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Section 2 Test methodology and assessment

Impact of climate change on wood deterioration - Challenges and solutions for cultural heritage and modern structures

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ABSTRACT

Deterioration of wood in cultural assets follows the same physiological mechanisms as in modern structures. Therefore rules and data for prediction of service life derived from old wooden structures can be used to model the service life of recent wooden structures and vice versa. The latter is done in this paper: From experimental test set ups in the field spread over Europe, climatic data, wood temperature, wood moisture content, and decay rates recorded for several years were correlated and used for mathematic modelling of decay. On that data basis a first attempt is made to quantify the influence of global warming on wood decay rates for different regions and scenarios, valid for both: wood in modern and historic structures.

Against this background conservation of cultural heritage is increasingly challenging and methods are sought to allow historic structures to survive without severe modifications in design, but also with limited use of preservatives. How moisture monitoring can contribute to this purpose is shown on the example of the Echo pavilion in Maksimir Park, Zagreb, Croatia.

Keywords: Climate change, cultural heritage, double layer test, global warming, material climate, moisture monitoring, wood moisture content, wood temperature

1. INTRODUCTION

Service life of wood is limited by its durability, which can be regarded as a material property and is caused by chemical and physical constitution of untreated, modified, or preservative treated wood. Besides this material inherent resistance, the service life of wood is influenced by environmental conditions, which are more or less favourable for decay organisms. Hereby the climate plays an important role, but different climate levels need to be distinguished: The macroclimate, which is described by the weather data of a certain site, the mesoclimate, which is described by influences provoked at the site (e. g. shading, wind breaks), and the microclimate which reflects the situation at and within the construction (surface conditions). The climate inside the material has a decisive influence on decay of wood. Therefore the "material climate" determined by wood moisture content and wood temperature and their dynamics should be considered for estimation of decay hazards in first instance (Brischke et al. 2006).

Wood may experience exponential fungal deterioration caused by variation in the climatic factors within a small area and by minor imperfection in the wooden element. Ross Gobakken et al. (2008) introduced therefore the term critical in-situ conditions (CIC), which can again be described by the material climate. For modelling decay and resulting service life of wooden structures material climate data are therefore very useful.

Deterioration of wood in cultural assets follows the same physiological mechanisms as in modern structures. Therefore rules and data for prediction of service life derived from old wooden structures can be used to model the service life of recent wooden structures and vice versa. The latter is done in this paper: From experimental test set ups in the field spread over Europe, climatic data, wood temperature, wood moisture content and decay rates recorded for several years were correlated and used for mathematic modelling of decay (Brischke et al. 2010, Brischke and Rapp 2010). On that data basis a first attempt is made to quantify the influence of global warming on wood decay rates for different regions and scenarios, valid for both: wood in modern and historic structures.

2 CLIMATE IMPACT ON WOOD DETERIORATION

2.1 Field trials in different climates

Horizontal double layer field trials were conducted with Scots pine sapwood (*Pinus sylvestris* L.) and Douglas fir heartwood (*Pseudotsuga menziesii* Franco) at 24 different European test sites, which were selected to provide a range of climate regimes. The trials ran between 2000 and 2008 with exposure times between four and eight years. A detailed description of the trials is given by Brischke and Rapp (2010).

All specimens were monitored in terms of MC, wood temperature, and the progress of fungal decay. Therefore they were assessed yearly by using the so-called “pick-test” and rating the extent and distribution of decay according to EN 252 (1989) as: 0 (sound), 1 (slight attack), 2 (moderate attack), 3 (severe attack), or 4 (failure).

Climate data at all sites were available from official weather stations, where measurements of daily precipitation and average daily temperature were recorded. At some sites additional test rigs were exposed in shade boxes and in a tropical greenhouse to provoke modifications in terms of the microclimate and to promote the conditions for decay. To calculate exemplarily the possible effect of global warming on decay in Europe, the sites Uppsala, Portsmouth, Freiburg, Bordeaux, and Zagreb with their recorded material climates were chosen (Table 1).

Table 1: Characteristic data of exposure sites.

Test site	**Uppsala**[1)] Sweden	**Portsmouth**[2)] UK	**Freiburg**[3)] Germany	**Bordeaux**[1)] France	**Zagreb**[3)] Croatia
Height above sea level [m]	7	1	302	4	123
Average air temperature [°C]	6.8	11.6	12.1	14.0	10.7
Sum of precipitation [mm]	579	667	911	798	910
Begin of exposure	05/2001	04/2001	07/2000	01/2001	08/2002
End of exposure	09/2008	09/2008	09/2008	09/2008	10/2008

1)average of 2000-2006
2)average of 2002-2006
3)average of 2000-2005

2.2 Estimation of site-specific decay potentials

For estimation of site-specific decay potentials and how they are affected by potential global warming dose-response functions were used. Coming from results of the long-term field trials at different sites a mathematical relationship was established between moisture and temperature induced dose and a response in terms of fungal decay. A detailed description of the experimental set up, the field test results and the modelling of dose-response functions are again given by Brischke and Rapp (2010).

It was assumed, that decay is the response on a dose, that

- is a combination of a MC-induced component and a temperature induced component,
- can be cumulated over the respective exposure intervals, and
- can be correlated with the decay ratings in form of the response.

The following relationship between MC and daily moisture induced dose d_{MC}, and between average wood temperature T_{av} and daily temperature induced dose d_T respectively were found after computed optimization (Figure 1).

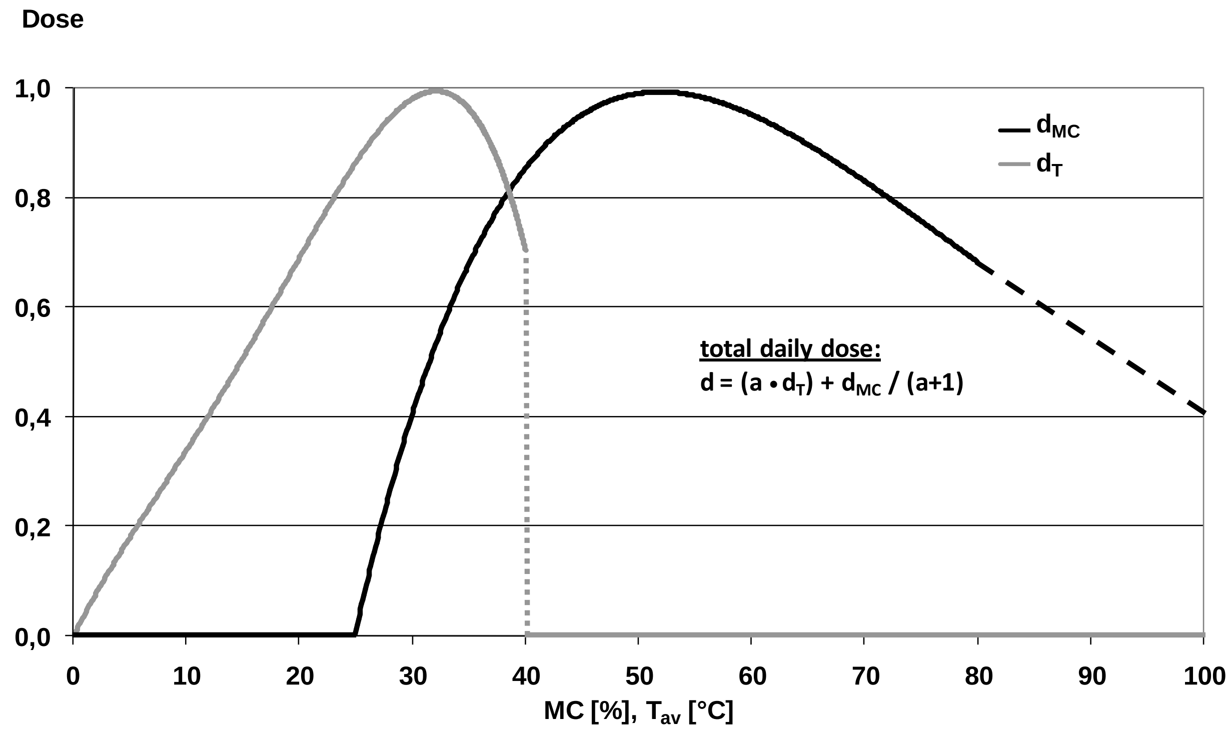

Figure 1: Relationship between MC and daily moisture induced dose d_{MC}, and between average wood temperature T_{av} and daily temperature induced dose d_T respectively. Dashed black line: MC>80% did not occur; therefore the curve progression is uncertain.

The daily dose was accumulated and correlated with the corresponding decay ratings for the different exposure intervals and test sites. The sigmoid course of the dose-response relationship was fitted with a Gompertz-function (*cf.* Figure 2). Based on the method of least squares for the dose-response function, all variables of the daily dose functions (d_{MC} and d_T) were optimized using MS Excel Solver. The following side conditions were considered: the total daily dose of days with a maximum temperature above 40°C, with a minimum temperature below –1°C, or with a MC below 25% was set as 0.

MC induced daily dose d_{MC}:

$$d_{MC} = 6.75 \bullet 10^{-10}\, MC^5 - 3.50 \bullet 10^{-7}\, MC^4 + 7.18 \bullet 10^{-5}\, MC^3 - 7.22 \bullet 10^{-3}\, MC^2 + 0.34MC - 4.98$$

; if MC ≥ 25% (1)

MC = daily moisture content

Temperature induced daily dose d_T:

$$d_T = 1.8 \bullet 10^{-6}\, T^4 + 9.57 \bullet 10^{-5}\, T^3 - 1.55 \bullet 10^{-3}\, T^2 + 4.17 \bullet 10^{-2}\, T$$

; if T_{min} > -1°C and T_{max} < 40°C (2)

T = daily average wood temperature

T_{min}= daily minimum temperature

T_{max}= daily maximum temperature

Daily dose d:

$$d = ((a \bullet d_T) + d_{MC}) / (a + 1)$$
$$; \text{if } d_T > 0 \text{ and } d_{MC} > 0 \qquad (3)$$

a = 3.2 (weighting factor of temperature induced daily dose component d_T)

The following dose response function (4) was determined for Scots pine sapwood and Douglas fir heartwood and will further on be used:

$$\text{Decay rating} = y = 4 \bullet \text{EXP} \bullet (-\text{EXP}(1.7716-(0.0032 \bullet D))) \qquad (4)$$

D = Total dose

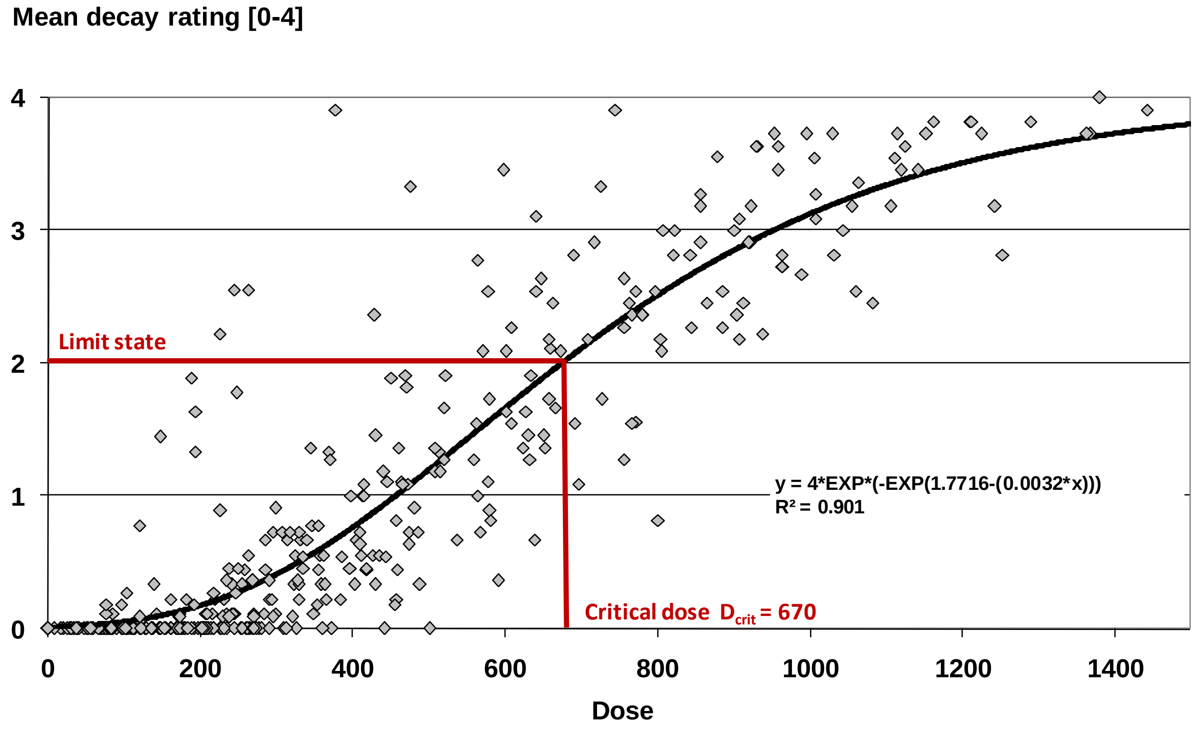

Figure 2: Relationship between the dose and the mean decay rating according to EN 252 (1989) of Scots pine sapwood and Douglas fir heartwood specimens exposed at 28 different field test sites (each dot represents the mean decay rating for one wood species at one exposure site at a certain time of exposure; black line: Gompertz smoothing function). Red lines: Determination of critical dose D_{crit} for service life estimation of wooden components. Limit state: Mean decay rating = 2 (moderate decay).

Service life estimations for wooden components were conducted to demonstrate the potential effect of global warming on wood durability. Therefore a critical dose was determined according to the dose-response function in Figure 2. The following assumptions were made: A mean decay rating = 2, corresponding to moderate fungal decay, was set as limit state. Any decay rating above this limit state means that the serviceability is not longer given. According to Equation 4 a critical dose D_{crit} = 670 is needed to be summed up to reach the limit state. Finally in the following the expected service life was considered to be the quotient of the critical dose D_{crit} and the mean annual dose D_a.

Expected service life ESL:

$$ESL = D_{crit} / D_a \quad [a] \tag{5}$$

D_{crit} = critical dose to reach decay rating 2
D_a = mean annual dose

From the recorded material climate (wood moisture content and wood temperature) at the different sites the daily dose was calculated as described above (see Figure 1). The cumulated daily dosages are plotted for Scots pine sapwood in Figure 3 and for Douglas fir heartwood in Figure 4. The different slopes of the curves mean different dose per year, translating to different decay potentials at the different sites. The steeper the slope the higher was the decay potential.

As could be expected the dose and therewith the decay potential was significantly lower for Douglas fir heartwood compared to pine sapwood, because it is characterized by lower moisture dynamics (Hedley et al. 2004; Stirling et al. 2007). Furthermore the ranking between the five sites was very different for both wood species. While pine sapwood revealed less dose at the coldest site Uppsala, lowest dose for Douglas fir was found in Bordeaux and Zagreb. This can be explained by the fact, that pine sapwood was wet enough for decay for long periods at all sites; thus, the colder climate in Uppsala had the most "negative" effect for decay on pine. In contrast, this dominating effect of wood temperature was compensated for Douglas fir, where moisture content was more important.

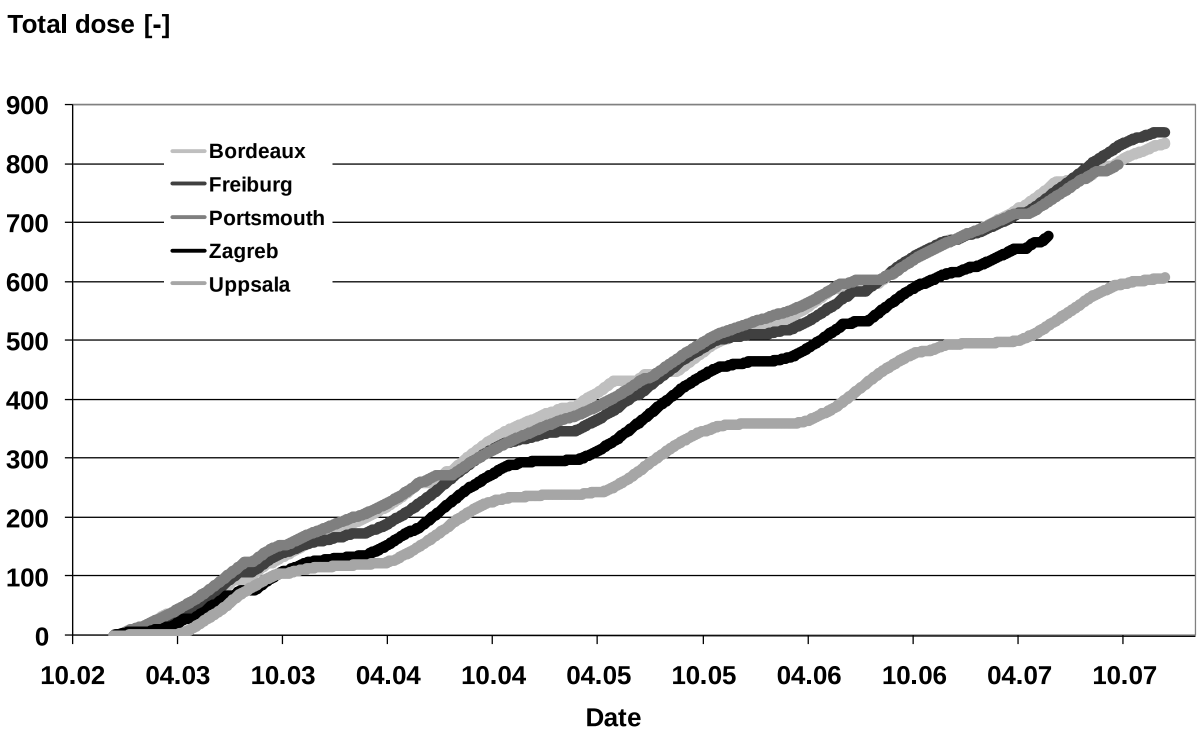

Figure 3: Accumulated dose (total dose) on Scots pine sapwood for the five chosen exemplary sites.

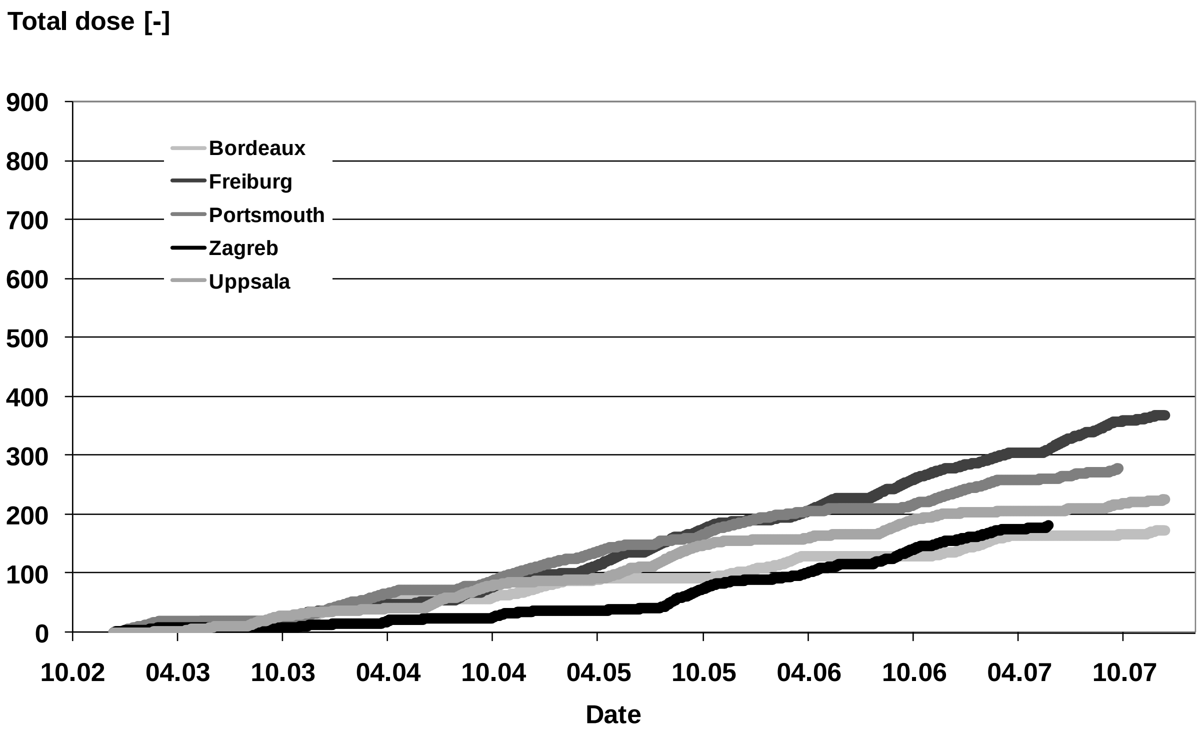

Figure 4: Accumulated dose (total dose) on Douglas fir heartwood for the five chosen exemplary sites.

2.3 Potential impact of climate change on decay

Emission of green house gasses is expected to lead to climate change, such as increased temperatures and a more humid climate (IPCC 2007). The dependency of wood durability on the material climate parameters moisture content and temperature expressed as dose-response functions strongly indicate, that conditions for decay fungi may become more favourable in the future.

In Table 2 the service life of double layer stakes is predicted for the five selected test sites. In addition to the current climate conditions, the annual dosage and resulting service lives were prognosticated for a homogenous warming by 1, 2, and 3 Kelvin. Therefore the following assumptions were made:

- Humidity as well as wood moisture content were not affected
- Increase in air temperature led to identical increase in wood temperature
- Temperature increased homogenously, e. g. by 1 K for every single day

Table 2: Prognosticated annual dosage and resulting service lives for double layer exposure at five different sites in Europe after different levels of global warming.

Wood species	Site	Annual dose[1)] after warming of				Expected service life [a] after warming of [2)]			
		0 K	1 K	2 K	3 K	0 K	1 K	2 K	3 K
Pine sapwood	Uppsala	121.4	135.9	149.3	162.6	5.5	4.9 (-11 %)	4.5 (-19 %)	4.1 (-25 %)
	Portsmouth	159.9	168.9	177.4	185.7	4.2	4.0 (-5 %)	3.8 (-10 %)	3.6 (-14 %)
	Freiburg	170.9	182.5	192.3	201.0	3.9	3.7 (-6 %)	3.5 (-11 %)	3.3 (- 15 %)
	Bordeaux	167.1	176.1	183.9	191.3	4.0	3.8 (-5 %)	3.6 (-9 %)	3.5 (-13 %)
	Zagreb	135.4	146.1	156.5	167.0	4.9	4.6 (-7 %)	4.3 (-13 %)	4.0 (-19 %)
Douglas fir	Uppsala	45.1	54.4	63.5	72.4	14.8	12.3 (-17 %)	10.5 (-29 %)	9.3 (-38 %)
	Portsmouth	61.3	66.6	71.7	76.8	10.9	10.1 (-8 %)	9.3 (-15 %)	8.7 (-20 %)
	Freiburg	73.6	81.9	89.4	96.2	9.1	8.2 (-10 %)	7.5 (-18 %)	7.0 (-23 %)
	Bordeaux	34.9	38.9	42.7	46.3	19.2	17.2 (-10 %)	15.7 (-18 %)	14.5 (-25 %)
	Zagreb	38.7	43.8	49.2	54.3	17.3	15.3 (-12 %)	13.6 (-21 %)	12.3 (-29 %)

1)average of the years 2003 to 2007
2)in brackets: percentage reduction of expected service life compared scenario without global warming

A homogenous warming by only 1 Kelvin led to a reduction of the expected service life between 5 and 11 % for Scots pine sapwood and 8 and 17 % for Douglas fir. The percentage reduction of service life was higher for the more durable Douglas fir heartwood, which can be explained by its moisture dynamics again. As Douglas fir heartwood is wet enough for fungal decay mainly during the winter half year, where the corresponding temperatures are too low for fungal activity, an increase in temperature would lead to significantly more days with favorable conditions in terms of both, temperature and moisture content. This coincides with the comparatively stronger impact of rising temperatures at colder places, *i.e.* Uppsala in Sweden.

With increasing temperature the service life decreases almost linearly, at least within the range between 1 and 3 K. For Douglas fir heartwood this means a reduction in lifetime to be expected between 20 and 38 %.

3. THE EXAMPLE OF THE HISTORIC ECHO PAVILION

3.1 Particularities in historic structures

There are differences when dealing with cultural heritage compared to modern buildings, e. g. faulty design, which leads to damage, has to be corrected in a modern building during renovation. However, faulty design in a class listed monument can’t be changed if the design and construction technique is considered as the historical cultural value to be preserved and documented for future generations. Conservation people are in a dilemma in that case. On the one hand there is the claim of monument protection to conserve a particular design (in spite of being faulty) on the other hand there are safety rules and a budget not allowing to replace failing components at short intervals. The paper describes at the example of the historic Echo pavilion built in 1843 in the Maksimir Park in Zagreb how such a situation can be dealt with: A chemical treatment combined with an electronic monitoring approach, allowing detecting precursors of deterioration. Measures can be taken before damage occurs to cut the costs.

3.2 Monitoring the material climate on ancient wooden pavilion

The Echo pavilion designed by Franz Schücht, built in 1843, was protected by law and declared as cultural monument of garden architecture in 1964 together with the whole park Maksimir, in which it is situated. Since then it is included in the official national register of cultural monuments of Croatia. However the fungi were unimpressed. When the moisture content was high enough due to construction faults in the roof and in the splash water area close to the ground decay progressed (Figure 5). It was necessary to restore the pavilion several times. Due to the rules of monument protection this historic (faulty) design had to remain unchanged. From the year 2000 to 2001 a necessary substantial restoration was done and accompanied by the Forestry Faculty of the University of Zagreb as scientific consultant (Despot et al. 2006).

Figure 5: Decayed poles (brown rot, mainly *Gleophyllum abietinum*) and soft rot found and replaced during the restoration in 2001.

The solution for the poles and the lower parts of the pavilion was chemical preservation using tebuconazole based products. All decayed wooden parts were checked and repaired. Instead of earlier used and now decayed silver fir (*Abies alba* Mill.) and spruce poles, larch (*Larix decidua* L.) and spruce heartwood were chosen for producing new poles. Each pole was built of beams glued with resorcin formaldehyde glue, and then turned. The bases and Toscan's bases were made of Slavonian oak heartwood (*Quercus pendunculata* L.) and protected with water repellent paste. Boron wood pills were put in the bottom of each panel and pole. All wooden parts were preserved by three minute immersions, or by spraying and brushing with tebuconazole solved in white spirit. After preservation and assembling, the poles and panels were coated with a three-coat alkyd based primer-undercoat-mat system for boats.

The solution for the roof construction was a silicone based permanently elastic sealant to prevent water running into the roof where the little top pillars (marked with yellow arrows in Figure 6) on top of the roof are connected to the roof sheeting.

Figure 6: Restoration work in 2001. Yellow arrows: critical connection between the little top pillars and the roof sheeting.

However since “permanently” elastic sealants are in reality never permanently elastic, but only for a limited duration, a wood moisture monitoring system was installed at different positions inside the roof (Figure 7). Stainless steel screws drilled into the spruce roof beams in a distance of 30 mm to each other served as electrodes for the MC measurement based on electrical resistance. Cables were attached to the electrodes and run to a little box in which the data logger (Materialfox mini, Scanntronik Mugrauer, Zorneding) was stored.

3.3 Minimization of decay risk for wooden structures through moisture monitoring

In the meantime for more than 5 years the data logger is delivering daily records of the MC of the roof beams in the 3 different positions. For better readability the monthly average values are shown in Figure 8.

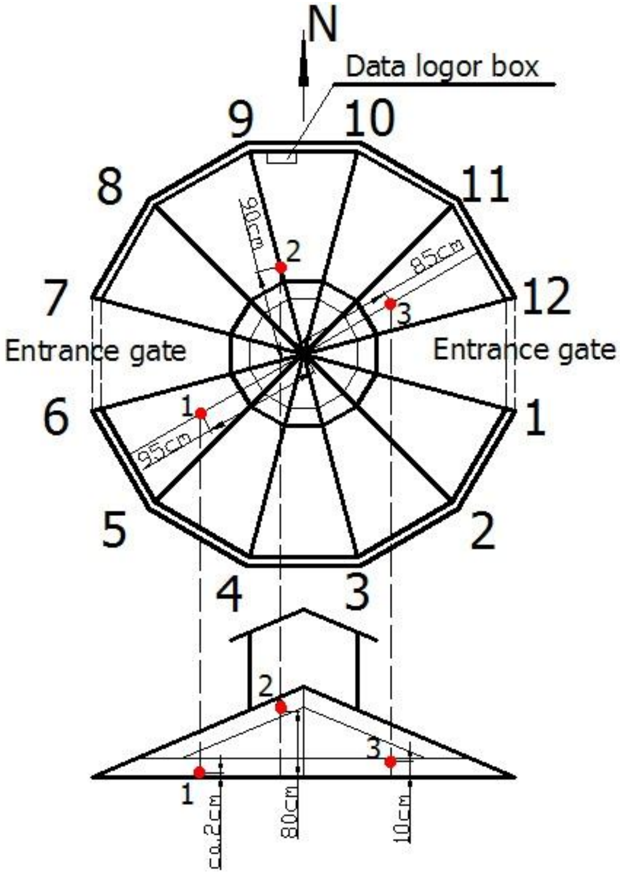

Figure 7: Installation of moisture monitoring device. Left: Position of the three measurement points in the roof. Right: Installation of data logger box.

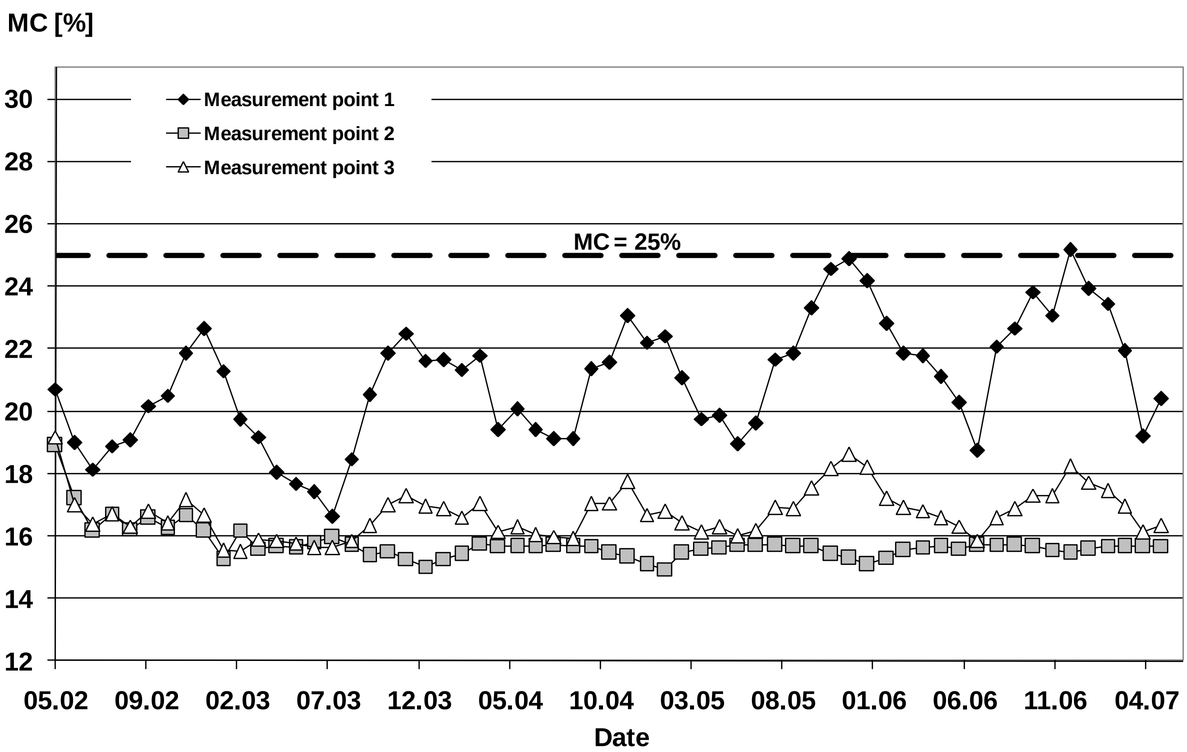

Figure 8: Course of wood moisture content MC for three measurement points within the roof construction of the Echo pavilion in Maksimir Park, Zagreb, during five years of monitoring.

Measurement point 1 in the lowest position is indicating highly increased MC, especially during the winter time. November is the month with the highest precipitation in Zagreb. The MC readings correspond with the precipitation peaks. Measurement point 1 is located the lowest within the roof construction, where leaking water is accumulating when leaking through the roof and running down the beam. At the end of the recording period the critical MC of 25 % was exceeded. This is a clear signal to open the roof construction now and do a revision including resealing of the connection between the little pillars on top of the roof and the roof sheeting.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

For this first attempt to estimate the magnitude of the influence of global warming on decay a certain rise of temperature (1, 2 and 3 Kelvin on each day of the year) was assumed and used for mathematical modelling based on the dose response function after Brischke et al. (2010). However, in order to get a realistic value for a certain place it is necessary to translate the complex prognosticated climatic changes for that place more precisely into daily changes of wood MC and wood temperature. For instance it can be expected that an increase of 1 Kelvin during the summer is of less influence than having the same temperature increase in spring, autumn or winter. Also an increase of precipitation during the cold season has less influence on decay than during the season when the temperatures are favourable for decay. Future work is therefore needed not only to improve dose-response relationships (material climate – decay functions), but also to understand the links between macro climate and material climate. To achieve useful algorithms considering the relationship between weather parameters and material conditions an interdisciplinary approach including experts in meteorology will be needed.

The example of the listed historical building of the Echo Pavilion has shown that moisture monitoring systems can substantially contribute to prevent cultural heritage from decay. The installed inexpensive and simple electronic system of early warning proved to be feasible and saved costs in the conservation of wooden cultural assets. In times of tight budgets and global warming with corresponding higher rates of decay MC monitoring systems will become increasingly important.

5. ACKNOWLEDGEMENTS

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