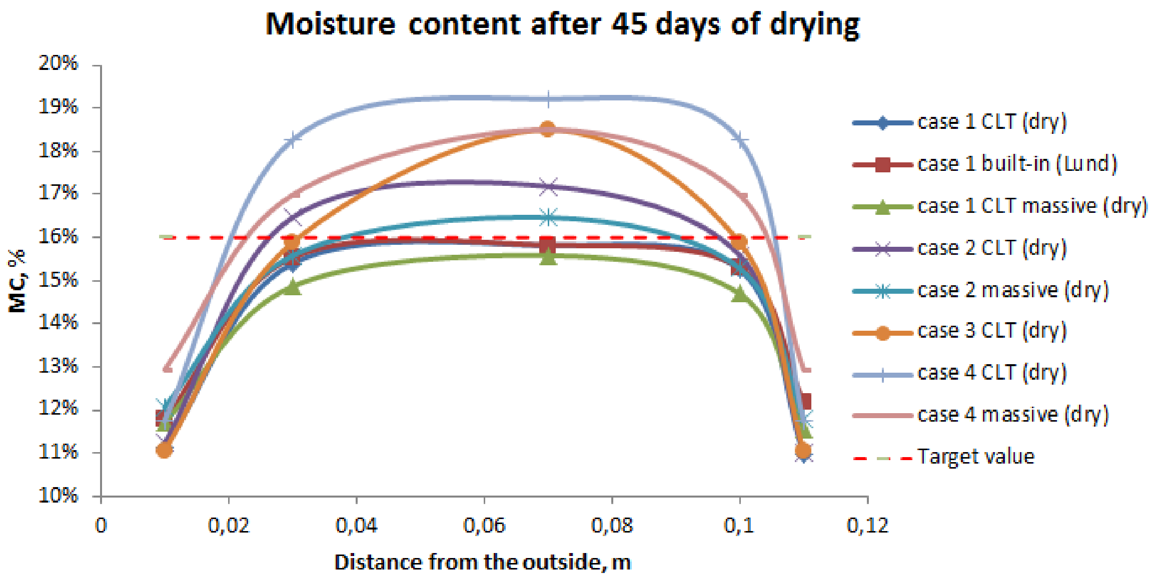

Figure 6.3-10 *Moisture profiles after 45 days of drying of walls. Cases refer to controlled or non-controlled climate and type of wall. The target profile of 16% is hardly reach if the moisture levels are initially increased.*

Cases 1, 2 and 4 are also tried without adhesives, i.e. massive wood. Case 1 is also evaluated once built in to an external wall in Lund with external insulation.

From the evaluation of the controlled climate and drying, it is evident that the adhesives have a great influence on the drying of the internal wood layers. Without adhesives the massive wood dries about twice as fast as with adhesives. The difference on outer layers are not as large, except if the internal layers have higher initial MC (case 4) and drives moisture towards the outer layers. For moderate moisture levels the natural drying inside a construction is not a problem and not significantly longer than for controlled drying. Cases with 16-18 % MC throughout the panels (cases 2 and 4) the internal drying takes still a long time; a few days or week on outside elements and 50-250 days for internal layers depending on the presence of adhesives or not. So even if the adhesive properties would be exaggerated in this study, massive wood dries very slowly. This is also stated by Nore et.al. (2014).

6.4 Available measurement data

6.4.1 Test and instrumentation

As mentioned in Chapter 5 there are two sets of measurements available from Gothenburg (F. Herrmann, personal communication, April 4, 2018):

- Test set-up outdoors (Nov.-Dec. 2017/18). Six horizontal pieces of CLT (each of about 1 m^2) were laid outside untreated and protected by coating and tape respectively. Figure 6.4-1.
- Instrumentation of floor elements in ongoing framing of an CLT building exposed to the weather.

The resulting moisture content (MC, %) was either logged manually or automatically. For the test pieces, Celsicom and Mitec was used as automatic logging on two pieces at various depths. Manual measurements were done using a Protimeter Timbermaster. Values are temperature corrected. Outdoor temperature and rain loads are also logged. No official or finalized test report was available, so the selection and analysis of results are done by the authors.

Figure 6.4-1 *Example of instrumentation with probes at various depths and positions on a test piece of a floor element. Courtesy of F. Herrmann.*

Results for a floor element with taped sides are given in Figure 6.4-2. The curves represent various measurement depths. Note that the tape came loose after about 20 days, causing the MC to rise rapidly.

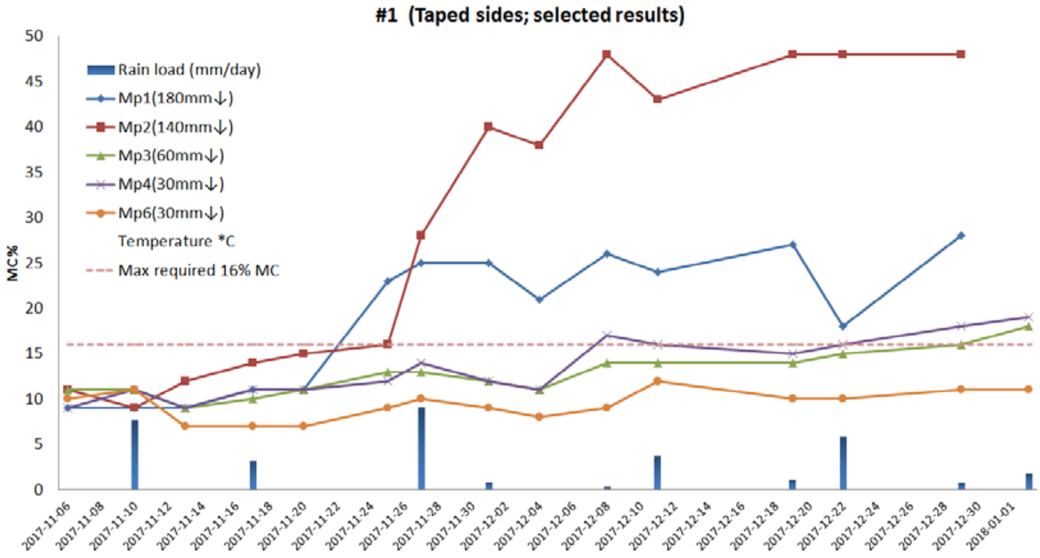

Figure 6.4-2 *Test with floor element and taped sides subjected to outdoor climate in Gothenburg. Measurement depths are given as the distance from the upper surface.*

Results for a floor element without treatment is given in Figure 6.4-3. Note the sudden increase in MC after about 25 days.

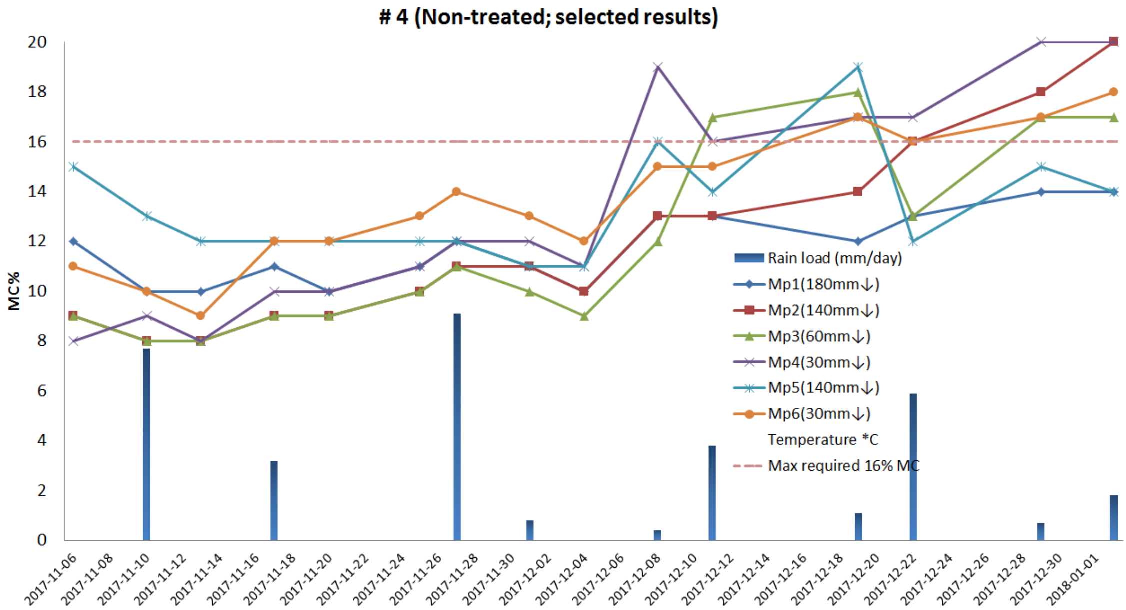

Figure 6.4-3 Test with floor element (no treatment) subjected to outdoor climate in Gothenburg. Measurement depths are given as the distance from the upper surface.

The accumulated rain load for the first 30 days of the tests is about 20 mm. Results from the instrumentation of an ongoing build had only two measurement points in floor elements at the time of the evaluation. One of the measuring points was affected directly by rain so only one remains valid. This logging shows a low MC of approximately 15 +/-0.5 % during March to June. Other probes were put in wood columns and show no critical MC levels for the period analyzed.

6.4.2 Simulation of moisture content for test species and actual building

A few simulation runs were performed on a floor element subjected to the same time period and location as the test pieces. At first the result did not show any increase in moisture content as clearly as in Figure 6.4-3. By including the effect of liquid water intrusion in the inner lamellas, comparable results were achieved.

The layers are given separate moisture sources, according to Table 6.4-1. Vertical rain load to the top surface is assumed to be not affected by wind (100% adherence). Climate according to WUFI climate file. During the period of November and December the rain load is about 200 mm, but only 20-30 mm until the moisture content change becomes evident. This is in the same order as was measured on the test site, so the climate data in WUFI is relevant for the evaluation.

Table 6.4-1 Assumed moisture intrusion defined in a horizontal CLT panel for measurement comparisons.

Layer	*Moisture intrusion, % of rain load*
Top layer #1	0.15
#2 & 3	0.2
#4 & 5	0.25
#6	0.35
#7 (bottom layer)	0.4

The moisture profile is based on a general assumption that rain runs down the sides and accumulates further down the CLT profile, before dropping off. The comparison is given in Figure 6.4-4. Note the similarities in overall behaviour of moisture content. Measurement data is repeated from Figure 6.4-3.

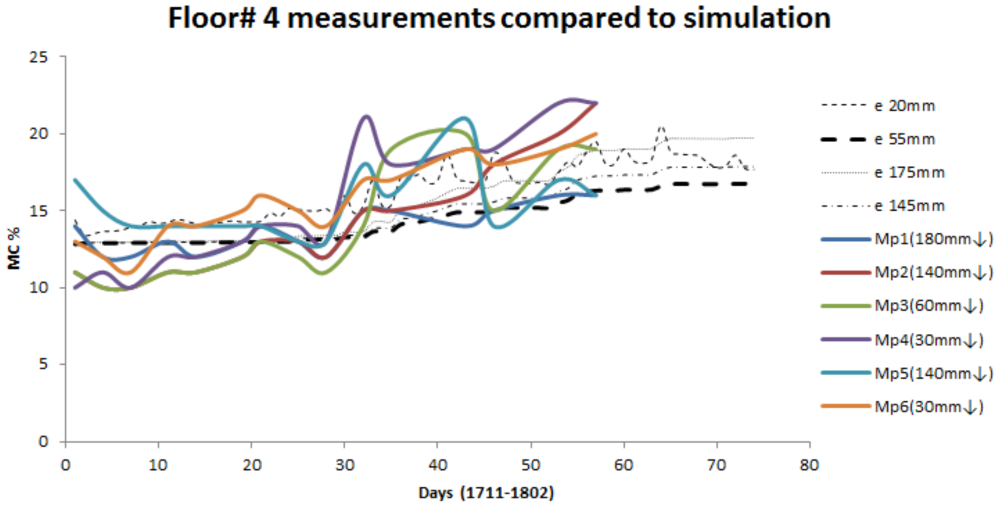

Figure 6.4-4 *Test with floor element (no treatment) subjected to outdoor climate in Gothenburg. Measurement depths are given as the distance from the upper surface. Comparable simulation results are represented by dashed lines for corresponding layers, influenced by rain water intrusion.*

Similar results were achieved for floor element #3, which also is untreated. Elements with sealed joints and/or sides should not show any major increase in MC besides the top layer. However, this was not clear from any of the tests with treated objects. The same increase in MC after about 20-30 days was visible in all test objects. Another simulation run without any rain loads is compared to the ongoing logging of moisture content in a CLT floor element in Gothenburg during construction in Figure 6.4-5.

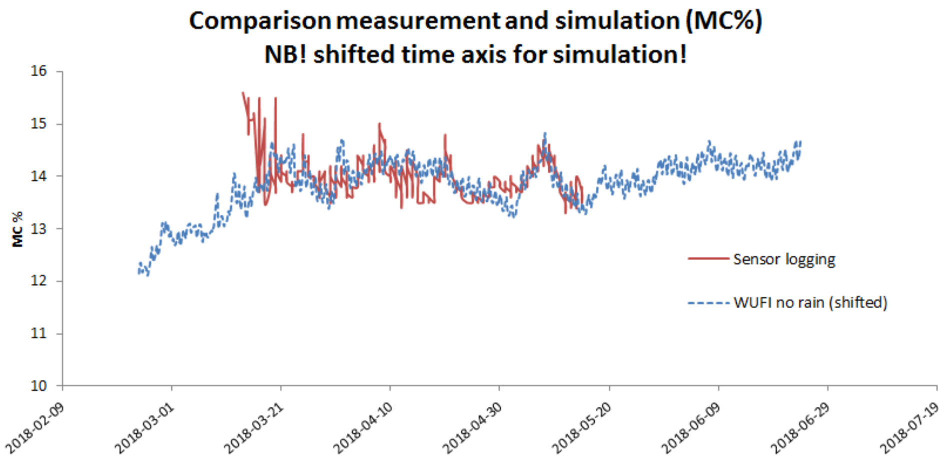

Figure 6.4-5 *History of automatic logging of MC in a floor element in a building being erected compared to simulation. The simulations are shifted in time by -6 days in order to achieve best correlation with the peak at 7:th of April.*

The time shift of the simulation results by 6 days is only to achieve a correlation for the peak value. Physically this would mean that the simulation results are delayed by 6 days compared to measurements. Refer to Chapter 7 for an analysis of the results.

6.4.3 Source of errors

The measurement data are by nature influenced by various errors. These have been generally addressed in Chapter 5. Limitations of available measurement are also limiting any possible comparison and validation of simulations. Results should therefore be viewed as indicative.

7 Analysis

7.1 Chapter outline

The analysis section is divided on the following sub chapters and contents:

- 7.2 - Hygrothermal properties. The main results from the material data search are compared and discussed in detail. This forms a selection for the base case used in simulations.
- 7.3 - Hygrothermal modelling. The results of the main study are condensed.
- 7.4 - Measurements and test. In this section the measurements from two different setups are briefly discussed.
- 7.5 - Moisture management and control, deals with the main findings in the literature survey related to moisture safety management of CLT in particular.

Referring to the objectives of the study (Section 1.4) the first point corresponds to 7.3; the second to 7.2; the third to 7.3 and 7.4; and the fourth to 7.5.

7.2 Hygrothermal properties

Based on the results of the literature survey, the material properties of CLT are analyzed and compared. This chapter gives an overview of these properties after necessary recalculations to common units etc. Bulk density varies somewhat based on source, due to different wood species, moisture content, quality etc. This parameter is however known for a certain CLT product. The variation is mostly in the range of 350 and 500 kg/m^3. See Figure 7.2-1. For further analysis, an average value of 430 kg/m^3 is chosen.

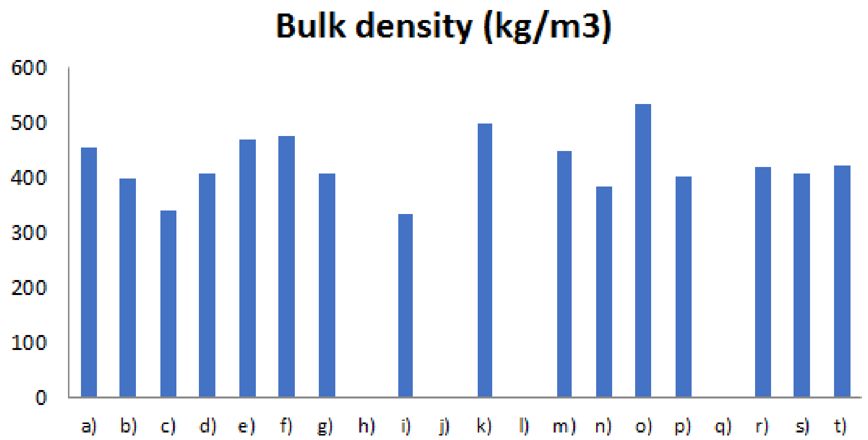

Figure 7.2-1 Densities found on CLT in the literature survey. References a)-t) are defined in Table 6.1-1.

Heat transfer coefficients also varies with the same properties as density and thereby also depend on density of wood. There are also dependencies of moisture content and even temperature. Typical variation is between 0.1 and 0.14 W/m^2, K. This is same as ordinary wood across fibres, and a value of 0.12 W/m^2, K is chosen for computations. See Figure 7.2-2. In general a weak increase in heat transfer is observed from increasing density, but the relation is not obvious.

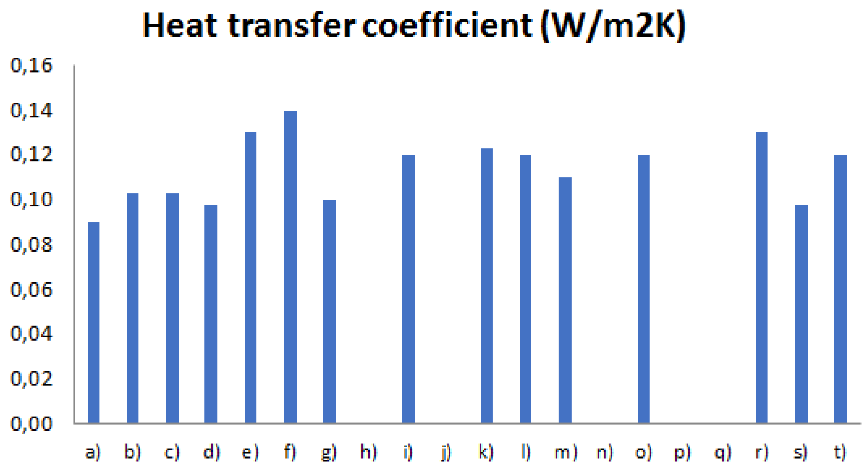

Figure 7.2-2 *Heat transfer coefficients found for CLT in the literature survey. References a)-t) are defined in Table 6.1-1.*

A number of previous studies define sorption data, but different material data and test setups make them difficult to compare. Figure 7.2-3 shows a comparison of sorption data between eight studies. Most sorption curve for CLT are in fact relevant for pure wood. In Figure 7.2-3 the comparison of sorption isotherms are derived from the same density (420 kg/m^3) from various references.

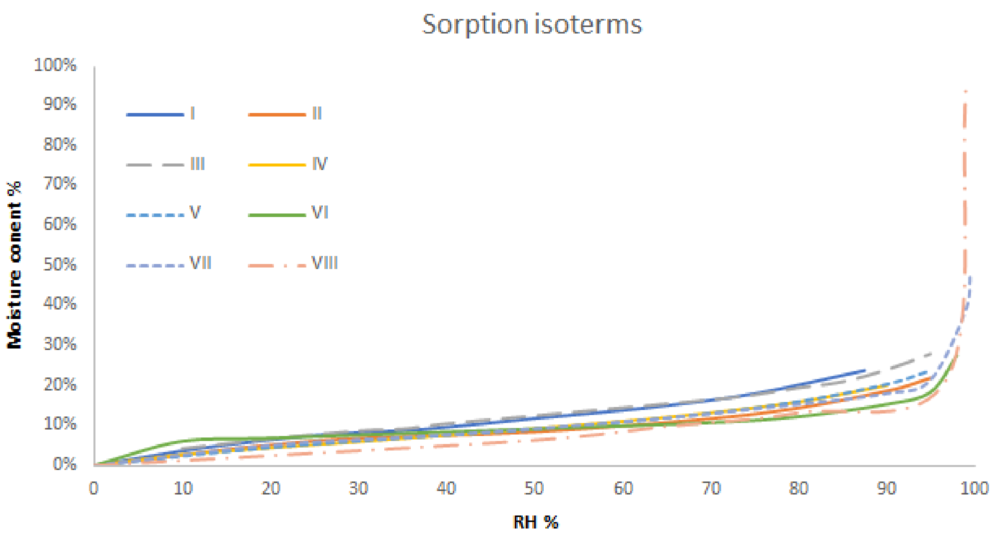

Figure 7.2-3 *Sorption isotherms given for the same bulk density of CLT based on the literature survey. The legend is defined below.*

A ‘zoom’ of the sorption curves is given below in Figure 7.2-4.

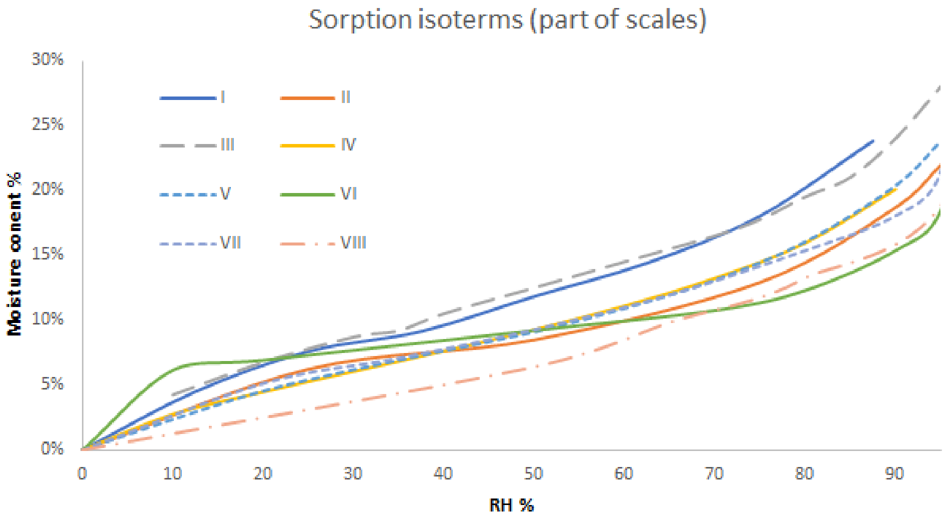

Figure 7.2-4 *Sorption isotherms from previous figure with shortened scales. The legend is defined below.*

Legend:

I *Sandin (2010), p.135.*
II *Alsayegh (2012) Table 5.6 Euro set 1, 22 ºC.*
III *Moisture Handbook (Arfvidsson et.al., 2017) p. 469 fig. 8.2.2.*
IV *Saft & Kaliske (2011).*
V *Glass (2013) CLT Handbook ch 10, pure wood.*
VI *Wang & Ge (2016) fig. 6.*
VII *Stora Enso (2017) (cut-off at 100% RH).*
VIII *KLH (WUFI Pro 5.3) Sorption (cut-off at 100% RH).*

Several curves are derived from manually digitization and impose some natural round-off accuracy errors. By ‘cut-off’ the curve is limited in moisture content from what is actually defined in the references. This is done solely for comparative reasons. There are differences in the sorption curves, although the ones for pure wood and CLT respectively are very similar. Some of the curves are in fact desorption isotherms which are elevated compared to sorption isotherms. Also wood adhesives have sorption properties and even moisture capacity. Figure 7.2-5 compares common adhesive types in wood products such as CLT.

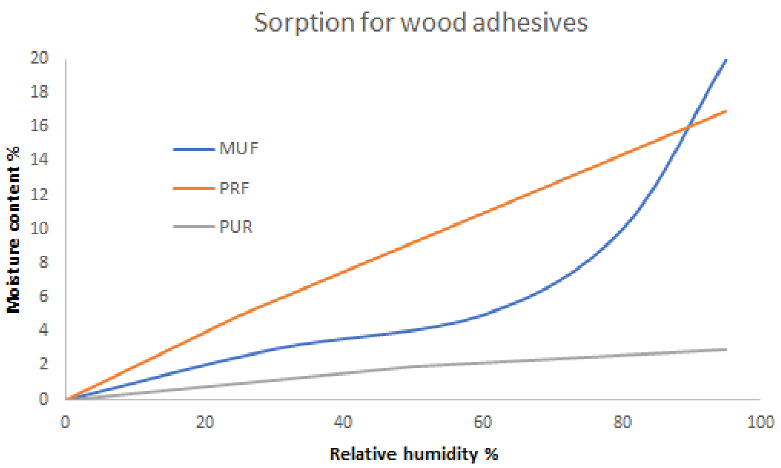

Figure 7.2-5 *Sorption isotherms for wood adhesive. Source: Digitized from Kläusler et.al. (2012). MUF= melamine urea formaldehyde; PRF= phenol-resorcinol; PUR= polyurethan. PUR is curve closest to the x-axis, followed by MUF.*

In CLT the PUR adhesives are common (see further below) and their moisture capacities are very low. The densities of adhesives are assumed to be around 1000 kg/m^3 based on various manufacturing information.

The by far most difficult quantities to compare are the moisture transport coefficients. In Figure 7.2.5 the vapour coefficient δ (m^2/s) is given as a function of relative humidity from various sources, both for pure wood and CLT products. Some of these functions have been manually digitized from figures given in the references rather than access to numerical data. Some have been recalculated from other units as well as derived for comparative moisture content using the appropriate sorption isotherms. This impose some interpretation and accuracy errors, but these should still be small in comparison to the overall results. Some references state only a constant vapour resistivity and those are not included in Figure 7.2-6. Refer also to the comments and further clarifications made below the figure.

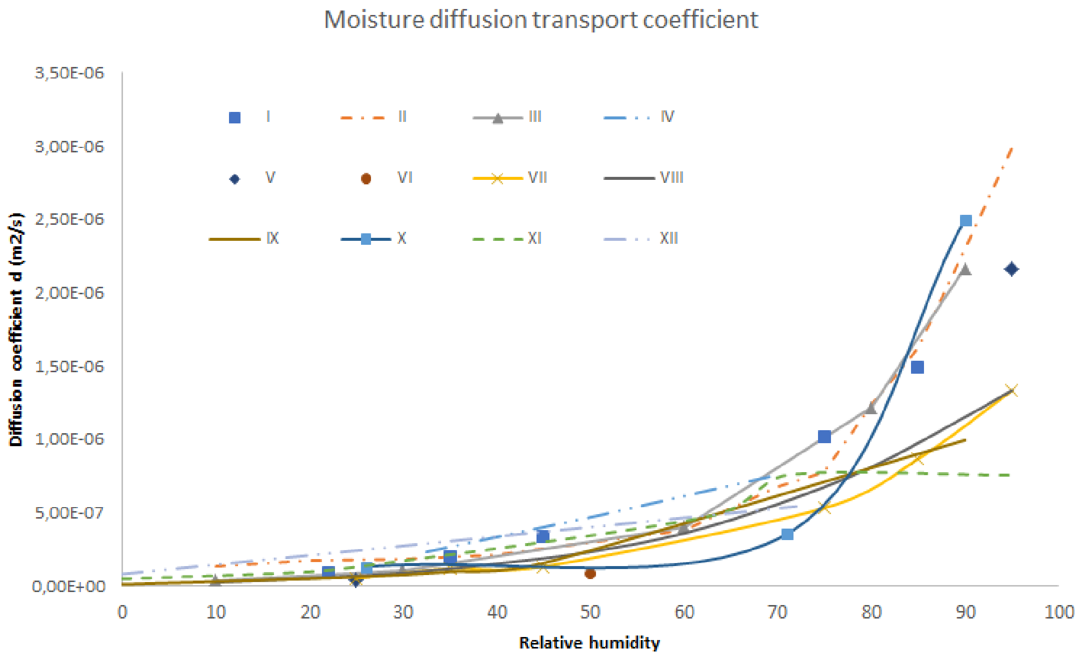

Figure 7.2-6 Diffusivity for vapour transport of wood and CLT based on the literature survey. The legend is defined below.

Legend:

I Alsayegh (2012). Fig5.3. Recalculated units from kg/ms,Pa to m^2/s. Refers to CLT and cup tests with adhesive joints.

II Sandin (2010), p.95. digitized values from original chart.

III Wu (2007) according to Alsayegh (2012), Fig 5.3. Refers to pure wood.

IV STORA ENSO (2017) Recalculated values given for different moisture contents of CLT. The sorption curve 'III' from Figure 7.2.3b was used for rough recalculation of moisture content to RH.

V Alsayegh et.al. (2013) different thickness.

VI Kukk & Hortaa (2017). Glued lamella

VII McClung (2013) recalculated values for comparison.

VIII Glass (2013). CLT Handbook ch10 fig 3 pure wood

IX Wang & Ge (2016). Fig. 6.

X WUFI database (WUFI Pro 5.3). BFU 100 Sperrholz (plywood)

XI WUFI database (WUFI Pro 5.3). Diffusion CLT from StoraEnso.

XII WUFI database (WUFI Pro 5.3). CLT from KLH.

One conclusion is that all of the examined materials have an increased vapour transport when RH increases. It is also noted that for the high range of RH, massive wood show about twice the diffusion compared to CLT. It is believed that these differences are attributed to both adhesives and type of wood. Some references concludes that wood and CLT are very similar in moisture transport, thus reducing the importance of adhesives (Alsayegh, 2012).

Another comparison is made between references of diffusion coefficient d and diffusivity D. The difference is the driving potential of moisture transport. Whereas d is driven by difference in moisture contents in g/m^3, D is driven by moisture content in kg/m^3. By calculating $D{\cdot}dw/dv$, a comparative d is achieved. Refer to Section 4 for the mathematical equations. Figure 7.2-7 compares the moisture transport coefficients from three references for wood in the range of 3 to 28 % moisture content. Note the similarity between moisture transport coefficients, given the recalculation of diffusivity for 'II'.

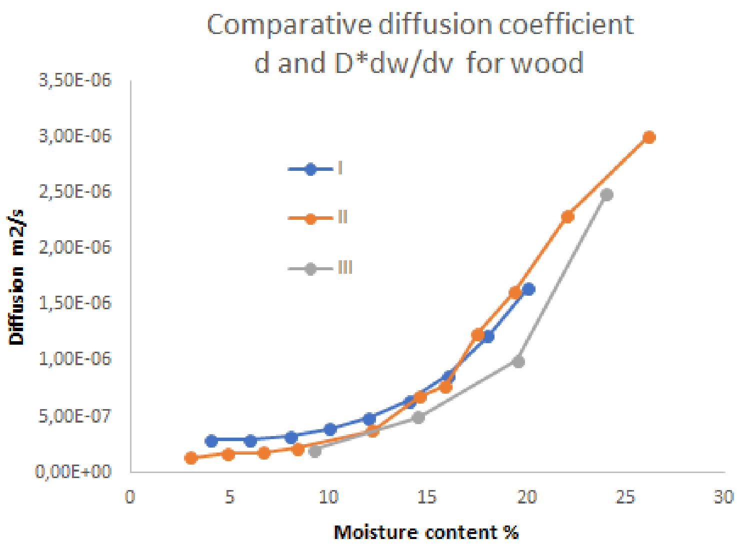

Figure 7.2-7 Diffusivity for vapour transport of wood based on the literature survey and calculations. The legend is defined below.

Legend:

I Hassani (2010). Norway Spruce radial, diffusivity as a function of MC
II Sandin (2010), p.95
III Moisture Handbook, (Arfvidsson et.al., 2017), p.472.

Values proposed by Lepage (2012) on capillary suction and redistribution significantly overestimate the liquid water uptake compared to pure wood and other references on CLT (such as the WUFI material database). Alsayegh (2012) reports on tested values even lower than those of ordinary wood. This is not to say that the results from the experiments by Lepage are wrong; on the contrary it is suspicious that the data available on CLT differ that much from input to experimentally calibrated simulations.

However, the consequently water intrusion in CLT should not be considerably larger than that of wood. Such differences could only be explained by the presents of cracks, lack of adhesives or along-grain water uptake (which is considerable faster than transport in radial direction). Measurement on pieces of CLT made by Lepage (2012) indicates that the capillary coefficient is in the order of 0.011 $kg/m^2,\sqrt{s}$ which is order of magnitudes higher than that of wood in radial direction of 0.004 (Arfvidsson et.al., 2017). The high value is also commented by Lepage. However we believe that the experimental CLT panels had cracks or that water leaked into the end grain when having them in a water tray.

It should be mentioned that Lepage (2012) used data for spruce within WUFI and modified those data to better coincide with experiments on real CLT panels. The experiments and parameter modifications suggests that WUFI underestimates the wetting and drying speeds of CLT when free water is present

It is tempting to use different values for suction and redistribution within each layer of wood, but there are very limited references on these parameters and no real method of measuring redistribution (Künzel, 1995). The moisture diffusion is generally low at low RH and increases when the relative humidity in pores of the material increases. This is caused by an increasing capillary transport above the hygroscopic range. In real situations both vapour transport and capillary transport can occur simultaneously (Sandin, 2010).

It may even be so that vapour transport goes in one direction and capillary in the other when a temperature gradient is present. For wood in particular there is no capillary transport until the fibre saturation point is reached (about 30% moisture content). When the moisture content of wood increases it becomes difficult to describe the moisture transport by difference in vapour concentration as potential (L.O. Nilsson, personal communication, April 16, 2018). This is also why it is common to use a constant vapour diffusion resistance factor and a separate liquid water transport coefficient, such as softwares like WUFI does.

In theory it is possibly to describe all moisture transport by one equation, but the difference between moisture transport coefficients driven by vapour concentration and moisture content respectively differs by several orders of magnitude. It is therefore common to assume that the vapour transport is dominating within the hygroscopic range (Sandin, 2010). For the very same reasons it is not possible to mathematically deduce the moisture transport coefficients for different driving potentials, based on a total transport function. Such differencing must be made based on measurements. For a pure isothermal approach, whatever mathematical solution that splits the driving potentials and still fulfils the total moisture transport can be executed (L.O. Nilsson, personal communication, April 16, 2018).

In practice both the vapour and capillary transport coefficients (functions) must be defined. In order to compare these, despite their differences in order of magnitude, it is found that the resulting moisture transport from both vapour and liquid water makes a good quantity for comparisons. Refer to Figure 7.2-8 for an example of isothermal moisture transport, divided into a vapour part and liquid part. The envelope stated the total moisture transport. The liquid phase requires free water and is the consequence of exceeding the fibre saturation point (some 25-30 %). The example is based on selected data for the base case of simulation.

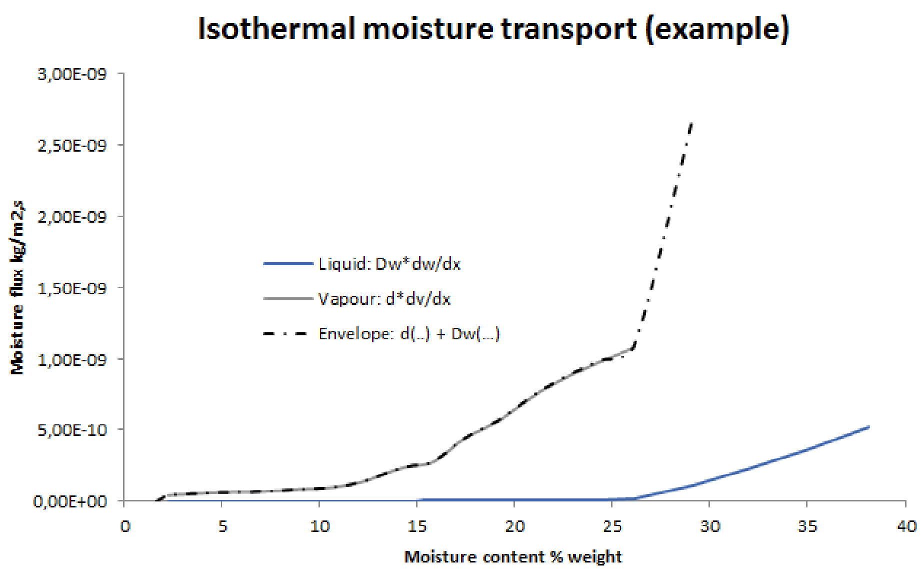

Figure 7.2-8 *Moisture transport defined by both vapour and liquid terms. The principle illustrates that both vapour and liquid water may be present simultaneously.*

More thorough and elaborated discussions on moisture transport below and above the hygroscopic range are provided by Nilsson (1988), Straube & Burnett (2005), Tong (1986) among others.

In CLT products the PUR adhesive is commonly used and gains increasing market share (Messmer, 2015), (StoraEnso, 2017). Also other types of adhesives are used but PUR has environmental benefits since it is formaldehyde-free.

PUR is used as an representative adhesive in this study. The diffusion coefficients have been derived from calculations. Values on diffusivity for various adhesives are found in (Hassani, 2015). Those data are based on tests on specific adhesives for engineering wood products. However, it was necessary to convert the given transport coefficient governed by moisture content to that of a moisture concentration to be used in the simulation software. The relation between diffusion and diffusivity was used (Section 4.3) to manually derive the coefficients. The sorption curves from (Hassani, 2015) were used to convert between moisture content and relative humidity and the density of the adhesive was set to 1000 kg/m^3. The results are presented in Figure 7.2-9 and the diffusion of wood is added for comparisons (Sandin, 2010).

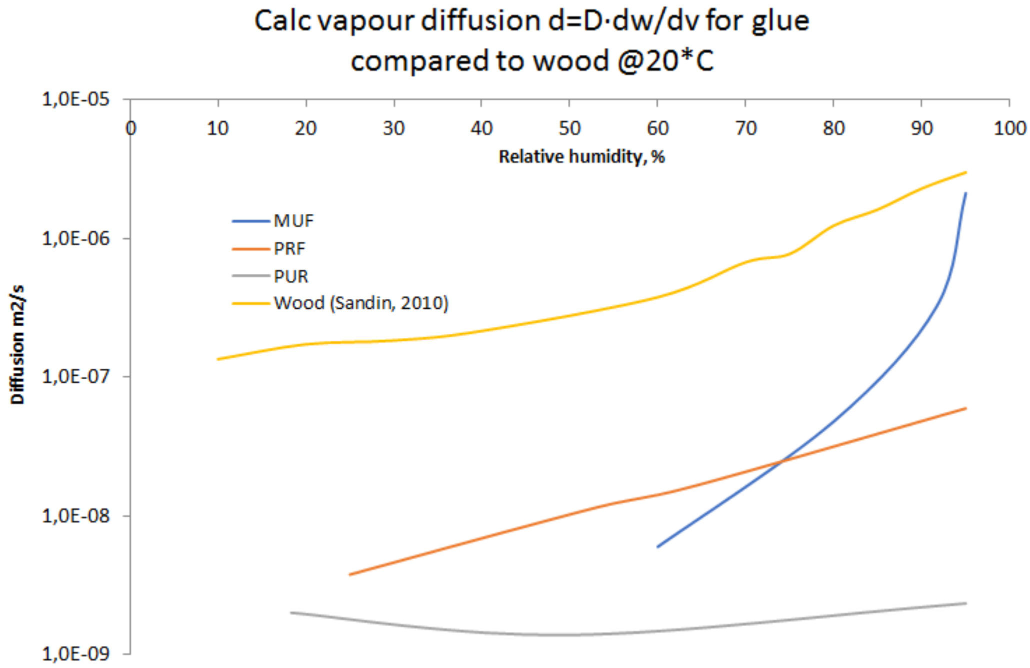

Figure 7.2-9 *Diffusion coefficient for adhesives, calculations based on Hassani (2015). Wood is given for comparisons. PUR is the curve closest to the x-axis, then PRF and MUF.*

Certain types of adhesive have an increasing coefficient with increasing relative humidity, as wood behaves. On average, the diffusion coefficient for PUR adhesive is calculated to 1.5E-9 m^2/s. This corresponds to a my-value of around 17 000 or vapour diffusion resistance of Z= 70 000 s/m for a 0.1 mm layer thickness.

Based on results by Belleville (Belleville et.al., 2008) the diffusion transport coefficient is estimated to be roughly 10 times lower for adhesives compared to wood (PVC adhesive in this case). According to results on wet and dry cup test on both adhesives and wood, generalizing data from Volkmer et.al. (2012) yields that the adhesives are about 10-100 times less moisture permeable compared to wood. This is in the same order of magnitudes as found in the recalculation of the diffusion transport coefficient from Hassani (2010). Finally it is relevant to compare the calculated figure Z= 70 000 s/m for PUR adhesive to that of polyurethane coatings with Z= 90 000-120 000 s/m according to the Moisture Handbook (Arfvidsson, et.al., 2017).

Adhesives diffusion increase with increasing RH according to StoraEnso (2017). They express the diffusion relative to wood. For low humidities (26.5%) the coefficient corresponds to 6 mm spruce and at high humidities (71.5%) to 13 mm, although it is not clear what the comparison with corresponding air thickness means (refer to the material table in Chapter 6). A 6 mm spruce lamella has a moisture resistance of Z=30 000 s/m (dry) and 6 mm (wet) has Z about 16 000 s/m (authors' calculations). If the adhesive thickness is 0.1 mm the diffusion coefficients for dry and wet are in the range 3-6E-8, which is between PRF adhesives and pure wood. In practice the adhesive coverage is not 100 % so there will be areas where CLT will behave as massive wood. Due to limited information on equivalent adhesive properties, those of the specific adhesive types will be used. In this study PUR will therefore also become somewhat conservative.

In summary the adhesives could approximately be modelled as moisture barriers with a constant vapour diffusion resistance in the order of polyurethane coatings, or about 10 times that of pure wood. There will be areas where glue is not fully covering the surface (there are some minimum 80% coverage required in production, crack formation etc.) and those spots will locally behave like massive wood. It has been showed that during wetting the adhesive layers play no important role, but in drying they do. Therefore - and because PUR adhesives are the most moisture resistive - it is more conservative to consider the specific layers as separate moisture barriers than ignoring them, or using some weighted wood and adhesive property combination.

7.3 Hygrothermal modelling

This chapter refines the base case for simulation and discuss the revisions. Also the modelling aspects of building covers are discussed. Finally the results of the main study are analysed. The initial base case from Appendix II (first setup) is revised after the pre-study. Table 7.3-1 defines the refined base case used in the main simulation study.

Table 7.3-1 Base case for moisture data used in the main study. Appendix III defines the details.

Moisture related parameters	*CLT model approach*	*Comment*
Sorption	Moisture handbook (Arfvidsson et.al., 2017 p. 469) Data is complemented by saturation point at RH 100%. Adhesive data is based on sorption according to Klaüser (2012).	The sorption curve is weighed against the density of 430 kg/m^3 (Section 7.2).
Diffusion	Wood data from Sandin (2010). Calculated vapour resistance for adhesives based on Hassani (2010). Section 7.2.	Not pure vapour diffusion above wood saturation.
Liquid suction and redistribution	Spruce data according to WUFI database.	Otherwise limited information available from literature survey.
Other data	Typical or average values on other wood parameters.	Section 7.2.

It is evident from a theoretical perspective that adhesive layers greatly influence the moisture transport coefficients, since adhesives are more vapor resistive (Section 7.2). However, almost no reference considers adhesives as specific layers. It is showed in the initial simulations that the adhesives are relevant for the moisture profile development over time, especially during drying and redistribution. For wetting the adhesives are generally not as important as the water uptake should not reach the adhesive layer passing solid wood. Cracks however, may direct water further into the panels.

The suction transport is probably overestimated, since the diffusion coefficient for vapour also varies (increases) with (increasing) moisture concentration. Since these data come from different sources and thereby combines different results, it is not possible to establish an explicit division between suction and vapour transport. Some trial simulations using all required input data from the same reference compared to using a combination of references have been carried out. The results show about the same overall behaviour, although it is suspected that the liquid water transport could be slightly overestimated in the calculations of moisture profiles in CLT. This is still justified by:

1) In reality there might be cracks in the surface, exposed end grains (edges, fastening elements, cut-throughs etc.) and even non-glued longitudinal lamellas; and
2) there are in principle only two material references - which are both part of the WUFI database -that includes all relevant data, but with constant vapour resistances;
3) the importance of the differences are reduced when conducting parametric and relative comparisons.

The spruce data in WUFI on suction and redistribution is said to be tested from outdoor rain influence, which is valid for our task. The layered wooden laminated of CLT should behave similar to those of wood. However, since CLT is made up of glued lamellas, both with and without glue between longitudinal joints, there is an realistic risk that water may penetrate these voids. It is also believed that mounting holes and other intrusion points should justify an even bigger water uptake speed. This could be modified in terms of the surface absorption coefficient.

Lepage (2012) found that the redistribution from experiments on CLT is much higher than given for spruce within WUFI. Due to lack of additional data, this value is not considered here. It was however an initial hypothesis that data from experiments in real conditions should be ranked higher than theoretical or even laboratory ones. A multitude of initial simulation runs did not consider free water and thus no real effect from such experimental data. In progressing results the effect of free water was found decisive and the need for more reliable data apparent. A qualitative interpretation of intrusion depth and moisture content served as a guideline for choosing base data. To some extent data is also compared to a limited amount of measurements.

Suction in radial direction should evidently be small and the major effect is in the longitudinal direction (Arfvidsson, et.al. 2017). This is also confirmed by various literature dealing with water uptake in wood (Lepage, 2012; Alsayegh, 2012; Alsayegh et. al., 2013; Fredriksson, 2013; Glass & Zelinka, 2011). The CLT-data in WUFI is lacking information about liquid transport, but values exist for spruce. There is a function for generating these values within WUFI, but these became very different from the one given for spruce. The coefficients may also be derived from capillary coefficient (the ‘A-value’), but the result is believed to be too high. The present study concludes that there are limited amount of data available on liquid transport and redistribution in wood (and other materials). For the purposes of the current study it has not been possible to state values better than those provided by WUFI on spruce. The main argument is that these material data are derived from tests with rain exposure, which is our main concern. Other data suggest different values, sometimes by the order of magnitude difference. Future work should further clarify the range of data required to recover these uncertainties.

Generally the building cover in the simulations impose some vapour resistance between the outside air and the ventilated inside air. Even if the ventilation rate is high, there will be an interference from the building cover (it also has an slight insulation effect). This is why the cover is more resembling an complete building cover compared to a roof cover, which only protects from rain. These cases have also been evaluated in simulation. The effect of a ventilated cover compared to a simple roof cover may be significant. This is believed to be caused by an reduction of the RH inside the cover due to heating and limited ventilation, as well as a simplified one-dimensional approach where convection and lateral movement of moisture and air is not considered.

The cases with rain diversion is simply rain switched off, so there are no roofs in the simulation model. Our interpretation of the simplified models are that the influence of a building cover is both protection from rain and a slight reduction in humidity levels around the building. A simple roof cover only divert rain and do not cause any influence to the surrounding climate. This is the analogue used in the interpretations of results. The true effect of a simple building cover without controlled environment is somewhere in between these approaches. In all cases the explicit radiation balance should be ‘switched on’, according to its importance described in 6.2. The effects of initial heat and moisture capacity balancing are small in comparison to the lengths of simulation. Although there might be steps and transient behaviour in the result during the initial hours of simulation, these effects rapidly vanish. Any time dependence on the sorption isotherms is not considered. For wood subjected to seasonal climate, the acclimation to humidity is believed to be fulfilled. For fast variations the time delays become very important.

The simulations of floor elements have showed that the building cover has a major effect on the moisture content in wood. Various locations and time periods have been tested. The moisture content will vary with the external climate and seasonal changes, but rain will always increase it. The increase in moisture content is intrinsically depending on rain load (accumulated and momentary), relative humidity in air and surrounding temperature. Specific dependencies are although not easily derived. A clear time delay between moisture content development and rain load is observed. Regarding the change in moisture content due to building cover or not (Figure 6.3-2) it is a measure of the influence of rain load and relative humidity, whereas the change in moisture content from a roof cover (Figure 6.3-3) is a measure of the influence of rain load. These differences follow the reasoning above.

Evaluating the simulation results according to the principles outlined in 5.6:

- Change in moisture content. Not more than 3-4 %-units based on an initial 13 % MC. This would correspond to a limit value of 18 % in average.
- Mould index and the rate of mould index growth.
- Exceedance of the critical relative humidity, RHC.

A change in moisture content of about 3% corresponds to a tangential deformation of wood of about 1.4 % (calculated from 0,36 %/% deformation; Svenskt Trä, 2018). 1% is for example a 2 mm crack on a 200 mm wide board. The natural variation of moisture content in wood principally varies between 8 and 20% (RH 30-90 %), but surfaces are not allowed to built in at MC above 18% (AMA hus, 2014). Moreover, 18% is the upper range of average values of MC for wood species of target MC 16% (EN 14298:2004). Therefore 18 % is considered an upper limit. It is also important that the panels are manufactured under low RH to avoid subsequent cracking. From the cumulative distribution charts the influence of weather protection is evaluated for an 90% probability of the distributed simulation results. This means that 90% of all calculated changes in moisture content due to weather protection or not, does not exceed a certain change in moisture content. This quantity is named ‘dMC90’. Below follows an evaluation location by location. Climate data is taken from the Moisture Handbook (Arfvidsson, et.al., 2017; CantyMedia, 2018).

Gothenburg GBG

dMC90 (Moisture content difference due to weather protection)

- Autumn case: < 2% if covered with a roof. For a building cover dMC90 is 3%.
- Spring case: 2% if covered with a roof. For a building cover dMC90 is 2.5%

MC (moisture content if unprotected)

- Reaches 18% after about 8 weeks in the autumn case (140 mm rain) and 3 weeks in spring (90 mm rain). Starting at 13%.

MI (Mould Index)

- Autumn case is worst. MI is growing but slightly below 1 over 3 months if not protected.
- Continuous growth in November. With rain diversion the MI is halved.
- In May the MI is reduced, but grows in June.

RHC

- Generally <10% above limit in spring and close to 20% above in the autumn case.

Climate autumn/spring

- Acc. rain 355/300 mm
- Average rain 100/118 mm/month
- Average RH 78/70%

Bergen BER

dMC90 (Moisture content difference due to weather protection)

- Autumn case: <7% if covered with a roof. For a building cover dMC90 is above 7%.
- Spring case: For a building cover dMC90 is 3.5%.

MC (moisture content if unprotected)

- Reaches 18% after about 1 week in the autumn case (40 mm rain) and 3 weeks in spring (115 mm rain). Starting at 13%.

MI (Mould Index)

- Continuous growth entire autumn case. With rain diversion the MI is halved to about 1 at maximum.
- With building cover the growth is subsided. Even simple roof cover may result in mould after longer time.

RHC

- Generally <10% above limit in spring and close to 20% above in the autumn case.
- More continuously above limit during autumn.

Climate autumn/spring

- Acc. rain 830/445 mm
- Average rain 275/150 mm/month
- Average RH 83/75%

Lund LUN

dMC90 (Moisture content difference due to weather protection)

- Autumn case: <4% if covered with a roof. For a building cover dMC90 is 6%.
- Spring case: For a building cover dMC90 is 2.5%.

MC (moisture content if unprotected)

- Reaches 18% after about 4 weeks in the autumn case (40 mm rain) and 1 week in spring (50 mm). Starting at 13%.

MI (Mould Index)

- Continuous growth entire autumn case. Similar to Bergen. MI above 1 in 1.5 months and finally reaches 3.
- Even with rain diversion MI is still growing above 2. With building cover the growth is subsided.

RHC

- 10-20 % above limit even with rain diversion. Requires some building cover.

Climate

Sep-Dec:

- Acc. rain 265 mm
- Average rain 66 mm/month
- Average RH 84%

Jan-Apr:

- Acc.rain 245 mm
- Average rain 61 mm/month
- Average RH 85%

May-Aug:

- Acc. rain 290 mm
- Average rain 73 mm/month
- Average RH 74%

Kiruna KRA

dMC90 (Moisture content difference due to weather protection)

- Spring case: <1% if covered with a roof. For a building cover dMC90 is 6.5%.

MC (moisture content if unprotected)

- Reaches 18% after about 6 weeks in spring (15 mm rain). Starting at 13%.

MI (Mould Index)

- No mould is growing even without protection. Note that snow that melts is not included.

RHC

- Small exceedances and late during the spring period. Melting snow is although not included!

Climate spring

- Acc. rain 105 mm
- Average rain 35 mm/month
- Average RH 70%

In general a autumn case is more sensitive to any protection against weather. *I.e. it is more important to protect buildings during autumn and winter*. Also warmer months with less relative humidity is less critical than the vice versa. In principle protecting from rain will cause the wood to adopt to the outside humidity, which could be in the order of 80-90 % and thus a moisture content of 20-24 %. See Figure 7.3-1 for comparisons. In addition, *all MI are higher during autumn cases compare to spring cases*.

The difference between the probability plots for rain diversion and building cover (reduced rain and RH) respectively is lower than the difference between no cover and some rain protection. That is to say that rain has the major influence on the development of MC.

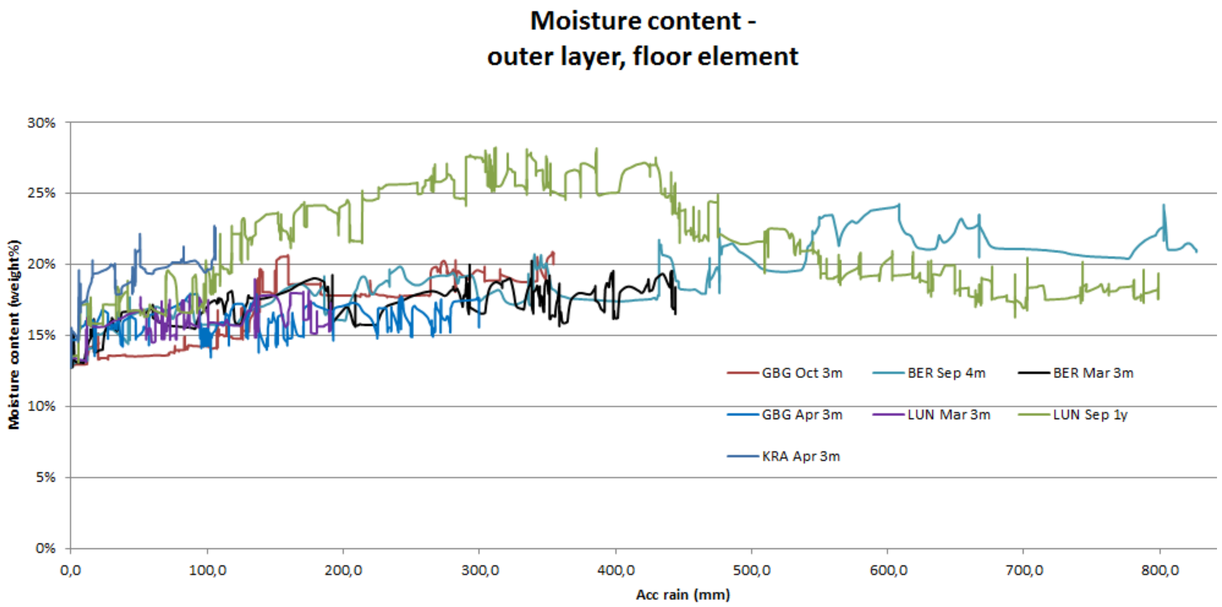

Figure 7.3-1 *Moisture content development with respect to rain load.*
The numbers correspond to the time period length in months starting from the month indicated.

The relation between MC and RH are very scattered, depending on time period and climate. The relation between MC and rain load is also somewhat fluctuating, but with a clear overall increase with accumulating rain. *Thus diverting rain is more important than the surrounding RH*. Still *a controlled climate is better than simply diverting rain*. Note that the different accumulations of rain load correspond to different time periods, i.e. there is no one-to-one relation between a certain point in time and the rain load for the different cases. This is important to have in mind when comparing the curves. A peak value of one curve may very well be exceeded later in time by another case, if if would have covered the same time period. Most cases are of length 3-4 months and start in the same month, in spring or autumn respectively.

The probability of a certain moisture content depending on location and time period is given in Figure 7.3-2. The Figure is derived from the results in Chapter 6 and represents cases with no rain/weather protection. A certain probability corresponds to the highest expected MC.

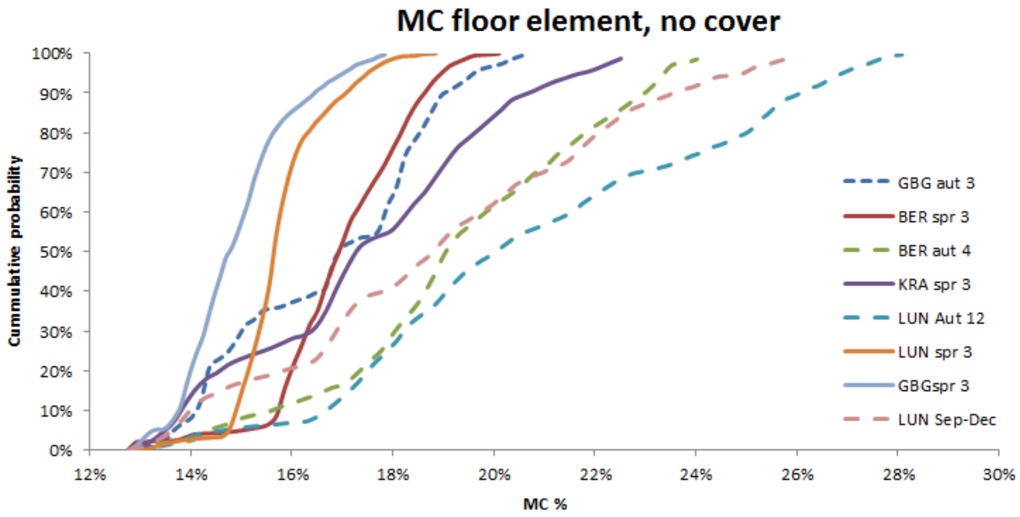

Figure 7.3-2 Probability of moisture content distribution depending on location and time period. Autumn (aut) and spring (spr) are somewhat arbitrary names for the months included. Specfied months in Section 6.3.1. The numbers correspond to the time period length in months.

It is clear that a autumn/winter case is more likely to give high MC if unprotected. The time it takes to achieve a certain MC (say 18%) differs between the autumn and spring cases. This is indicated above and may seem contradictory, since it takes longer time in most autumn cases. The reason for this is that the moisture flux is influenced by the rain load and temperature gradient. If the moisture flux in and out of the surface as well as the surface temperatures are more closely analysed it is found that:

- In Gothenburg and Lund the inward fluxes are higher for the spring case, since the temperature and/or the rain intensity is higher in those cases. In Bergen it is the opposite. For all cases the relative humidity on the surface is always higher in the autumn cases. It is thus concluded that a high surface temperature may cause a moisture transport inwards, since it results in a moisture concentration gradient. For Gothenburg the spring case cause higher surface temperatures at the beginning of the period than the autumn case (but the initial rain loads are about the same). Thus the MC raise quickly in the spring.
- For Lund the spring temperature is lower than corresponding autumn case, but the rain intensity during the first month of the spring period is higher, so it drives water into the surface. For Bergen it is vice versa compared to Lund and the increase in MC is more rapid during autumn due to much more heavy rain loads.
- A rain load of about 10-20 mm can increase the MC by 5% but still dry naturally within days if the climate allows.

To conclude the complexity, the MC depend not only on RH and rain load, but also on temperature and rain intensity. Also it is clear that an autumn cases is generally worse in terms of mould risk and increase in MC, whereas a spring case tends to more rapidly increase the MC. To generalize it could be said that *it is important to protect the building from rain at all locations and at all times! Short building times are crucial.* It is also evident that the wood layers experience periods of drying due to surrounding temperature and RH. The natural seasonal changes may dry or further wet the surface depending on location and time period. Although the cases used here with time periods shorter than a quartal year show overall continuously increasing MC, the one year period in Lund demonstrates the seasonal changes. Still natural drying takes time and would definitely result in damage. In addition, the MC will most likely not return to the initial levels. The delayment effects of rain load as well as the influence from rain intensity and vapour concentration variations makes it close to impossible to utilize natural drying. Besides requirements on building time, the climatic uncertainties also makes it impossible to plan with respect to future rain load, rain intensity and drying periods.

Of the sites investigated, it appears that protection is always required in Bergen - moreover than just rain-repellent. Building in June and November should be avoided in Gothenburg and no more exposure than 3 months. This is due to higher rain loads in June and November, respectively. Very short building times (1-2 weeks) could be handled without protection but with great caution. Kiruna appears to have minor problems with mould and moisture, but it is also due to snowfall which is not included as rain the the simulations. This is also true for other locations and it is indeed important to remove snow so that it does not melt and becomes a moisture source. With respect to mould and mould growth, lower RH is more important than the rain load. RH is lower during spring when the temperatures are increasing and thus reducing the mould limit. In autumn the temperatures and RH are high and the mould criteria is sensitive. Note that no case with cover produce growth nor increasing the mould risk.

What is said about floors are also generally true for walls since there are correlations between the moisture uptake and weather exposure. A wall may even be more critical since it is not protected from the floor element above or from any natural roof. Wall elements have been simulated using various initial moisture conditions. It is obvious that drying out takes a very long time, but for constructions with "open" materials (at least one sided) this is generally not a problem for roof and floor elements. Lepage (2012) also concluded that different wall constructions with a substantial moisture content have the ability to dry over time as long as they are 'breathable'. Also refer to McClung et.al., (2013) who concludes that built in moisture alone is unlikely to cause failure of a building.

The lengths of the simulation periods do not necessarily reflect actual building time with or without rain protection. The periods are rather chosen to identify long-term behaviour of moisture risks and illustrate the wetting process. There are numerous ways of selecting the time sequence to simulate, but here the differences over longer time are primarily interesting for breaking down the influences to short-time behaviour. Also Lepage (2012) suggested longer time periods when simulating constructure moisture uptake in CLT panels and concluded that uncovered CLT will have an unsafe moisture content after been exposed to rain for a longer time. For more results on different type of assemblies see Lepage.

There is a certain delayment effect in the moisture response of CLT panels (and other materials with high moisture capacity). This effect is obvious when studying the moisture content development i the outer layers of wood subjected to rain loads over time. Although this delayment is difficult to quantify, it is roughly calculated to 0.3-0.8 % units of corresponding moisture content. Therefore it is a cautious estimate to subtract 1% from any limit values of moisture content in order to include this effect.

7.4 Measurements and tests

From the tests (6.4) it is clear that the end grain protection is important. The MC increased rapidly when the tape on the sides fell off. It is also concluded that the moisture content is different at different depths and once subjected to rain it is not necessarily the top layers that are most wet, due to the end grains, cracks etc. After about a month, the MC had raised from around 10 to 16% at the most. For a non-treated CLT panel the MC raised rapidly after about 30 days or 20 mm accumulated rain.

Simulations assuming internal wetting through rain intrusion in all layers corresponds remarkably well with the measurements on all depths (Figure 6.4-4). This demonstrates that water intrusion and transport occur not only from the surface but also in layers. The change in slope of moisture content after about 25 days is also reflected in simulations, believed to be caused by delayment effects from the historic rain load. Also note that the exact climate is not input to the simulation, but the same period and location are matched in WUFI climate files. Obviously this comes with uncertainties, but the overall effect is still the same.

The measurements from the building site in Gothenburg is more poorly recreated in simulations. Only by not considering rain and introducing a time shift of 6 days is the correlation improved. This is however believed not to be physically representative since:

- The measurements reflect sudden changes in surrounding environment and the results are averaged over a time window.
- The time period of less than 2 months during the spring is not extensive enough to make a the comparison relevant.
- It is not clear what the peak at the beginning of May really is and there is a similar peak at the beginning of the measuring period. Neither one of these peaks are attributed with any explaining sensor errors, from the sensor log.

On the whole, and at current state, what can be said is that the measurements do not show any critical levels of moisture contents. The same levels are also predicted in simulations.

7.5 Moisture management and moisture damage control

Moisture uptake in end grains is crucial and may occur in joints, cut-throughs, gaps, wall-to-floor connections etc. Such moisture uptake takes much longer time to dry out than moisture that influence surfaces (Fredriksson, 2013). Therefore it is crucial to protect end grain from moisture uptake. It is important to consider the variation within a certain moisture content class. In this study, initial MC of 13% and target values of 16% are used. These are close to the limits of moisture class 12% (EN 14298). Actually, class 12% means that the average MC of all samples could vary between 10.5% and 13.5%, but in 93.5% of individual samples a maximum value of 15.6% is still allowed. It is important to reduce and follow up on the allowed MC.

The following selection of moisture principles are brought forward as a checklist (see further Section 6.1.5):

- ❏ Short building times are important.
- ❏ Use weather protection/cover.
- ❏ Plan and predict moisture damage both qualitative and quantitative.
- ❏ Moisture content should be kept low at delivery and storage.
- ❏ Do not store CLT outside more than a month, and keep emballage and clearance of ground.
- ❏ Remove snow so that it does not melt and becomes a moisture source.
- ❏ Use wax or sealants on areas where covering is difficult or delayed.
- ❏ Mounting on rain free days.
- ❏ Follow up with measurements at least weekly.
- ❏ If water leaks in, be prepared with equipment to remove it quickly and instruct everyone at site.

Especially in large buildings where several or temporary covers are used, the following principles reduce moisture risks:

- ❏ Instead of taped joints, consider water collection and diversion by rubber gutters at joints.
- ❏ Seal joints by pressurized barriers, which force any water out.
- ❏ Around windows use boxes of plywood to protect from moisture intrusion and simplify mounting.
- ❏ Apply controlled and drying climate as soon as possible, preferably sectioning large buildings.
- ❏ Use temporary weather protection with drainage around staircases and larger holes.
- ❏ Preassembled moisture barriers. Peel and stick weather barrier.
- ❏ Reduce exposed openings.
- ❏ Apply weather vapor resistive barriers on walls as soon as possible.

8 Conclusions and recommendations

8.1 Executive conclusions from the study

The current study has focused on the moisture behavior of an unprotected cross laminated timber (CLT) panel subjected to rain and outdoor Nordic climate. By a literature survey the material properties and modeling issues of a CLT panel have been investigated and compared. The material properties have been summarized in a comprehensive table, which was not found elsewhere in literature (Section 6.1.3). Following computer simulation, the moisture response of wall and floor elements subjected to different time periods have been evaluated at different geographical locations. The evaluation was made based on not only one, but a set of criteria. Wetting and subsequent drying were analyzed. What is found in the present study is principally valid for various thicknesses and layer arrangements of CLT and to some extent also massive wood. The drying process is mostly affected by the number of layers and thicknesses.

It was found that not only a mould index (MI), but also the rate of growth of mould, moisture content (MC) and exceedance of the materials critical relative humidity play important parts in the overall moisture risk assessment. For this purpose, the 'MIRHT' chart was constructed (Section 5.4.4). It was found that an equivalent massive wood model is not sufficient to explain the moisture redistribution over time. It was also found that the intrinsic variations of rain loads over time is difficult to express in simple relations to the moisture response.

Four research objectives were defined (Section 1.3) in order to fulfill the aim, answering the main question on the amount of wetting a CLT panel can withstand without weather protection. The following conclusions are formulated as a checklist regarding *moisture management and moisture safety*:

- 1 Short building times are crucial.
- Very short building times (1-2 weeks) without weather protection requires great caution.
- Small amounts of rain (below some 10-20 mm) have the ability to dry within days if the outside climate allows.
- In Lund the climate effect is worse than in Gothenburg and in Bergen it is worse than Lund.

- 2 Rain protection and diversion.
- It is *indicated* that a CLT panel may withstand some 30-40 mm rainfall before the MC is accelerated. Individual rain falls may be sufficient to increase MC and MI which is also confirmed by real measurements (referenced by S.Olof, 2013). However, larger overall rainfall is always worse.
- It is *indicated* that a monthly average of RH in spring/summer that exceeds 70% at the same time as the accumulated rain load exceeds 100 mm is sufficient for mould growth.
- Diverting rain is more important than the surrounding relative humidity in air.
- There exists good and bad experience from real cases not using weather protection (6.1.4).
- The present study concludes that it is important to protect a building from rain at all locations and at all times. A wet surface may be crucial in summer with respect to moisture transport. All mould indices are higher during autumn cases compare to spring cases.
- Some protection is better than none, and some type of waxing or coating is believed to be a good alternative for difficult positions. A separate, continuous cover is better than directly applied surface coatings or tape on horizontal surfaces. The risk of condensation and moisture trapping could be mitigated by the choice of cover and allowance for drying.

- 3 Building cover.
  - A building cover has a major effect on the moisture content. Sometimes it is enough to use a simple roof and sometimes a complete cover is needed.
  - it is *indicated* that a controlled building environment is required in a climate where the annual average of RH is above 80 % or if the annual rain load exceeds 1200 mm;
  - A controlled climate is better than simply diverting rain.
  - A controlled climate reduce the need of subsequent drying, especially of internal layers.
  - Also wind exposed areas require building covers.
  - Although costs are not judged here, building covers may be expensive but increases productivity.

- Moisture behaviour.
  - The initial moisture content is decisive for the allowed additional increase in MC due to weather. This means that the moisture content on delivery (quality class) is important with respect to the expected final MC.
  - If a CLT panel has a high internal moisture content but dry on the outer layers, it could lead to extensive wetting of the outer surfaces after being built-in.
  - Wetting is quick but it takes very long time for internal moisture to dry out; and even longer if the drying occurs only one-sided.
  - However, a wall or floor construction with built-in CLT panels have the ability to dry over time as long as they are made ‘breathable’, using materials with limited vapour resistance.
  - During wetting the adhesive layers of CLT should not play an important role. The penetration depth of the moisture profile is the same in wood and CLT and do not generally reach the adhesive layers. On the other hand, cracks or gaps will obviously lead water into the material.
  - From the limited amount of measurements that were used for comparisons in this study it is concluded that the end grain water uptake is crucial for wood and CLT panels. This could affect the moisture content close to joints, cracks, and wall to floor connections, mounting holes and other.
  - Walls can be equally sensitive or even more sensitive than floors due to their vertical surfaces and longer exposure time to outdoor climate.
  - A warm summer day may cause moisture to be driven in to a wet surface and internal wood layers due to differences in moisture concentration.
  - Although massive wood has a moisture capacity comparable to concrete, it still behaves very different and is much more sensitive to moisture. Building with concrete and massive wood thus requires completely different approaches, even if the materials often have similar usage.

The following conclusions are formulated regarding *physical properties and modeling issues* of CLT:

- Material data.
  - The sorption properties of adhesives are relevant to consider, although the moisture storage capability is limited.
  - Material data on CLT exists but is limited. From the extensive comparison made in this study there are several data that is similar to wood. Different test performances and definitions make it challenging to compare moisture transport coefficients.

- Hygrothermal modelling.
  - It is concluded that the adhesive layers influence the moisture transport coefficients in a way that the CLT panel can not be accurately modeled as massive lumped wood. The latter is dominating in literature (Section 6.1).
  - Any mould model will only be an indicative measure of the risk of mould growth, since models are not developed for fluctuating and short-term climates. In this work the VTT model is used. The relative comparisons are most relevant.
  - The long-wave radiation is important to consider for the surface temperatures during night cooling of a horizontal surface. In the current study this is considered, but it in some other work it is not.

8.2 Recommendations

Based on the conclusions, the following *recommendations* are brought forward:

- It is recommended to reduce building times as much as possible by early planning. The benefits of prefabricated building elements and short building times should be maximized in order to reduce the risks of building with CLT. The concept of CLT do allow for very short building times even for larger and higher buildings.

- Rain loads should be limited. If there is a risk of a total rainfall above 10-20 mm during 1-2 weeks of production, arrangements to divert rain loads should be undertaken. This could be the use of over-pressurized joints and gaps and tape on transitions between walls and floors, combined with some rain protection that do not collect or trap water. However, such protection must be vapour permeable or removed before enclosure of the building parts. Due to the short building time, also the risk of wetting is reduced.

- If the expected rain loads are above 40 mm or if the building time exceeds a few weeks, a roof cover will be required. It is however always important to protect a building from rain regardless of location and time of year. A simple roof cover or rain screen that diverts rain from the building and protects surfaces from wetting is better than no cover. A simple plastic cover that is applied directly to the surfaces require caution due to risk of condensation and water trapping.

- Use a complete building cover made of external roof and walls if the surrounding environment has an annual average of RH above 80 % or if the annual rain load exceeds 1200 mm. Since it is beneficial for the drying process to construct buildings in protected environment, a building cover has several advantages.

- Free water on surfaces must always be avoided and taken care of immediately. Also snow must be removed directly not to become a moisture source. See further the checklist in Section 7.5.

Require a specific and maximum moisture content at delivery of CLT and during production. Often CLT is sufficiently dry at delivery and should be kept below the maximum values of moisture class 12% (EN 14298). Plastic wrapping of CLT elements should be kept as long as the elements are stored. The external insulation should be installed within at the most a few months after the building is erected. Walls need to be protected as well as floors. The external layers could act as sufficient weather protection. It is recommended to measure on several positions and in several depths/layers, establishing in site reference values on moisture content. This should always be monitored and especially close to joints, wall-floor connections and similar.

It is recommended to use the refined base case (Appendix III) for further studies and improvements of the CLT model developed in the present study. It is important to consider adhesive properties and adhesive layers in hygrothermal modelling of CLT. Simulations in WUFI allow for detailed considerations of hygrothermal behaviour of materials, including assemblies such as CLT. The long-wave radiation should be considered as well as the combined judgement of moisture content, mould index and exceedance of the critical relative humidity (Section 7.3).

The authors’ opinion is that mould should not be allowed for even if it could be removed during production. It is evidently virtually impossible to control all connections and hidden places where water may be trapped in a CLT building. Also it is our interpretation that allowing for a wooden structure to become wet (and later drying it with dehumidifiers) is not in line with the Swedish building requirements for moisture safety. It says that the critical levels of moisture never should be exceeded (BFS 2011:6, §6:51).

9 Further work

The following tasks are identified as the most relevant further work, given with suggested prioritization:

1. Evaluate longer time periods of the ongoing logging measurements of moisture content in a CLT building in Gothenburg.
2. Drying and protection by controlled climate of CLT is only briefly addressed in the current study and have not been found elsewhere in literature. This should be further investigated.
3. Extend the simulation set to cover additional locations and more extreme climate. Preferably the rain loads, RH and temperatures could systematically be varied for the same location and time period. This would create an even better possibility to find the limiting climate boundaries.
4. Perform experiments on CLT to provide material data, especially on capillary moisture transport and adhesive layer.
5. Investigate if and how adhesive layers are affected by the moisture and if they may act as effective moisture/water barriers. Maybe this could be a design feature.

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Appendices

Appendix I - Initial simulations using KFX

KFX is an Excel based tool for time dependent moisture transport. It does not handle free water. During initial simulations it is used to gain better understanding of the moisture transport and importance of adhesive layers in wood. The input data are defined below. Note that this is no manual for using KFX, simply an overview of input data used.

The element thicknesses are all 15 mm wood. Equivalent CLT is a modified massive wood with respect to adhesive layers. CLT is massive wood with adhesive layers.

Sorption wood (w, kg/m^3)	*Diffusion massive wood (d, m^2/s) "CLT"*	*Diffusion equivalent CLT (d, m^2/s)*
We60= 48	d0=1.4E-7	d0=2.7E-8
We100= 105	d95=3.0E-6	d95=1.3E-6
Wemax= 200	d100=4.5E-6	d100=1.6E-6
Form factor a=3		

The data on wood are to some extent based on values by Sandin (2010), Arfvidsson, et.al. (2017) with slight modifications. Data for equivalent CLT is based on the CLT Handbook by FP Innovation (Glass, et.al., 2011).

Heat transfer	*Adhesive data as moisture barrier*
External coefficient= 0.04 m^{2}K/W	CLT 5 layers= 1e6 s/m
Internal coefficient= 0.13 m^{2}K/W	CLT type 2= 200 000 s/m
Conductivity= 0.12 W/mK	CLT PUR= 70 000 s/m

Climate data is 40% RH 20 ºC inside and 90% Rh and 20 ºC outside. Simulation period 200 days, time step 0.1 h.

Appendix II - Initial simulations using WUFI

WUFI is used both during initial and final simulations. The input data are defined below. Note that this is no manual for using WUFI, simply an overview of input data used. Data may be copied directly from here. Figure II-1 is a screen dump from the input interface dealing with material assembly.

Two initial sets are used: ‘massive wood’ and ‘CLT’. The difference is inclusion or exclusion of the adhesive layers. Later several comparisons are made with different material properties.
Case common data is presented first. The head lines follow the structure within WUFI.

Set 1 and 2 (initial test of models)

Component

Assembly/Monitor positions

- 10 layers of 15 mm wood.
- Spruce

Basic values		*Approximation parameters*	
Bulk density, kg/m^3	455	Moisture-dep. thermal cond., %/M-%	1.3
Porosity, -	0.73	Temp-dep. thermal cond., W/mK	0.0002
Spec. heat capacity, J/kgK	1500		
Thermal cond., W/mK	0.09		
Water vapour diffusion.. -	100000		

Moisture storage function	*Liquid transport suction*	*Liquid transport redistribution*	*Water vapour diffusion resistance*
0 0 0.2 18.7 0.45 36.5 0.65 52.5 0.75 63 0.87 79 0.97 97 0.999 105 1.0 600	0 0 20 3.2E-13 600 9.2E-12	0 0 20 3.2E-13 600 9.2E-12	0 100000 0.1 926 0.2 463 0.3 278 0.4 167 0.5 109 0.6 69 0.7 45 0.8 24 0.86 16 0.92 10 0.955 8 0.98 6.6 1.0 5.6

- Automatic, type 1 fine grid generation.

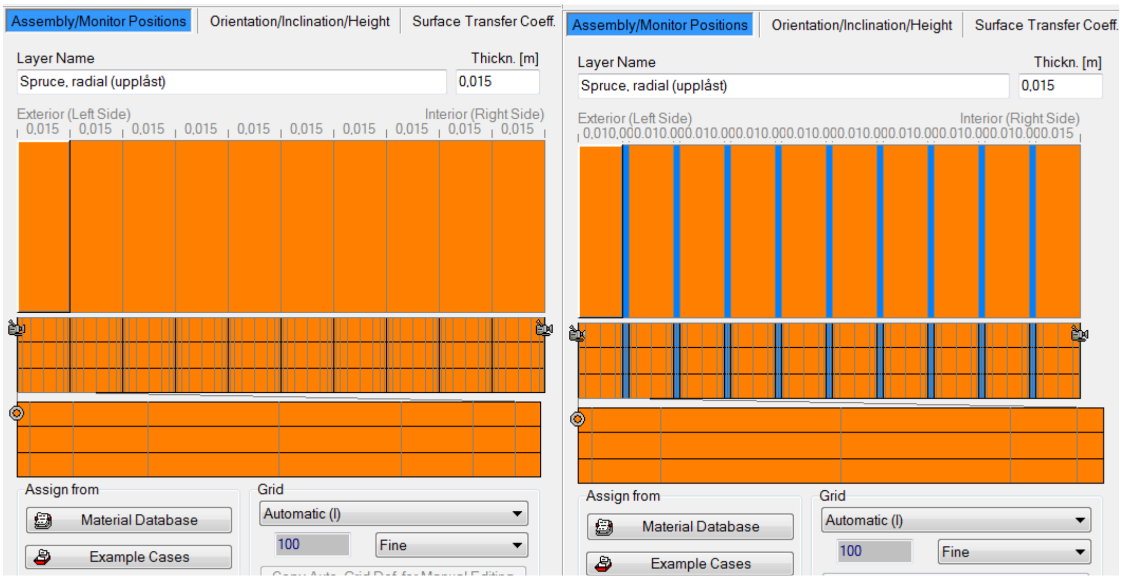

Figure II-1 Examples of assemblies with and without adhesives.

Orientation/inclination/height

- South-East (most rain load).
- Inclination 90 degrees.
- Rain load R1=0, R2=1 s/m.

Initial conditions

- *Moisture content 61 kg/m^3 in each layer.*
- *Temperature 20ºC across component.*

Surface transfer coeff.

- Exterior heat transfer coeff. 17 W/m^{2}K.
- No wind-dependence.
- No external coating.
- No absorption (short, long wave).
- Explicit radiation balance switched off.
- Ground short-wave reflection 0.2.
- Adhering fraction of rain 1.0.
- Interior heat transfer coeff. 8 W/m^{2}K.
- No interior coating.

Control

Calculation period/profiles

- 2018-10-01 - 2019-02-01
- Time step 1h.

Numerics

- Heat and moisture transport calculations.
- Use temperature and moisture dependency.
- Exclude latent heat of evaporation.
- Exclude latent heat of fusion.

Numerics cont.

- Increase accuracy.
- Adapted convergence.
- Enable adaptive time step control 3-5 steps.
- Cartesian geometry.

Climate

Outdoor (left)

- Stockholm; LTH Data

Indoor (right)

- Stockholm; LTH Data

In the CLT case adhesive layers are added in between all wood layers. In this step, adhesives are simply modelled as vapour barriers (sd=1500m) from WUFI database. Initial moisture content 0 kg/m^3.

Initial base case 'CLT equ' (later revised), note only changes from set 1,2 are given below

Component

Assembly/Monitor positions

- 7 layers of wood 40+30+30+...+30+40 = 230 mm.
- Spruce

Basic values		*Moisture storage function*	*Water vapour diffusion resistance*	*Suction (above) and redistribution*
Bulk density, kg/m^3	430	0 0 0.2 21 0.35 29 0.5 38 0.65 49 0.8 63 0.9 74 0.95 88 0.99 160 0.995 197 0.999 297 0.9995 344 0.9999 449 1 500	0 1e5 0.1 924 0.2 462 0.3 277 0.4 163 0.5 107 0.6 69 0.7 44.7 0.8 30.8 0.9 21.7 0.95 18.7	0 0 54 7.6E-12 420 3.0E-9
Porosity, -	0.74			0 0 54 7.6E-12 108 2E-10 408 0.0001 420 100
Spec. heat capacity, J/kgK	1500			
Thermal cond., W/mK	0.12			
Water vapour diffusion.. -	1e5			

Orientation/inclination/height

- Inclination 0 degrees.
- Rain load R1=1, R2=0 s/m.

Initial conditions

- *Moisture content 55 kg/m^3 in each layer.*

Surface transfer coeff.

- Exterior heat transfer coeff. 0.04 m^{2}K/W.
- Interior heat transfer coeff. 0.04 m^{2}K/W.

Control

Calculation period/profiles

- 2018-11-01 - 2018-02-01
- Time step 1h.

Numerics

- Include latent heat of evaporation.
- Include latent heat of fusion.

Climate

Outdoor (left)

- Stockholm; LTH Data
- Göteborg; LTH Data

Indoor (right)

- Stockholm; LTH Data
- Göteborg; LTH Data

A summary of the base case is given below (Table II-1). Note that the "CLT-equ" defined above is later revised. The base case for CLT as separate wood and adhesive layers ("CLT-layered") is defined in the next Appendix and constitutes the derived base case for the main study.

Table II-1 Inital base case for simulation (later revised)

Quantity	*CLT model approach*		*Comment*
	"CLT-equ"	*"CLT-layered"*	
Sorption	An average corresponding to StoraEnso data cut-off at saturation 500 kg/m3.	Moisture handbook (Arfvidsson et.al., 2017 p. 469) Data is complemented by saturation point at RH 100%	The sorption curve is weighed against the density of 430 kg/m3.
Diffusion	CLT-Handbook	Wood data (Sandin, 2010).	Not pure vapour diffusion above saturation.
Liquid suction and redistribution*	Test values (Lepage , 2012)**	Spruce data according to WUFI.	Otherwise limited information available from literature survey.
Other data	Typical or average values according to literature selection.	Glue data is based on sorption according to Kläusler et.al. (2012) and calculated vapour resistance (Section 7.2).	Same values on other data for both CLT model approaches.

*Later revised according to Section 6.3.
**A capillary suction based on an increased A-value for wood and equation (Based on the general equation for capillary coefficient in WUFI, Equation [4:8]. However, a more cautious choice of A-value is that of radial wood. Density of adhesives assumed to be 1000 kg/m^3 and porosity 0,001. No heat properties and equilibrium moisture content of 20 kg.Refer to Section 7.3 for discussion and analysis of the refined base case. In Appendix III the complete base case for the main study is given.

Appendix III - Simulations using WUFI

III.1 Overview

WUFI is used both during initial and final simulations. The input data for the main simulations are defined below. Note that this is no manual for using WUFI, simply an overview of input data used. Data may be copied directly from here. Refer to Section 7.3 for discussion and analysis of the refined base case. Following input data are some processed output results on mould and critical RH.

III.2 Simulation input data

Base case for main study of floors

Component
Assembly/Monitor positions

- 7 layers of spruce wood 40+30+30+...+30+40 = 230 mm.
- 6 layers of adhesives, 1 mm thick.

Basic values		*Approximation parameters*	
Bulk density, kg/m^3	430	Moisture-dep. thermal cond., %/M-%	1.3
Porosity, -	0.74	Temp-dep. thermal cond., W/mK	0.0002
Spec. heat capacity, J/kgK	1500		
Thermal cond., W/mK	0.12		
Water vapour diffusion. -	1e5		

Moisture storage function wood	*Liquid transport suction wood*	*Liquid transport redistribution wood*	*Water vapour diffusion resistance wood*
0 0 0.10 18.275 0.20 29.025 0.30 37.41 0.35 39.56 0.40 45.15 0.50 53.75 0.60 62.35 0.70 70.95 0.75 76.325 0.80 83.85 0.85 90.3 0.90 103.2 0.96 120.4 1.0 500	0 0 20 3.2E-13 600 9.2E-12	0 0 20 3.2E-13 600 9.2E-12	0 100000 0.1 185.19 0.2 144.51 0.3 135.87 0.4 115.74 0.6 66.14 0.7 36.98 0.75 32.22 0.8 20.13 0.85 15.4 0.9 10.87

- Automatic, type 1 fine grid generation.
- Adhesives

Basic values		*Approximation parameters*	
Bulk density, kg/m3	1000	Temp-dep. thermal cond., W/mK	0.0002
Porosity, -	0.03		
Spec. heat capacity, J/kgK	2300		
Thermal cond., W/mK	2.3		
Water vapour diffusion. -	2000		

Moisture storage function adhesive	*Liquid transport suction adhesive*	*Liquid transport redistribution adhesive*	*Water vapour diffusion resistance adhesive*
0 0 0.95 30	-	-	0 2000

Parameters are scaled to 0.1 mm thickness.

Orientation/inclination/height
- South-East (most rain load).
- Inclination 0 degrees.
- Rain load R1=1, R2=0 s/m.

Surface transfer coeff.
- Exterior heat transfer coeff. 25 W/m^2K.
- No wind-dependence.
- No external coating.
- Short wave absorption 0.4.
- Long wave 0.9.
- Explicit radiation balance switched on.
- Cloud index 0.67.
- Ground short-wave reflection 0.2.
- Adhering fraction of rain 1.0.
- Interior heat transfer coeff. 25 W/m^2K.
- No interior coating.

Initial conditions
- *Moisture content 55 kg/m^3 in each wood layer.*
- *Moisture content 20 kg/m^3 in each adhesive layer.*
- *Temperature 20 ºC across component.*

Control

Calculation period/profiles
- Multiple time periods
- Time step 1h.

Numerics
- Heat and moisture transport calculations.
- Use temperature and moisture dependency.
- Include latent heat of evaporation.
- Include latent heat of fusion.

Numerics cont.
- Increase accuracy.
- Adapted convergence.
- Enable adaptive time step control 3-5 steps.
- Cartesian geometry.

Climate

Outdoor (left)
- Stockholm; LTH Data
- Göteborg; LTH Data
- Lund; LTH Data
- Kiruna; LTH Data
- Bergen; NBI / NTNU
- (Vancouver; cold year)

Indoor (right)
- Stockholm; LTH Data
- Göteborg; LTH Data
- Lund; LTH Data
- Kiruna; LTH Data
- Bergen; NBI / NTNU
- (Vancouver; cold year)

Base case for main study of walls (only changes from floors)

Component

Assembly/Monitor positions
- 5 layers of wood 20+20+40+20+20 = 120 mm.
- 4 layers of adhesives, 1 mm thick.
- Spruce

Orientation/inclination/height

- South-East (most rain load).
- Inclination 90 degrees.
- Rain load R1=0, R2=0.1 s/m.

Base case for main study of covers (only additions to floors/walls)
Component

Assembly/Monitor positions

- weather resistive barrier (sd=0,1m) 1 mm thick.
- Spruce, radial 5 mm (mostly as heat barrier).
- Air Layer 2 mm (scaled from air layer 100 mm).
- Air Layer 96 mm; without additional moisture capacity (scaled from air layer 100 mm).
- Air Layer 2 mm (scaled from air layer 100 mm).
- Surface of wall or floor assembly.

The 96 mm air layer is ventilated by outside air at a rate of 200 /h.

- Short wave absorption 0.2.
- Long wave 0.9.
- Explicit radiation balance switched on.
- Ground short-wave reflection 0.2.
- Adhering fraction of rain 0.

Other cases with built-in CLT has added layers of insulation and gypsum from the standard database in WUFI.

III.3 Simulation result data

Below are the MIRHT and FOLOS charts (Figures III-1 to III-16) from different locations and time periods for floors with and without rain protection. The chart is described in Section 5.4.4.

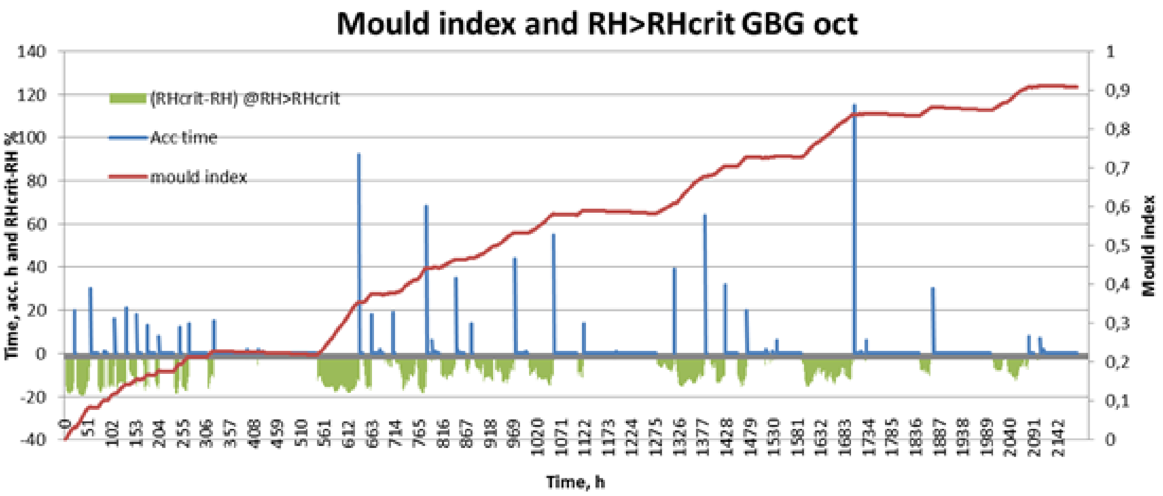

Figure III-1 Mould growth and critical RH in Gothenburg during October-December without rain protection.

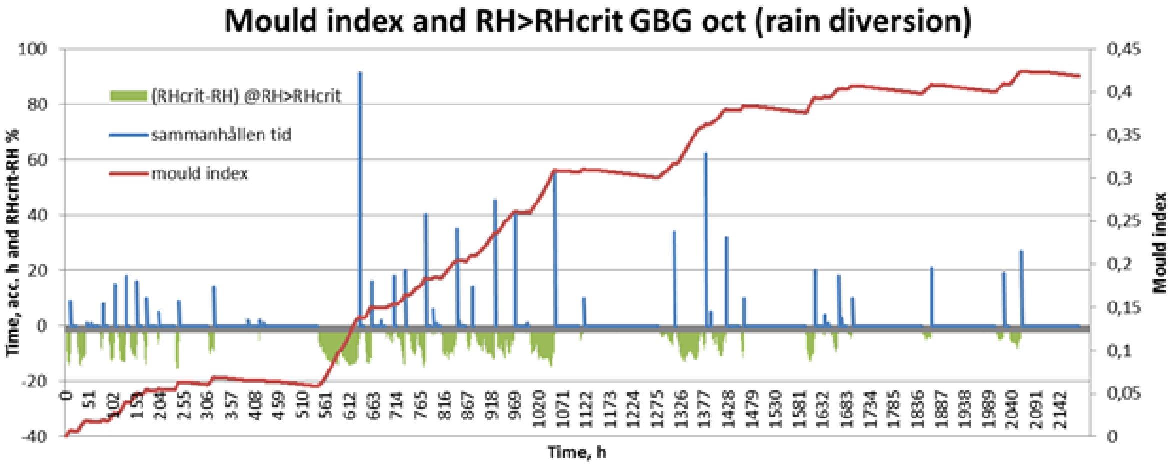

Figure III-2 *Mould growth and critical RH in Gothenburg during October-December with rain diversion (no rain adheres to the surface).*

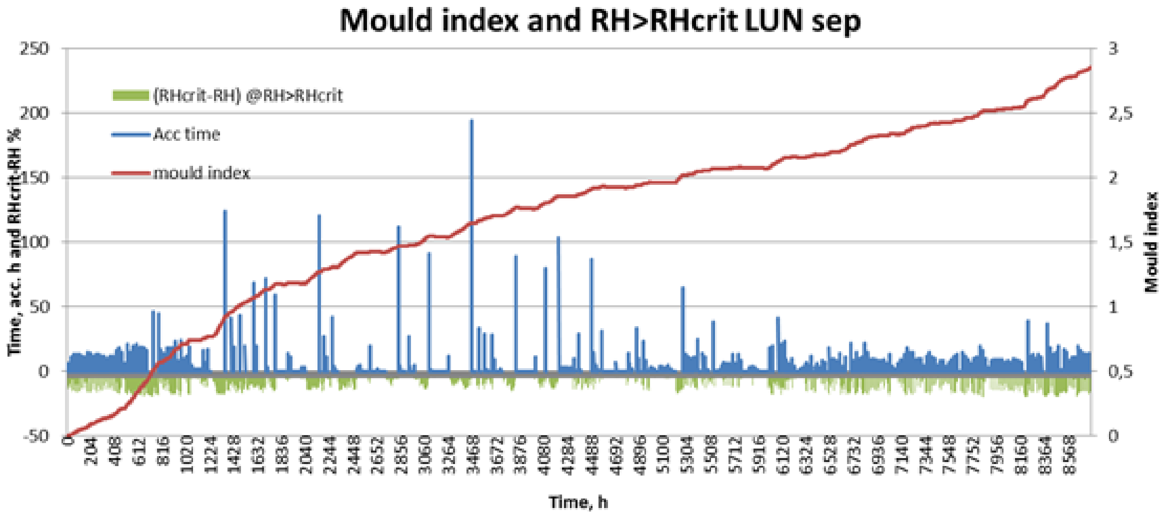

Figure III-3 *Mould growth and critical RH in Lund during September and one year ahead with no rain protection.*

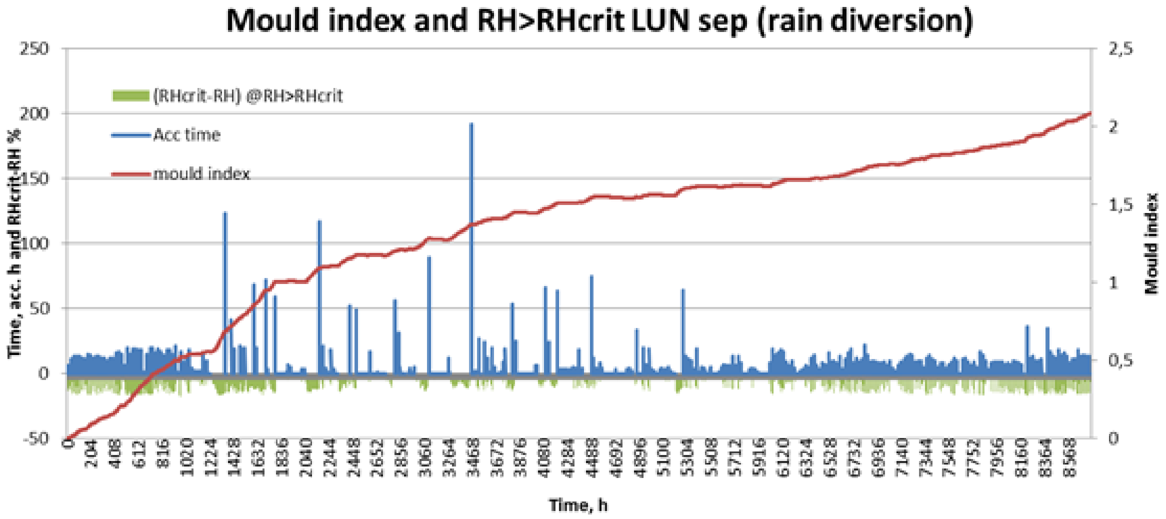

Figure III-4 *Mould growth and critical RH in Lund during September and one year ahead with rain diversion (no rain adheres to the surface).*

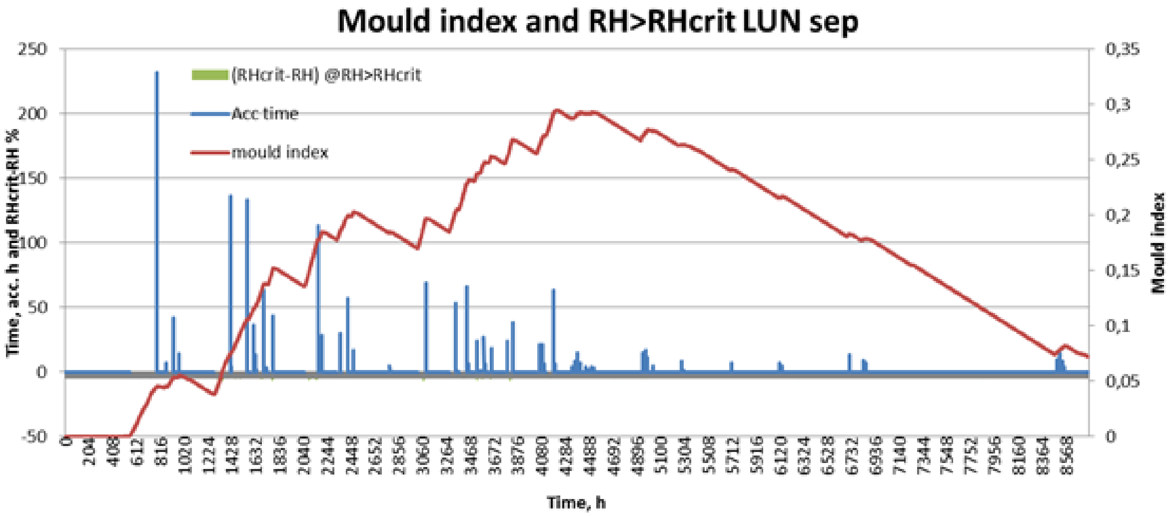

Figure III-5 *Mould growth and critical RH in Lund during September and one year ahead with building cover.*

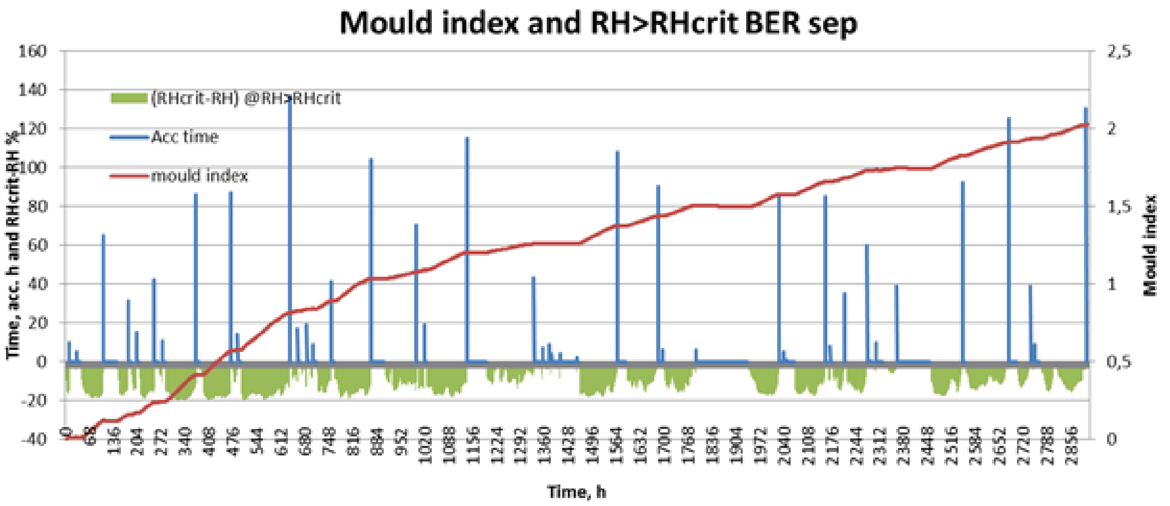

Figure III-6 *Mould growth and critical RH in Bergen during September to December with no rain protection.*

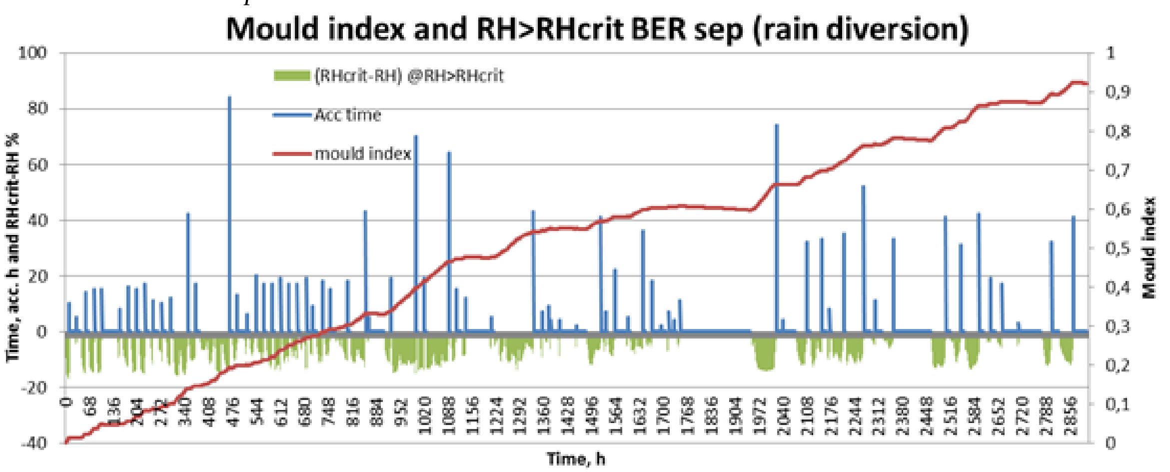

Figure III-7 *Mould growth and critical RH in Bergen during September to December with rain diversion (no rain adheres to the surface).*

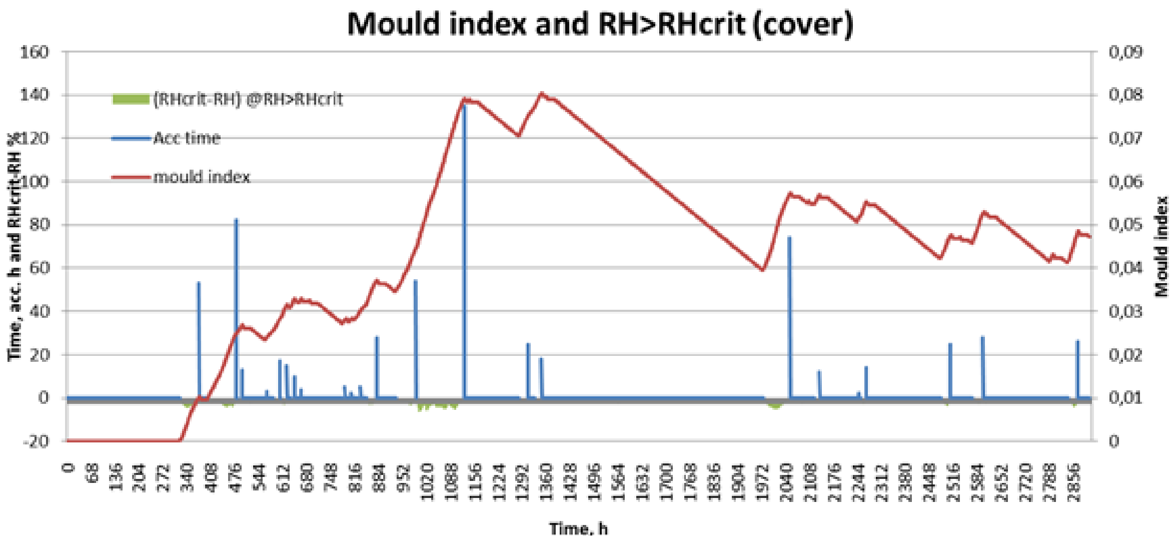

Figure III-8 *Mould growth and critical RH in Bergen during September to December with building cover.*

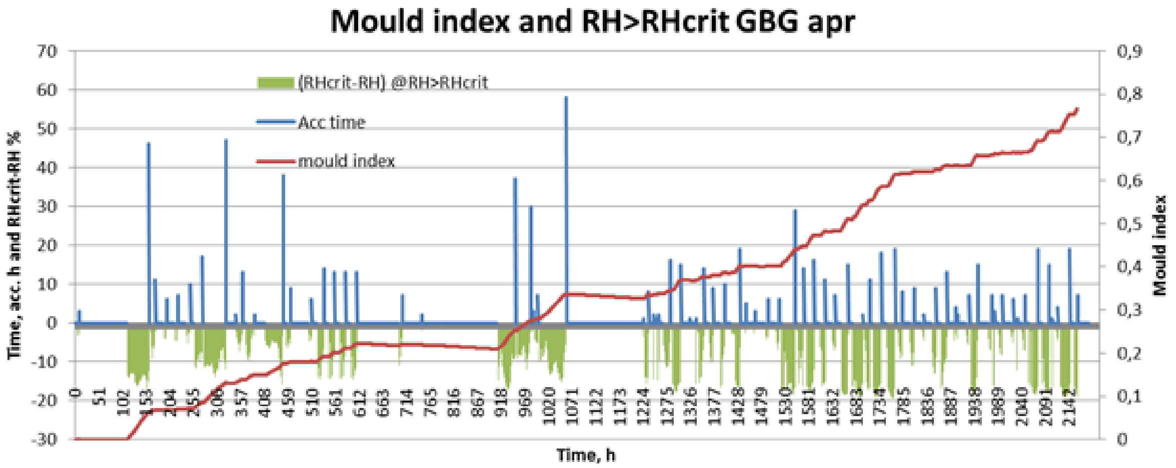

Figure III-9 *Mould growth and critical RH in Gothenburg during April to June with no rain protection.*

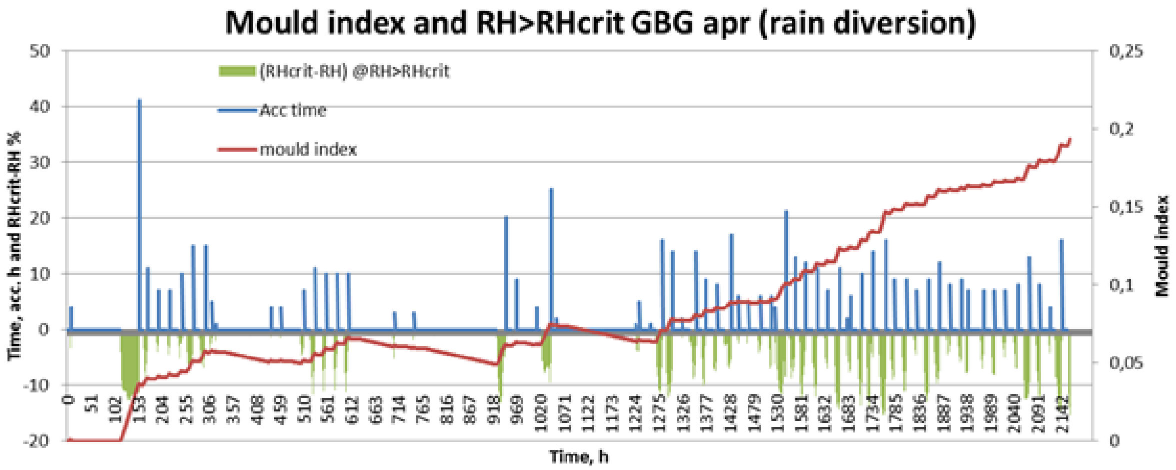

Figure III-10 *Mould growth and critical RH in Gothenburg during April to June with rain diversion (no rain adheres to the surface).*

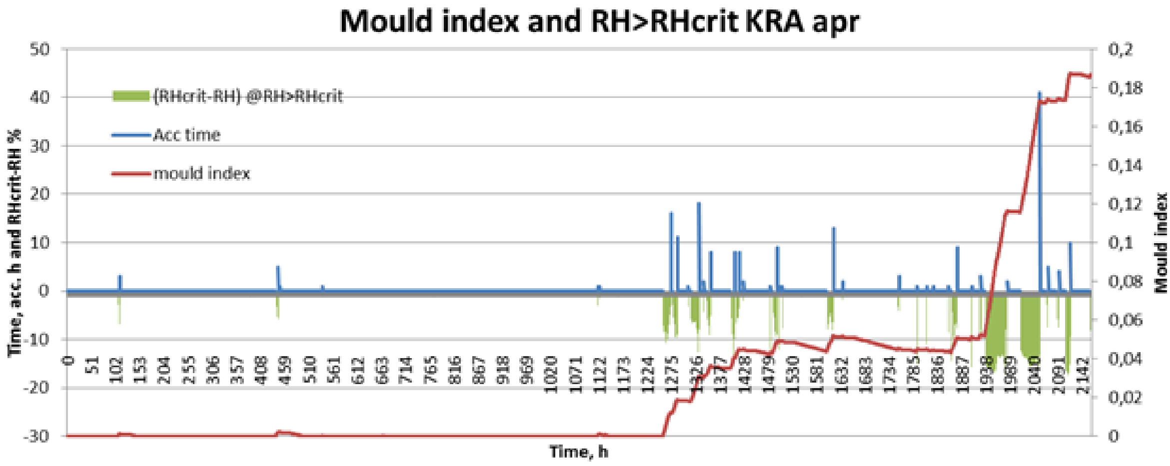

Figure III-11 Mould growth and critical RH in Kiruna during April to June with no rain protection.

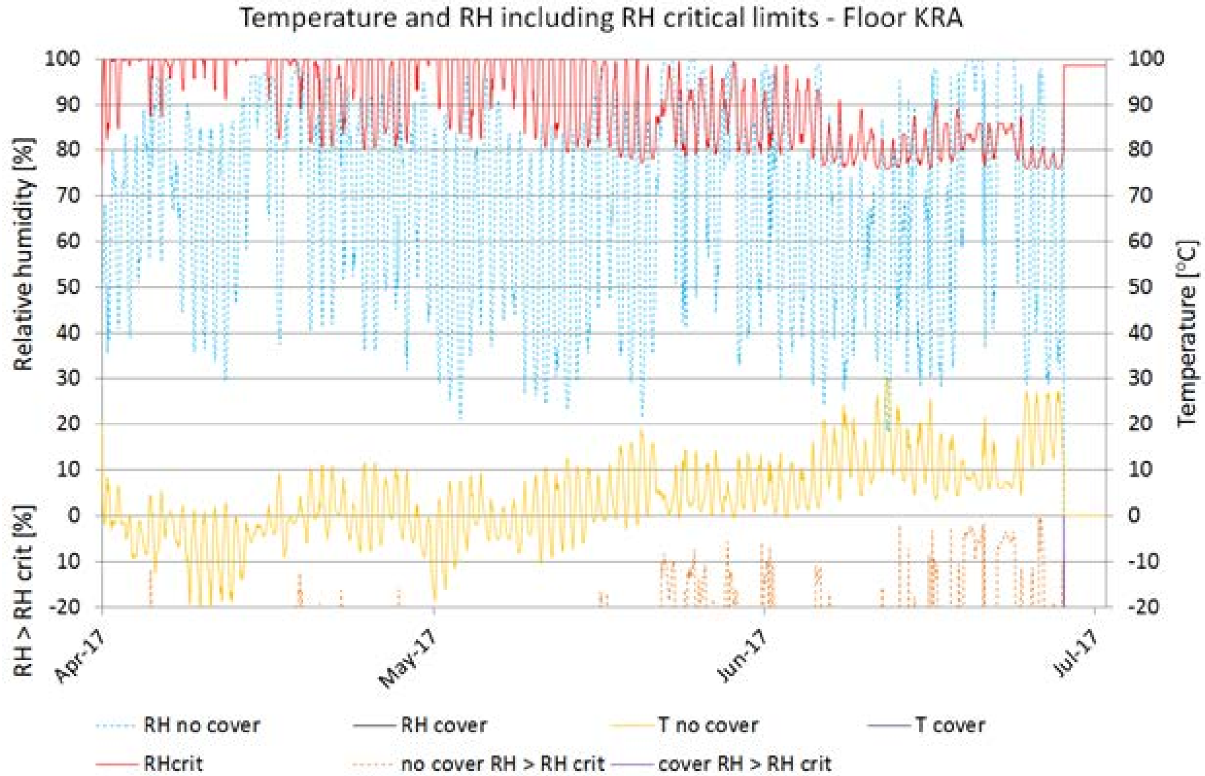

Figure III-12 Temperature, RH and critical RH with and without cover for a floor in Kiruna.

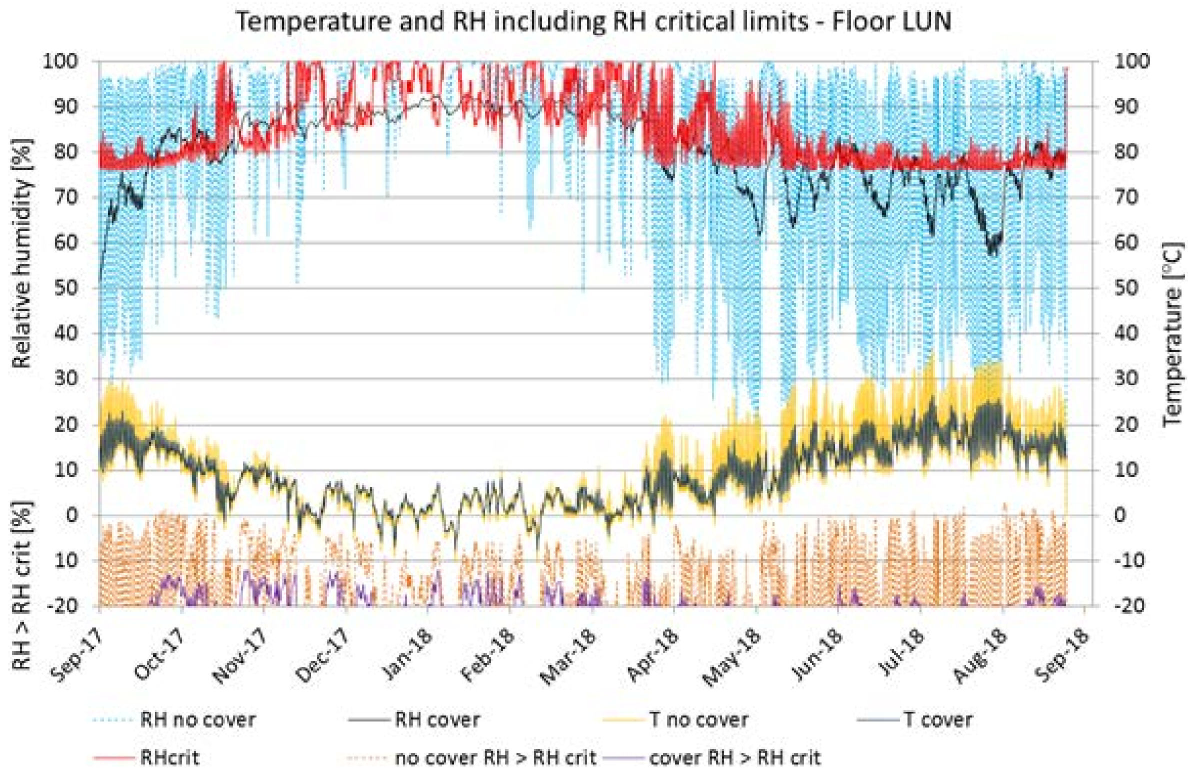

Figure III-13 Temperature, RH and critical RH with and without cover for a floor in Lund.

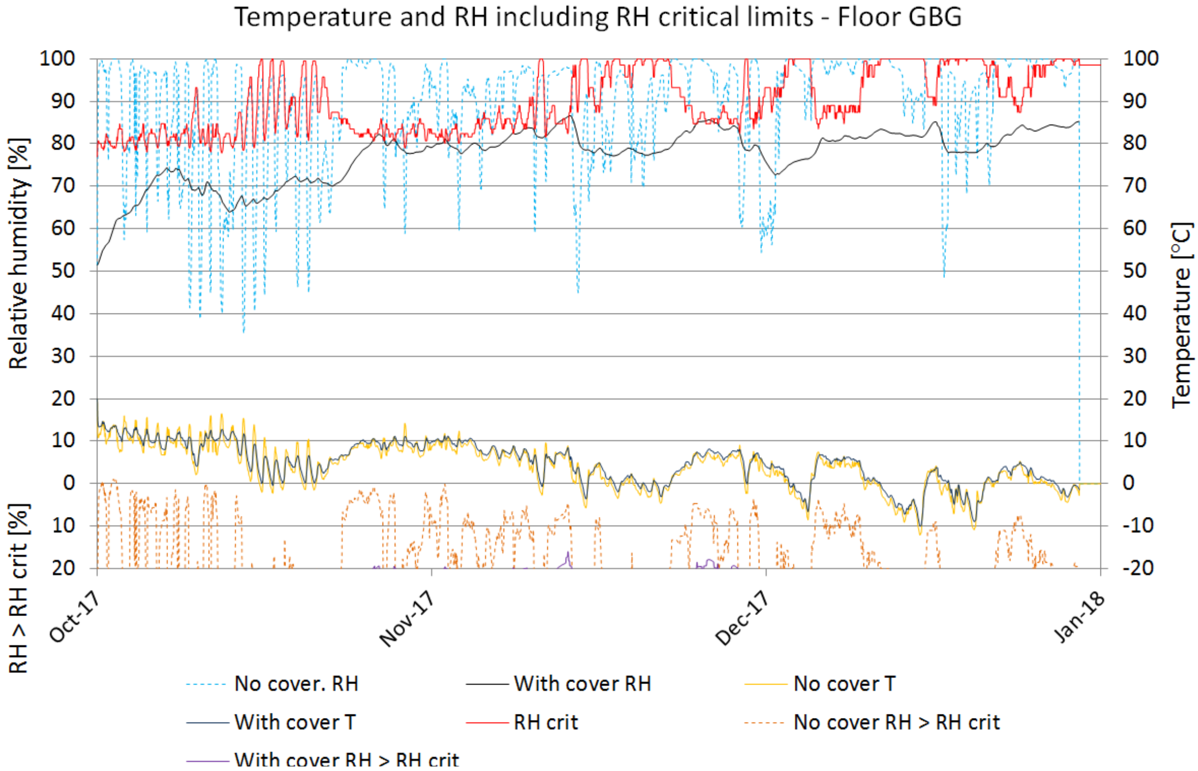

Figure III-14 Temperature, RH and critical RH with and without cover for a floor in Gothenburg.

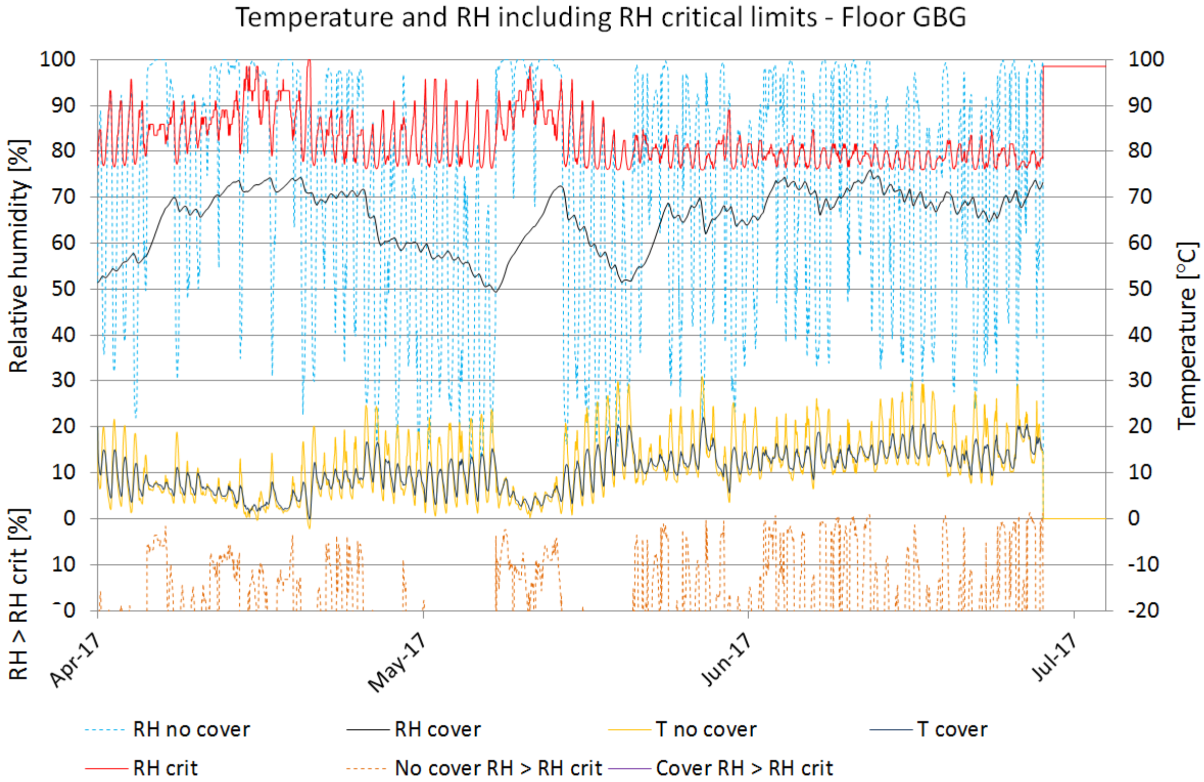

Figure III-15 Temperature, RH and critical RH with and without cover for a floor in Gothenburg (spring).

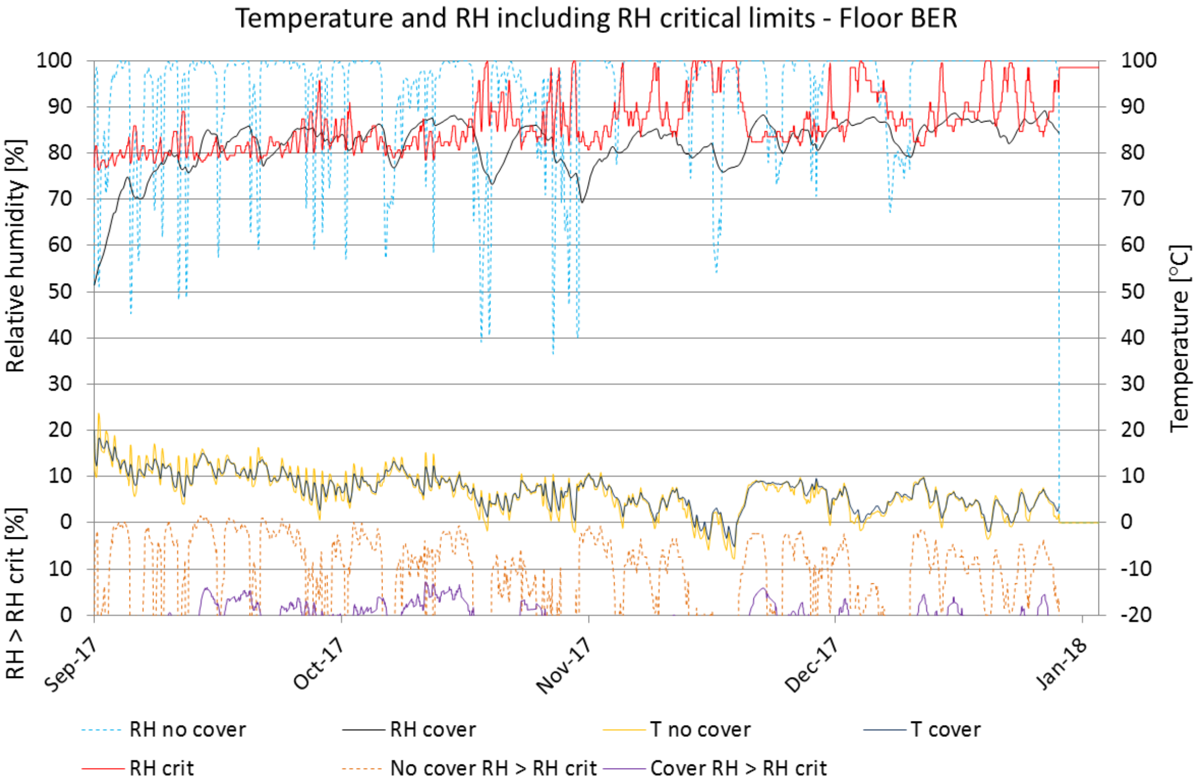

Figure III-16 Temperature, RH and critical RH with and without cover for a floor in Bergen.