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Mechanical deformation of a wooden panel due to a varying climate – Numerical simulations

Master's thesis

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ABSTRACT

Wood has been used for thousands of years as interior decoration. It is therefore logical that many objects made of this material are found in a cultural heritage context. A large amount of historical art pieces, such as decorated wooden panels, have been stored in historical buildings. Heating systems are not common in historical buildings, not even after renovations. In some occasions it is not allowed to apply an HVAC-system because of the cultural heritage value of the building itself. Since these buildings are often not climate controlled it is important to know how the indoor climate is affecting the historical art.

The aim of this study is to understand the cause-effect relationship between a fluctuating climate and wooden panels. Wood is a hygroscopic material, meaning that it will absorb and desorb moisture during changes in relative humidity and temperature of the ambient air. Changing moisture content in the wood comes with expansion or contraction of the wood cells, which could cause deformations of the panel.

A simulation model is developed to compute the state of deformation, which is expressed in curvatures. Two types of simulations are made; simulations of moisture transport in wooden panels subjected to a fluctuating climate during a year; and isothermal simulations for mechanical deformation of the panel due to changes in the vapour concentration at the surface. Before running the simulations, a literature study was done to get a greater view of the possible outcome of the simulations. With the numerical tool, moisture transport was analysed first and afterwards the curvature of the panel was computed. Six indoor climates were taken as an input, which gave six simulations of the curvature for one panel. The model confirms that deformation of the panel is in line with fluctuations of relative humidity of the ambient air. By increasing the surface vapour resistance factor of the panel, the range of the curvature decreases.

The calculations show many repetitive and alternating cycles of curvature. However, it is not known how many and how big these cycles need to be before cracks occur. Therefore a proposal for future research is to develop a scale that represents damage against deformation.

Keywords: Wood, relative humidity, moisture content, temperature, moisture transport, moisture transport coefficients, expansion coefficients, deformation, pores, paintings, historical buildings

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NOMENCLATURE

c	Specific heat capacity (J/kg K)
d_{pv}	Periodic penetration depth (mm)
D	Thickness (m)
g	Density of moisture flow rate (kg/m^2s)
h	Lift (m)
I	Moisture induced moment (-)
L	Length (m)
R	Radius of the plate curvature (m)
t	Time (s)
T	Temperature (°C, K)
u	Moisture ratio (content) mass by mass (kg/kg)
v	Humidity by volume (kg/m^3)
w	Moisture content mass by volume (kg/m^3)
Z	Surface vapour resistance (s/m)
β	Coefficient of hygroscopic expansion or contraction (mm/mm per 1%MC)
δ_v	Vapour permeability (m^2/s)
ϕ	Relative humidity (-)
ρ	Density (kg/m^3)

SUBSCRIPTS

ECY	Extreme Cold Year
EMC	Equilibrium moisture content
EWY	Extreme Warm Year
IQR	Interquartile range
MC	Moisture content
PDE	Partial differential equation
RH	Relative Humidity
T	Temperature
TDY	Typical Downscaled Year
1D	One-dimensional

1. INTRODUCTION

1.1 Background

In living trees, the cell walls of wood are always in the fully swollen condition. Expansion or contraction does not occur except for hydrostatic tensions and thermal changes in the fibre saturation. The moment a tree is felled, the drying process starts and hygroscopic shrinkage takes place. From now on, the wood is influenced by relative humidity (RH) and temperature (T) of the ambient air. Wood is normally dried to a moisture content (MC) that approximates the equilibrium moisture content (EMC). Environmental conditions are rarely constant which causes continually changing ECM. The MC of wood is constantly adapting to the ambient RH and T.

Many historical art objects were made of hygroscopic materials such as wood. These objects have been affected by the cycling climate in the past. The way in which art is conserved has always been important in order to preserve the value of it. Therefore it is essential to take the future climate change into account, because different conditions of the ambient air (RH and T) might affect the objects in a different way. The aging process could speed up because of more intense fluctuations in the climate can result in permanent damages such as cracks.

By mapping moisture transport in wooden art objects and subsequently also simulating deformation of the objects, it can be defined how aggressive a fluctuating climate could be for these objects. In this thesis, one specific area of art has been studied, namely decorated wooden panels.

In the article, 'Simulation of moisture gradients in wood subjected to changes in relative humidity and temperature due to climate change' by Bylund et al [1] simulation models have been developed to study the moisture transport. This thesis continues with the used models for moisture transport and additional the mechanical deformation is simulated.

1.1.1 Indoor environments in historical buildings

The indoor environment in historical buildings is difficult to control, because their own high cultural heritage value renders interventions to make it climate-controlled challenging or even impossible. Some historical buildings contain historical objects. If there is no active climate control, the cultural heritage is only protected against rain and wind by the structure of the building. In unheated historical buildings indoor climate is fluctuating on a seasonal as well as a daily basis. There are a few different ways to install climate controlling systems in historical buildings, but controlled heating systems still goes together with cyclic changes of the indoor climate. Fluctuating RH and T are considered to be a major threat to wooden objects stored in these buildings. Research on the influence of RH and T on cultural heritage in wood is mainly based on steady-state conditions. In a stable environment, equilibrium moisture content (EMC) can be reached, but under varying conditions ECM may never be reached [2] [3].

1.1.2 Properties of wood

The moisture content of wood varies in accordance with the moisture conditions of the ambient air. It is a natural characteristic for hygroscopic materials to strive towards equilibrium. Wood is a hygroscopic material. This means that it is able to bind moisture directly from the ambient air. In a high RH-zone wood can gain moisture, by contrast, in zones with low RH wood will release moisture. Dry wood is less flexible and will crack more easily; humid wood is a suitable milieu to grow fungi. The process of striving towards ECM causes problems to safely preserve wooden cultural heritage objects [4].

1.2 Aim and limitations

The overall aim in this thesis is to understand the cause-effect relationship between a fluctuating environment and wooden objects – more specifically, decorated wooden panels. Because a large number of cultural heritages are stored in poorly heated historical buildings, it is important to know how the combination of high RH and low temperatures (winter conditions) affect wooden objects. An estimation of the future global climate change has been used to define if future settings would cause damage. The study has two main objectives to relate damage of wooden objects to the past and present indoor climates of historic buildings: simulation of moisture transport under certain conditions of ambient air; simulation of the deformation of the wooden panels.

Variables in the simulation are chosen to describe one specific case. These variables are, for example, one specific type of wood – namely Scots pine (Pinus Silvestris L.) – specific ambient air conditions. In the simulation model, a panel was exposed to six types of weather data (RH and T). The weather data was used as input in the model. The output gave a simulation of the deformation for one panel subjected to the six different weather data sheets. It's also important to increase the expertise in energy efficiency of historical buildings, but this is not a focus in this study.

In Figure 1-1 an illustration of a wooden decorated panel is given. In this set up, a rectangular panel is fixed at the four corners. The front of the panel is interacting with the ambient air of the room and the back is considered moisture tight, meaning that it is not interacting with the ambient air. The decoration layer has a certain vapour resistance factor *Z* [s/m], which affects the interaction between the wood and the ambient air.

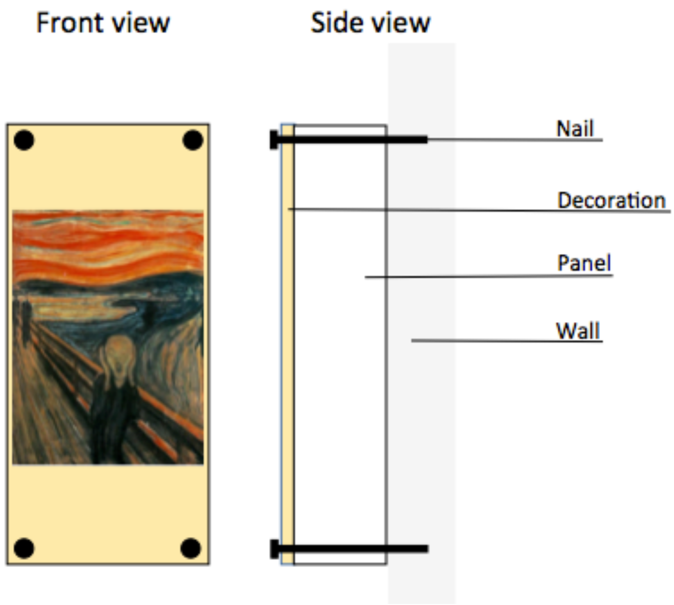

Figure 1-1 Illustration of the set up (painting from [5])

1.3 Problem identification

Wooden objects in historical buildings are often exposed to large temperature and moisture gradients. As mentioned before wood is a hygroscopic material, i.e. a material that is able to absorb or desorb moisture.

Moisture can be transported trough the pore system of wood. This transfer is non-uniform, which results in differential levels of moisture contents in a sample. In this study, moisture was absorbed at the front and spread inwards at high RH conditions. In conditions where the RH of the ambient air is low, moisture is instead released outwards. Moisture is gathered from other areas onto the front. When wood cells gain moisture, they will expand. If the cells lose moisture, they will contract, this will give a curvature to the whole panel.

If the moisture transfer is non-uniform, the expansion or contraction of the cells also will develop non-uniformly. The differences in volume of the cells will cause internal stress and strain in the panel. Eventually, non-uniform moisture distribution leads to deformation of the panel. Figure 1-2 illustrates moisture transport and deformation.

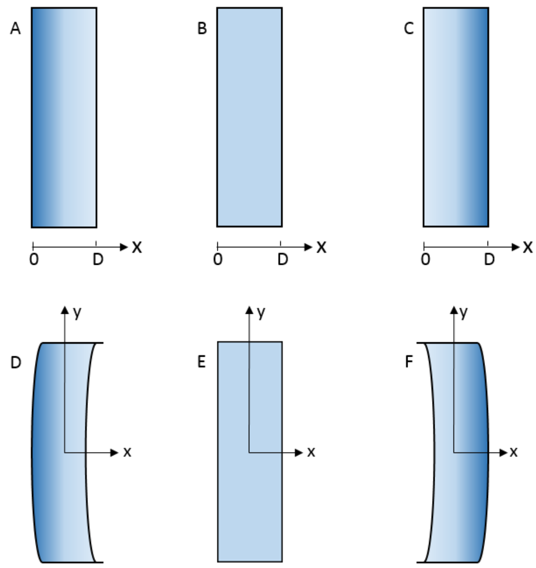

Figure 1-2 A, B & C moisture transport; D, E & F deformation

Illustration A, B & C clarify moisture transport. In figure A and C, a non-uniform moisture content is showed through a colour nuance. A dark colour illustrates a high level of moisture; a light colour equals a low level. The front of the panel in illustration A has been absorbing moisture from the ambient air. More water molecules are situated in the front ($x = 0$) than in the back ($x = D$). In illustration B, ECM is reached, and the MC is uniform in the whole panel.

Illustration D, E and F demonstrate the deformation. The cells in areas with high levels of moisture will expand, while cells in areas with low levels will contract, this is shown in D. Illustration F shows the opposite and in situation E there is no deformation because of ECM, all cells have swelled/shrunk uniformly.

The simulation in this study is based on fluctuating conditions of the ambient air. Moisture flows in the direction shown in illustration A and C. In non-constant conditions, the EMC (illustration B) can never be reached.

These phenomena of moisture transport and mechanical deformation causes problems such as cracks, permanent deformation, etc. Permanent damage like this needs to be avoided.

1.4 Outline of the thesis

This thesis can be divided into four main sections. The first section contains a brief introduction and a literature study of wood-moisture relationships (Chapter 1 and 2). The second section is divided in four parts; Chapter 3, which discusses the simulation model; in Chapter 4 the climate data and the material properties are deliberated; Chapter 5 is used to discuss analytical and numerical examples; in Chapter 6 the final results are presented. The third section handles the discussion of the results in comparison with the literature study. All previous sections are concluded (Chapter 7) and a propose for further research is made in (Chapter 8). Finally, in the last section (Chapters 9 and 10), references and an appendix are included.

2. LITERATURE STUDY

2.1 Cultural heritage: wooden panels stored in unheated historical buildings

Moisture change is potentially disastrous for hygroscopic objects. This is why it has been essential to set a safe range for objects and collections in museums or climate-controlled buildings [4]. A safe range is based on research that defined worst-case scenarios for different climate situations and different materials. Though, not all historical objects are housed in museums or other climate controlled buildings. Wood has been used for thousands of years to make tools and weapons, as interior decoration, as a building material, etc. Therefore, it is logical that these objects are found in a cultural heritage context. A lot of historical art, like decorated wooden panels, have been stored in historical buildings, which are not climate controlled at all [2]. It is not only essential to evaluate how these objects have been affected by climate changes in the past, but also to try to predict changes in the future. In unheated historic buildings, RH and T are fluctuating on a seasonal as well as daily basis. Skaar [3] said that because of the constantly fluctuating indoor environment, objects rarely or never reach EMC.

Scots pine (Pinus sylvestris L.) is a wood species that is very common in cultural heritage objects in Sweden. Further on in the report, the properties of this species are explained, and variables are used in the simulation models. To study the correlation between a fluctuating climate and the deformation of wooden objects, it is important to take the building type and the HVAC[1]-system into account. The indoor climate is affected by the response of the building to the outdoor climate. With fluctuating indoor climates, indoor environments can be adjusted with HVAC-systems. Different building types have different responses and, as a result, different indoor climates [1].

Data from a heavy and a light building are used for this study. A building with large concrete or stone walls is considered 'heavy'; a wooden cabin with thin walls qualifies as a 'light' building. These buildings have a different capacity for storing heat. The specific heat capacity c [J/kg*K] is the amount of heat per unit mass required to raise the temperature by one Kelvin. Although the specific heat capacity of concrete is lower than the capacity of wood, a heavy concrete building is more inert to fluctuations in temperature. The density of the material, which needs to be taken into account, can explain this. Looking at the volumetric heat capacity in the Table 2-1 below, the capacity of concrete to store heat is more than twice as high as the capacity of wood [6] [7].

Table 2-1 Approximate values of heat capacities

Material	Density ρ [kg/m^3]	Specific heat capacity c [J/kg*K]	Volumetric heat capacity $\rho * c$ [MJ/ m^{3}K]
Water	1000	4186	4.2
Wood	500	1400	0.7
Concrete	2200	900	2.0

[1] HVAC: Heating, Ventilation and Air-conditioning.

Historical buildings are normally not equipped with thermal insulation neither they are designed to be airtight. This makes the indoor climate even more vulnerable to fluctuations of the outdoor climate. The structure and the value of the volumetric heat capacity of the building are important factors related to the indoor temperature. For a light building, fluctuations of temperature outdoors go almost directly trough the building structure, while it takes time to heat up or cool down a heavy building. The heavy structure has some sort of buffer to short-term fluctuations. Long-term fluctuations will affect the indoor climate anyway. The airtightness of the structure is a very important factor related to the indoor RH. Historical buildings are not designed with an airtight seal, meaning that the indoor airflow depends on the building structure. Heavy structures may be more airtight than light structures – if the contractor delivered qualitative work. The higher the airtightness, the lower the airflow will be. If rooms are not ventilated adequately, the humidity rises [7] [8].

HVAC-systems are not common in historical buildings, not even after renovations. Sometimes it is not allowed to build an HVAC-system because of the cultural heritage value of the building. Climate control in historical buildings can be accomplished through: background heating, used to generate a general temperature above freezing point; intermittent heating, higher temperatures when the building is open for visitors, lower temperatures when the building is closed; conservation heating, which is used to differ the temperature to adjust RH [2].

2.2 Wood characteristics

Wood is an anisotropic[2] and porous material. The anatomical structure of wood has an impact on technological applications, e.g. bonding with adhesives. Hygroscopic materials, such as wood, have the capacity to store water molecules at the inner surface of their pore system. RH and T of the ambient air affect the EMC [9]. In areas with a low RH, wood is able to release moisture. This makes the wood less flexible; consequently the fibres could crack more easily. In high RH percentage conditions it is less likely that damage, such as cracks, occur since the wood is more flexible [4].

Woody plants have two principal groups according to their anatomy. Conifers, softwood or evergreens form one group, they have needle-like leaves and naked seeds. The other group is called broad-leaved trees, hardwoods or deciduous trees, which commonly possess broad leaves and enclosed seeds. Hardwood and softwood are terms with no implication about these woody plants actually being hard or soft. Both the hardest and the softest woods are divided in the hardwood-group. However, the main part of the hardwood group is denser, so usually they are harder than softwoods [10].

Pinus sylvestris a.k.a. Scots pine, categorised as softwood, is a species of pine that is common in cold regions of Europe, such as Scandinavia. However, the trees can be found almost anywhere in Europe: England, France, Austria, Spain, and even sometimes in Central Asia.

The way a tree provides itself with water and minerals through the root system, the stem and the crown system as well as the (chemical) structure of the cell wall is very interesting. Even though this thesis does not treat this topic, it is important to briefly discuss the pore system in which the nutrients move. The pore system makes moister diffusion in the wood possible. To know more about the pore system, some research about the micro and macro structure of wood is done.

Softwood species have no more than three to five types of cells; this makes the microstructure quite simple and uniform. Tracheids are held together by the 'middle lamella', which is

[2] Anisotropic materials have differed properties in different directions, as opposed to isotropic ones.

something like glue or cement. Resin ducts are found in the same direction as well. Wood rays are located in the radial direction; they are responsible for the transportation of nutrients and water. Pit pares connect the different cells, while bordered pit pares are the most important for moisture transport [11]. In Figure 2-1 an illustration of the location of the different cell types is given.

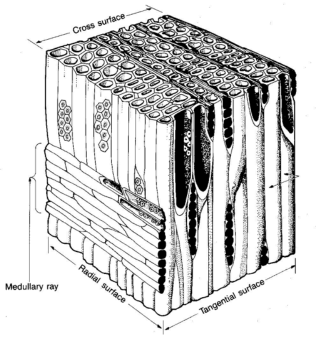

Figure 2-1 Softwood microstructure, from [12]

Figure 2-2 Annual rings, from [13]

In the macrostructure, seasonal differences can be observed. Earlywood and latewood form one growth season generates an annual ring or growth rings (Figure 2-2). Early and late wood refers to early and late in the season. The cycle of seasons brings more or less nutrients than others. In seasons with plenty of nutrients, the cell walls are thin with large cavities, this is the early wood, it is fairly light in colour. In this period, nutrients will be stored for the winter seasons. In this season nutrients are less provided. In winter no growth takes place. The cell walls are thicker with small cavities and the colour is darker [14].

Moisture can exist in wood as free or as bound water. Free water is liquid water or water vapour in cell lumina and cavities; bound water is held by intermolecular attraction within cell walls. The forces between bound water and the wood are stronger than the forces in so-called ‘free’ water. The terms ‘free’ and ‘bound’ are relative since capillaries force subject water in the cell cavities. Since the forces between free water and the wood are weaker, free water is the first part a tree loses when green wood[3] starts to dry. The moisture content where all the free water has left the cavities and only water vapour remained in the cavities, and where the cell wall is fully saturated, is called the fibre saturation point, MC_f. The physical and mechanical properties of wood are considered constant above this point. Above the fibre saturation point these properties are not a function of the MC. Below this point, strength properties of wood increase with decreasing MC. Simply put: the presence or absence of liquid water in the cell cavities has no effect on the strength properties of wood, because only the cell wall is of importance for mechanical strength. In theory, fibre saturation differentiates free and bound water. In reality, a gradual transition occurs between the two ways in which water is held in the structure. The sell wall may begin to dry before all water has left the lumen of that cell [3] [15].

2.3 Painted panels

Under the influence of fluctuating RH and T, hygroscopic materials start to swell or shrink. This causes changes in size and shape. Many museum objects are made out of different materials that were joined together. The materials will deform in a different way and when slight differences in mechanical deformation occur, the different materials could crack. Painted panels are situated in the most sensitive category [4].

[3] Green wood: wood that has been recently cut.

Stanzani et al [16] investigated paintings on wooden panels from the 16th century. Samples of paintings were analysed with an optical microscope to define a stratification or layering in the paint. The first layer on the panel is called 'preparatory coating'. In accordance with the name, this layer is used to prepare the panel. It can be compared to a 'primer'. A primer or preparatory coating has 2 functions: on the one hand it is used to make sure that the surface won't absorb paint and on the other hand it prevents any dirt (e.g. sand or dust) from penetrating the pictorial layer. The second layer is the 'pictorial layer', this is the actual painting. To finish, a darker layer is used. It is a transparent coating to protect the actual painting from mechanical damage or degradation of colours.

Lukomski [17] has been researching the properties of the layers. The preparing coating is called 'gesso', 'glue gesso' or 'Italian gesso'. It is a traditional mixture of chalk, white pigment and an animal glue binder. The expansion coefficient of the gesso is very low; according to the properties, the layer isn't able to bend much and will break easily [18]. Expansion and contraction of the wood, initiated buy a fluctuation climate will develop internal stresses and fractures of the wood and eventually these changes could trigger cracks in the gesso layer. This means that the gesso layer is particularly vulnerable to humidity fluctuations.

2.4 Fatigue

The book *Fracture and fatigue in wood* [10] explains more about the phenomenon of fatigue in wood. Fatigue is defined as the process of permanent structural changes that occur in a local place of materials subjected to permanent or cyclic loads. Loads can be imposed as both compression and tension or only one of both, in a repetitive or alternating way. Cyclic changes in RH may cause deformation, and deformation comes with compression and tension [19]. The cyclic process of repeated or alternating compression and tension produce fluctuating stress and strains. After a certain amount of time or number of fluctuations, this may result in cracks. Fatigue failure occurs when the frequency and amplitude of the cyclic loading is high enough, but not so high that it would cause in-elastic behaviour.

Initial microcracks can subsequently aggregate into macrocracking and failure. Exhibited fatigue depends on the number of stress cycles and the rate of stressing and/or time under stress. Smith et al. [10] have pointed out that traditionally, attention has mainly been focused on fatigue damage in wood caused by sustained loads. Relatively little attention has been paid to cyclic loads (repetitive or alternating). Nonetheless, certain behavioural aspects of wood are (unanimously) accepted:

- Cycles where there is solely compression or tension are worse than cycles that cumulate both. The number of cyclic to failure for repetitive loads is lower than the number of alternating cyclic [10];
- The number of cyclic to failure decreases as the moisture content increases between 5% and the fibre saturation point [10].

Luxford et al. [19] said that there is very little information on how cycling RH may affect the fatigue failure of wood. Furthermore, there is little knowledge about whether there are maximum allowable numbers of cycles within the safe range of RH fluctuations.

In the article *Residual strength of thermally modified Scots pine after fatigue testing in flexure* [20] Scots pine was thermally modified. The residual strength of the samples was tested after a certain amount of repetitive cyclic loads. In the results of the study it is cleared out that the initial moisture content and the maximum thermal modification temperature of the samples were classified as the main influence on the residual modulus of rupture (fatigue failure). The amount of repetitive loads was identified as an insignificant parameter to the residual modulus of rapture. It is important to take note that the cyclic creep[4] deflection (deformation) significantly increased with an increasing number of loadings. Furthermore, the cyclic creep deflection increased with increasing moisture content before testing. This is because the modulus of elasticity: the higher the moisture content, the higher the elasticity.

[4] When a load is placed on a material during a longer period, creep could occur. It is the permanent deformation of a material under the influence of mechanical stress. 'Cyclic creep' is a term for creep caused by repetitive or alternating cyclic of loads.

3. SIMULATION MODEL

3.1 Introduction of the model

First of all, the available numerical tool – taken from the previous study by Bylund et al [1] and adopted to MATLAB – is used to simulate moisture transport in wood under certain conditions. Secondly, the information of moisture transport and moisture content will be taken into account to predict the deformation caused by the changing MC in the wood.

As explained in the topics 2.2 Wood characteristics and 2.3 Painted panels wood cells are directed in a specific way. In addition, the material swells differently in different directions. It is logical that absorption, desorption and moisture transport are not the same in all directions. This means that the way wood samples are cut and how they are exposed, affect the results of moisture content. However, the simulation model does not account for this. In the previous study, two simulation models have been compared in relation to measured data. The article showed that the models could simulate moisture diffusion and transport with a sufficient accuracy.

3.2 Moisture balance equation

Water in its three states[5] is presented in the physical conditions of buildings. Both vapour (hygroscopicity) and water (capillary suction) can be stored in pores of a porous material. Vapour transport is caused by diffusion due to differences in partial pressures or vapour concentration. Water molecules are transferred by capillary suction. It's a physical explanation for attraction between water molecules and hygroscopic tube walls, and a surface tension phenomenon [6]. Absorbed water will not be desorbed in the same way. Usually, during desorption, more moisture is retained in the structure. This phenomenon results in a hysteresis effect. Effects of the hysteresis are relatively small and can usually be neglected.

In the Figure 3-1 below, a slab with thickness *D* is illustrated. $g(x,t)$ [kg/m^{2}s] represents the one-dimensional moisture flux or flow. The water vapour concentration is v_{Front} at the front and v_{Back} at the back of the panel.

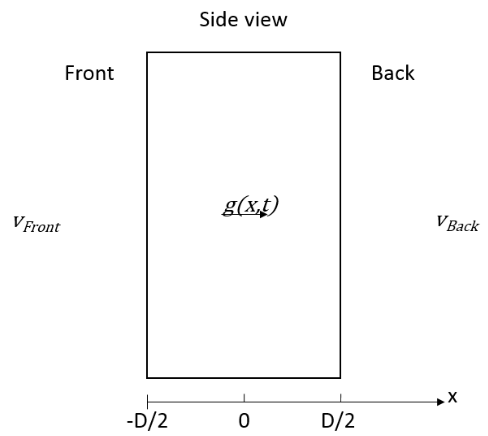

Figure 3-1 One dimensional moisture flow g in a slab with thickness D

[5] Water can exist in tree states or phases: solid, liquid and gas. Respectively: ice, water and vapor

The water storage capacity of a material is given by *w(φ)*, moister content mass by volume [kg/m^3] [7]. The moister content can vary from place to place. The network of pores makes it possible for moister to move trough the system.

Fick's law of diffusion is applicable:

$$g = -\delta_v \frac{\partial v}{\partial x} \tag{1}$$

This law is used to describe the moisture flow in materials. δ_v [m^2/s] is the vapour diffusion coefficient and ν[kg/m^3] is the humidity by volume. In the case study, δ_v is assumed to be constant. For a one-dimensional approach the moisture balance gives:

$$-\frac{\partial g}{\partial x} = \frac{\partial w}{\partial t} \tag{2}$$

The moisture content, $w(x,t)$, depends on depth and time. At isothermal conditions, the sorption isotherm only depends on RH:

$$\frac{\partial w}{\partial t} = \frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial t} \tag{3}$$

Combination of formula (2) and (3):

$$-\frac{\partial g}{\partial x} = \delta_v \frac{\partial v}{\partial x} = \delta_v \frac{\partial \varphi}{\partial x}\frac{\partial v}{\partial \varphi} = \delta_v \frac{\partial \varphi}{\partial x} v_s(T) \tag{4}$$

The sorption isotherm, with slope ξ [kg/m^3], is assumed to be linear (Figure 3-2):

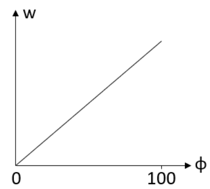

Figure 3-2 Sorption isotherm, assumed linear in this study

A new parameter a_v [m^2/s*]* is introduced; vapour or moisture diffusivity:

$$\frac{\partial^2 \varphi}{\partial x^2} = \frac{1}{a_v}\frac{\partial \varphi}{\partial t} \qquad a_v(t) = \frac{\delta_v v_s(T(t))}{\xi} \qquad (5)\ (6)$$

3.3 MATLAB

The program MATLAB is used to simulate moisture diffusion and deformation of a wooden panel. MATLAB is a programming platform that allows computing mathematical problems. Partial differential equations (PDE) can handle phenomena such as heat transport, moisture diffusion, etc. A key defining property of a PDE is that there is more than one independent variable and a PDE is a relation between an unknown function and its partial derivatives. MATLAB is equipped with a 'PDEPE-solver'. Using the PDEPE commando it's possible to compute initial-boundary value problems for small systems in one space variable *x* and time *t* [21].

Table 3-1 illustrates that three functions are built into the PDE-solver. The *pdefun* is a function that defines the components of the partial differential equation. For the case of constant transport (linearization of the sorption curve) in isothermal conditions, the general equation is given by the moisture diffusivity a_v. For every x and t a value for $c=1/a_v$ is noted in a column vector. A function to declare the initial conditions is handled in *the icfun*. With this function a RH can be calculated for every x. The last function, *bcfun*, defines the boundary conditions. *ul* and *ur* are the approximate solutions for the left and right boundary, i.e. the front and the back of the panel. For this example the RH at the left hand boundary is 100%, the right hand border is moisture tight.

Table 3-1 Example of the MATLAB code – PDE-solver

```
% PDE-solver
sol = pdepe(m, pdefun, icfun, bcfun, x, t);
u = sol(:,:,1);    % Solution [-]
function [c, f, s] = pdefun(x, t, u, DuDx)
c = 1/av;
f = DuDx;
s = 0;
function u0 = icfun(x)
u0 =0;             % At time t=0
function [pl, ql, pr, qr] = bcfun(xl, ul, xr, ur, t)
pl = ul-1;         % Left/Front fixed value RH=100%; φ=1
ql = 0;
pr = 0;            % Right/Back tight
qr = 1;
```

In Figure 3-3 a slab with thickness *D* is illustrated. The panel can be divided into a mesh i.e. a number of calculation layers. The RH is calculated for each layer. The denser the mesh, the more accurate the calculation. With this method, the RH can be determined for every point of the panel in one direction.

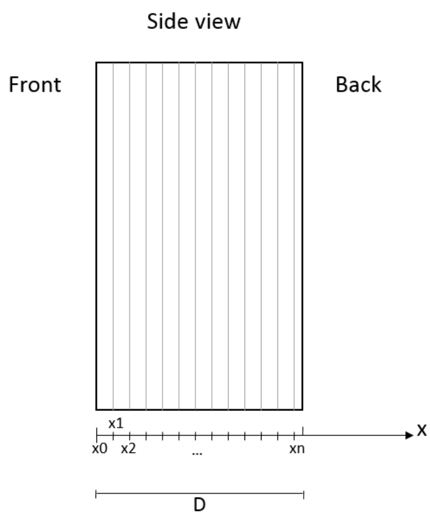

Figure 3-3 Panel with xmesh

3.4 Mechanical deformation

Non-uniform absorption, desorption and transport of moisture in a material causes expansion or contraction, which leads to internal stresses and strains. This may result in mechanical deformation of the material.

3.4.1 Displacement and deformation

When a hygroscopic sample is fully exposed to a high level of RH it will absorb moisture over the entire surface. When the sample increases in volume, every single point of the sample undergoes a displacement. In case of free movement, no deformation of the panel appears. When the sample is wedged, there will be deformation of the panel. If wood cells start so swell in a wedged model, they have no place to expand except to leave their regular structure. Outside the regular structure, deformation appears. Figure 3-4 is a simplified illustration of displacement and deformation. The illustration presents an expansion in the length of the sample only; in reality swelling appears in three dimensions [22] [3].

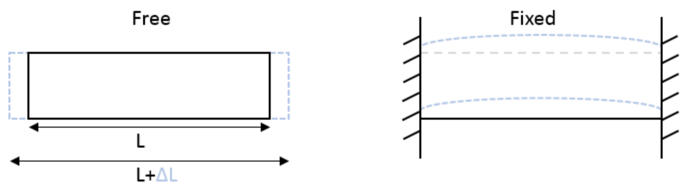

Figure 3-4 Displacement and Deformation - 1

If the sample is not equally exposed, deformation will appear as well. The expansion will not occur simultaneously and this causes dimensional changes. In Figure 3-5 the top of the sample is exposed; the bottom may be placed against another surface and therefore it is not exposed. In the free model, the bottom can slide over the other surface, however the top expands more than the bottom since the surfaces are not exposed equal. In the fixed model, the sample may be glued or nailed, meaning that it is not free to move. Wood cells have no place to expand except to leave their regular structure. Again, the illustration presents an expansion in the length of the sample only; in reality swelling appears in three dimensions [22] [3].

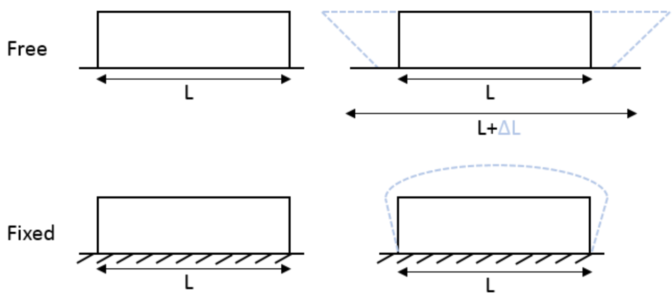

Figure 3-5 Displacement and Deformation - 2

In the study case, a wooden decorated panel is both wedged and placed against a wall. However, the numerical simulation model takes only the effect of the exposure into account. Meaning that the front of the panel is interacting with the ambient air of the room and the back is considered moisture tight. The fact that the panel is fixed is not simulated with this model.

3.4.2 The Thermal and Moisture Expansion Coefficient

Wood that is heated or chilled tends to expand or contract because of its thermal expansion capacity. Thermal expansion coefficients of completely dry wood results in expansion in all directions. Nevertheless, when wood is very dry, initially (3 to 4% MC or less) the swelling or contraction caused by increasing or decreasing moisture content is greater than thermal expansion. If a sample of wood is heated, deformation appears. On the one hand, the sample will swell because of the thermal expansion; but on the other hand, the sample will contract because the moisture content decreases. The effect of the decreasing moisture content is superior to the thermal change. The totality of dimensional change in regards to heating will be negative. In the longitudinal grain direction, dimensional changes are less than parallel to the grain. [15]

Hygro-expansion is caused by moisture or humidity. It's a phenomenon of attracting and holding water molecules from the surrounding environment. Hygro-expansion in wood is traditionally given in terms of shrinkage percentage or swelling percentage. Figure 3-4 illustrates the expansion in the length of the sample. In accordance with the illustration, the following formula was set:

$$\frac{L+\Delta L}{L} \tag{7}$$

Here, the unit is given as mm/mm or %. Commonly, the shrinkage percentage is lower than the swelling percentage. The amount of moisture that is desorbed is less than the amount that was absorbed. Meaning that a part of the moisture stays in the wood. These moisture parts take more effort to desorb (longer time, or lower RH of the ambient air). This phenomenon is referred to as hysteresis. The phenomenon is neglected in the simulation.

The moisture ratio (mass by mass) is given by u [%]:

$$u = \frac{w}{\rho_{dry}} \tag{8}$$

ρ_{dry} is the density of dry wood. This relation to the moisture ratio can be used to translate between units. For each given RH, equilibrium can be reached. Whit a given RH (φ), the correlated moisture content ($w(\varphi)$) is defined according to the sorption isotherm [2] [6].

The coefficient of hygroscopic expansion or contraction β [mm/mm per 1%MC] is a useful index. It is the ratio for relative dimensional changes to the moisture changes. This coefficient is correlated to the absorption and desorption isotherm (hysteresis) [3]. According to the article of O'Halloran et al [23], the average coefficient of hygroscopic expansion in thickness is approximately *0.003* mm/mm for each *1%* change in MC.

3.4.3 Dimensionless Moisture Induced Moment Factor

The expansion and/or contraction caused by moisture diffusion leads to internal stresses and strains. Assuming that the stress gradient has a negligible effect on the moisture diffusion process, the deformation of the panel can be estimated [9]:

$$I = \frac{1}{D^2}\int_{-\frac{D}{2}}^{\frac{D}{2}} \Delta u \cdot x \, dx \tag{9}$$

This factor identifies the level of the moisture induced moment I [-]; it is the level of the moment caused by moisture diffusion over the thickness of the panel and for differences in the moisture content. For this formula the thickness of the panel is D, and u is the moisture ratio.

With the moisture induced moment factor, the magnitude of the displacement at the centre of the panel can be calculated. Now the radius of the plate curvature, R [m], can be introduced:

$$R = \frac{D}{12 \cdot \beta \cdot I} \tag{10}$$

The displacement at the midpoint of the panel is called lift, h [mm], it can be calculated with the next formula:

$$h \approx R \cdot \left(1 - cos\left(\frac{D}{2R}\right)\right) \tag{11}$$

Figure 3-6 concludes the previous formula. When the humidity by volume at one side of the panel is higher or lower than the other side, deformation occurs according to the moisture induced moment factor because of a different moisture content at both sides.

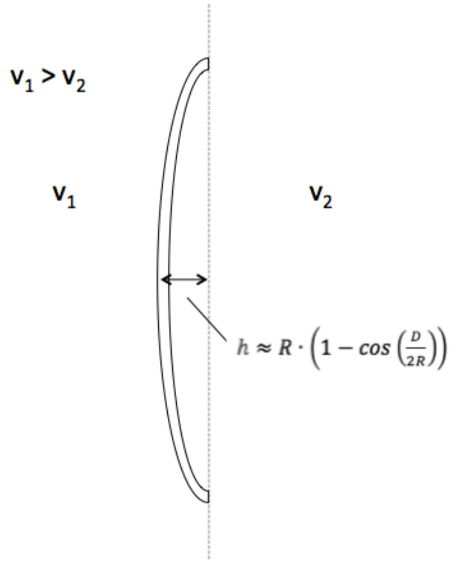

Figure 3-6 Displacement at the midpoint of the panel. v_1 and v_2 are the humidity by volume of the ambient air

4. CLIMATE AND MATERIAL PROPORTIES

4.1 Building types

The indoor climate depends on the response of the building to the outdoor climate. It is important to take the type of building into account because different buildings have different responses. In article Bylund et al [1] the indoor climates was simulated for different building types. In one part of the article, they chose to compare an uninhabited light building to a heavy building.

- Light building
  - Vapour concentration indoor = outdoor;
  - Indoor temperature is based on floating 24 hours of the outdoor temperature plus 2°C.
- Heavy building
  - Vapour concentration indoor = outdoor + 0,5 g/m^3;
  - Indoor temperature is based on floating 24 hours of the outdoor temperature plus 1°C.

4.2 Material properties

To analyse decorated panels, two material layers have to be considered. In Table 4-1, variables for the layers are presented.

The first material is the decoration layer (preparing layer, pictorial layer and coating, topic 2.3 Painted panels). This is an important layer since it affects how the surface responds to the conditions of the ambient air. The decoration layer and the boundary surface resistance are combined into a total *surface vapour resistance Z* [s/m], which is used in the simulation model.

The second material that needs to be considered is wood; Scots pine. The next paragraphs explain properties of wood that are used in the simulation model.

The dry density of wood varies between 320-800 kg/m^3. It is the density obtained for wood that has been dried in an oven with a temperature of 105°C for a certain period of time. In the model, the mean value for pine (500 kg/m^3) is used [6].

The coefficient of hygroscopic expansion or contraction is different for expansion of contraction. This is partly due to the sorption and desorption curve with hysteresis effect. An average value of *0.003* mm/mm per 1%RH is used [23].

In the model, the value for the slope of *the sorption isotherm* is taken into account. The higher the value for the sorption isotherm, the slower the pore system transports moisture. In the model, the curve is assumed to be linear. The slope of the sorption isotherm is *120 kg/m^3* at *T = 21°C* [1]. This value was kept constant during the whole study, even when the temperature was much lower than 21°C.

A problem with moisture flow is that *the vapour or moisture diffusion coefficient* can vary strongly at high RH's. However, in this study the coefficient is assumed to be constant, meaning that it is independent on moisture levels. Typically, the moisture or vapour diffusion coefficient for wood amounts 0.5*10^{-6} m^2/s [1].

4.3 Variables

It is clear that the value for *the dimension of the panel* can be altered for every specific sample of wood that is available. The model works in a one-dimensional way, i.e. only the thickness is important here.

Finally, the *length of simulation* is the time variable of the model. The simulation can be performed for different periods of time.

Table 4-1 Variables used in the model

Unit	Symbol	Name MATLAB	Value
Surface vapour resistance (s/m)	Z (s/m)	Z	Variable
Dry density (Wood-pine) [1]	ρ [kg/m^3]	rho	500
Hygroscopic expansion coefficient [18]	β [mm/mm]	beta	0.003
Slope of the sorption isotherm [13]	ξ [kg/m^3]	xi	120
Vapour diffusion coefficient [13]	δ_v [m^2/s]	deltav	$0.5*10^{-6}$
Dimension of the panel	$L*D$ [m*m]	Length * Thickness	1*0.025
Length of the simulation	t [s]	tmax	Variable

4.4 Climate

Sets of one-year weather data, which represent the future climate conditions for 2070-2099, were set up [1]. The three climate scenario's:

- Typical downscaled year (TDY);
- Extreme cold year (ECY);
- Extreme warm year (EWY);

These three sets were applied on the heavy and light building, which results in six different indoor climates (Figure 4-1).

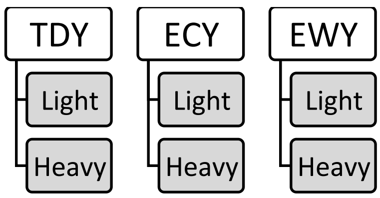

Figure 4-1 Sets of one-year weather data

In Figure 4-2 the outdoor temperature for a typical downscaled year is presented. The indoor temperature is obtained by subjecting the outdoor temperature to a light and heavy building (Figure 4-3). In 10.1 Appendix A: Exposed Climate – Temperature the graphs for the extremely cold and extremely warm year are included as well. The differences between the fluctuating outdoor and indoor climate are remarkable. In these simulations, it is clearly visible that the structure of the building has a buffering effect. Besides the differences between in- and outdoor climate, the differences between the light (red line) and the heavy (blue line) building are clearly noticeable. As mentioned in 2.1 Cultural heritage: wooden panels stored in unheated historical buildings different kinds of structures have different responses to the fluctuating climate. The heavy building has a more stable climate compared to the light building. The frequency of the fluctuation is more ore less the same for the light and heavy building. In one natural day (24h) higher temperatures are measured during the daytime and lower temperatures during the night. A natural day can be seen as one period. The difference is, that for the light building, the top to bottom distance of a period is much higher.

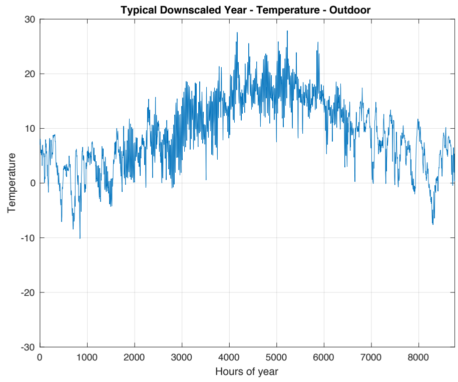

Figure 4-2 Typical Downscaled Year - Temperature - Outdoor

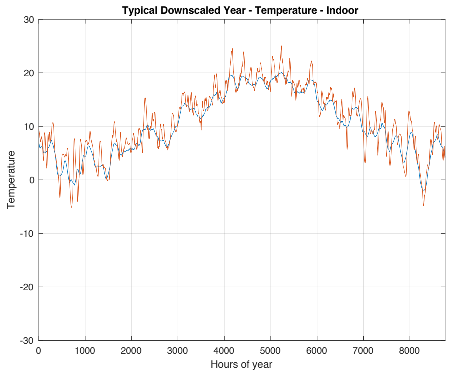

Figure 4-3 Typical Downscaled Year - Temperature - Indoor

The difference between a monthly minimum and maximum in a typical downscaled year is less than ten degrees Celsius for the heavy building, and around ten to fifteen degrees Celsius for the light building. The minimal temperature occurs during winter, the maximum during summer (10.3 Appendix C: Climate dat).

Below, boxplots are given for the RH and the temperature for the six future climates, Figure 4-4 and Figure 4-5.

Closer look at the RH

The RH (%) of the ambient air in the light building type is generally higher and less spread out than in the heavy building. The interquartile range (IQR) and the median for the light buildings are lower compared with heavy buildings. Heavy buildings have a buffering effect on temperature alterations because of their mass, and partly because of the heavy structure, they may also be more airtight than a light building. When a building is not ventilated adequately, the humidity rises. The light structure is less airtight causing a better airflow through the building; this explains the differences in measurements between the heavy and the light building. The indoor climate of the extremely cold year seems to be more stable compared to the other future climates. The differences between the heavy and light building are small, fluctuations are similar, but in general the light building has a higher RH.

Closer look at the temperature

The trends credited to the RH are clearly not reflected to the data for temperature. In contrast to the RH trends, the temperature seems to have less outliers in the climate of a heavy building (buffering effect of the building). However, the IQR and the median for every climate (TDY – ECY – EWY) are quite similar for both building types.

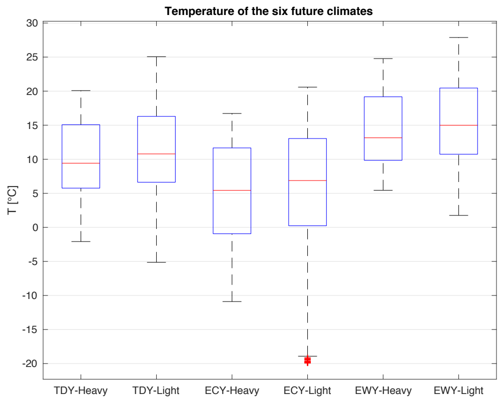

Figure 4-4 Boxplot – Future Climate – Temperature

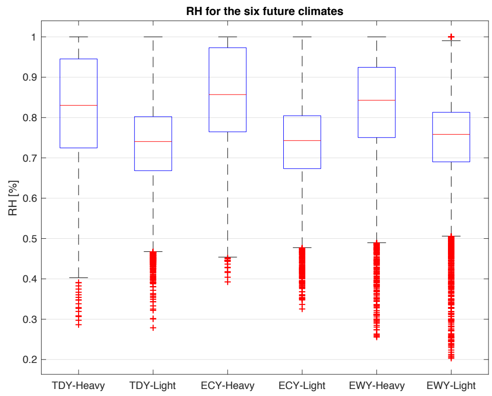

Figure 4-5 Boxplot – Future climate – RH

5. SIMULATION RESULTS – ANALYTICAL AND NUMERICAL EXAMPLES

5.1 Penetration depth – Analytical expression

The response to step-change in RH

At the surface of the wooden panel, at $x = 0$, a certain vapour surface resistance, Z (s/m), is assumed. This factor can be expressed as a thickness d_v *(m)* [6]:

$$d_v = \delta_v \cdot Z \qquad (12)$$

If the surface resistance is equal to zero, the equivalent material thickness is zero as well. The RH in the material becomes:

$$\varphi(x,t) = \varphi_0 + \Delta\varphi\ .erfc\left(\frac{x}{\sqrt{4a_v \cdot t}}\right) \quad x \geq 0;\ t \geq 0;\ d_v = 0 \qquad (13)$$

The penetration depth i.e. how far half the disturbance has reached into the material, $x_{0.5}$ (mm), becomes:

$$x_{0.5} = \sqrt{a_v t} \qquad (14)$$

Typical values of penetration depth, $x_{0.5}$, for wood are: $x_{0.5}$(1h) = 0.5mm; $x_{0.5}$(2h) = 0.7mm; $x_{0.5}$(24h) = 2.6mm; $x_{0.5}$(168h) = 6.5mm. [6]

The response to periodic RH variations

If there are periodic variations in the boundary humidity, the surface moisture ratio of the panel varies periodically; the time period is denoted t_p.

The analytical solution for periodic variations in isothermal conditions can be computed with the formula:

$$\varphi_i(x,t) = \varphi_0 + \Delta\varphi_A \cdot e^{-x/d_{pv}} \cdot \sin\left(\frac{2\pi t}{t_p} - \frac{x}{d_{pv}}\right) \qquad (15)$$

Here, d_{pv} denotes the periodic penetration depth:

$$d_{pv} = \sqrt{\frac{a_v \cdot t_p}{\pi}} \qquad (16)$$

Typical penetration depths for wood as a function of the time period are: *d_{pv}(24h) = 1.4mm; d_{pv}(8760h) = 27.3mm.*

Example: step-changes

If there is a sudden change in RH at the surface at time *t=0*, the initial RH φ_0 changes to $\varphi_0 + \Delta\varphi$. The step-change of the RH is then $\Delta\varphi$.

The analytical solution for a semi-infinite domain in an isotherm situation is given by (13). More information can be found in the book: Introduction to building physics [6].

Simulation for one step with: $\varphi_0 = 0;\ \Delta\varphi = 1;\ T = 21°C$:

$$a_v(t) = \frac{\delta_v v_s(T(t))}{\xi} = \frac{0.5 \cdot 10^{-6} * 18.32 \cdot 10^{-3}}{120} = 7.633 \cdot 10^{-11}$$

$$\varphi(x,t) = erfc\left(\frac{x}{\sqrt{4 \cdot 7.633 \cdot 10^{-11} \cdot t}}\right) \quad x \geq 0; t \geq 0$$

A comparison between the numerical and analytical solution is made for one day (Figure 5-1). The dotted line represents the analytical solution, the other results represent the moisture distribution for a period $t=t_{max}$; $t=\frac{1}{4}\,t_{max}$; $t=\frac{1}{2}\,t_{max}$ and $t=\frac{3}{4}\,t_{max}$.

5.2 Step change – Numerical simulation

The numerical simulation, rendered with the MATLAB program, is presented in this section. This mathematical model is set up to solve the physical problem. To study the behaviour of the phenomenon, the simulations are made under certain constant conditions:

- Relative humidity at $T=21$°C: $v_{sat}=18.32*10^{-3}$ kg/m3
- Thickness of the panel: $D = 0.025$m
- RH of the ambient air: $\%RH = 100\%$

1 Day

The first graph (Figure 5-1) illustrates moisture transport in *1* day (t_{max}), *18*h, *12*h and *6*h. The RH at $x=5$mm increased with approximately *5*% in only *12*h. It increases further with *10*% in *18*h and *16*% in *1* day. In a period of *1* day, the penetration depth is limited to the first millimetres of the panel. The graph also shows that the moisture distribution is non-uniform. Moisture penetrates the front and is then slowly spread inwards. The diffusion becomes clearer in the next graphs.

The cells in the front start to swell and make the panel bend (Figure 5-3). The graph shows the lift in the middle of the panel. The negative value signifies that panel is bending to the front (towards the left side). For a panel with $L = 1$m, the lift slowly grows from *0* to *2.2*mm in only one day.

7 Days

After *7* days (Figure 5-4), the RH at $x=5$mm has increased with almost *60*%. In approximately *3.5* days the back of the panel was reached for the first time, after *7* days the RH in the back increased with less than *2*%.

The panel further bends till almost *3.5*mm (Figure 5-4). After *3.5* days all cells in the wood are slightly starting to swell.

28 Days

In *28* days the RH in the back of the panel increased with approximately *40*% (Figure 5-5). At $x=5$mm RH increased with *80*% and *40*% at $x=20$mm. Those points are both 5mm from the surface of the panel, and only *15*mm from each other, they have a *40*% differed increase.

It is clearly noticeable that the panel first bends forward, and when the cells at the back starts to swell, the bending slowly disappears. The panel is straightening itself since all cells are swelling (Figure 5-7).

3 Months

In *3* months the increasing RH difference between the points is only *10*% (Figure 5-7 and Figure 5-8).

8 Months

After *6* months the increasing difference between the front and the back is *2*%. After *8* months the RH in every single point of the panel has increased with *100*%. It takes about *7* to *8* months to achieve EMC in the panel (Figure 5-9).

After *7* to *8* months EMC is reached, from that point the panel is straight again, since every cell in the panel contains the same amount of moisture and so they are swollen in the same way or size. (Figure 5-10) In this last phase, where ECM is reached, the swelling appears over the full dimensions of the panel, it is called displacement, not deformation. The difference between displacement and deformation is explained in Section 3.4.1 Displacement and deformation.

Remark

- This is what happens theoretically for a free panel; in reality the panel is fixed which causes another bending of the panel since it is not free to move in every direction. This is not taken into account in the model. It means that even when EMC is reached, there will be some deformation because of how the panel is fixed.

The graphs show how the panel is deforming when moisture is penetrating until EMC is reached. Contrary, when the surface is exposed to a climate where the humidity by volume at saturation is lower, moisture will be released outwards. The initial reaction of the panel is that the surface (front) starts to dry, the RH in this point (surface/front) lowers, the cells in the front contract, and the panel bents towards the back.

Remark

- The sorption/desorption isotherm is assumed linear in the model; in reality moisture is not diffusing linearly. This affects the deformation;
- The sorption-desorption hysteresis is neglected in the model; the import and export of moisture does not follow the same function. This definitely affects the deformation, since it is directly connected with the RH of the panel. The 'drying' process takes longer than the 'wetting' process;
- The expansion coefficient of wood is assumed constant for expansion and contraction. However, the value for contraction is normally lower than the one for expansion. I.e. in an equal time period, wood can swell more than it is able to contract.

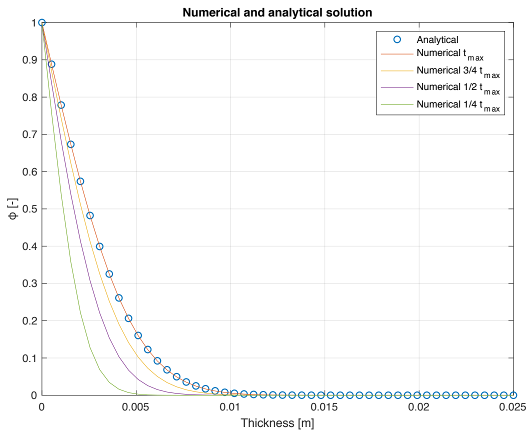

Figure 5-1 Numerical and analytical simulation – 1 day

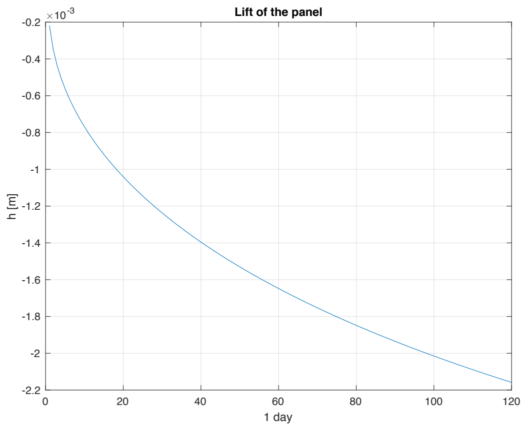

Figure 5-2 Lift of the panel - 1 day

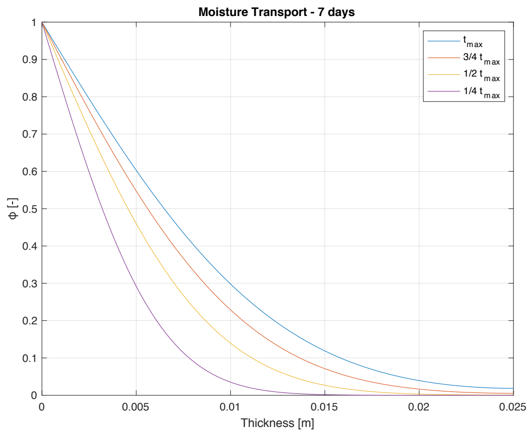

Figure 5-3 Moisture transport – 7 days

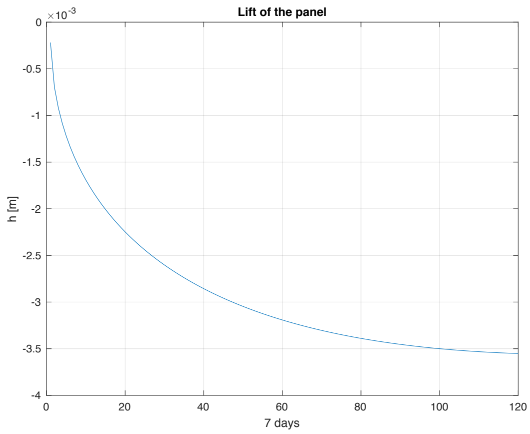

Figure 5-4 Lift of the panel - 7 days

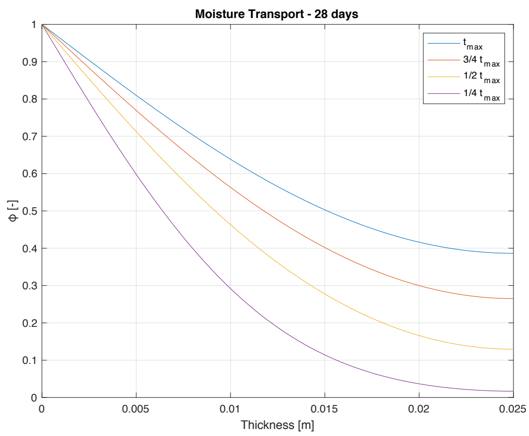

Figure 5-5 Moisture transport – 28 days

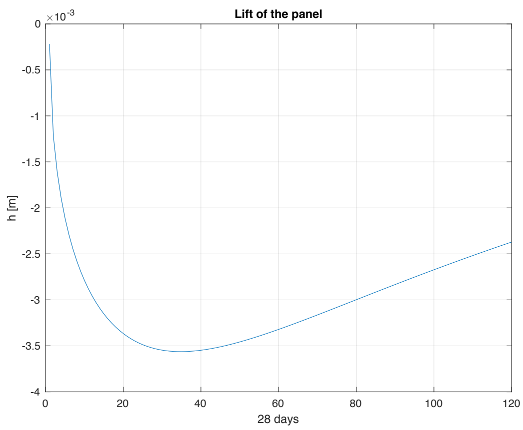

Figure 5-6 Lift of the panel – 28 days

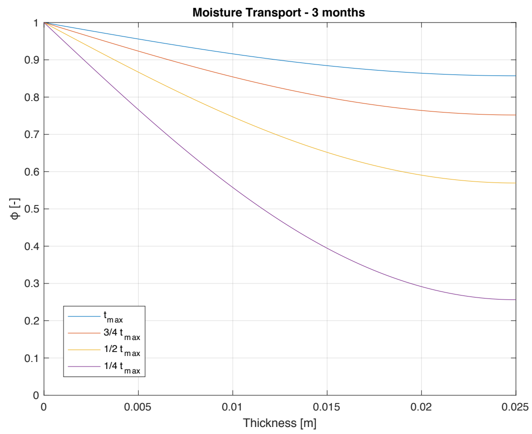

Figure 5-7 Moisture transport – 3 months

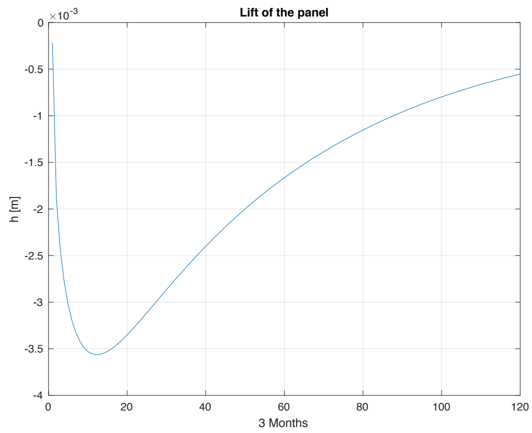

Figure 5-8 Lift of the panel – 3 months

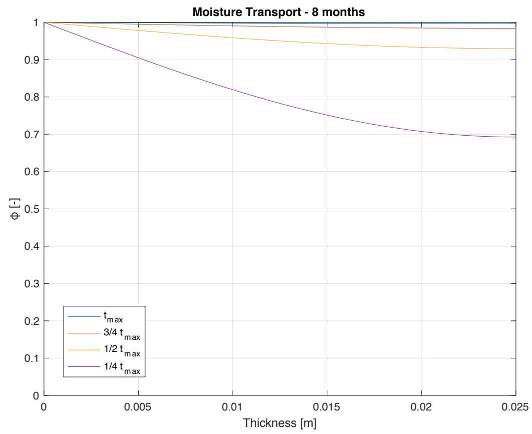

Figure 5-9 Moisture transport – 8 months

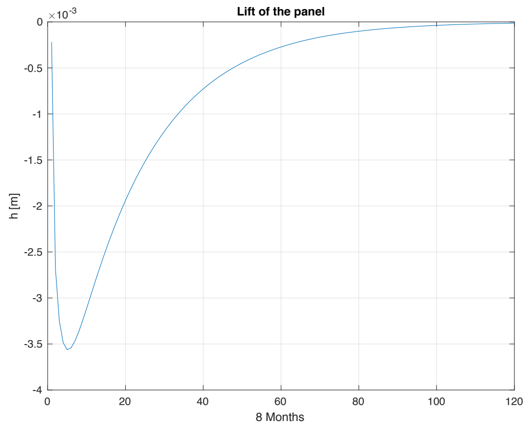

Figure 5-10 Lift of the panel – 8 months

6. RESULTS – MECHANICAL DEFORMATION OF WOOD DUE TO A VARYING CLIMATE

In this simulation, the boundary RH, φ_i, changes with each step according to the measured data. For each hour of the year, there is a value of indoor temperature and a value of indoor RH recorded. 8760 values are taken into account in the model.

The temperature is processed in the MATLAB function: *pdefun*, the measured RH has been taken into account in the *bcfun* as a boundary condition. At time zero the panel is flat and has a uniform RH of 50% (Table 6-1).

Table 6-1 Example of the MATLAB code – PDE-solver – Influence of the vapour surface resistance Z [s/m]

```
% PDE-solver
sol = pdepe(m, pdefun, icfun, bcfun, x, t);
u = sol(:,:,1);                 % Solution [-]
function [c, f, s] = pdefun(x, t, u, DuDx)
T = climatinterpT(t);           % Interpolation from climate data file
c = xi/deltav/vsat(T);
f = DuDx;
s = 0;
function u0 = icfun(x)
u0 =0.5;                        % RF =50% at time zero
function [pl, ql, pr, qr] = bcfun(xl, ul, xr, ur, t)
RHboundary = climatinterpRH(t); % Interpolation from climate data file
 if Z>1                        % Influence of the vapour surface resistance
   pl = (ul-RHboundary)/deltav/Z;
   ql = -1;
 else
   pl = ul-RHboundary;
   ql = 0;
 end
   pr = 0;                      % Right/Back tight
   qr = 1;
```

6.1 Results – Surface resistance neglected

To study the behaviour of the varying climate, the simulations are made under the following conditions:

- Length of the panel: $L=1$m;
- Thickness of the panel: $D = 0.025$m;
- Hygroscopic expansion coefficient: $\beta=0.003$mm/mm;
- RH and Temperature: Variable.

The moisture fluctuation has a greater effect on wood than a thermal fluctuation. (3.4.2 The Thermal and Moisture Expansion Coefficient) The curvature of the panel, represented by the following graphs, is in line with the fluctuation of the RH of the ambient air, which is shown in 10.2 Appendix B: Exposed Climate – Relative Humidity.

Typical Downscaled Year

The lift is negative during most of the year. A negative value represents a curvature in the middle of the panel, where the centre moves to the front (left). When the lift is positive, the panel bends towards the back (right). For Figure 6-1 and Figure 6-2, the largest deformation occurs in the beginning of the year (winter season), where the curvature for the heavy building rises till approximately *-1.74*mm. In the light building, the lift amounts to approximately *-1.18*mm. In both climates, the panels have alternating[6] deformations to the front and back. In the heavy building, there are 40 shifts. The panel in the light building swaps 34 times. The alternation starts around spring/summer, it continues during the whole summer and autumn, at wintertime it attenuates.

Extreme Cold Year

In the extremely cold year, there is clearly a visual difference in the performance of the panel in the first months of the year, compared with the rest of the year (Figure 6-3 and Figure 6-4). In the first trimester, curvatures of about *-1.85*mm occur for panels in the heavy building, and a lift of approximately *-1.38*mm for panels stored in the light building. With these values, the extremely cold year brings the highest level of deforming. In the beginning of this year, temperatures of -20°C are reached, along with the highest amount of %RH of the ambient air.

In the first trimester, there is no alternating between positive and negative values yet, the alternating starts after the first trimester and keeps on going until the end of the year. However, the cold year has de most compact boxplot for RH of the ambient air, the panel in the heavy building alternates 30 times and 35 times in the light building. This is more or less the same as in the typical downscaled year.

Extreme Warm Year

Similarly to the other climates, the lift is negative during the first trimester of the year. After the first trimester, the panel starts to alternate during the rest of the year (Figure 6-5 and Figure 6-6). There is a major switch during the summertime; the curvature goes all the way from approximately *+1.4*mm till *-0.85*mm for panels in both the heavy and the light building. Over the whole year, curvatures of *-1.29*mm till *+1.43*mm for the light simulation and *-1.74*mm till *+1.50*mm for the heavy structure were computed. The extremely warm year has the most spread values of RH of all three future climates. Panels in the heavy building swap 43 times from negative to positive, 35 times in the light building.

Remark

- The extremely warm year has the most extreme values for the performing curvature, however during the whole year the consecutive fluctuations are smaller compared with the other climates;
- The panel is bending alternately to the front and the back a few times a year. During the whole year the curvature is changing constantly, i.e. bending less or more to the same side. It is not known which movement of the panel is worse.

[6] Alternating cycles are cyclic from negative to positive curvatures. Repetitive cyclic are negative or positive cycles only.

Trend

- A trend in all climates is that the indoor climate of the heavy house is more aggressive to the wood. The climate in the heavy building generates more alternations in absorption and desorption of moisture;
- At the end of the simulation the distance between top and bottom is declining. Meaning that the panel adapted to the indoor climate and the response to the fluctuations of the ambient air is more moderate.

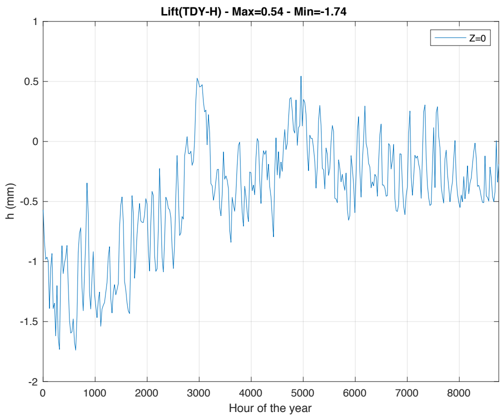

Figure 6-1 Lift – TDY-H – Z=0 s/m

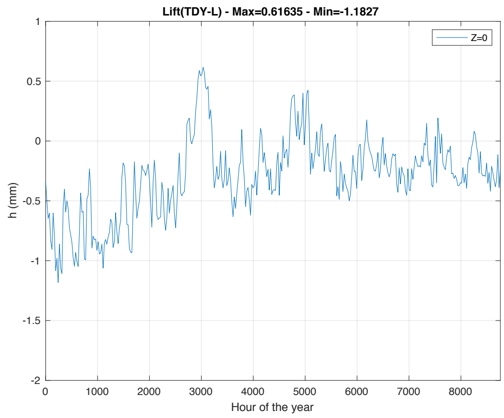

Figure 6-2 Lift – TDY-L – Z=0 s/m

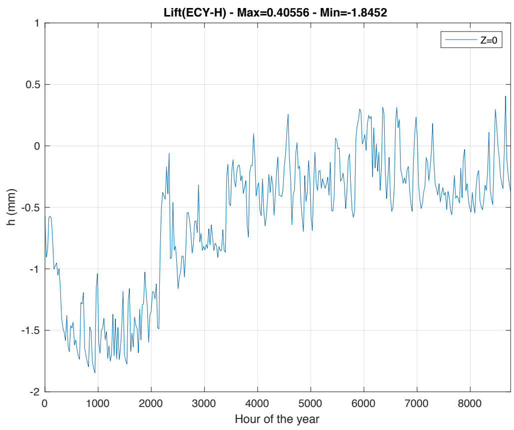

Figure 6-3 Lift – ECY-H – Z=0 s/m

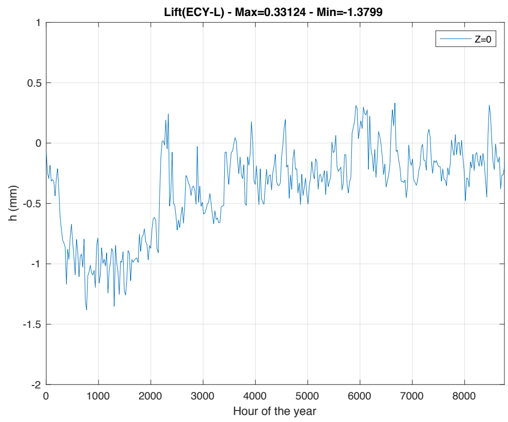

Figure 6-4 Lift – ECY-L – Z=0 s/m

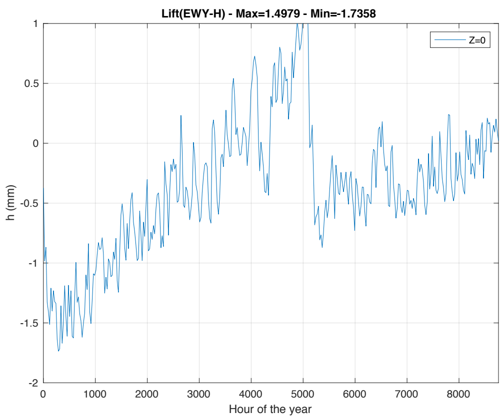

Figure 6-5 Lift – EWY-H – Z=0 s/m

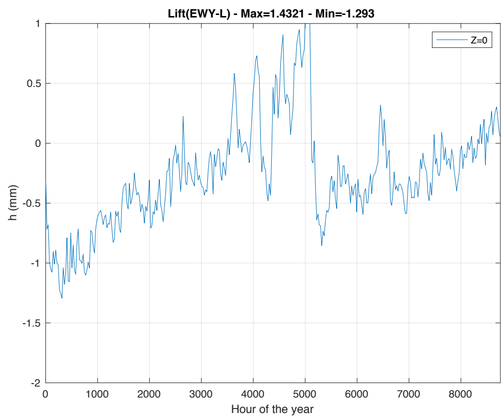

Figure 6-6 Lift – EWY-L – Z=0 s/m

6.2 Results – Influence of the surface resistance

Introducing a general surface resistance refines the influence of the decorative layer (or any other surface layer). Simulations were performed for a surface resistance of *Z = 0* s/m; *Z = 1000* s/m; *Z = 5000* s/m and *Z = 10000* s/m. The results for the Typical Downscaled Year – Heavy building are presented in the graphs below. The results of the other climates where summarized in Table 6-2.

Table 6-2 Results – Influence of the surface resistance.

RESULTS				
	Z [s/m]	# Alternations [-]	min Lift [mm]	Max Lift [mm]
TDY - Heavy	0	40	-1,74	0,54
	1000	26	-1,63	0,46
	5000	16	-1,30	0,24
	10000	10	-1,05	0,13
TDY - Light	0	34	-1,18	0,62
	1000	22	-1,11	0,56
	5000	8	-0,83	0,37
	10000	6	-0,69	0,21
ECY - Heavy	0	30	-1,85	0,41
	1000	22	-1,73	0,26
	5000	10	-1,40	0,12
	10000	3	-1,17	0,01
ECY - Light	0	35	-1,38	0,33
	1000	26	-1,22	0,25
	5000	9	-1,01	0,16
	10000	4	-0,84	0,06
EWY - Heavy	0	43	-1,74	1,50
	1000	36	-1,62	1,39
	5000	18	-1,32	1,27
	10000	8	-1,10	0,91
EWY - Light	0	35	-1,29	1,43
	1000	27	-1,21	1,34
	5000	15	-0,96	1,09
	10000	10	-0,80	0,90

Vapour surface resistance: Z = 0s/m

Figure 6-7 presents the minimum (*-1.74* mm) and maximum (*+0.54* mm) values for the lift. A histogram of the lift is given in Figure 6-8. The number of alternations is 40. The most common values fall into the interval of *h = [-0.6; 0]*mm.

Vapour surface resistance: Z = 1000s/m

According to Figure 6-9 and Figure 6-10 the distance between top and bottom of the curve decreases if the vapour surface resistance increases. h_{Max} = *0.46* mm and h_{min} = *-1.63* mm. The number of alternations decreased till 26. The most common values are divided in the interval of *h = [-0.6; 0]*mm, which is the same as in the case where *Z = 0* s/m. The Difference can be noticed for the maximum values, the bins for *[-1.8; 1.6]*mm (minimum) and *[0.4; 0.6]*mm (maximum) contain less values comparing to the previous case.

Vapour surface resistance: Z = 5000s/m
The trend continu's, the distance between minimum and maximum decreases as the vapour surface resistance increases. For Figure 6-11 $h_{Max} = 0.24$ mm and $h_{min} = -1.30$ mm and for Figure 6-12 the number of alternations is 16.

Vapour surface resistance: Z = 10000s/m
For Figure 6-13 $h_{Max} = 0.13$ mm and $h_{min} = -1.05$ mm and in Figure 6-14 the number of alternations amounts 10.

The results for the Typical Downscales Year for a heavy building can be compared more accurate by plotting them with boxplots (Figure 6-15). The median increases by increasing vapour surface resistance. The IQR (interquartile range) lowers slightly, from *[-0.66; -0.12]*mm till *[-0.21; -0.63]*mm and the first and third quartile decreases remarkable, from [-1.74; 0.54]mm till *[-1.05; 0.13]*mm. In 10.4 Appendix D: Boxplot of Lift Boxplots are given for the six climate data sheets.

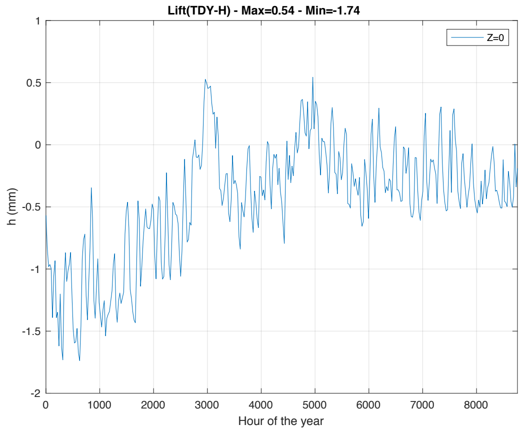

Figure 6-7 Lift – TDY-H – Z=0 s/m

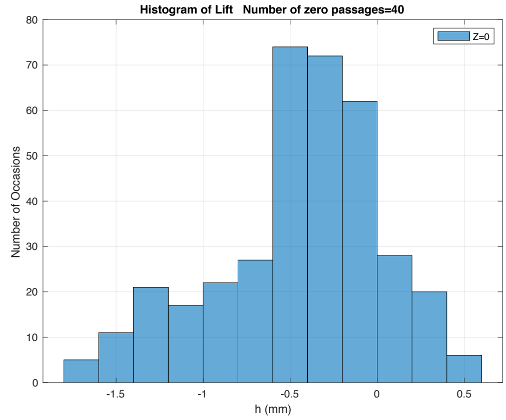

Figure 6-8 Histogram of Lift – TDY-H – Z=0 s/m

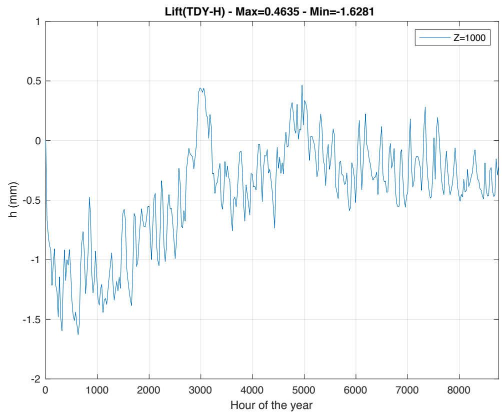

Figure 6-9 Lift – TDY-H – Z=1000 s/m

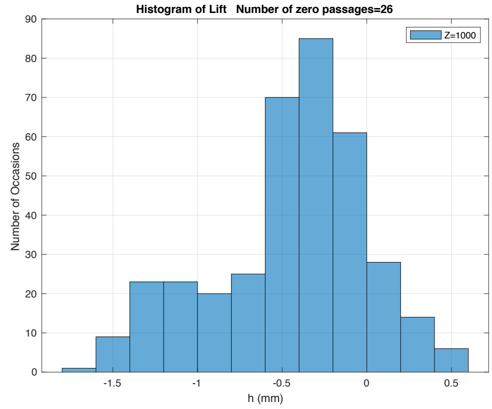

Figure 6-10 Histogram of Lift – TDY-H – Z=1000 s/m

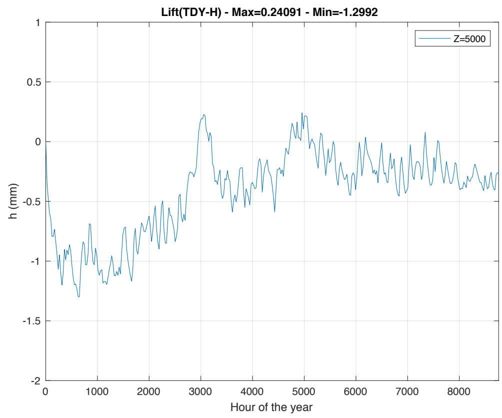

Figure 6-11 Lift – TDY-H – Z=5000 s/m

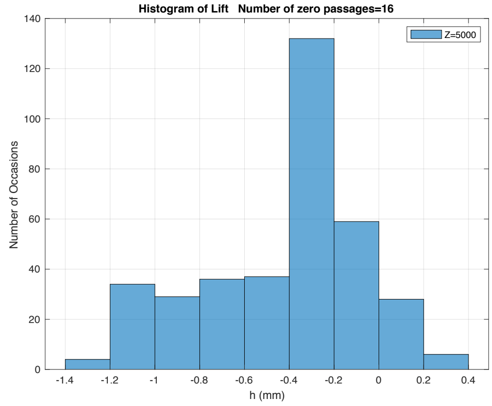

Figure 6-12 Histogram of Lift – TDY-H – Z=5000 s/m

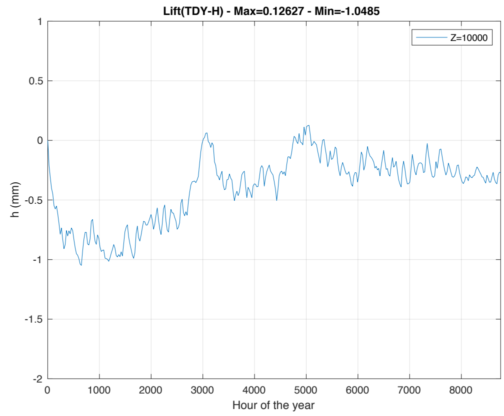

Figure 6-13 Lift – TDY-H – Z=10000 s/m

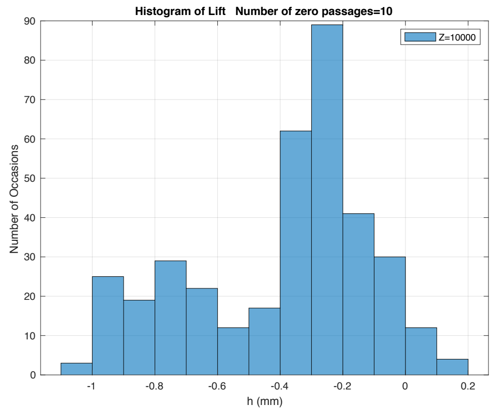

Figure 6-14 Histogram of Lift – TDY-H – Z=10000 s/m

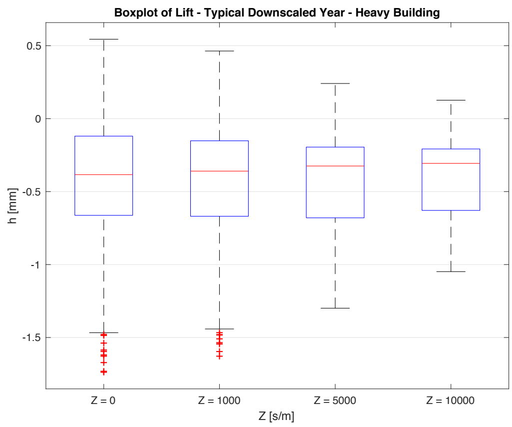

Figure 6-15 Boxplot of Lift –TDY-H

7. DISCUSSION

The climate in historical buildings is often unstable. The literature study had pointed out that wood tries to reach EMC, but it may be impossible to reach due to fluctuating climate. The moisture transport simulation proved that for a panel with *Thickness * length = 0.025m*1m* EMC could be reached in seven to eight months, provided that the conditions are stable. By submitting the future climate data into the simulation model, it is clear that moisture is constantly absorbed and desorbed and transported back and forward in the panel if the climate is fluctuating.

Wood is anisotropic, which means that the reaction on the RH of the ambient air is not the same in different directions. The vapour diffusion coefficient (δ_v) was assumed constant. In reality, this factor is different parallel and perpendicular to the grain and it varies with the RH and temperature. An average value of $\delta_v = 0.5*10^{-6}$ m^2/s had been taken into account. In the test runs of the model, it was ruled out that mainly the order of magnitude (10^{-6}) was a decisive factor.

In the literature, a difference had been made between free and bound water that causes a certain delay on the moisture movement in the panel, when it is exposed to a varying climate. This phenomenon should be included in the vapour diffusion model, which is assumed linear in this study.

The coefficient of hygroscopic expansion or contraction (β) was assumed constant. This factor is different parallel and perpendicular to the grain. An average factor had been taken into account in the model, $\beta = 0.003$mm/mm *per 1*% change in the MC below the fibre saturation point. In reality there is a hysteresis effect since contraction occurs slower than expansion. This is partly related to the absorption-desorption isotherm with hysteresis, which was neglected.

The literature study had pointed out that the effect of the decreasing moisture content is superior to the thermal change. The results of the simulation for deformation of the panels indicate a similar behaviour. Panels deform due to the effect of moisture in the ambient air. The RH in the panel varies which causes expansion or contraction of wood cells and this will make the panel deform. The curvature of the panel follows the fluctuating RH of the ambient air.

To build the simulation model some assumptions were made, and some factors where neglected. This could affect the reliability of the model. However, the model for moisture transport had been compared with measured data in a previous study [1]. Which proves that the simulation model for moisture transport works accurate. The results of the model for deformation were not compared with measured data yet. Since some factors, such as the effect of hysteresis (sorption/desorption and expansion/contraction) were neglected, it can be assumed that the model is too sensitive for fluctuations.

The results of the deformation model have indicated that there are multiple alterations for the curvature of the panel during one year. Meaning: a swap in the direction of bending, to the front or to the back. In the literature, the phenomenon fatigue was studied. Smith et al [10] said that: the number of alternating cyclic, which leads to failure, is lower than repetitive cycles. The model shows many repetitive cycles and 30 till 40 alternating movements (TDY – Heavy building – $Z = 0$ m/s). So far, there is no scale developed to predict how many cycles are needed before failure occurs. By adding a surface vapour resistance, the number of cycles and the minimum and maximum deformation decreases. The indoor climate of the heavy building seems to be more aggressive to the wood since more cycles are generated.

A noticeable trend at the end of all simulations is that de distance between top and bottom of the curve is declining. Meaning that the panel is adapting to the indoor climate. To have a better view of how the model adapts to the climate, the simulations should be made over longer periods of time, $t > 1$ year.

8. CONCLUSION

The aim of the study was to understand more about the cause-effect relationship of how a fluctuating climate affects wooden panels. The simulations performed in this study have pointed out that it is mainly the fluctuating RH of the ambient air that affects the wood. Deformation, like curvature of the panel, occurs with changing RH of the ambient air. The simulation models were made to compute moisture transport over the width of the panel and to compute the curvature of the panel due to an increasing or decreasing RH.

Mechanical deformation could cause problems such as cracks, which needs to be avoided at all times. With the numerical tool deformation could be mapped. The calculations show many repetitive cycles and alternating cycles of curvature. However, it is not known how many and how big cycles need to be before cracks occur. A proposal for future research is to develop a scale that represents damage against deformation.

The simulations show the affect of a vapour surface resistance on the wood. The higher the factor, less moisture penetrates the panel. In addition, by increasing the factor, the number of cycles and the minimum and maximum deformation decreases.

The numerical tools used in this project were based on the theory of moisture transfer and hygro-elastic deformation of wood. To build the model, assumptions were made, and some effects were neglected. Proposals for future studies could be to compare the model for deformation to measured data and check the sufficiency of the model. Improving the assumptions and include neglected phenomena, could further develop the numerical tool.

Simulations were made for one direction, a future study could take two and three dimensions into account to get a complete picture of the cause-effect relationship between a fluctuating climate and how it affects wooden objects.

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10. APPENDIX

10.1 Appendix A: Exposed Climate – Temperature

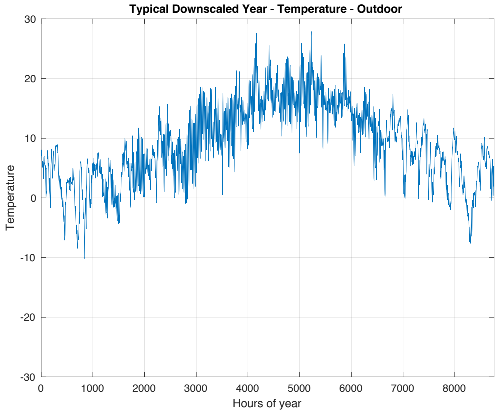

Figure 10-1 TDY - Temperature - Outdoor

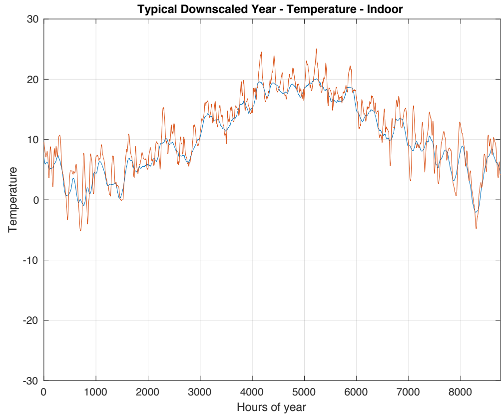

Figure 10-2 TDY - Temperature - Indoor

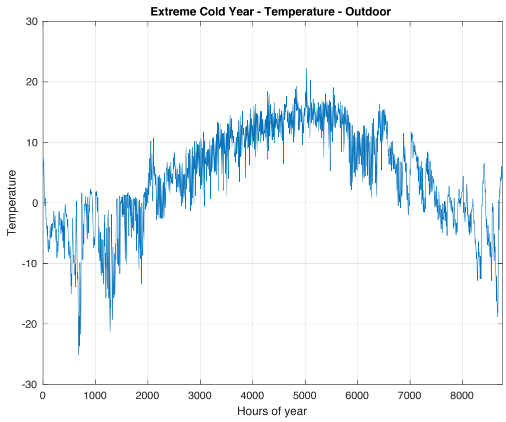

Figure 10-3 ECY - Temperature - Outdoor

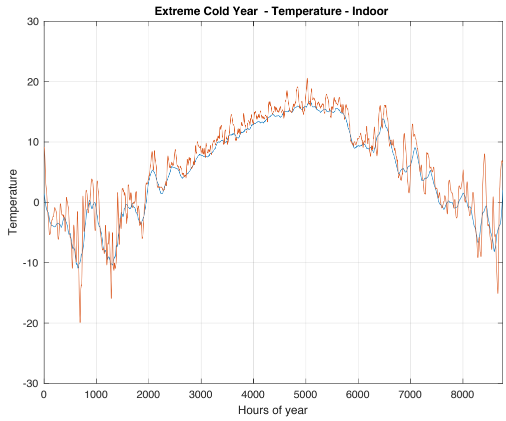

Figure 10-4 ECY - Temperature - Indoor

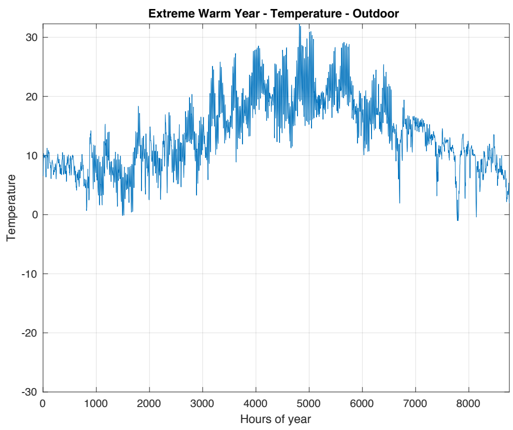

Figure 10-5 EWY - Temperature - Outdoor

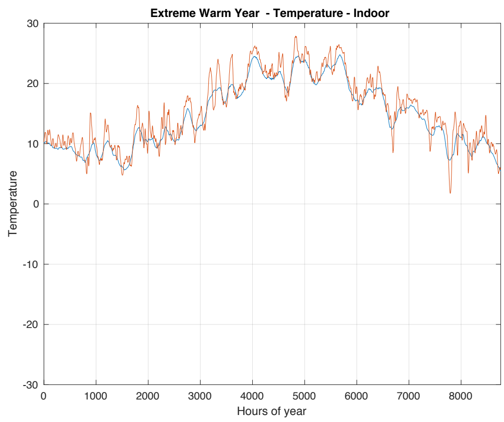

Figure 10-6 EWY - Temperature - Indoor

10.2 Appendix B: Exposed Climate – Relative Humidity

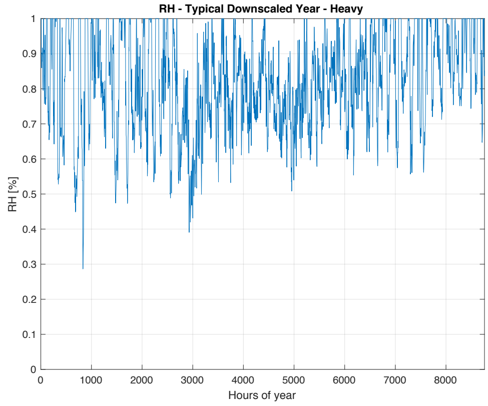

Figure 10-7 TDY-H – RH

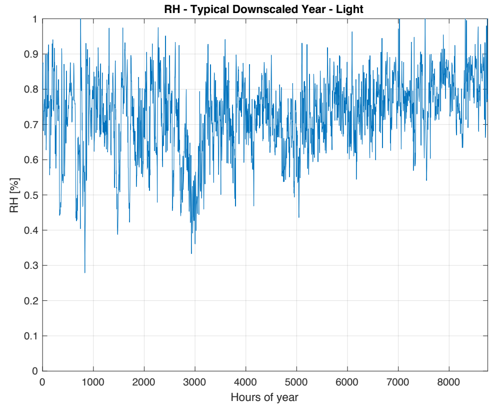

Figure 10-8 TDY-L – RH

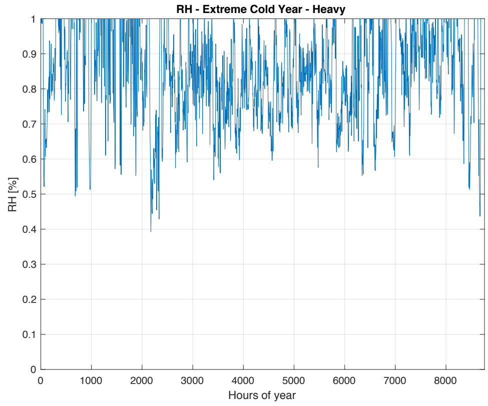

Figure 10-9 ECY-H – RH

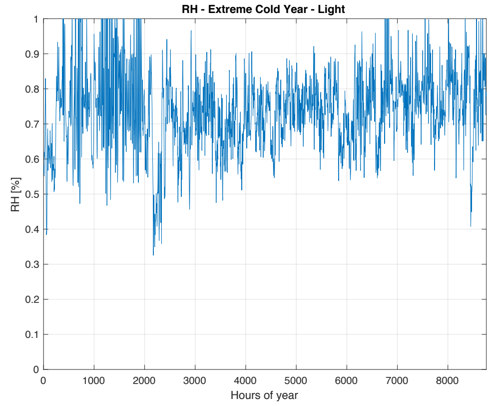

Figure 10-10 ECY-L – RH

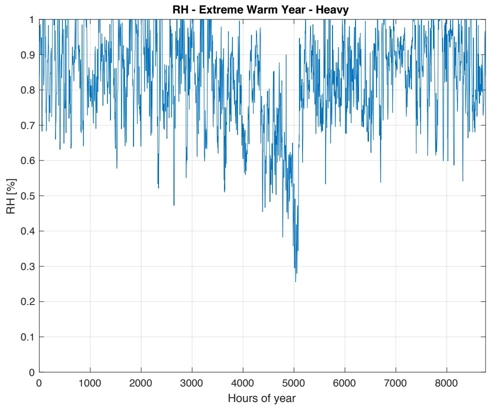

Figure 10-11 EWY-H – RH

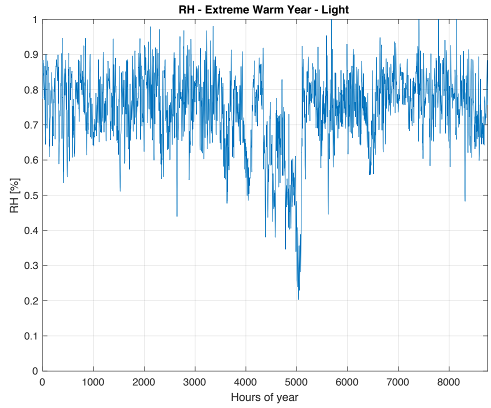

Figure 10-12 EWY-L – RH

10.3 Appendix C: Climate data

Table 10-1 Climate Data

	January	February	March	April	May	June
Heavy_TDY_Tin						
Mean	3,5588	3,0294	4,9342	8,2003	12,2932	16,4189
Maximum	7,3698	6,3442	6,9065	10,2144	14,3048	19,5928
Minimum	-0,6081	-0,9987	0,2505	6,1712	8,5408	13,3729
Light_TDY_Tin						
Mean	4,3523	4,3279	5,875	9,1774	13,358	17,334
Maximum	10,7377	9,1672	10,9023	15,3162	16,4498	24,5531
Minimum	-5,1405	-4,0369	-0,1599	5,051	8,9318	12,9457
Heavy_ECY_Tin						
Mean	-4,9834	-5,1716	-0,1554	4,4058	9,0262	12,5816
Maximum	1,4232	0,3326	5,3595	6,6692	11,3991	14,4533
Minimum	-10,8964	-10,3855	-5,4984	1,4279	6,6689	10,6553
Light_ECY_Tin						
Mean	-4,0908	-3,9427	0,9497	5,239	10,156	13,5471
Maximum	9,1498	3,8936	8,5725	8,755	14,568	16,7085
Minimum	-19,9088	-15,9228	-6,9727	1,9735	7,4388	10,1873
Heavy_EWY_Tin						
Mean	9,1503	8,5966	9,2063	12,123	16,6528	21,0773
Maximum	10,3872	10,5243	12,6983	15,8495	19,8431	24,5193
Minimum	7,3136	6,8934	5,6389	9,2582	12,1138	17,5033
Light_EWY_Tin						
Mean	10,2037	9,5238	10,2585	13,1403	17,7342	21,9124
Maximum	12,3358	15,121	16,3787	17,9698	24,8489	26,251
Minimum	7,0911	4,9989	4,7823	7,8807	10,1505	17,4484

	July	August	September	October	November	December	Year
Heavy_TDY_Tin							
Mean	18,4171	17,9594	14,3218	10,3924	7,1045	4,1922	10,1106
Maximum	19,4029	20,078	18,6844	13,5706	10,6046	8,915	20,078
Minimum	16,9875	16,1601	10,648	8,0773	3,1657	-2,0854	-2,0854
Light_TDY_Tin							
Mean	19,5617	18,7987	15,4442	11,4452	8,0625	5,1045	11,1098
Maximum	23,938	25,054	22,2324	17,1871	14,5625	11,1647	25,054
Minimum	16,4539	14,8441	9,5112	3,1375	0,6528	-4,833	-5,1405
Heavy_ECY_Tin							
Mean	15,2091	15,0075	10,218	6,6017	1,0087	-3,2057	5,1072
Maximum	16,7184	16,6568	13,8524	12,2131	5,2951	2,0057	16,7184
Minimum	14,0803	11,7414	8,273	3,6038	-1,1625	-8,164	-10,8964
Light_ECY_Tin							
Mean	16,1623	16,1415	11,1989	7,3631	2,2263	-2,1028	6,1312
Maximum	20,5878	18,8174	16,0982	14,0338	8,2556	8,0427	20,5878
Minimum	13,9034	12,978	7,6267	1,3641	-2,5978	-15,1009	-19,9088
Heavy_EWY_Tin							
Mean	21,947	22,1813	18,1518	14,9249	11,0188	9,1174	14,5481
Maximum	24,577	24,7762	20,0023	16,4124	14,0165	11,5746	24,7762
Minimum	18,5088	19,7653	16,1022	12,3928	7,2578	5,4403	5,4403
Light_EWY_Tin							
Mean	23,0628	23,1434	19,1529	15,8657	12,0398	10,0699	15,5466
Maximum	27,8744	26,4723	22,8951	19,5044	15,5766	14,7218	27,8744
Minimum	17,0646	20,1207	15,6187	8,5016	1,7539	5,0231	1,7539

10.4 Appendix D: Boxplot of Lift

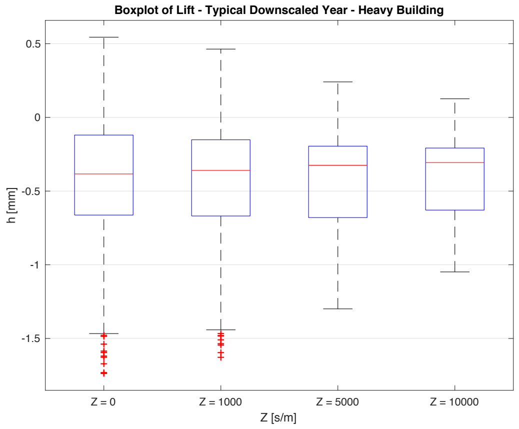

Figure 10-13 Boxplot of Lift – TDY-H

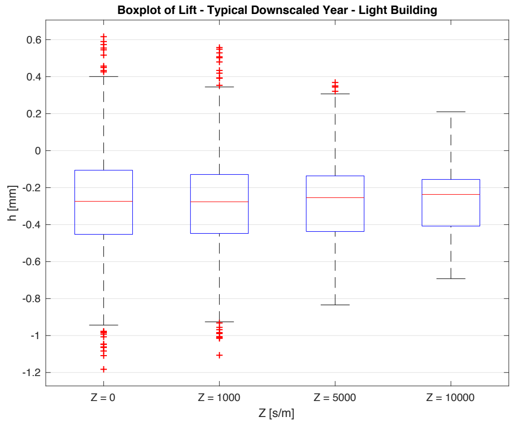

Figure 10-14 Boxplot of Lift – TDY-L

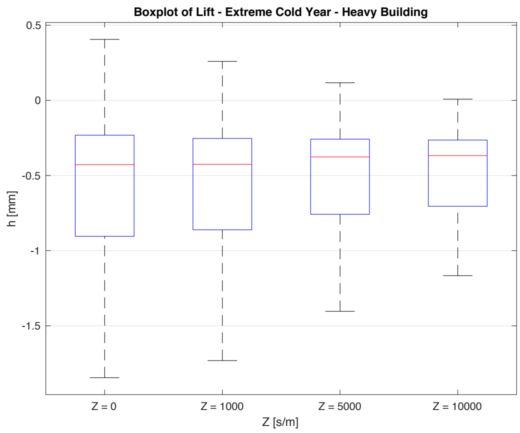

Figure 10-15 Boxplot of Lift – ECY-H

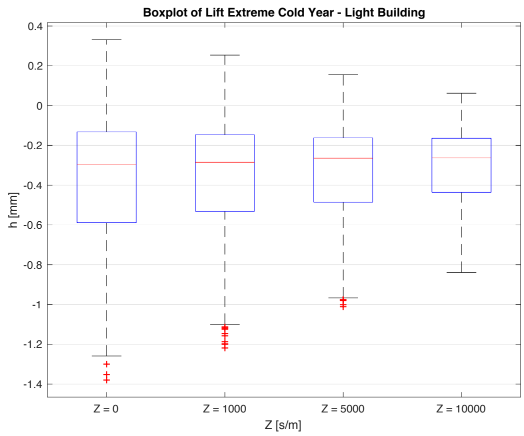

Figure 10-16 Boxplot of Lift – ECY-L

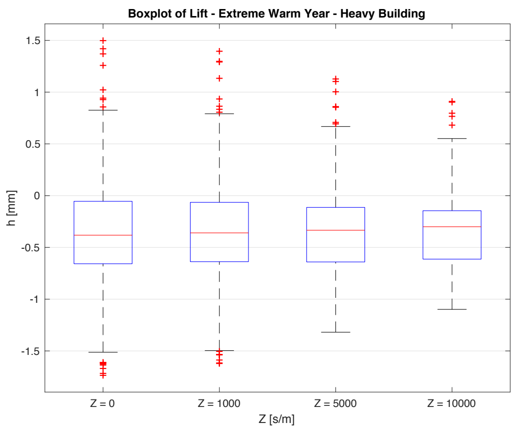

Figure 10-17 Boxplot of Lift – EWY-H

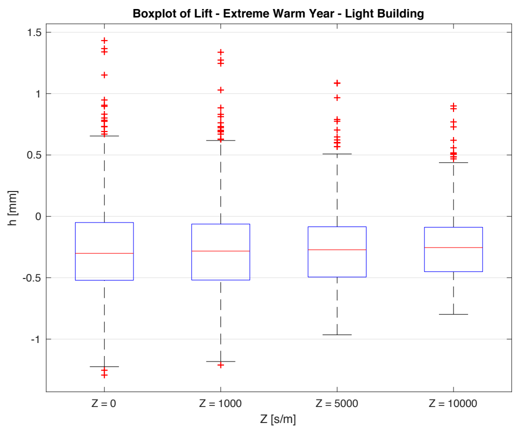

Figure 10-18 Boxplot of Lift – EWY-L