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DURABILITY OF TIMBER OUTDOOR STRUCTURES – MODELLING PERFORMANCE AND CLIMATE IMPACTS

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ABSTRACT: In this paper, a dose-response model for above-ground decay as well as a climate model transferring macro climate data to wood climate data are presented. The models base on data from field trials, at 28 European test sites, and were used to calculate the relative risk for decay caused by climate variability in Europe. A decay hazard map is drawn to illustrate the climate induced variability within the European continent. For comparative purposes also the Scheffer Climate Index (SCI) is applied to the same European data base. It can be concluded that valuable information for service life prediction of timber structures will be gathered from performance-based decay hazard estimation and mapping.

KEYWORDS: dose-response functions, limit state design, service life prediction, durability, modelling

1 INTRODUCTION

One of the key issues in wood construction is durability. Traditionally, durability design of wooden components and structures is based on a mixture of experience and adherence to good building practice, sometimes formalised in terms of implicit prescriptive rules. Therefore, the expected performance cannot be specified in quantitative terms. The design cannot be optimised and any change of design will be associated with uncertain risks. A modern definition of durability is: *The capacity of the structure to give a required performance during an intended service period under the influence of degradation mechanisms*. Conventional durability design methods for wood do not correspond to this definition.

The development of performance-based design methods for durability requires that models are available to evaluate performance in a quantitative and probabilistic format. This means that the relationship between product performance during testing and in service need to be quantified in statistical terms and the models should be calibrated to ensure that they provide a realistic measure of service life, with reasonable degree of certainty.

Attempts have been made to develop empirical models for service life prediction. One example is the so called factor method which is intended as a tool for predicting the service life of components and structures. This concept has been introduced in the standard ISO 15686-1 [1]. The method is based on a reference service life which is multiplied by a series of empirical factors taking into account various aspects of material characteristics, environmental conditions and operation conditions. The standard itself states that the method does not provide an assurance of a service life in quantitative terms. It merely gives an empirical estimate based on available information and may serve as a guide when choosing between different components.

Currently, efforts in research on service life prediction have been intensified in several countries. A very comprehensive approach was taken in Australia, resulting in a 'Timber service life design guide'[2] and a corresponding software program 'TimberLife'. The information provided for estimating timber service life with respect to different exposures is based on several models concerning decay in and above ground, and attack by termites and marine borers. In Europe different projects are focusing on service life prediction of timber components as well, but are partly tracking very different experimental approaches and conceptions for modelling [3-11]. Recently, an engineering design guideline for service life of wood in outdoor above ground applications (cladding and decking) was presented [11]. The climate exposure is determined as a function of geographical location, local exposure conditions, sheltering, distance to ground and design of

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details. The exposure is then compared to the material resistance defined in five classes and the design output is either OK or NOT OK. The data included in the guideline have partly been derived with the help of a dose-response model for decay, which was used to derive relative measures of decay risk between different locations and between different detail solutions. Other parts in the guideline have been estimated in a semi-subjective manner based on expert opinions and experience from field testing. The guideline was verified by reality checks of real buildings. Finally, various studies from North America and Asia deal with decay hazard estimations and other service life prediction issues [12-17]. Remarkable progress in service life planning and prediction was observed for different materials during recent years, also for wood, but still the need for advanced test methods is evident [18] and finally comprehensive data bases containing service life records for the various building materials and components are lacking. Methods for performance based durability design are much more developed for e.g. concrete with a firm foundation in physical models; see e.g. [19].

This paper focuses on the presentation of two models: a dose-response model for decay of timber exposed outdoors above ground and a climate model linking macro climate and wood moisture content. The models are then used to classify risk for decay caused by climate variability in Europe. A decay hazard map for Europe is drawn, showing the influence of regional climate on the decay hazard for wood exposed outdoors above ground.

2 METHODS

A proposed principle for a performance-based service life design model is illustrated in Figure 1. The problem is here described in terms of climatic exposure on one hand and resistance of the material on the other hand. The design model is based on a clearly defined limit state, which could be onset of decay alternatively a specified acceptable degree of decay. The performance requirement in a certain situation could e.g. be that onset of decay is not accepted during a specified service life. Since most factors affecting the performance are associated with uncertainty, the probability of non-performance must be assessed so that it can be limited to an accepted maximum level. The advantage with the approach is that exposure can be described as a function of global climate, component design and surface treatment in a general way independent of the exposed wood material. Likewise, the resistance of different types of materials can be expressed in terms of response to quantified micro-climate conditions independent of practical design situations.

As illustrated in Figure 1, the criterion for acceptable performance is that the resistance of the material is sufficient to withstand the exposure in a given situation. This has to be verified by a performance model, related to a specified performance criterion. The performance criterion may be associated with requirements of different types such as load-bearing capacity of a structure, serviceability requirements or aesthetics. A key element is the performance model, which must be available if a quantitative evaluation shall be possible.

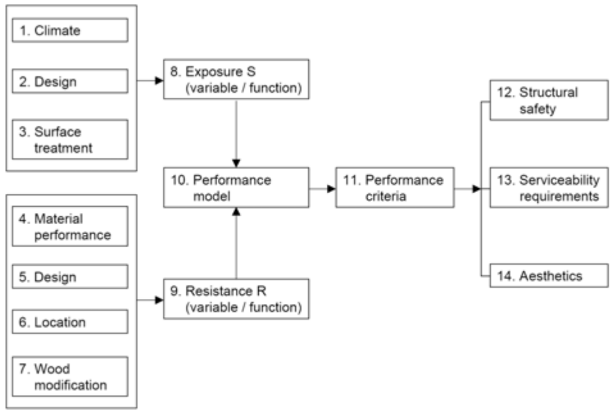

Figure 1: *Principle for performance-based service life design of wood elements.*

2.1 PERFORMANCE MODEL

A performance model shall be able to predict violation of the limit state as a function of all relevant influencing parameters.

The limit state in this case might be defined as onset of rot decay in wood. It is mainly relevant for exterior wood elements above ground under exterior climate exposure including rain. Onset is here defined with reference to decay level 1 "slight attack" according to the standard EN 252 [20]. This rating is frequently used in evaluation of decay in field durability tests of wood products. Alternatively, higher decay levels as shown in Figure 2 can be used.

Coming from results of long-term field trials, 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 modeling of dose-response functions are given by Brischke and Rapp [21], and therefore only summarized here briefly:

The field test specimens cut from Scots pine sapwood (*Pinus sylvestris* L.) and Douglas fir heartwood (*Pseudotsuga menziesii* Franco) were monitored in terms of moisture content (MC), wood temperature, and the progress of fungal decay up to a period of eight years. The specimens (500x50x25 mm^3), according to EN 252 [20], were exposed horizontally in double layer test rigs, whereby the whole test set-up formed a closed deck (73x65x21 cm^3). To avoid the growth of grass it was placed on paved ground or horticultural foil. The test rigs were exposed at 28 sites in Europe, which were selected to provide a range of climate regimes. Climate data at all sites were available from official weather stations, where measurements of daily precipitation and average daily temperature were recorded. The specimens were evaluated yearly by using a pick-test and rating the extent and distribution of decay according to EN 252 [20] as: 0 (sound), 1 (slight attack), 2 (moderate attack), 3 (severe attack), or 4 (failure). The moisture content (MC) of three pine sapwood and three Douglas fir heartwood samples in the bottom layer of each test set

was recorded once a day. Minimum and maximum temperature below the bottom layer of each test set were recorded daily with a miniature data logger and used to calculate the average daily temperature.
Dose-time functions and resulting service life estimations are based on the following functions:
MC induced daily dose d_{MC}:

$$d_{MC} = 6.75 \cdot 10^{-10} MC^5 - 3.50 \cdot 10^{-7} MC^4 + ... + 7.18 \cdot 10^{-5} MC^3 - 7.22 \cdot 10^{-3} MC^2 + 0.34 MC - 4.98 \quad (1)$$

if MC ≥ 25%, MC = daily moisture content

Temperature induced daily dose d_T:

$$d_T = -1.8 \cdot 10^{-6} T^4 + 9.57 \cdot 10^{-5} T^3 - 1.55 \cdot 10^{-3} T^2 + 4.17 \cdot 10^{-2} T \quad (2)$$

if T_{min} > -1°C and T_{max} < 40°C, T = daily average wood temperature, T_{min}= daily minimum temperature and T_{max}= daily maximum temperature

Daily dose d:

$$d = \frac{(a \cdot d_T) + d_{MC}}{a+1} \quad (3)$$

if d_T > 0 and d_{MC} > 0, a = 3.2 (weighting factor of temperature induced daily dose component d_T)

Dose response function:

$$\text{Decay rating} = y = 4 \cdot \exp\left(-\exp\left(1.7716 - \left(0.0032 \cdot D\right)\right)\right) \quad (4)$$

D = Total accumulated dose

The dose response function (Equation 4, shown in Figure 2) was determined for Scots pine sapwood and Douglas fir heartwood and will further on be used for other wood species as well.

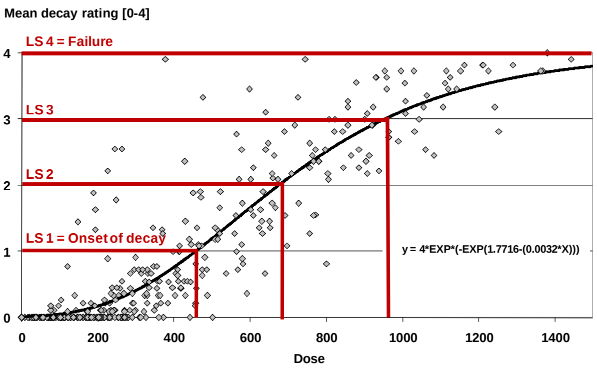

Figure 2: *Dose-response relationship for fungal decay in above-ground exposures, determined on the basis of field trial results performed at 28 test sites. Dose is expressed as a function of wood MC and wood temperature and accumulated from daily values over the whole exposure period of 4-8 years. Response is expressed as decay rating to EN 252 [20]. LS = limit states.*

2.2 CLIMATE MODEL

The effect of climate variability on risk for decay of wood exposed outdoors at different places in Europe was investigated using the performance model described above. The climate data used was obtained with the program Meteonorm (www.meteonorm.com, [22]). In Meteonorm, desired climate parameters for any place can be obtained. The program includes a database with more than 8000 stations where the climate has been measured during many years, and a "standard year" is produced from these measurements. Then for any location, the climate can be modeled by interpolation between different stations. For this research, as output values, hourly values of temperature, relative humidity and rain were chosen. In the performance models, however, daily values are used. Therefore, hourly values of temperature and relative humidity are averaged and hourly rain is accumulated to daily values.
In the climate model, wood moisture content (MC) is calculated from the global climate data. Moisture content u_{01} depends on the relative humidity ϕ and is calculated as follows in Equation 5 [21]:

$$u(\phi) = 0{,}7\phi^3 - 0{,}8\phi^2 + 0{,}42\phi + 0{,}0077 \quad (5)$$

The moisture content in equilibrium with relative humidity is estimated on the basis of the average value of relative humidity ϕ for two full days (Equations 6 and 7). This is assumed to account for a certain delay corresponding to diffusion into the wood.

$$u_{01}(t_i) = u\left[\bar{\phi}(t_i)\right] \quad (6)$$

$$\bar{\phi}(t_i) = \frac{\phi_1(t_{i-1}) + \phi_1(t_i)}{2} \quad (7)$$

Additionally, moisture content is increased by rain events. For each 24 hour period it is assumed that rain occurs if the accumulated rain is at least 4 mm. A rain period is then defined as an uninterrupted sequence of 24 hour periods with rain. The duration of a rain period is denoted t_r. A drying period is defined as the time after a rain period during which the moisture content returns to equilibrium with ambient relative humidity. The duration t_d of the drying period depends on the length t_r of the rain period. Based on measurements on plywood [8] the drying duration can be estimated as $t_d \approx a \cdot t_r$ where *a* is an empirical parameter of the order 2-3. Here, *a*=2.5 was used. Of course, this rough value does not give completely exact results. However, more exact results are not necessary, as the daily rain accumulated during 24 hours is used in the model, disregarding when during that 24-hour period the rain period occurs.
For each day *i* with rain the daily average moisture content $u_1(t_i)$ is calculated according to Equation 8 where k_r is the relative increase of moisture content due to rain. According to data in [8], k_r is in the range of 0.3 to 1.5 for different plywood samples using hardwood and softwood species, and different lengths of rain events. In general, the longer the rain event, the higher is the observed MC increase. For plywood produced from different wood species, the MC change can be in the range of k_r=0.3 to 0.8 for different species and a rain shower (1 hour) or between k_r=0.3 and 1.5 for a longer rain period. In the present paper k_r=0.8 is used. When better information about the influence of rain on the MC is available, this model should be updated. Right now,

testing is ongoing at several sites; however, no final results are available yet.

$$u_1(t_i) = u_{01}(t_i)[1 + k_r] \qquad (8)$$

At the end of each rain period t_r and $t_d = a \cdot t_r$ are determined as well as the difference Δu_{1r} between relative humidity-induced moisture content (Equation 6) and rain-induced moisture content (Equation 8), shown in Equation 9. Here, t_e denotes the last day of the rain period.

$$\Delta u_{1r} = u_1(t_e) - u_{01}(t_e) = k_r \cdot u_{01}(t_e) \qquad (9)$$

For day k after a rain period, MC is determined by Equation 10:

$$u_1(t_k) = \max[(u_1(t_{k-1}) - \frac{k}{t_d}\Delta u_{1r}), u_{01}(t_k)] \qquad (10)$$

Note that as soon as a new day with rain occurs the moisture content is again determined by Equation 8.

Numerical problems may appear when a rain period happens during the last days of the year. Then the drying period may fall partly outside the 365 days that are simulated. In this case, the last rain period(s) are not considered in the model. This results in a somewhat lower dose, as the MC is not increased due to rain. However, this happened for only 26 % of the sites, with one to three neglected rain periods. Furthermore, due to the low temperatures, the daily doses at the end of December usually are very low anyhow.

It is assumed that the wood temperature T_i is equal to the surrounding (global) temperature given by Meteonorm. This assumption may seem too simplified; however, there can be found research results that show that this is sufficiently correct [24]. In a future model, however, the relationship between surrounding temperature and wood temperature will be modelled more thoroughly according to test results from ongoing tests in Lund, Sweden and Hannover, Germany.

Having interconnected values of daily average moisture content u_i and temperature T_i for one year the daily dose can be calculated according to Equations 1 to 3. Furthermore, the daily doses are accumulated to give the annual dose as a relative measurement for decay risk.

An example showing the use of climate model and performance model is presented for Uppsala, Sweden in Figures 3 to 5. Figure 3 shows climate data from Meteonorm from day 100 (April 9th) till day 200 (July 18th) as well as the modelled wood moisture content. It can be clearly seen that the MC increases during rain events (daily rain >4mm), and that MC increase due to rain is faster than the drying when MC decreases again to equilibrium with the surrounding climate. Figure 4 shows MC-induced dose, temperature-induced dose and daily dose for the same time interval. It can be seen that MC is the limiting factor for the daily dose, being zero during many days of that time period, while the temperature dose steadily increases. However, as the daily dose is only calculated for days with nonzero values of temperature-induced dose and MC-induced dose, the dose is limited by the low MC. Figure 5 finally shows the accumulated dose for Uppsala during the whole year. Here it can be clearly seen that the dose increases slowly during winter and early spring when the temperature is low, and the increase in dose is much faster during summer and fall (warm and moist), to be finally limited by decreasing temperatures again.

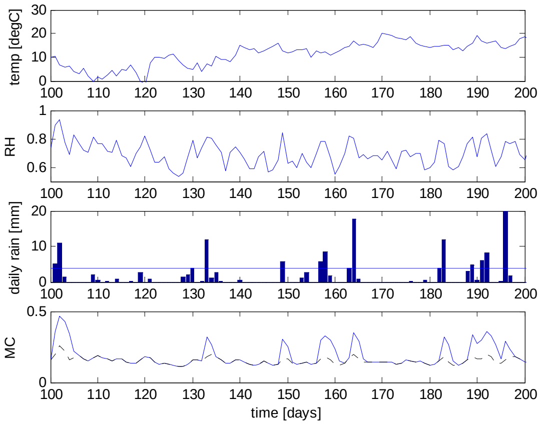

***Figure 3:** Climate data (temperature, relative humidity and accumulated daily rain) and MC calculated with the climate model for Uppsala, between day 100 and 200. In the lowest diagram, the differences in MC between dotted line and solid line are the effects of rain events.*

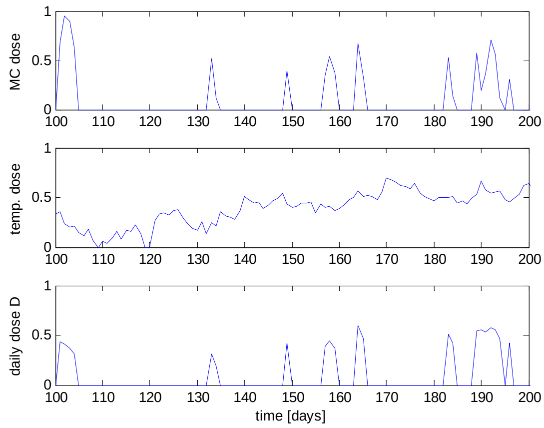

***Figure 4:** MC-induced dose, temperature-induced dose and daily dose D for Uppsala between day 100 and 200.*

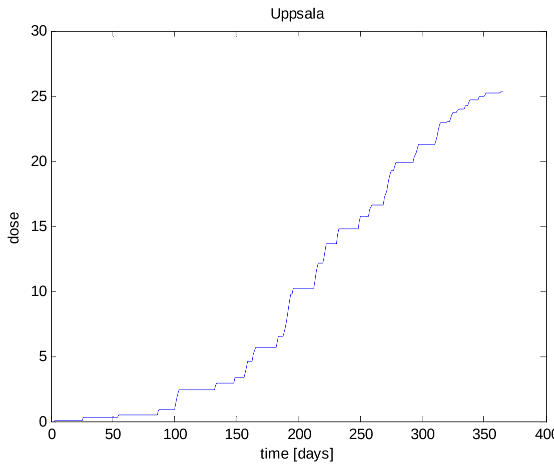

***Figure 5:** Accumulated dose for Uppsala, Sweden during one year.*

3 RESULTS AND DISCUSSION

3.1 CLIMATE MODEL VS MEASURED MC

The climate model was verified against measured climate and moisture content data available for Hannover, Germany. Mean temperature, mean relative humidity and accumulated daily rain were recorded. At the same time, moisture content was measured once a day (at midnight) in horizontal boards with cross-section 20 mm x 100 mm, 5mm below the surface. The boards were made of Norway spruce (*Picea abies* Karst.), Scots pine sapwood and Douglas fir heartwood. Measured values are available for the time interval December 1st to August 31st. Figure 6 shows recorded average temperature, relative humidity and rain as well as the modelled moisture content. In Figure 7, both the modelled MC and the measured MC are shown. During the first 80 days, the temperature is below zero (see Figure 6) and the climate model overestimates the MC compared to the measurements (not shown). For temperatures above zero (from day 80 onwards), the model underestimates the MC slightly for both pine sapwood (dash dot line) and spruce (dotted line). Due to rain events, MC increases and gives good coherence with the MC measurements in the pine sapwood board. However, the less permeable spruce board is not influenced by the rain events that much and thus MC does not change significantly (due to high rain events, the measured MC increased about one 1%). The climate model can predict MC fairly well for pine sapwood and even partly spruce (then the MC increase due to rain should be eliminated). In further modelling, the climate model will be improved to better represent less permeable materials such as spruce. Also the size of the MC peaks due to rain events should then be adjusted to different wood species.

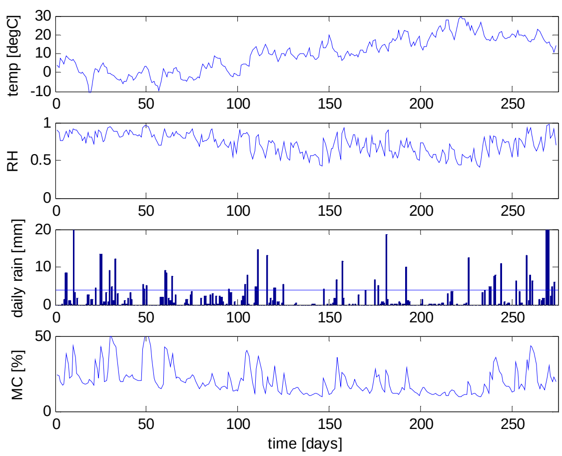

Figure 6: *Verification of climate model with climate data from Hannover, Germany. MC modeled with mean temperature, RH and daily rain. Showing a time period from December 1st to August 31st.*

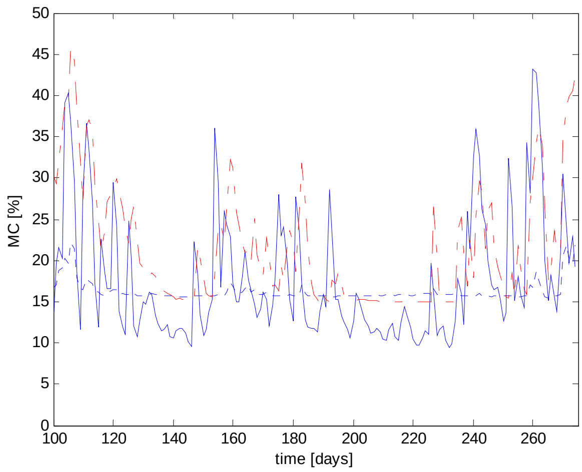

Figure 7: *Comparison between modeled moisture content (solid line) and measured moisture content in a horizontal spruce board (dotted line) and a horizontal pine sapwood board (dashdot line) from day 100 (March 10th) to end of time period (August 31st)*

3.2 RELATIVE DECAY MAPPING

For the decay hazard mapping, the decay risk at 206 sites in 38 European countries was calculated and related to the decay risk (annual dose) of the site of Uppsala, Sweden. A decay hazard above one means higher decay potential compared to Uppsala, a number below one means lower decay potential than in Uppsala. Isopleths of the same decay hazard have been calculated by interpolation using splines in GEOgraf® and are shown in Figure 8.

As can be seen from Figure 8, there is a general trend of higher decay hazard along the (west) coast of Europe with maritime climate and decreasing decay hazard towards the east which has more continental and drier climate. Along Europe's west coast, the decay hazard is highest at the latitudes of the United Kingdom and Ireland (maximum value of 3.3 at the western tip of Ireland) with decreasing hazard towards the North (Norway, relative decay potential ranging from 0.35 far North to 1.9 in the South) and the South (France, Spain, Portugal, decay hazard between 1.8 and 2.6).

Figure 8 also shows the influence of height above sea level on the decay potential, which is very prominent in the Alps region (Switzerland, Austria, and Southern Germany). Here, large changes in decay potential between sites situated in a valley and sites on mountain tops happen despite very short distance. Influencing factors are of course the height above sea level, which decreases the temperature, but also the mountain ranges which are obstacles for clouds, leading to lower annual rainfalls and lower relative humidity on the leeward side of the mountains. As an example, at the four sites investigated in Switzerland, the relative decay potential varied from 0.89 at Col du Grand St. Bernard (2472 m above sea level) to 1.98 in Zürich (471m above sea level, situated at the lake Zürich, which also increases the relative humidity in the region).

Figure 8: *Relative decay potential for Europe indicated as relative doses for 206 European sites (circles) based on Meteonorm climate data. Relative dose compared to Uppsala, Sweden (●).*

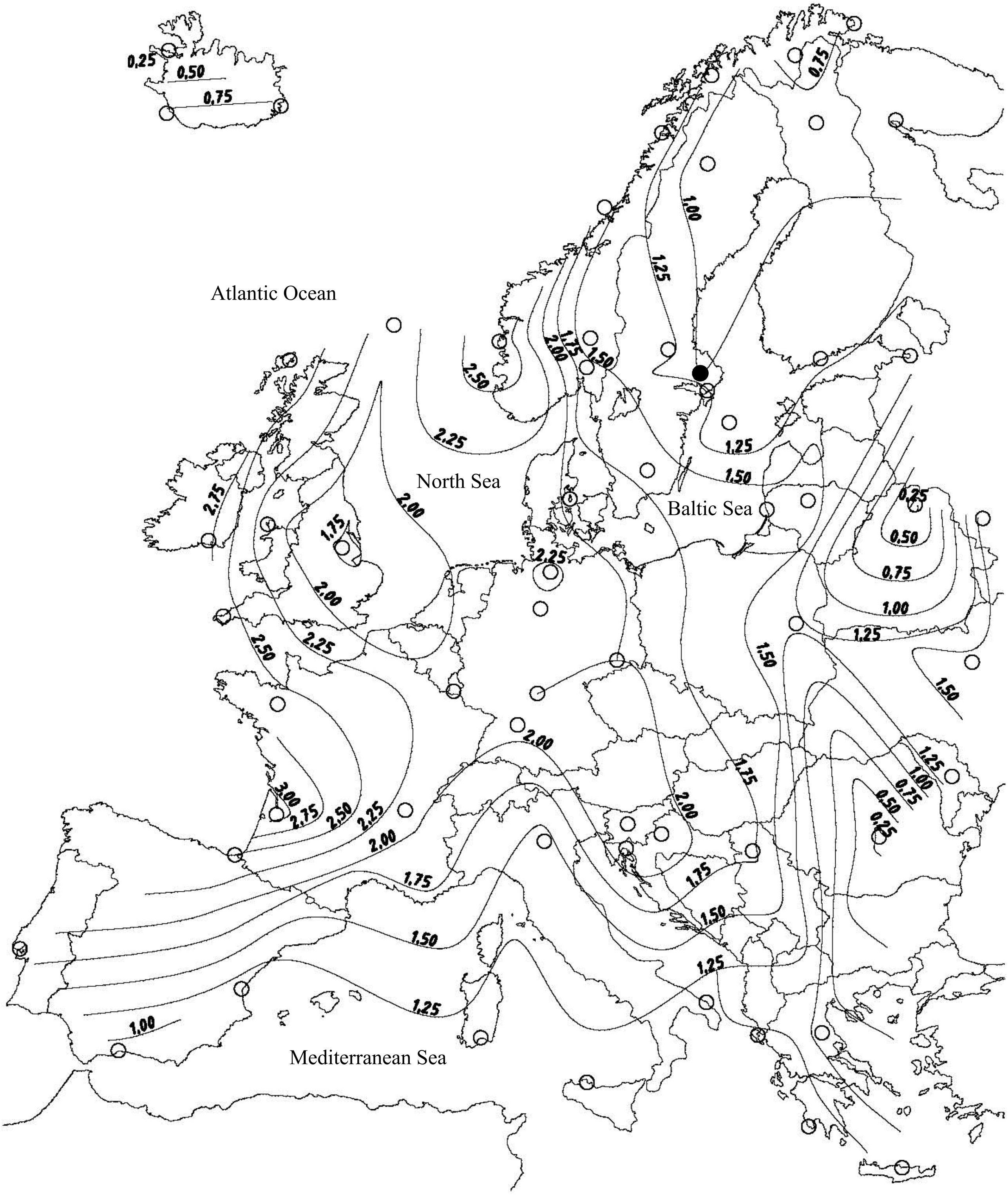

Figure 9: *Relative decay potential for Europe indicated as relative values for Scheffer's Climate Index for 60 European sites (circles) based on data from ECA & D [26]. Relative values compared to Uppsala, Sweden (●).*

Pioneer work on decay hazard mapping has been carried out by Scheffer [25], who developed a climate index for estimating the potential for decay in wood structures above ground. Originally the index was developed to estimate the decay potential of sites in the continental part of the United States, later on it had also been applied to other parts of the world. The decay hazard map obtained with the dose-response performance model in the present study (Figure 8) was therefore compared with a mapping based on Scheffer's Climate Index (SCI), which is known to be the most established index of its kind.

The following formula (Equation 11) has therefore been used and applied to climate data for 60 European sites (taken from ECA & D, [26]) for calculation of Scheffer's Climate Index:

$$SCI = \frac{\sum_{Jan}^{Dec}[(T-2)(D-3)]}{16.7} \qquad (11)$$

Where
T = mean monthly temperature [°C]
D = mean number of days in the month with 0.25 mm or more precipitation
Note: Negative monthly values have been set as zero to avoid negative SCI values.

Applied on Europe, Scheffer's Climate Index ranged between 81.0 in the Southwest of France and 3.9 in Northern Norway, and 5.6 in Romania respectively [27]. Thus all three climate zones, which had been distinguished by Scheffer (1971) in the USA, can also be found in Europe:
$SCI < 35$
$35 \leq SCI < 65$
$SCI \geq 65$

The relative Scheffer Index (relative index compared to index for Uppsala, see Figure 9) is higher for most sites in Europe compared to the dose response model (Figure 8). This is not surprising since the Scheffer index is a different measure on another scale, which also will be reflected when relative values between different locations are calculated. However, the same tendencies as indicated by the performance model became visible through the SCI. Hot spots (i.e. sites with relatively high decay potential) have been identified on the West coast of Norway, Ireland, UK, and France. Generally, the decay potential decreases towards the East due to the increasingly continental character of the climate and to the South due to increasing aridity. These findings and also the distribution of isopleths in between these extremes coincide fairly well with the mapping based on the dose response model in Figure 8. However, it should be kept in mind that the two decay hazard maps are based on different sites, 206 sites for the map in Figure 8 and 60 sites for the map in Figure 9.
On a European basis, one should be careful to draw borders for different zones, as the climate highly influences the risk for decay and the climate can change locally very much, for example in the Alps region due to different heights above sea level or due to situations near the coast or big lakes. Maps showing risk for decay should therefore only be drawn with care and on national or regional basis, so as to improve the scale of the map.

4 CONCLUSIONS

The climate model and dose response model presented in this paper can be used to classify risk for decay caused by climate variability in Europe. As the results from simulations using Meteonorm weather data and from measured wood climate are concordant as was shown in [28], simulated weather data may be used to specify decay risk for different sites in the world. Comparisons with mappings based on Scheffer's Climate Index revealed fairly good accordance at least in qualitative terms. In quantitative manners the SCI indicates higher differences in decay risk within Europe. However, with respect to service life prediction, the macro climate is only one of many factors, which needs to be considered. In this respect the dose-response based performance model will provide the possibility to consider also other decay influencing factors such as design detailing, material-related moisture dynamics, and microclimate.
Evaluating sites in terms of their relative decay potential needs to be replaced by quantifying factors for the service life prediction under certain reference conditions. Therefore a series of studies is ongoing within the Swedish WoodBuild program.

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