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Effects of considering moisture hysteresis on wood decay risk simulations of building envelopes

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Abstract

Wood decay risk assessment of building envelopes is commonly performed by engineers, architects and practitioners using results of Heat and Moisture Transfer (HMT) simulations and damage models. The commonly accepted HMT models use bijective sorption functions, accepting that materials reach hygrothermal equilibrium with the humidity contained in the air of the material's pores and of the environment at a single MC. On the other hand, due to moisture hysteresis, equilibrium can be reached at different MCs for the same air condition, depending on previous equilibrium states. The aim of this work is to quantify the effect of considering hysteresis in HMT simulations and to evaluate its propagation in the risk assessment procedure for the case of wood decay. The software MATCH is used, implementation of an HMT model with hysteresis. Three timber walls are simulated in seven locations (Bolzano, Copenhagen, Hong Kong, Ottawa, Shanghai, Udine, and Vienna), first with hysteresis and then with simplified bijective sorption functions (adsorption, desorption, and mean sorption curve). MC and temperature time series are used to perform wood decay risk assessment with two damage models. The results show that the influence of hysteresis can be relevant, and that the choice of the sorption curve used in the simulations should be discussed. For the case of a CLT wall in Shanghai, simulated using the adsorption curve, a mean difference of 1.6% MC is found from the hysteresis case. This resulted in a difference of 0.7 decay rating in 10 years and 6% mass loss in 30 years.

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1. Introduction

Damage, health, and safety risk assessments are a critical part of the design process of building envelopes, and several of these depend on the presence of uncontrolled moisture. Depending on the materials in use, the moisture related risks could be assessed with the calculation of the local relative humidity, moisture content and temperature values in a given point of a building detail [1]. Generally, the damage is caused by organisms or chemical reactions activated by the presence of excessive moisture in the material pores or on the material surface for an excessive time. In order to perform the risk assessment from simulation results, the damage mechanism should be represented with a mathematical model able to calculate the damage entity from the time series of the hygrothermal variables of the material [2].

When considering the hygrothermal state of the porous material, wood decay phenomena depend on the moisture content values, but some of the assessment methods presented in literature are expressed in terms of relative humidity, for example the VTT wood decay method (from VTT Technical Research Centre of Finland) [3]. Relative humidity is considered as a parameter to describe the presence of moisture in the material and this is considered an acceptable approximation when the sorption curve is represented with a bijective function. When moisture hysteresis is considered, it could lead to deviations.

Using a sorption function defined as a bijective function between relative humidity φ and moisture content u is a commonly accepted simplification of the moisture accumulation behaviour of materials even if experience shows that several of them (especially bio-based materials such as wood) can reach equilibrium at different moisture contents. The equilibrium states are dependent on the history of the previous equilibrium states. This behaviour, known as moisture hysteresis, could be modelled implementing the hysteresis of the sorption function in the heat and moisture transfer (HMT) models, instead of using bijective sorption isotherm functions.

The choice of considering moisture hysteresis in simulations depends on the studied phenomena and on the applications. In the last decade, with the availability of more sophisticated simulation models and accessible software tools, more accurate simulations were possible and the interest in the topic is increased, not only for bio-based materials, but also for cementitious materials [4, 5, 6, 7, 8, 9].

The aim of this work is to evaluate the error on the risk calculation when the hysteresis of the materials in HMT models is not considered. It is shown that the effects are relevant for applications in risk analyses based on a moisture content threshold and not on relative humidity threshold.

The effects of hysteresis are quantified on the simulation results and on two risk assessment procedures using comparisons between calculations with and without moisture hysteresis. The sensitivity of the model to moisture hysteresis is calculated also for CLT walls with an intentional low hygrothermal performance (CLT-C) and for extreme climates that would require special wood treatments and protection. The extreme weather cases (obtained with the Shanghai weather file) are useful to visualize and interpret the effects of moisture hysteresis on the results of the simulations and on the risk calculation methods.

In the following sections, a short review of related research on the relevance of moisture hysteresis models in HMT calculations will be presented, followed by a short presentation of the wood decay calculation models used in the Methods section.

1.1. Moisture hysteresis - related research

In literature, the influence of hysteresis in HMT calculations has often been considered negligible and was rarely implemented in the simulation tools. With the availability of more computational power and accessible software tools, hysteresis has been implemented in the simulations and its effect has been extensively analysed also for other applications and with several models.

The influence of hysteresis on the moisture balance of a room is presented in [10], with the comparison between two hysteresis formulations (the empirical model [11] and the phenomenological model, obtained as a modification of the Mualem model [12]). It is shown that considering hysteresis in the simulations has a small influence on the relative humidity in the room, while it has an impact on the moisture content calculated at the surface of the walls. The authors of [13] implemented the empirical hysteresis model in a whole building simulation software and a comparison with the non-hysteretic simulation results is presented for a room with gypsum board walls. The authors suggest that the most representative bijective function for the hysteretic behaviour is the mean sorption curve, calculated as the mean of the adsorption curve and the desorption curve. They also conclude that considering the desorption curve as sorption curve in the simulations leads to higher moisture contents, causing a calculation higher values of moisture buffering capacity of building materials.

In [14] the modification of the phenomenological model is compared with another model, presented in [15], considering hemp concrete. An HMT model is used to simulate the moisture buffering value test and the results are compared with experimental data. The authors conclude that, when considering hysteresis, the initial moisture content values of the sample are a critical information for the simulations and that a range of moisture buffering values could be used instead of a single value, to describe the buffering behaviour of a hysteretic material. Similarly, the authors of [16], evaluated the influence of a hemp concrete wall on the internal environment and on the energy accumulated by building material, also discussing the hysteresis influence. A temperature difference of about 0.1 °C and a difference of 10% in the accumulated energy are observed among the results with and without hysteresis.

In [4] it is reported that neglecting hysteresis in simulations of wood it is possible to make errors on the moisture contents up to 20% considering the adsorption curve and up to 30% considering the desorption curve. Moreover, different effects in hysteresis have been observed considering the anisotropy of wood. In [17] experimental results and simulations are compared for hemp concrete and rape straw concrete. The results show that the moisture contents and the relative humidity calculated with the hysteretic sorption curve are closer to the experimental results than the ones calculated with the mean sorption curve. The authors suggest that when non-stationary simulations are performed and moisture content values are needed or the vapour or liquid diffusion coefficients have to be estimated, then the hysteresis should be taken in account by the model. Recently, in [18], an office building with hemp concrete walls is studied. First, in terms of temperature and relative humidity and then considering the energy consumption for heating and cooling of the building. The results show that considering hysteresis in hemp concrete slightly affects indoor relative humidity values, as well as heating and cooling demands.

Fewer works with evaluations of the effects of hysteresis on risk evaluations are found in literature. For example, [19], where the influence of two models of hysteresis is evaluated for the mould growth risk assessment on a timber wall. The VTT mould growth method and time of wetness method are used, both based on the relative humidity values, thus the differences observed between the calculated risks are small.

Besides the already mentioned hysteresis models, others are described in literature [20, 21]. Moreover, it should be noted that in [22] it has been shown, with an extensive measurement of the equilibrium states, that the hygroscopic behaviour of wood changes also with temperature.

1.2. Wood decay - related research

Wood decay is one of the most relevant moisture related damages. This is proven by the variety of recent scientific publications on the topic [23, 24]. Due to fungi attack, the wooden structural parts are reduced in mass and strength. Many techniques of wood protection have been developed and tested with monitoring procedures [25, 24].

When monitoring is not an option, it is possible to simulate the moisture content of the timber with numerical simulations. One example is presented in [26], where moisture migration is modelled using Fick's second law of diffusion using moisture content as the driving potential. When indoor environments are involved, the moisture uptake in timber is modelled with heat and moisture transfer models (HMT), as presented in [27, 28, 29, 30, 31]. In this works, the temperature, the moisture content or the relative humidity are calculated from the weather files and then used to evaluate an indicator of the wood decay. Several uncertainties are involved in the process, thus the decay calculations have to be considered purely indicative, useful for example, for comparisons of design solutions and not as decay predictions. Often, the decay models of a wood species are not available for a given condition or are not available at all and other decay models could be used as moisture performance indicators for a conservative risk assessment.

In the following, wood decay models are used to perform the assessment of the risk of wood decay for a given building envelope with a timber structure using simulation results. This assessment is part of the design procedure of building envelopes and it is not intended to provide a detailed fungi growth prediction, but to calculate an indicator of the moisture performance of the wall.

It is well known that the fibre saturation region for the majority of woods is found between 20% and 30% moisture content by mass, so that 20% is used as lower limit value for wood decay providing a reasonable margin of safety [32, 33, 34].

Wood decay is considered to be driven by moisture content: when free water is present in cell voids for a certain time, fungi starts the degradation of the wood cellular structure with an additional production of water.

When HMT simulation results are available, the decay models can be applied directly to temperature and moisture content time series, and the following acceptable hypotheses are assumed in simulations:

- The geometry of the studied domain is constant in time;
- The properties of the materials depend only on moisture content and temperature, and are not influenced by the decay process;
- The fungi do not produce water during the digestion process (Even though [35] presented an application considering the water production of fungi).

All of these hypotheses are not realistic, but their effect is supposed to be negligible in order to perform the simulations for wood decay risk assessment.

In this work, to highlight the effect of neglecting hysteresis in the simulation results, three wall types are considered in different locations and for each of these cases four simulations with different sorption functions are performed. The VTT wood decay model and the simplified dose-response model are applied on the wood moisture content values to show the different results obtained considering HMT models with or without hysteresis. As shown in [29] and [30], the use of these models is not intended to simulate a realistic wood decay process, but to compare the hygrothermal performance of the walls, in this case, calculated with different sorption curves.

The widely used [36, 37, 28] VTT wood decay model considers the relative humidity and the temperature in the wood element and allows to calculate the loss of mass of wood (expressed in mass percentage) caused by the fungi. The model was based on laboratory experiments on brown rot fungi (*Coniophora puteana*) on pine sapwood and spruce specimens. The correlation between mass loss (ML) and the stationary environmental conditions (relative humidity and temperature) was first presented in [3], then the method to calculate the ML in dynamic conditions was presented in [38] including the time factor.

The simplified logistic dose-response model, presented in [39] as a simplified version of the logistic dose-response model presented in [40], was based on field test results on Scots pine sapwood and Douglas fir heartwood test specimens in 23 different European test sites and it is intended for the implementation in performance-based building codes and regulations. The model considers the daily mean values of moisture content and temperature. In [41] it has been observed that using the moisture content allows the model to be independent of the wood type. On the other hand, the field tests used to obtain the correlation were exposed to high moisture contents (above 25% in mass).

The simplified logistic dose-response model is here used because it has been designed to produce small positive decay rating values also for moisture contents lower than the critical limit, with acceptable risk levels, with the advantage of quantifying the “distance to the risk”. This feature allows to draw a comparison between results of simulations that do not have moisture contents higher than 25% for long periods during the year, with a reasonable margin of safety.

The model was obtained as a correlation of the moisture content and temperature values to the rot decay level, in terms of mean decay rating according to EN 252 (1990), which is a classification between 0 and 4. Even though the standard EN 252 exists in a more recent version it will be here referred as EN 252 (1990) in order to be coherent with [39].

0. **Sound**: No evidence of decay, discolouration, softening or weakening caused by microorganisms;

1. **Slight attack**: Limited evidence of decay, no significant softening or weakening up to 1 mm depth;

2. **Moderate attack**: Significant evidence of decay, with areas of decay (softened or weakened wood) from 2 to 3 mm depth;

3. **Severe attack** Strong evidence of decay, extensive softening and weakening, typical fungal decay at large areas from 3 to 5 mm depth or more;

4. **Failure**: Sample breaks after a bending test.

2. Method

To evaluate the effects of considering hysteresis versus not considering it in the wood decay risk assessment on cross laminated timber (CLT) walls first, HMT simulations are performed on three wall types in seven locations with internal conditions with high moisture loads, considering four different sorption functions. The objective of this work is to compare the main sorption modelling approaches that could be used in the HMT simulations to describe the moisture storage properties of the materials. These properties are usually described in the software tools by sorption curves represented as bijective functions obtained from material testing. The commonly considered curves are the adsorption curve, the desorption curve, or the mean sorption curve (a curve calculated as a mean of the previous two). These three are compared with the "empirical hysteresis model" presented in the next section. The four sorption models will be indicated for simplicity as follows:

- **Adsorption Curve**: obtained from measurements of equilibrium moisture content from the dry state to saturation, this modelling choice is expected to provide lower moisture contents than the other solutions, given that for the same values of relative humidity, lower moisture content equilibrium values are found;

- **Desorption Curve**: from measurements of equilibrium moisture content from saturation to the dry state, this curve is expected to provide higher moisture contents under the same relative humidity conditions;

- **Mean Sorption Curve**: calculated as the mean values of the equilibrium moisture contents of the adsorption curve and the desorption curve, this modelling solution is presented as an alternative to the implementation of a hysteresis model, because the moisture contents are theoretically expected to be bounded by the adsorption sorption curve and the desorption sorption curve;

- **Hysteretic Sorption Curve**: (the word "Curve" is used for simplicity) the equilibrium moisture content states are calculated at each time-step from the moisture content and relative humidity values of the previous time-step, following the "empirical hysteresis model" (Eq 2), which allows to calculate an approximation of the scanning curve followed by the material in the experiments at each time-step; the three previous modelling choices do not allow to follow the scanning curves, but are often considered to be acceptable simplifications (depending on the application).

Then, to show the effects of the different simulation results, the wood decay risk assessment is performed with two wood decay models, the VTT wood decay model and the simplified logistic dose-response model.

The HMT simulations presented in this work are performed with the software MATCH. The heat and moisture transport model is presented in [11] and [42], and it considers moisture hysteresis with the empirical model. The model assumes that materials are porous materials that are continuous, homogeneous, stabilized (chemical reactions are not considered) and non-deformable (for example shrinkage is not modelled), also the materials are considered in thermodynamic equilibrium, with moisture storage properties independent of temperature, but dependent on the previous equilibrium states (moisture hysteresis). The sorption curves of the materials in the MATCH database are described with piecewise linear functions. With these hypotheses it is possible to model a CLT without adhesive layers. It has to be noted that the situation described by the model is ideal and that many other sources of uncertainty are present: indoor and outdoor moisture and thermal loads might be different from the ones described, materials have variable properties and geometric imperfections (local imperfections in materials, geometric irregularities) and other moisture transport mechanisms (rainwater, water and air leakages) could be present and are not modelled in the simulations.

The simulations are performed for a 10-year-long period, imposing the initial conditions to 70% relative humidity and 20 °C for every material of the wall.

2.1. Moisture hysteresis

The main effect of hysteresis is that a material sample could reach equilibrium at different moisture contents even if the humid air in its pores and in the environment has the same constant value of relative humidity and temperature. This behaviour also affects the moisture capacity ξ, which is a material parameter of the moisture balance equation. Moisture capacity is defined as the derivative of the moisture content u with respect to relative humidity φ accordingly to Eq.1 [11].

$$\xi = \frac{\partial u}{\partial \varphi} \tag{1}$$

The moisture capacity variation could be used to define the next equilibrium positions in the moisture content-relative humidity plane, depending on the previous positions. The curves formed by these positions are intended to follow the scanning curves found experimentally, which are generally positioned between the adsorption and desorption curves (Figure 1). The adsorption curve is defined as the curve followed by the equilibrium states of the material starting from a dry state, which corresponds to u = 0%, and then conditioned at an environment with progressively higher values of relative humidity. The desorption curve is the curve of the equilibrium states obtained starting from the saturation state of the material and then conditioned to air with progressively lower relative humidity values, starting from the saturation state.

The hysteresis model implemented in the software MATCH used in this work is the "empirical hysteresis model" (described by Eq.2 and presented in [11]). The adsorption and desorption curves are used as lower and upper bound of the scanning curves and the next hygrothermal state is calculated at each time-step using the relation of Eq.2

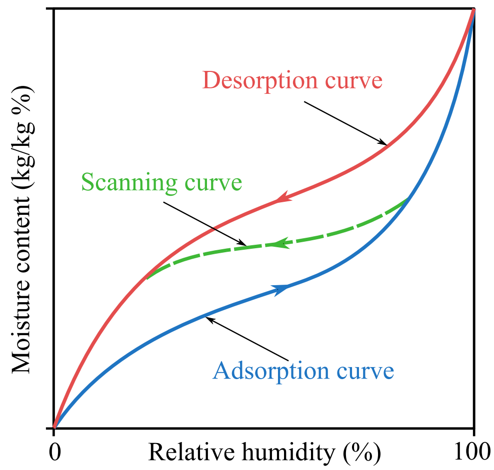

Figure 1: Qualitative generic description of adsorption curve, desorption curve and a scanning curve in the moisture content-relative humidity plane. The curves describe the succession of the possible equilibrium states of the material and the arrows indicates the direction of the adsorption/desorption process.

[11], based on the calculation of the moisture capacity.

$$\xi = \begin{cases} \frac{(u-u_a)^2\cdot\xi_d+0.1\cdot(u-u_d)^2\cdot\xi_a}{(u_d-u_a)^2} & \text{for desorption} \\ \frac{0.1\cdot(u-u_a)^2\cdot\xi_d+(u-u_d)^2\cdot\xi_a}{(u_d-u_a)^2} & \text{for adsorption} \end{cases} \tag{2}$$

u_a = moisture content at the current relative humidity, according to the adsorption function (kg/kg%)

u_d = moisture content at the current relative humidity, according to the desorption function (kg/kg%)

ξ_a = moisture capacity at the current relative humidity, according to the adsorption function (-)

ξ_d = moisture capacity at the current relative humidity, according to the desorption function (-)

u = moisture content at the current time step (kg/kg%)

ξ = moisture capacity at the current time step (-)

2.2. VTT wood decay model

The method consists in two phases, first, the calculation of the "starting period", a period of time necessary for the rot to start, and then the calculation of the mass loss (ML), integrating the time derivative of the ML expression for the stationary conditions, with the dynamic values of temperature and relative humidity.

The ML calculation method for stationary conditions for spruce sapwood follows Eq. 3 [38].

$$
\begin{aligned}
ML(\varphi, T, t) = & -41.224 \cdot t - 2.731 \cdot T - 0.0251 \cdot \varphi + \\
& 0.1724 \cdot T \cdot t + 0.0291 \cdot T \cdot \varphi + 0.416 \cdot \varphi \cdot t
\end{aligned}
\tag{3}
$$

Where φ, T and t are respectively the relative humidity expressed as percentage, the temperature in °C and the time of exposure expressed in months. ML is the mass loss expressed as percentage of the original mass. The values φ and T are considered to be constant over the period t. This correlation is valid only from 95% to 100% relative humidity, and for temperatures from 0°C to 30°C.

The model for the variable conditions requires first the evaluation of the activation process. For each time-step considered, the value of $\alpha(t)$, expressed as a number between 0 (dry condition) and 1 (rot process activated), has to be calculated. The function α is defined in such way that when it reaches 1, its value decreases linearly to 0 only after two years of dry conditions:

$$\alpha(t) = \int_0^t d\alpha = \sum_0^t (\Delta\alpha) \tag{4}$$

with

$$\Delta\alpha = \begin{cases} \frac{\Delta t}{t_{crit}(\varphi, T)} & \text{when } T > 0 \text{ and } \varphi > 95\%, \\ -\frac{\Delta t}{17520\text{ h}} & \text{otherwise} \end{cases} \tag{5}$$

Where Δt is the time step expressed in hours of the considered time series (in this case 1 hour), while t_{crit}, for spruce sapwood, has the following value:

$$t_{crit}(\varphi, T) = \frac{2.731 \cdot T + 0.0251\varphi - 0.0291 \cdot T \cdot \varphi}{-41.224 + 0.1724 \cdot T + 0.416\varphi} \cdot 30 \cdot 24\text{ h} \tag{6}$$

For each time-step with $\alpha(t) = 1$, mass loss occurs, and it could be calculated with the following equation:

$$ML(t') = \int_{t \text{ at } \alpha=1}^{t'} \frac{ML(\varphi,T)}{dt} = \sum_{t \text{ at } \alpha=1}^{t'} \frac{ML(\varphi,T)\cdot\Delta t}{dt} \quad (7)$$

with

$$\frac{ML(\varphi,T)}{dt} = -5.96\cdot 10^{-2} + 1.96\cdot 10^{-4}\cdot T + 6.25\cdot 10^{-4}\cdot\varphi \quad (8)$$

In this case, t and Δt are expressed in hours, while the mass loss ML in percent.

In this work, the VTT wood decay model will be applied on the values of relative humidity calculated from the moisture content of wood of the simulations. With this change of variable, performed with the sorption curves from [38], it is possible to obtain a wood decay calculation method based on temperature and moisture content.

The moisture content values considered are the lower bound values of the inoculated test samples presented in [3] for the spruce at each considered time of exposure. The critical minimum moisture content that could activate the rot process for a year of exposure is at 22% moisture content that corresponds to 95% relative humidity (considering the lower bound values of the moisture contents reported in [3]).

2.3. *Simplified logistic dose-response model*

The simplified logistic dose-response model is based on the dose-response relation. From the moisture content u and the temperature T respectively two doses are calculated, $D_u(u)$ and $D_T(T)$ [39]:

$$D_u(u) = \begin{cases} (u/30)^2 & \text{if } u \leq 30\% \\ 1 & \text{if } u > 30\% \end{cases} \quad (9)$$

$$D_T(T) = \begin{cases} 0 & \text{if } T < 0°\text{C} \\ T/30 & \text{if } 0°\text{C} \leq T \leq 30°\text{C} \\ 1 & \text{if } T > 30°\text{C} \end{cases} \quad (10)$$

$D_u(u)$ and $D_T(T)$ are then combined:

$$D = D_u(u)\cdot D_T(T) \quad (11)$$

Then, the decay rating DR is calculated:

$$DR(D(n)) = 4 \cdot \exp(-\exp(1.9612 - (0.0037 \cdot D(n)))) \tag{12}$$

The DR value could go from 0 up to 4 and, due to the model definition, for low moisture contents the values are likely to be larger than 0 and lower than 1. In this way, it is possible to compare the hygrothermal performance of two solutions that present low decay risk levels. On the other hand, the calculated values will be an overestimation of the actual decay rate and not an accurate prediction.

2.4. Study cases

In order to present the influence of neglecting hysteresis in HMT simulations, three cross-laminated timber (CLT) walls are considered. The first two wall build-ups (CLT-A and CLT-B) are designed to be representative of typical wall one-dimensional details used in residential buildings in Central Europe (found in [43] and [44]), while the third wall (CLT-C), includes a vapour barrier.

The wall build-ups are three CLT walls with rockwool insulation. The internal and external surfaces are covered with a fibre cement board panel. All the build-ups are described in Figure 2, while the utilised materials are presented in Table 1 with the material names used in the MATCH material database. The CLT-A wall is a common CLT wall with a single layer of 200 mm of insulation. The CLT-B wall is similar to CLT-A, but with the addition of another layer of insulation before the CLT layer. The total thickness of insulation of CLT-B is 275 mm. Finally, the CLT-C wall is designed as the CLT-A wall, but with a vapour barrier on the external surface of the insulation layer. The CLT-C build-up is here presented as a badly designed worst case scenario for the European locations: the vapour barrier is positioned on the cold side of the insulation, to increase the probability of moisture accumulation.

2.5. Boundary conditions

The walls are considered in seven different locations: Bolzano (Italy), Copenhagen (Denmark), Hong Kong, Ottawa (Canada), Shanghai (China), Udine (Italy) and Vienna (Austria). To achieve more representative results, the weather files are obtained from different sources:

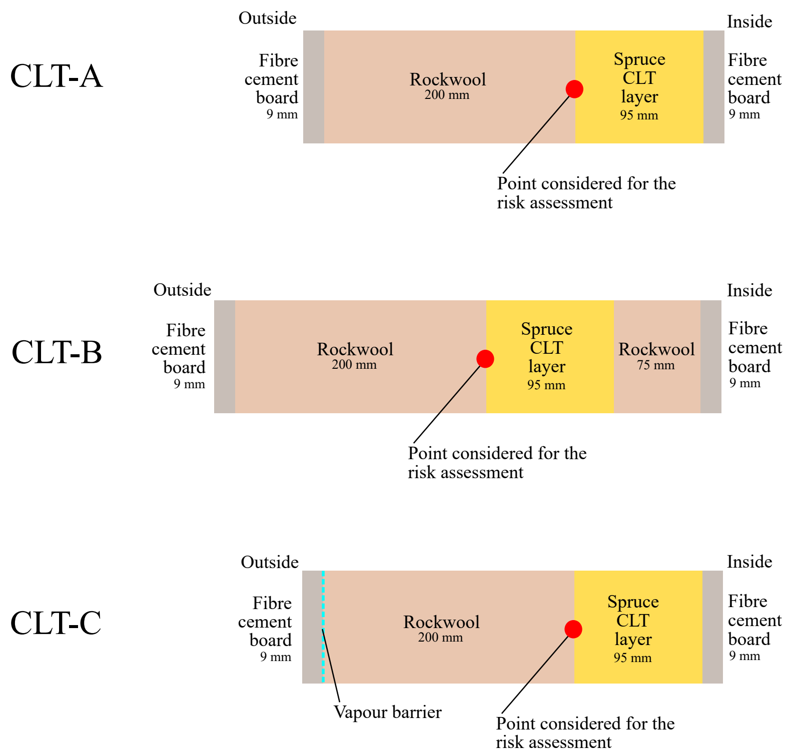

Figure 2: Wall types, layer thicknesses of the building envelope used in the simulations and location of the study case points considered for the wood decay risk analysis.

Table 1: Material properties

Material MATCH database name	ρ_{dry} (kg/m^3)	c (J/K·kg)	λ_{dry} (W/m^{2}K)	μ $(-)$	u_{80}^{ads} (%)	u_{80}^{des} (%)
Fibre cement board	1880	900	0.6	35	6.8	9.5
Rockwool	50	800	0.033	1	0.7	0.8
Spruce	420	2500	0.1	125	16.7	19.7

Note: the vapour barrier equivalent thickness is S_d=2500 m, ρ_{dry} is the density of the dry material, c is the specific heat capacity, λ_{dry} conductivity of the dry material, μ vapour resistance factor, u_{80}^{ads} and u_{80}^{des} are the moisture contents of the material at 80% relative humidity respectively of the adsorption curve and of the desorption curve.

- The weather file of Copenhagen is the Design Reference Year provided with the software MATCH;
- The weather file of Bolzano (Italy) is a typical year from the Italian Climatic data collection “Gianni De Giorgio”;
- The weather file of Hong Kong is a typical year from City University of Hong Kong (CityUHK) (TRY);
- The weather file of Ottawa is a typical year from the Canadian Weather for Energy Calculations (CWEC) (typical);
- The weather file of Udine (Italy) is the measured year 2014, provided by ARPA FVG, selected as the year with the highest relative humidity annual mean;
- The other weather files are typical years from the International Weather for Energy Calculations (IWEC).

The internal conditions are set for simplicity to a fixed value of relative humidity 80%, to represent an environment with high moisture loads, while the internal air dry-bulb temperatures are set to 21 °C during winter months and to 23 °C during summer months.

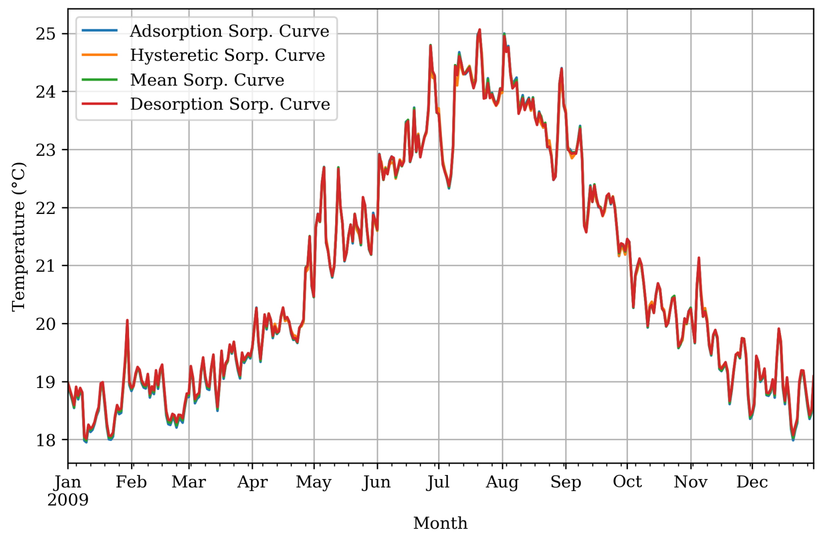

Figure 3: Daily average temperature (unit: °C) at the study case point resulting from the heat and moisture transfer simulation of the CLT-A wall in the city of Shanghai.

3. Results

The comparison has been performed on the results calculated with the simulations presented in the previous sections considering only one point for every build-up: the external surface of the timber layer, between the external layer of insulation and the timber. For each wall type, the analysed surface point is shown in Figure 2. First, the general differences between the calculation results are presented for a single case. As a representative example, the results of the simulation of the CLT-A wall in Shanghai will be presented. The differences between the values calculated with the bijective curves and the hysteretic sorption curve are presented visually in Figures 3, 4, and 5 while the maximum differences calculated among all the studied cases are presented in the text, in order to quantify the range of the variations. In this section the last of 10 years of simulation is considered.

The first comparison is performed in terms of temperature. Figure 3 shows the daily average temperatures calculated for the aforementioned case. The difference among the four sorption curve models is caused by the coupling between the moisture bal-

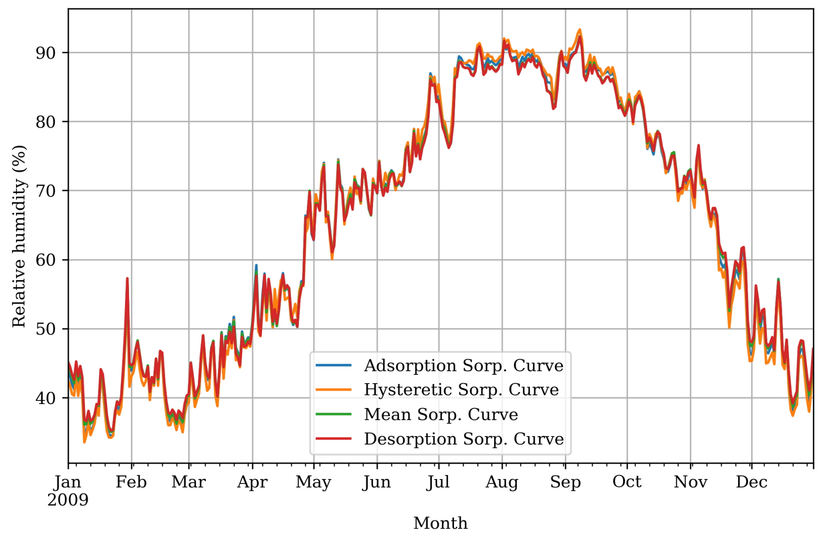

Figure 4: Daily average relative humidity (unit:%) at the study case point resulting from the HMT simulation of the CLT-A wall in the city of Shanghai.

ance equation and the heat balance equation (due predominantly to latent heat transfer mechanisms) meaning that changing the moisture transport and storage properties of the materials also has an effect on the heat transfer. In this case, the effect on the temperature at the considered point is small and the plotted lines are mostly overlapping. The maximum difference between the daily average temperatures calculated the bijective sorption curves and the ones with hysteresis is 0.2 K. This value is found for the adsorption curve and for the desorption curve. On the other hand, the annual average difference among the year is below 0.01 K for all the bijective sorption curves. Among the studied cases, the largest annual average temperature difference is 0.07 K, found for the Copenhagen weather file in the wall CLT-B considering the adsorption curve.

Similarly, also the plots of the daily average values of the relative humidity are overlapping. This is shown in Figure 4. The daily average absolute differences between the relative humidity calculated with the hysteretic sorption curve and the other curves are less than 4%. The annual mean differences are below 0.3% relative humidity. The extreme and mean values are shown in Table 2.

The other simulations with different weather files have daily average differences

Table 2: Relative humidity (unit:%) and Moisture content (unit: kg/kg%) mean, maximum and minimum daily values obtained in the simulation at the study case point of the CLT-A wall, with the use of the four sorption curves in Shanghai.

	Relative humidity (%)			Moisture content (%)		
	min	mean	max	min	mean	max
Desorption Sorp. Curve	35.2	64.8	92.3	9.1	16.2	25.9
Hysteretic Sorp. Curve	33.5	64.5	93.3	8.2	15.0	24.8
Mean Sorp. Curve	35.0	64.8	92.3	8.3	14.8	24.3
Adsorption Sorp. Curve	34.4	64.7	92.4	7.3	13.4	22.7

lower than 7% while the annual mean differences are below 0.6%, the largest being the case of the CLT-B wall in Shanghai.

The values of moisture content calculated for the study case are presented in Figure 5. The lines calculated with the bijective curves (the adsorption curve, desorption curve and mean curve) have similar trends but their positions are shifted vertically. The desorption curve line has the larger moisture content values, while the adsorption curve has the lowest and the mean curve is positioned in between. The moisture content values calculated with hysteresis and the ones of the mean curve have similar mean values, but if the hourly and daily values are considered the behaviour is not the same. Figure 6 shows a month of the hourly values of the moisture content.

It is observed that the moisture content values of the hysteretic curve follow the ones of the mean sorption curve, but with lower oscillations. Moreover, it could be seen that in the summer months (higher moisture contents), the hysteretic moisture content is closer to the desorption curve, while in the winter months (lower moisture contents) it is closer to the adsorption curve. This effect is caused by the moisture capacity values of the hysteretic curve, which are smaller than the other sorption curves. In this case the values are not calculated as the derivative of the sorption curve (Eq.1), but with Eq.2. As a result, the MC curve of the hysteretic case has smaller hourly variations.

This effect is also observable from the mean values of the moisture contents re-

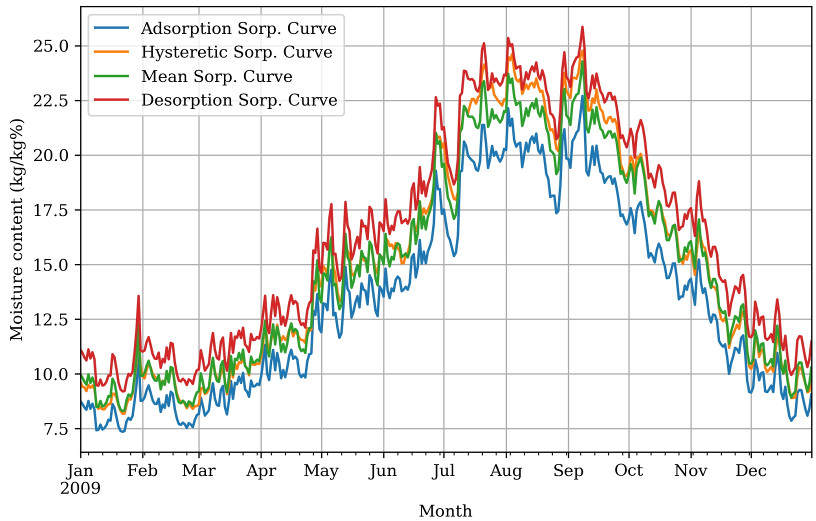

Figure 5: Daily average moisture content at the study case point (in terms of percentage of water mass over the dry mass of the timber) resulting from the heat and moisture transfer simulation of the CLT-A wall in the city of Shanghai.

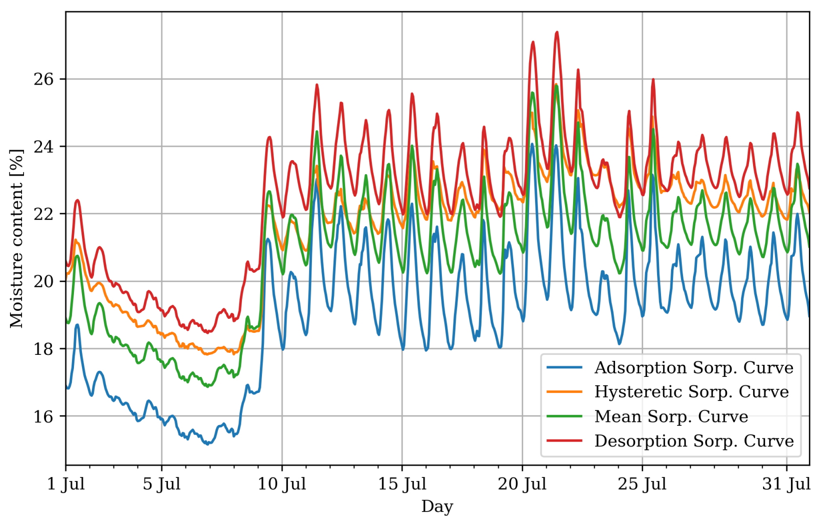

Figure 6: Hourly moisture content at the study case point (in terms of percentage of water mass over the dry mass of the timber) resulting from the heat and moisture transfer simulation of the CLT-A wall in the city of Shanghai for the days of July of the 10th year of simulation.

ported in Table 2: the desorption curve moisture contents have an annual mean of 16.2%, 1.2% higher than the annual average value calculated with hysteresis, while the adsorption curve gives values 1.6% lower than the ones of the hysteresis. The mean curve moisture contents are in average 0.2% lower than the ones of the hysteretic sorption curve. If the daily average values are considered, the maximum difference between the hysteretic curve values and the desorption curve results is 2.3%, the maximum difference between the hysteretic curve values and the ones for the adsorption curve is 3.6% while between the mean sorption curve and the hysteretic curve the maximum difference is 1.7%. When considering the other locations and walls, the maximum annual mean difference is 2%, found for the CLT-B in Hong Kong for the adsorption curve.

If the hygrothermal conditions are reported on a relative humidity-moisture content plane, obtained plotting the moisture content against the relative humidity calculated at the same time-step (Figure 7) it is possible to visualise the different paths that the sorption models are following in the simulation during the year. The slope of the curves represents the moisture capacity ξ, included in the moisture balance equation. The path of the hygrothermal states calculated with the bijective sorption curve is, by definition, constrained on the sorption curves, while the path obtained with the simulation of the hysteretic curve has variable slopes (calculated with Eq. 2) and it is constrained between the adsorption and the desorption sorption curves. The hygrothermal states draw cyclic paths due to the alternation of adsorption and desorption process. The paths drawn in two days are shown in Figure 8 with the respective simulation results obtained with the bijective curves.

3.1. Wood decay risk analysis

The wood decay risk analysis with the VTT model and the simplified logistic dose-response model has been performed on the time series of moisture content values and temperature values resulting from the previously presented series of simulations (three CLT wall types in seven different locations).

As an example, the decay ratings according to EN 252 (1990) for the case of CLT-A in Shanghai, are presented in Figure 9. At the end of the first 10 years, the decay

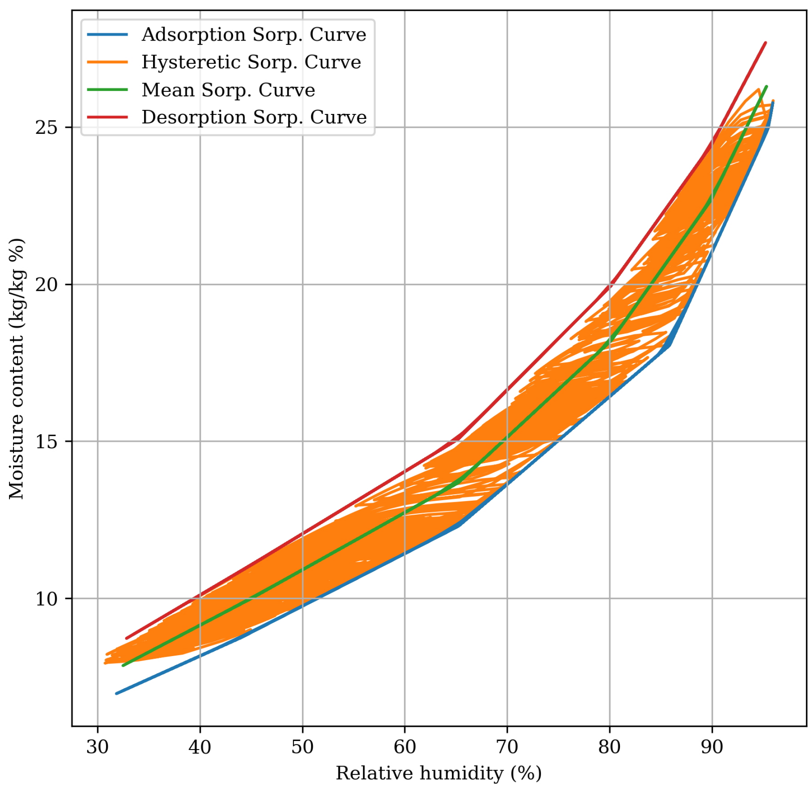

Figure 7: Hygroscopic behaviour at the study case point (in terms of percentage of water mass over the dry mass of the timber and relative humidity as percentage) of the timber resulting from the 10th year of the HMT simulation of the CLT-A wall type in the city of Shanghai.

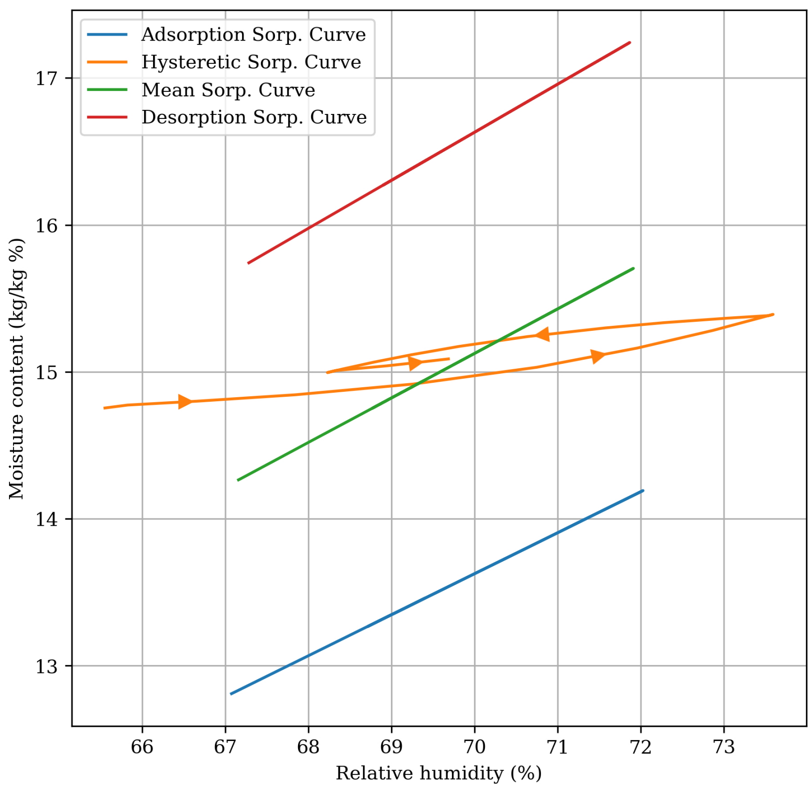

Figure 8: Hygroscopic behaviour (hourly values) at the study case point considering the hysteresis in the model (in orange) and the other results (obtained neglecting the hysteresis) of the 1st of June of the 10th year of simulation of the CLT-A wall type in the city of Shanghai.

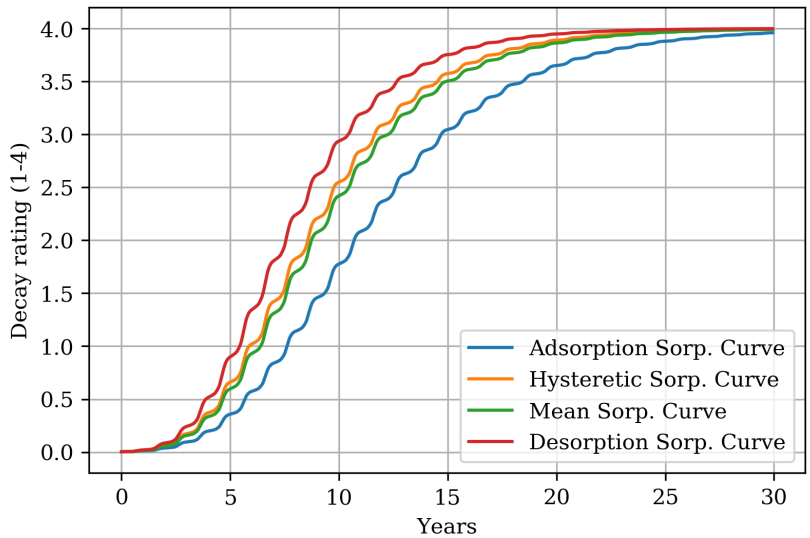

Figure 9: Decay rating at the study case point in time according to the simplified logistic dose-response method for the CLT-A wall in Shanghai for a 30-year-long simulation.

ratings obtained are of 2.9, 2.6, 2.5 and 1.8 respectively for the desorption curve, the hysteretic model, the mean sorption curve, and the adsorption curve. At the end of 30 years (a short service life for a building) all the four curves reach the decay rating 4 (Failure). The time needed to reach decay rating 3 (Severe attack) is 10.4, 11.6, 11.7, and 14.7 years respectively for the desorption curve, the mean sorption curve, the hysteretic curve, and the adsorption curve.

The results of the simulations have been also used to calculate the mass loss with the VTT model applied on the moisture content series. The values of mass loss are plotted in Figure 10. In 30 years, the desorption curve simulation returned 10% mass loss, the hysteretic sorption curve almost 6%, the mean sorption curve and the adsorption curve 0%. If 10% mass loss is considered as the acceptable performance, the maximum service life reached by the hysteretic sorption curve is 45 years, while the mean sorption curve results reaches 65 years. The desorption curve obtains 29 years and the adsorption curve, with 0% mass loss does not reach risk condition. The VTT model applied on the relative humidity returned about 0% mass loss, with the same

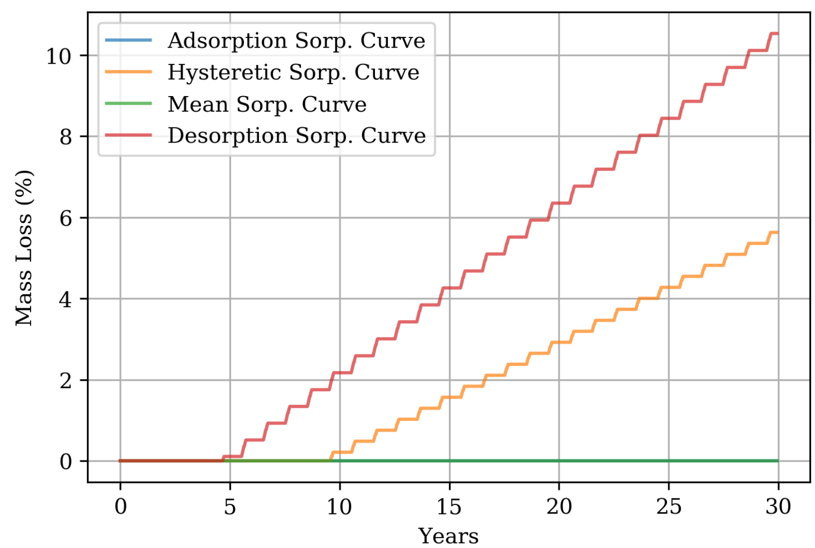

Figure 10: Mass loss at the study case point in time according the VTT model applied on the moisture content for the CLT-A wall in Shanghai calculated at each day of the last year of a simulation of 30 years.

simulation results.

The results of the simplified logistic dose-response risk assessment for all the locations and for the CLT-A, CLT-B, and CLT-C wall types are presented in Figure 11. The decay ratings presented are for a period of 30 years. For each simulation, the desorption curve simulations have the higher ratings, followed by the mean sorption curve and the hysteretic model, that have decay rating values with small differences, and finally by the adsorption curve. The adsorption curves and the desorption curves have 1 rating level of difference, while the hysteretic model and the mean curve have similar values, between the adsorption and the desorption ratings. The decay ratings for the CLT-A and CLT-B walls in Hong Kong and Shanghai, and for the CLT-C wall in the cities of Bolzano, Hong Kong, and Udine have a decay rating of 4 for all four models.

The values of service life calculated with the simplified logistic dose-response model are presented in Figure 12. It is shown that, when the moisture contents are lower, longer service life are calculated, with larger differences in the results. The mean sorption curve and the hysteretic model calculated similar values and the dif-

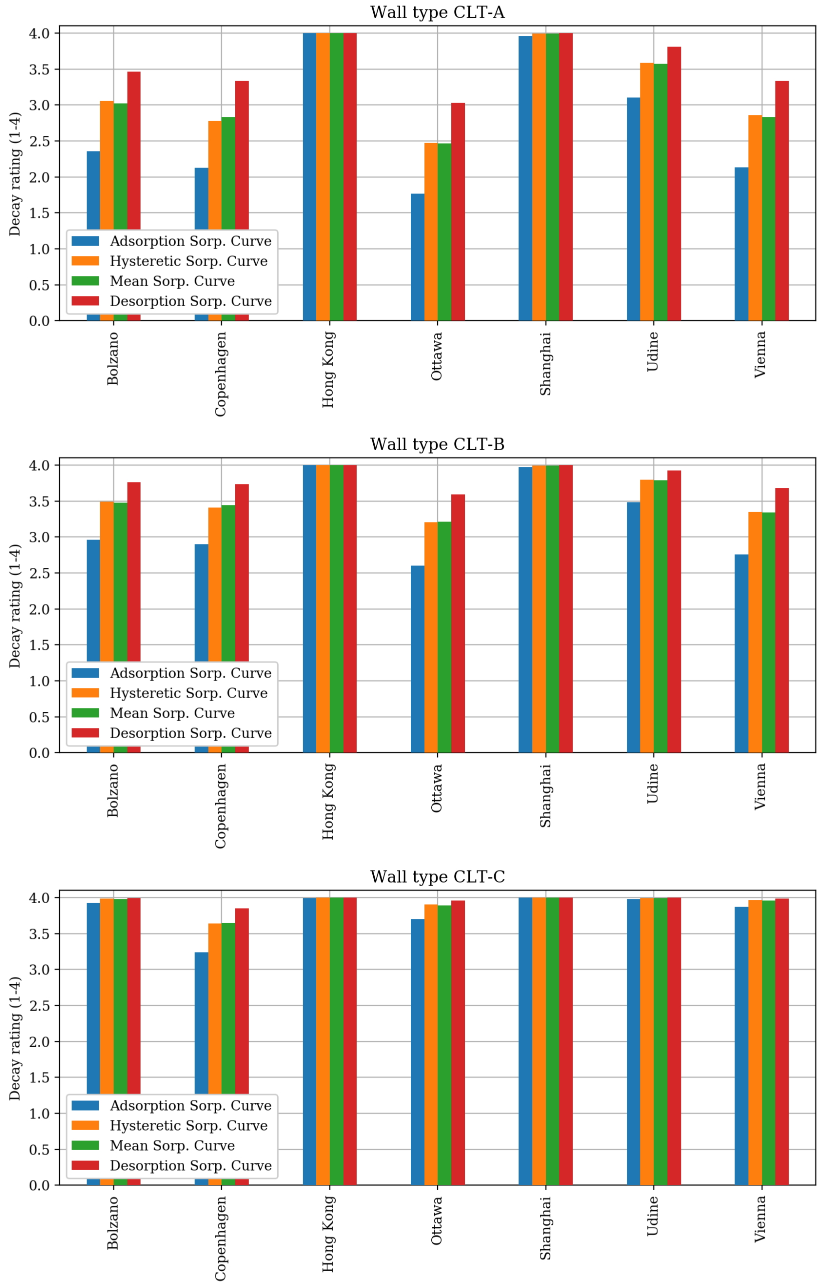

Figure 11: Decay rating at the study case points in 30 years according the simplified logistic dose-response method for the three walls simulated in seven locations.

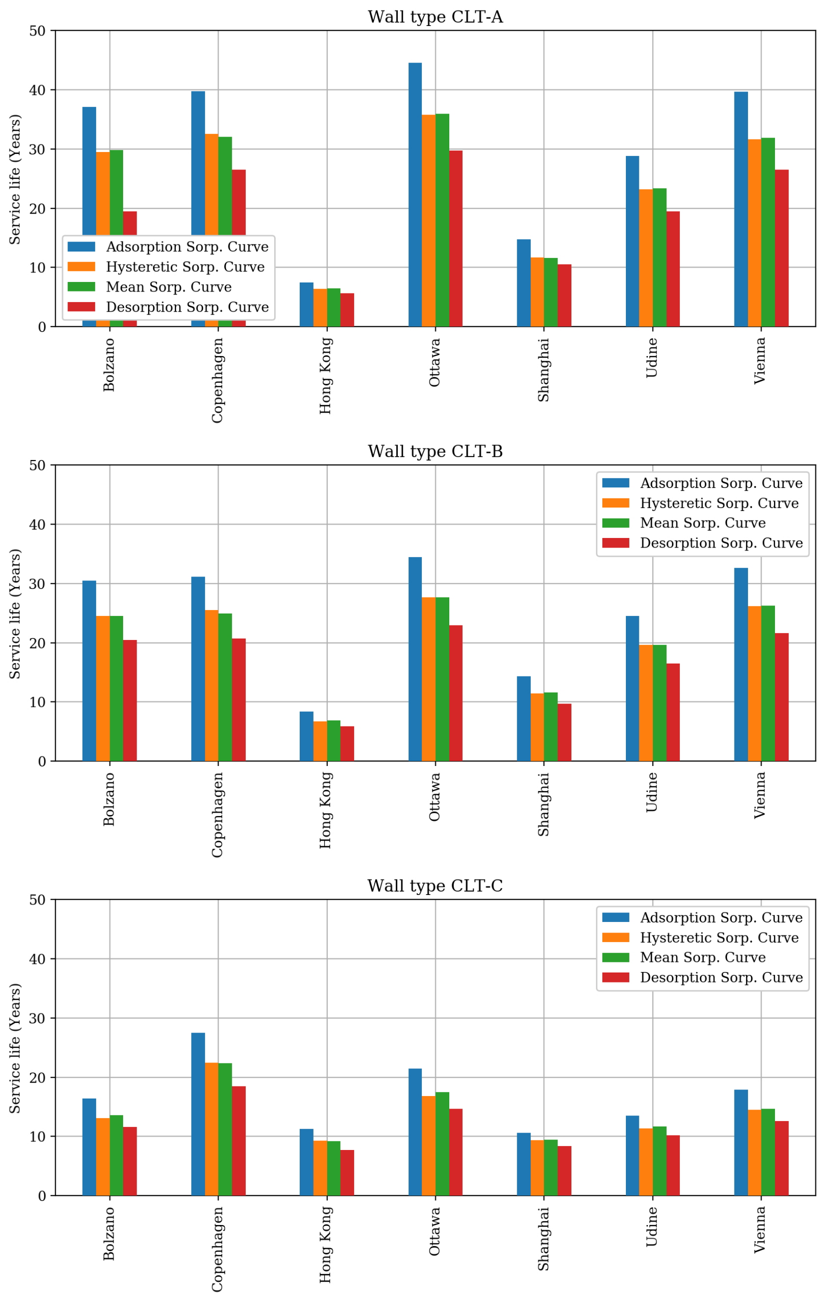

Figure 12: Service life of the considered walls calculated with the simplified logistic dose-response method for the three walls simulated in seven locations. The service life is calculated as the time needed to reach decay rating 3.

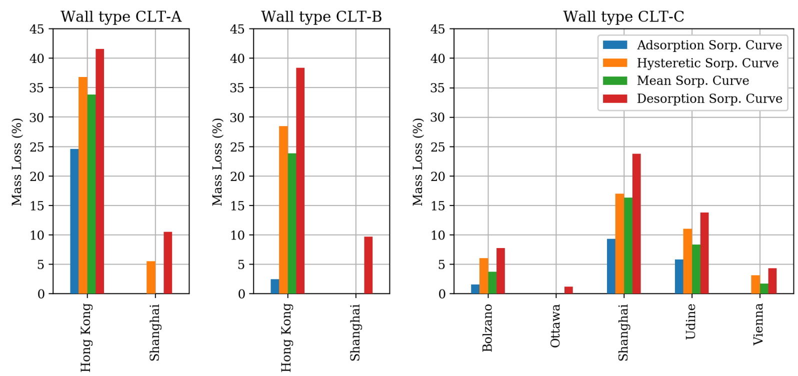

Figure 13: Mass loss at the study case point in 30 years according to the VTT wood decay model, applied on the moisture content, for the three walls simulated in seven locations. The locations not shown reported 0 mass loss values for all the four sorption models.

ference between them is lower than 1 year. Differently, the adsorption curve and the desorption curve have relevant differences from the hysteretic model (larger than 5 years) for the cases with lower moisture contents and longer service life values.

For the same set of simulations, the VTT wood decay model is used to calculate the mass loss from the moisture contents. The mass loss values are presented in Figure 13. The cases that obtained a decay rating of 4 with the simplified logistic dose-response obtained positive values of mass loss. For the CLT-A and CLT-B walls, the cases of Hong Kong and Shanghai has mass loss values larger than 0%, while for the CLT-C wall, mass loss values larger than 0% are found for the cities of Bolzano, Ottawa, Udine, and Vienna. The different sorption curve models have different values of mass loss, causing different outcomes in the wood decay risk assessment. For example, the Shanghai mass loss of the CLT-B wall is about 10% for the desorption curve, while for the other curves it is 0%.

The ML time series are used to calculate the service life of the considered walls for the four considered sorption curves. The service life is calculated as the time needed to develop a ML of 10% in the studied point of the wall. The value of 10% ML loss is here considered for the sake of example. The values are reported in Figure 14 and they are different from the ones obtained with the simplified logistic dose-response model.

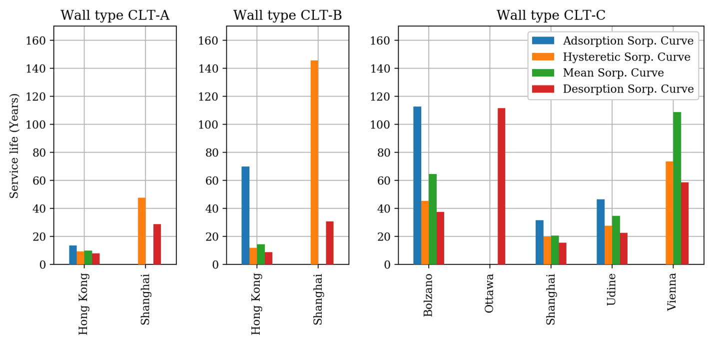

Figure 14: Service life of the considered walls calculated according to the VTT wood decay model, applied with moisture content, for the three walls simulated in seven locations. The absence of a bar and of a location indicates that the calculated service life is longer than 200 years. The service life is calculated as the time before reaching a mass loss of 10%.

Using this method, most of the considered locations are reported to have service life periods longer than 200 years, thus their values are not reported in Figure 14. Moreover, the resulting periods are strongly influenced by the sorption curve model used in the calculations. Not only, the adsorption curve and the desorption curve have different outcomes, but also the hysteretic curve and the mean sorption curve have differences larger than 20 years. For the CLT-C wall, the case of Vienna is the one with the larger differences. The adsorption curve resulted in a service life longer than 200 years, while the desorption curve has only 59 years. The mean sorption curve resulted in a service life of 110 years, while, considering hysteresis the period is 73 years, 37 less than the mean sorption curve.

4. Discussion

The aim of this work is to compare the results of the simulations of the HMT model that considers hysteresis with the simplified models that uses bijective functions to describe the sorption process of the materials. These simulations are typically performed by practitioners, engineers, and designers on building envelopes that have not been realized yet when measurements are not available to perform validations. Wood decay risk calculations are used as indicators of hygrothermal performance (not as realistic predictions of the damage entity [29]). Considered this, some observations could be added on the effects of moisture hysteresis on simulation results.

For the presented case of the CLT-A wall in Shanghai, if the adsorption curve (or the desorption curve) is used, the results are about 1.5% mass moisture content lower (or higher) than the results obtained considering hysteresis. These values correspond to the difference between the sorption curves moisture contents of spruce calculated at the mean relative humidity of the simulation: at 65% relative humidity, the moisture contents of the material spruce from the MATCH database are 11.3% for the adsorption curve and 14.3% for the desorption curve.

Similar results are presented in [19] and [4], even if other hysteresis models and materials are used. Though the annual average moisture content values of the hysteretic case and of the mean sorption curve are similar, this effect is not a general property of the HMT simulations with hysteresis. It is possible for the moisture content to be closer to the adsorption curve when the material is accumulating moisture (or to the desorption curve if it is in a drying process). This effect is observed in the summer months of the presented cases (Figure 6) and it corresponds to hysteresis solution having higher moisture contents than the mean sorption curve.

Considering the desorption and adsorption curves, the difference of 1.5% (up to 2%) of moisture content is a relevant quantity, given that the maximum moisture content during the year for the presented study case is 25%, and it could affect the outcome of a risk assessment based on a threshold.

Finally, the simulation results have been used to perform two wood decay risk assessments, using the VTT wood decay model (applied on the moisture content values, in order to show the different results given by the moisture content time series of the four sorption curves) and the simplified logistic dose-response model. Both models, showed that for every studied case, the desorption curve model results have higher values of decay rating, while the adsorption curve model calculated lower values, with respect to the non-simplified HMT model that considers hysteresis.

The results of the mean sorption curve model provided ratings very close to the ones of the hysteretic model. The largest differences among the two are found for the VTT model. If the curves of the mass loss in time are considered (Figure 10), the hysteretic sorption curve reaches 2% mass loss more than 5 years before the mean sorption curve and, if 10% mass loss is considered as the acceptable performance, the service life reached by the hysteretic sorption curve is 20 years less than the mean sorption curve service life. The desorption curve reaches 10% 26 years before the hysteretic curve and the adsorption curve does not show risk conditions. This is explained by the fact that the hysteretic model calculates higher ratings than the mean sorption curve because the equilibrium states are closer to the desorption curve, allowing the material to store higher moisture contents for the same relative humidity values.

The errors of neglecting hysteresis are up to 20% mass loss in 37 years for the VTT model and it could cause the wrong classification of the simplified logistic dose-response model decay rating by 1 level for a simulation of 30 years. In the case of CLT-B wall in Shanghai the desorption curve resulted in the presence of wood decay risk, while risk occurred with the hysteretic model. Similarly, for the CLT-A wall in Shanghai, the adsorption curve calculations provided the absence of risk, while the hysteretic model did not. The mean sorption curve simulations with high moisture loads resulted in lower values of risk. For the general applications with low moisture contents, these estimations could be acceptable, but if a higher degree of accuracy is required and the moisture contents are higher than 20%, the hysteretic model might be required in the simulations and the calculated service life of the structures could be relevantly affected (20 years of difference).

5. Conclusions

In this study, the effects of neglecting moisture hysteresis in HMT simulations have been evaluated in three different cross laminated timber walls, first in terms of moisture content, relative humidity, and temperature values. Then, a risk analysis has been performed using the simplified logistic dose-response method and the VTT wood decay model applied on the moisture content values. The study cases are presented to quantify the effect of the simplification that a designer would make using a simplified HMT model that considers a bijective sorption curve, neglecting moisture hysteresis, for the wood decay risk assessment.

Temperature and relative humidity values of the studied cases are not largely influenced by hysteresis, while moisture content values have relevant differences. Using the adsorption curve in the simulations provided always lower moisture contents, while the desorption curve resulted in higher moisture contents. The wood decay risk assessment is performed with the moisture content values with the VTT wood decay model and with the simplified logistic dose-response model. If the model that considers hysteresis is used as a reference, the results show that the mean sorption curve leads to smaller deviations in the results, but provides generally lower risk values. The desorption curve and the adsorption curve, resulted in respectively higher and lower values of risk in every case.

In conclusion, neglecting moisture hysteresis in the wood decay risk evaluation processes could cause different estimations of the decay ratings, of the service life and, in general, it could cause deviations in the moisture content evaluations. These deviations are shown to be relevant for high moisture loads (depending on the required performances) and they could change the outcome of the risk assessment (if the performance required is, for example, absence of calculated mass loss) and in the service life calculations. If possible, its implementation in HMT simulation software should be taken into consideration, while, for the hygrothermal characterization of materials, both adsorption and desorption curves should be measured and provided in material database to allow to perform simulations with both curves (to be used to calculate the lower and upper boundaries of the moisture content values). For the studied results, the mean sorption curve can be used as valid alternative to hysteresis for cases with small moisture loads, but further research is necessary to confirm if it is a valid solution also for the over-hygroscopic range, for other materials and for other boundary conditions.

Future studies are also required to evaluate the effects of moisture hysteresis on wood in other conditions (other species, age or treatments) other materials subject to other damage models dependent on moisture content. Other known damage mechanisms depend on moisture content and temperature values, for example the freeze-thaw damage, typically affecting stones and bricks, is analysed using the degree of saturation below the freezing point of water in the material pores [45, 46, 47] obtained from simulated moisture content values. Similarly, this happens also for risk assessment methods regarding corrosion of steel embedded in porous materials presented in [48] and [49]. This approach will also be extend to other applications involving other heat and moisture transfer models, for example the moisture buffering effect for the indoor moisture prediction, that could be calculated with complete models, with hysteresis, or simplified models (for example [50] or [51]).

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Conflict of interest

The authors declare that they have no conflict of interest.

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