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The Performance of Wood Decking after Five Years of Exposure: Verification of the Combined Effect of Wetting Ability and Durability

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Abstract: Wood is one of the most important construction materials, and its use in building applications has increased in recent decades. In order to enable even more extensive and reliable use of wood, we need to understand the factors affecting wood's service life. A new concept for characterizing the durability of wood-based materials and for predicting the service life of wood has recently been proposed, based on material-inherent protective properties, moisture performance, and the climate- and design-induced exposure dose of wooden structures. This approach was validated on the decking of a model house in Ljubljana that was constructed in October 2013. The decay and moisture content of decking elements were regularly monitored. In addition, the resistance dose D_{Rd}, as the product of the critical dose D_{crit}, and two factors taking into account the wetting ability of wood (k_{wa}) and its inherent durability (k_{inh}), were determined in the laboratory. D_{Rd} correlated well with the decay rates of the decking of the model house. Furthermore, the positive effect of thermal modification and water-repellent treatments on the outdoor performance of the examined materials was evident, as well as the synergistic effects between moisture performance and inherent durability.

Keywords: decay; decking; inherent durability; moisture performance; resistance model; service life

1. Introduction

Wood is one of the most important building materials. It is frequently used outdoors, where it is exposed to weathering and degradation. In Europe, wood-degrading fungi are the predominant reason for failures of wood used in outdoor applications [1,2]. Various solutions are used to prevent fungal decay and to achieve the desired service life, namely the use of biocides, wood modification, proper design and the use of domestic or imported durable wood species [3]. More recently, consumers are avoiding tropical wood species, so the importance of domestic wood species is increasing [4]. Unfortunately, the majority of European wood species do not provide a sufficiently high durability [5]. Particular emphasis is therefore placed on the utilization of domestic wood species [4].

Service life prediction of wooden objects is challenging, because the time during which a particular wooden structure will fulfil its function depends on a variety of factors, including the wood material used, the protection applied and various climate-related parameters [6]. In addition to the material-inherent durability, the moisture and temperature conditions inside the wood, i.e., the material climate, are the most important factors influencing the ability of fungi to decompose wood [2,7,8]. These two factors are influenced by the design of the construction, the exposure conditions and local climatic conditions (microclimate).

Building information modelling (BIM) software packages nowadays require information about service life and maintenance intervals for key materials used in the planning phase [9]. This information is required by the European Construction Products Regulations [10] and is needed for performance-based design [11]. The Eurocode [12] provides indicative design working lives of 10 years for temporary structures, 50 years for building structures and 100 years for monumental building structures and bridges. These values are set for objects regardless of the materials used. The expected service life of wooden structures under the given exposure conditions is a key parameter in the selection of materials for construction. Unfortunately, the current European standardization system provides neither information about expected service lives nor a methodology for the service life prediction of wood-based materials and components.

A new concept for characterizing the durability of wood-based materials and for predicting the service life of wood was recently proposed by Meyer-Veltrup et al. [13,14], based on the material-inherent protective properties, the moisture performance and the climate- and design-induced exposure dose of wooden structures. This approach has been successfully applied to untreated wood [15–17]. In this study, this modelling approach will be expanded to variously modified and preservative-treated woods.

2. Materials and Methods

2.1. Materials

This study investigated the performance of 19 different wood species and wood-based materials used in a decking application (Table 1). The selected materials were eight untreated wood species, Norway spruce (*Picea abies* (L.) H. Karst), European larch heartwood (*Larix decidua* Mill.), European beech (*Fagus sylvatica* L.), European ash (*Fraxinus excelsior* L.), Scots pine heartwood and sapwood (*Pinus sylvestris* L.), sweet chestnut (*Castanea sativa* Mill.) and European oak heartwood (*Quercus* sp.), and 11 materials that had been treated or modified in different ways. Although the authors are aware that not all these materials are traditionally used in decking, we have included them as reference wood species. In addition, the objective of this paper was not only to determine the performance of decking per se, but to validate the model [13]. In order to address this objective, materials of various durability have to be investigated.

Thermal modification (TM) was performed according to a commercial process (Silvapro®, Silvaprodukt, Ljubljana, Slovenia), with an initial vacuum in the first step of the treatment [18,19]. The modification was performed for 3 h at the target temperature (ranging between 210 °C and 230 °C, depending on the wood species). Impregnation was performed with a commercial copper–ethanolamine solution Silvanolin® (Silvaprodukt, Ljubljana, Slovenia), which consisted of copper, ethanolamine, boric acid and quaternary ammonium compounds [20]. The concentration of active ingredients and consequent retention met use class 3 (UC 3) [21] requirements. Impregnation was performed according to the full cell process in a laboratory impregnation setup. It consisted of 30 min vacuum (80 kPa), 180 min pressure (1 MPa) and 20 min vacuum (80 kPa). The same procedure was applied for the impregnation of wood with 5% commercially available natural wax dispersion with a solid content up to 50% by weight (Montax 50, Romonta, Germany) [22]. The acrylic surface coating Silvanol® Lazura B (Silvaprodukt, Ljubljana, Slovenia) was manually applied on the wood by brushing in two layers, with a 24-h drying time between them.

Table 1. Nineteen different investigated wood species and wood-based materials.

	Wood Species								Treatment			
	Norway Spruce (*Picea abies*)	Scots Pine – Sapwood (*Pinus sylvestris*)	Scots Pine – Heartwood (*Pinus sylvestris*)	European Larch (*Larix decidua*)	European Ash (*Fraxinus excelsior*)	European Beech (*Fagus sylvatica*)	Sweet Chestnut (*Castanea sativa*)	English Oak (*Quercus* sp.)	Thermal Modification	Impregnation with Natural Wax	Copper–Ethanolamine Impregnation	Water Borne Acrylic Surface Coating
Abbreviation	**PA**	**PS**	**PH**	**LD**	**FE**	**FS**	**CS**	**Q**	**TM**	**NW**	**CE**	**AC**
PA	PA											
PA–NW	PA									NW		
PA–AC	PA											AC
PA–CE	PA										CE	
PA–CE–NW	PA									NW	CE	
PA–TM	PA								TM			
PA–TM–NW	PA								TM	NW		
PA–TM–CE	PA								TM		CE	
PS		PS										
PH			PH									
LD				LD								
LD–TM				LD					TM			
FE					FE							
FE–TM					FE				TM			
FS						FS						
FS–TM						FS			TM			
FS–TM–NW						FS			TM	NW		
CS							CS					
Q								Q				

2.2. Outdoor Exposure

Figure 1 shows the wooden model house unit at the Department of Wood Science and Technology in Ljubljana, Slovenia (46°02′55.7″ N, 14°28′47.3″ E, elevation above sea level 293 m), where the in-service performance of decking elements was tested. This object has been used in several studies. The objective of this model house was to comprehensively assess the technical and aesthetic service life of wood. The aesthetic service life has been reported already [23], so this manuscript focusses on the technical service life only. The average temperature in Ljubljana is 10.4 °C, the annual precipitation is 1290 mm and the Scheffer Climate Index is 55.3. The test specimens, with a cross section of 2.5×5.0 cm^2, were exposed on the decking of the model house. At least seven samples of the wood material were exposed on the decking. The in-service testing started in October 2013 and the prime objective was to monitor the occurrence and development of decay (functional service life) and the moisture performance. Decay was visually evaluated annually and rated (0—no attack; 1—slight attack; 2—moderate attack; 3—severe attack; 4—failure) as prescribed by EN 252 [24]. Only the decking specimens were considered within this study.

Figure 1. Wooden model house unit in October 2013 at the beginning of the exposure. Yellow arrow is pointing north.

Moisture content (MC) during service life is one of the indicators of moisture performance. For MC measurements, resistance sensors were applied at 19 positions, with one pair of sensors for each wood material. They were linked to a signal amplifier (Gigamodule, Scanntronik, Zorneding, Germany) that enabled wood MC measurements between 6% and 60%. Pairs of stainless-steel screws with a diameter of 3.9 mm and length of 25 mm served as resistance electrodes, fastened in the middle of the tangential surface with a longitudinal distance of 32 mm between them. The screws were insulated with a universal heat-shrinking tube, except for the tip, which served as the point of measurement. Hence, the measurements take place approximately 10 mm below the surface. Sensors were located at least 20 cm from the cross section. The electrical resistance of the wood was measured every 12 h, and these data were used for calculating the wood's MC. Resistance characteristics for each material were determined as reported by Kržišnik et al. (in press) [25], using the methodology described by Brischke and Lampen [26] and Otten et al. [27].

2.3. Determination of Factors Describing Inherent Durability (k_{inh})

Agar block tests with pure fungal culture were used for the assessment of inherent durability. A decay test was performed according to a modified CEN/TS 15083–1 procedure [28]. Specimens (1.5 × 2.5 × 5.0 cm^3) made of 19 wood materials (Table 1) were conditioned in a standard laboratory climate (T = 25 ± 1; RH = 65 ± 2) and steam-sterilized in an autoclave before incubation with decay fungi; 350-mL experimental glass jars with aluminium covers and cotton wool with 50 mL of potato dextrose agar (DIFCO, Fisher Scientific, Franklin Lakes, NJ, USA) were prepared and inoculated with white rot fungi *Trametes versicolor* (L.) Lloyd (ZIM L057) and two brown rot fungi *Gloeophyllum trabeum* (Pers.) Murrill (ZIM L018) and *Fibroporia vaillantii* (DC.) Parmasto (ZIM L037). The fungal isolates originated from the fungal collection of the Biotechnical Faculty, University of Ljubljana, and are available to research institutions on demand [29]. Information regarding the origin of the fungal isolates and details about identification are available in the appropriate catalogue. One week after inoculation, two random specimens per jar were positioned on a plastic high-density polyethylene (HDPE) mesh, which was used to avoid direct contact between the samples and the medium. The assembled test glasses were then incubated at 25 °C and 80% relative humidity (RH) for 16 weeks, as prescribed by the standard. After incubation, specimens were cleaned from adhering fungal mycelium, weighed to the nearest 0.0001 g, oven-dried at 103 ± 2 °C, and weighed again to the nearest 0.0001 g to determine mass loss through wood-destroying basidiomycetes. Five replicate specimens for each of the selected materials/wood species were used in this test.

2.4. Determination of Factors Describing Wetting Ability (k_{wa})

For the assessment of wetting ability, a range of laboratory tests were performed. Tests was performed on five replicate samples (1.5 × 2.5 × 5.0 cm^3) of each material. One set of specimens was used for sorption tests, and the other for various immersion tests. The average relative values of the multiple test were combined to calculate the wetting ability factor.

Short-term capillary water uptake was carried out at 20 °C and 50 ± 5% RH, on a Tensiometer K100MK2 device (Krüss, Hamburg, Germany), according to a modified EN 1609 [30] standard, after conditioning at 20 °C and 65% RH until constant mass. The axial surfaces of the specimens were positioned to be in contact with the test liquid (distilled water), and their masses were subsequently measured continuously every 2 s for up to 200 s. Other parameters used were: velocity before contact with water 6 mm/min, sensitivity of contact 0.005 g, and depth of immersion 1 mm. The uptake of water was calculated in g/cm^2 on the basis of the final mass change of the immersed sample and the surface in contact with water.

Long-term water uptake was based on the ENV 1250–2 [31] leaching procedure. Before the test, specimens were oven-dried at 60 ± 2 °C until constant mass and weighed to determine the oven-dried mass. The dry wood blocks were placed in a glass jar and weighted down to prevent them from floating; 100 g of distilled water was then added per specimen. The mass of the specimens was determined after 24 h, and the MC of five replicate specimens was calculated. MC was determined gravimetrically, as a ratio between the retained water and the oven-dried mass of the specimens.

To determine the sorption properties of the samples, a water vapour uptake test in a water-saturated atmosphere with a drying process above freshly activated silica gel was performed. Specimens were oven-dried at 103 ± 2 °C until constant mass and weighed. The specimens were stacked in a glass climate chamber with a ventilator above distilled water. Specimens were positioned on mesh above the water using thin spacers [13]. After 24 h of exposure, they were weighed again and the MC was calculated. Specimens were then left in the same chamber for an additional three weeks until a constant mass was achieved. In addition to wetting, outdoor performance is also influenced by drying. After three weeks of conditioning, most specimens were positioned above freshly activated silica gel for 24 h in a closed container, and the MC of the specimens was calculated according to the procedure described by Meyer-Veltrup et al. [13]. Five replicate specimens were used for this analysis.

2.5. Factor Approach for Quantifying the Resistance Dose D_{Rd}

A modelling approach was applied according to Meyer-eltrup et al. [13] and Isaksson et al. [32] in order to predict the field performance of the examined materials. The model describes climatic exposure and the resistance of the material. The acceptability of the chosen design and material is expressed as follows:

$$\text{Exposure} \leq \text{Resistance}. \tag{1}$$

The exposure can be expressed as an exposure dose (D_{Ed}), determined by daily averages of temperature and MC. The material property is expressed as the resistance dose (D_{Rd}) in days [d], with optimum wood MC and wood temperature conditions for fungal decay [33]:

$$D_{Ed} \leq D_{Rd}, \tag{2}$$

where D_{Ed} is the exposure dose [d] and D_{Rd} is the resistance dose [d].

The exposure dose D_{Ed} depends on the annual dose at a specific geographical location and several factors describing the effect of driving rain, local climate, sheltering, distance from the ground and detail design. Isaksson et al. [32] give a detailed description of the development of the corresponding exposure model. The present study focussed on the counterpart of the exposure dose, which is the resistance, expressed as resistance dose D_{Rd}. This is considered to be the product of the critical dose D_{crit} and two factors expressing the wetting ability of wood (k_{wa}) and its inherent durability (k_{inh}). The approach is given by Equation (3), according to Isaksson et al. [32] (Table 2):

$$D_{Rd} = D_{crit} \times k_{wa} \times k_{inh}, \tag{3}$$

where D_{crit} is the critical dose corresponding to decay rating 1 (slight decay), according to EN 252 [24], k_{wa} is a factor accounting for the wetting ability of the tested materials [-], relative to the reference Norway spruce, and k_{inh} is a factor accounting for the inherent protective properties of the tested materials against decay [-], relative to the reference Norway spruce. Namely, the wetting ability and inherent durability of the Norway spruce were set to 1. Materials with either of these values better than the one determined for Norway spruce have higher values overall, but limited to a value of 5.

Table 2. Description of key terms addressed in respective article.

Term	Description
k_{wa}	Factor describing the wetting ability of wood-based materials. Factor is expressed in relative values, relative to the wetting ability of the spruce.
k_{inh}	Factor describing the inherent durability of wood-based materials. Factor is expressed in relative values, relative to the inherent durability of the spruce.
D_{Rd}	Resistance dose reflects the material property and is expressed in days (d), with optimum wood MC and wood temperature conditions for fungal decay, before the first evidence of decay.
Rel. D_{Rd}	Relative resistance dose. Usually spruce is used as the normalisation factor.

Based on the results of the various moisture tests presented in this paper, the wetting ability factor k_{wa} was calculated. The methodology for the calculation of k_{wa} followed the Meyer-Veltrup procedure [13], except that the size of the specimens differed. The original model prescribes specimens ($0.5 \times 1.0 \times 10.0$ cm^3) that are of a different shape from that used in the present study ($1.5 \times 2.5 \times 5.0$ cm^3). Since the methodology is based on relative values, the sample size has a minor influence on the outcome. Results from durability tests were used to evaluate the inherent resistance factor k_{inh}, and both factors were used to determine the resistance dose D_{Rd} of the 19 wood materials examined in this study. Only basidiomycetes were applied to determine k_{inh} in this research. Terrestrial microcosm tests and in-ground durability tests were not performed, as prescribed by the original Meyer-Veltrup approach [13].

2.6. Dose–Response Model

A dose–response model for the fungal decay of wood in aboveground situations, as described in detail by Brischke and Meyer-Veltrup [34], was applied to the recorded material–climatic data (***MC, T***). For comparative analysis, the total dose D (= cumulative daily dose d over time) was determined. A moisture-induced dose component $\boldsymbol{d_{MC}}$ and a temperature-induced dose component d_T were therefore calculated based on the physiological needs of decay fungus and optimized on the basis of long-term field tests at several climatically different locations in Europe by Brischke and Rapp [7]. The model considers wood MC and T as the key parameters for fungal growth and decay and allows a daily dose between 0 for adverse conditions and 1 for favourable conditions. The two-dose components $\boldsymbol{d_{MC}}$ and $\boldsymbol{d_T}$ are calculated separately, as follows:

$$\boldsymbol{d_{MC} = 6.75 \times 10^{-10} MC^5 - 3.50 \times 10^{-7} MC^4 + 7.18 \times 10^{-5} MC^3 - 7.22 \times 10^{-3} MC^2 + 0.34 MC - 4.98};\ \text{if MC} \geq 25\% \quad (4)$$

$$\boldsymbol{d_T = -1.8 \times 10^{-6} T^4 + 9.57 \times 10^{-5} T^3 - 1.55 \times 10^{-3} T^2 + 4.17 \times 10^{-2} T};\ \text{if } 40\ ^\circ\text{C} > \text{T} > -1\ ^\circ\text{C}, \quad (5)$$

where $\boldsymbol{d_{MC}}$ is the moisture-induced daily dose (*d*), $\boldsymbol{d_T}$ is the temperature-induced daily dose (*d*), ***MC*** is the daily wood ***MC*** (%), and *T* is the daily average wood temperature (°C). To consider the impact of ***MC*** and temperature on decay, a weighting factor (a) was added to calculate the daily dose (*d*), as follows. The following conditions were considered: the daily dose (d) of days with a temperature above 40 °C, with a temperature below −1 °C, or with an ***MC*** below 25% was set to 0:

$$\boldsymbol{d = ((a \times d_T) + d_{MC})/(a + 1)};\ \text{if } d_T > 0 \text{ and } d_{MC} > 25\%, \quad (6)$$

where ***d*** is the daily dose (*d*) and a = 3.2 is the weighting factor of the temperature-induced daily dose component $\boldsymbol{d_T}$.

For n days of exposure, total exposure dose is given by:

$$d(n) = \sum_1^n d_i = \sum_1^n (f(d_T(T_i), d_{MC}(MC_i))), \quad (7)$$

where T_i is the average temperature (°C) and MC_i is the average moisture content for day (%).

Decay is initiated when the accumulated dose reaches a critical level. The dose is thus defined as a material–climate index and the response is considered to be the mean decay rating according to EN 252 [24], or the resulting decay rate (i.e., the decay rating per year). Expected service lives were estimated according to Equation (8) using a mean decay rating 2 (moderate decay) as a limit state. Any decay rating above this limit state means that serviceability is no longer given. A critical dose d_{crit} = 670 (for white and soft rot) and d_{crit} = 356 (for brown rot) was needed to reach the limit state.

$$ESL = \frac{d_{crit}}{d_a}, \quad (8)$$

3. Results and Discussion

3.1. Resistance Dose Based on Inherent Durability and Wetting Ability

Our data clearly confirm that the resistance of different wood species and treated or modified wood products in aboveground applications is primarily dependent on the degree of inherent material resistance against fungal decay (k_{inh}), but also on the wetting ability (k_{wa}) of the particular material. The material resistance dose D_{Rd} is a product of both factors and the respective critical dose D_{crit}, as summarized for all materials in Table 3. Since k_{inh} and k_{wa} are normalized to Norway spruce, the relative material resistance dose (rel. D_{Rd}) of Norway spruce is 1.0. The rel. D_{Rd} of Beech (FS) is 0.88, while the rel. D_{Rd} of Ash (FE; 1.22) and Scots pine sapwood (PS; 1.32) are slightly higher. The highest relative D_{Rd} among the nontreated wood species was determined for Oak (Q; 5.92) and Sweet chestnut (CS; 6.40) (Table 3). Rel. D_{Rd} of Oak (Q; 5.92) and Scots pine heartwood (PH; 2.97) were similar to those reported by Meyer-Veltrup et al. (2017) (Q; 5.10; PH; 2.75). This confirms the robustness and reliability of the approach. However, the main objective of the study reported by Meyer-Veltrup et al. [13] was to determine the rel. D_{Rd} of nontreated wood. In contrast, this study focused on the comparison of the performance and validation of the methodology with wood treated with biocides (copper–ethanolamine) or water repellents (wax) and (thermally) modified wood.

Table 3. Material resistance dose D_{Rd} and MC data for k_{inh} and k_{wa} calculated based on the Meyer-Veltrup et al. (2018) methodology [14].

Material	k_{inh}	k_{wa}	D_{Rd}	rel. D_{Rd}
PA	1.0	1.0	325	1.00
PA–NW	1.3	2.4	977	3.01
PA–AC	1.1	2.9	1009	3.10
PA–CE	5.0	1.5	2356	7.25
PA–CE–NW	5.0	2.9	4705	14.48
PA–TM	3.1	1.8	1763	5.43
PA–TM–NW	3.4	2.5	2698	8.30
PA–TM–CE	5.0	1.2	1978	6.09
PS	1.1	1.2	430	1.32
PH	2.5	1.2	966	2.97
LD	1.6	1.9	1002	3.08
LD–TM	2.7	3.2	2746	8.45
FE	1.2	1.0	396	1.22
FE–TM	2.9	1.9	1771	5.45
FS	0.9	1.0	284	0.88
FS–TM	2.6	2.1	1773	5.46
FS–TM–NW	3.3	2.6	2815	8.66
CS	5.0	1.3	2080	6.40
Q	3.9	1.5	1923	5.92

The treatment of Norway spruce wood with water repellents (wax) had a positive effect on the wetting ability. The factor k_{wa} increased from 1.0 (reference spruce) to 2.4 for wax-treated wood. A similar effect was noted for Norway spruce wood when applying an acrylic coating (PA–AC; 2.9). As a consequence, the rel. D_{Rd} of wax-treated Norway spruce (PA–NW; 3.01) was similar to that of Scots pine heartwood (PH; 2.97) or larch heartwood (LD; 3.08) (Table 3). As expected, the highest inherent durability against fungal decay was found for copper–ethanolamine-treated wood. Biocidal ingredients (copper, boron and quaternary ammonium compounds) effectively prevent decay [35,36]. The respective factor k_{inh} increased up to the defined maximum of 5.0. When the wetting ability of copper-treated wood was improved with a wax treatment (PA–CE–NW), rel. D_{Rd} reached the highest value (14.48). The positive effect of water repellents on the outdoor performance of preservative-treated wood has been shown previously by Obanda et al. [37] and Lesar et al. [38], who showed that hydrophobic treatments reduced the water uptake and limited leaching of active ingredients.

Thermal modification has a positive effect on both the inherent protective properties against fungal decay and the wetting ability. This is in line with findings from previous studies [39]. The highest improvement was observed for larch heartwood. The rel. D_{Rd} increased from 3.08 to 8.45 (Table 3). Larch was modified under fairly mild conditions, so the treatment presumably did not degrade biologically active extractives but had a positive effect on the wetting ability [40]. Thermal modification combined with a wax treatment resulted in the second highest rel. D_{Rd}, for wax-treated and thermally modified Beech (FS–TM–NW, 8.66). Apparently, wax treatment and thermal modification act synergistically. Thermal modification improves the durability and sorption properties of wood, while wax treatment improves its resistance against liquid water uptake [22].

3.2. Moisture Performance of Decking

Moisture dynamics are an essential parameter for the overall outdoor performance of wood, in addition to the inherent durability. In order to present the data more clearly, we have decided to summarize the data and present them in Table 4 and Figure 2. In addition to average and extreme data, the percentage of wet days was found to be an important parameter as well. The term "wet day" refers to days when the wood MC exceeds the predefined threshold of 25% while the temperature stays between 4 °C and 40 °C. Respective wood moisture measurements were performed in the centre of the wood samples, approximately 10 mm below the surface. It should be considered that the MC on the surface of the wood might have been even higher, as the surface is directly exposed to weathering. In addition, the authors are aware that different thresholds could be taken into account, depending on the wood sorption properties. For example, the threshold for thermally modified wood might be lower than that for beech. In general, the 25% wood moisture threshold is considered to be the minimum MC required for fungal decay on the majority of untreated woods from temperate regions. This value represents a conservative fibre saturation (FSP) value. However, it should be considered that lower threshold values are possible if fungi can transport water from a neighbouring moisture source to the wood [41,42]. In addition, it is generally accepted that fibre saturation is a range rather than a fixed threshold [43] and varies between 22% and 36% [42,43], depending on the wood species. In modified wood these values can be considerably lower.

Table 4. Measurements of moisture content (MC) of wood decking at the wooden model house unit. Calculated median and average values of all measurements, and the number and percentages of the measurements with MC equal to or higher than 25% are shown. Measurements were performed in the period between 11.4.2014 and 26.11.2018 (n = 3381).

Material	Average MC (%)	Median MC (%)	No. of meas. MC > 25%	% of meas. MC > 25%
PA	27.9	21.7	1.075	31.8%
PA–NW	20.1	17.8	838	24.8%
PA–AC	18.5	16.9	672	19.9%
PA–CE	16.9	15.9	247	7.3%
PA–CE–NW	20.1	18.9	242	7.2%
PA–TM	25.4	25.5	1.764	52.2%
PA–TM–NW	16.1	12.4	643	19.0%
PA–TM–CE	19.1	14.0	927	27.4%
PS	49.4	55.3	2.841	84.0%
PH	19.5	15.9	844	25.0%
LD	19.3	17.8	723	21.4%
LD–TM	13.3	12.0	6	0.2%
FE	14.6	14.0	94	2.8%
FE–TM	17.5	16.8	779	23.0%
FS	27.3	25.7	1.747	51.7%
FS–TM	18.9	19.5	811	24.0%
FS–TM–NW	17.7	14.0	771	22.8%
CS	17.3	15.6	608	18.0%
Q	16.6	15.8	370	10.9%

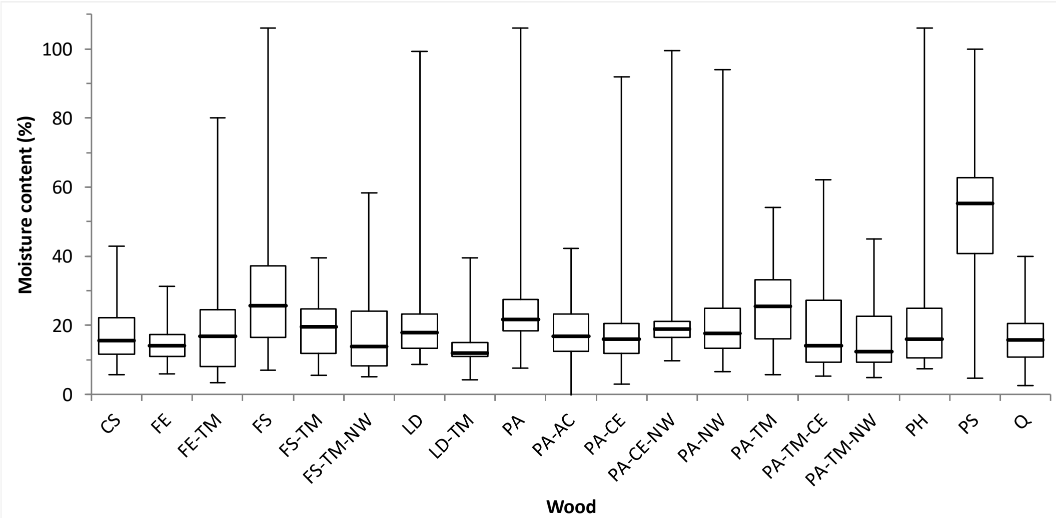

Figure 2. Distribution of moisture content in various wood-based materials exposed as decking of the model house in Ljubljana in the period between 11 April 2014 and 26 November 2018 (n = 3381).

Median values are more indicative than average values, since resistance-based measurements are fairly inaccurate at higher MC, above 50% to 60%, depending on the wood species. We will focus on median values below. The highest median value was reported for Scots pine sapwood. The median MC was 55.3%, with 84.0% of the measurements being above the threshold of 25%. The low moisture performance of Scots pine sapwood was expected and has been reported, for instance, by Žlahtič-Zupanc et al. [44]. The second-highest median MC was for beech wood decking elements. This coincides with its good permeability [4]. Surprisingly, thermally modified wood did not exhibit a good moisture performance. However, the moisture performance of freshly modified wood was fairly good (Table 3). The excellent moisture performance of freshly thermally modified wood has often been reported [39]. However, as can be seen from the data presented in Table 4, exposure under use class 3.2 [21] (above ground, exposed to weathering) conditions apparently led to an increased water uptake [44–46]. The drop in moisture performance can be ascribed to the formation of microcracks, bacterial degradation of pit membranes and blue staining [47]. The combination of thermal modification and wax treatment considerably improved the moisture performance of decking elements (Table 4, Figure 3, and Figure 4). Wax formed a hydrophobic layer on the surface that limited the penetration of liquid water into the wood [22]. Wax-treated, thermally modified Norway spruce wood thus exhibited the lowest median MC, 12.0%. A similar but less prominent effect was also observed for wood coated with acrylic coatings. Due to their anatomical features (tyloses, aspirated pits, etc.), heartwoods (PH, Q, and CS) revealed a fairly good moisture performance (Figure 2).

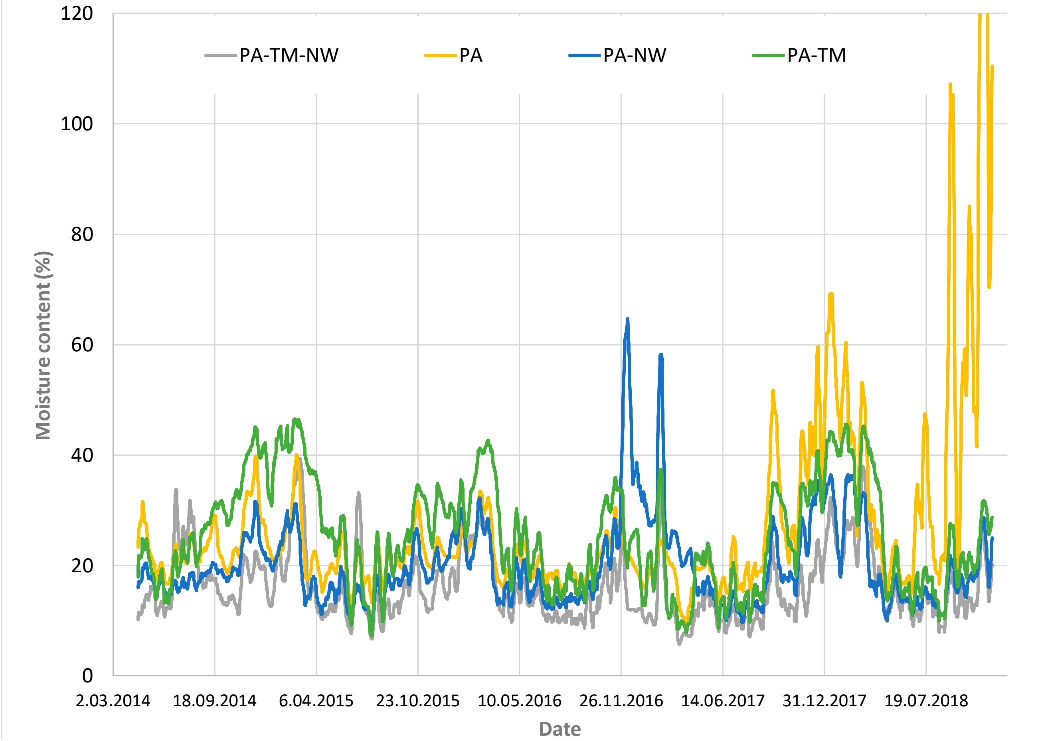

Figure 3. MC of spruce (PA), thermally modified spruce (PA–TM), wax-treated spruce (PA–NW) and wax-treated thermally modified spruce (PA–TM–NW) decking of model house in Ljubljana in the period between 11 April 2014 and 26 November 2018. Plots displayed are moving averages of 20 measurements.

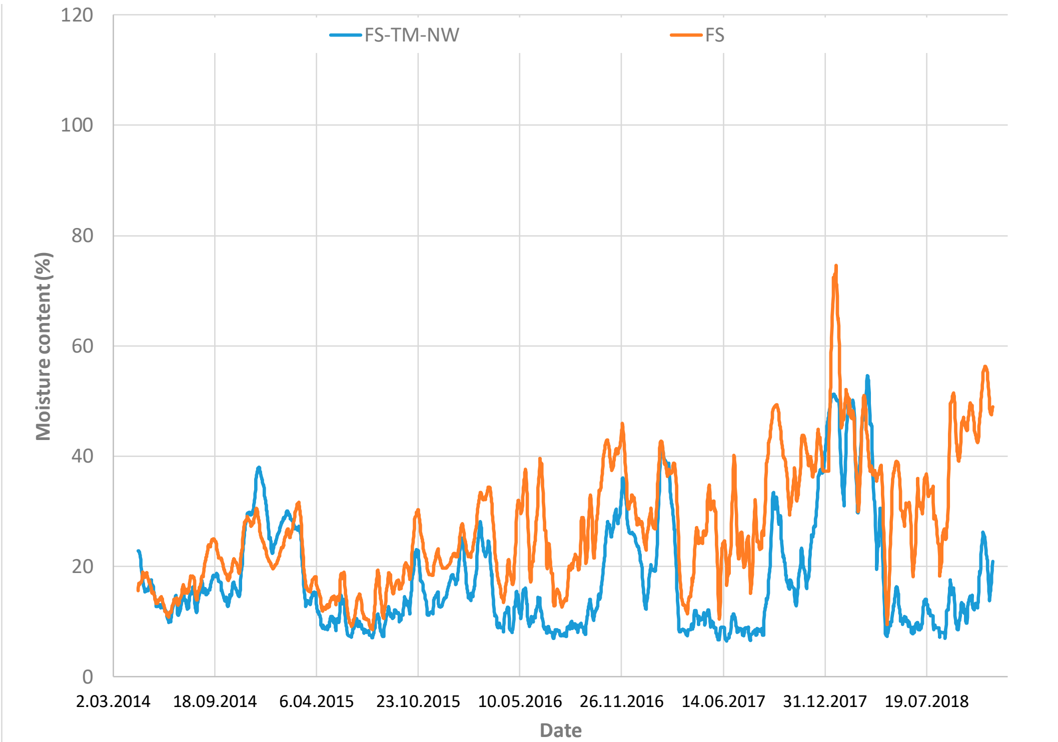

Figure 4. MC of beech (FS) and wax-treated, thermally modified beech (FS–TM–NW) decking of model house in Ljubljana in the period between 11 April 2014 and 26 November 2018. Plots displayed are moving averages of 20 measurements.

The high moisture performance of wax-treated, thermally modified wood (PA–TM–NW; FS–TM–NW) is evident from Figures 4 and 5. At almost any time, the MC of the thermally modified and wax-treated wood was significantly below that of the untreated reference. This is further evidence of the synergistic effect of wax and thermal modification. However, from Figures 3 and 4 it can be seen that the moisture performance of untreated spruce wood and untreated beech wood decreased after a certain period of exposure. We assume that the decreased moisture performance may be associated with fungal decay. Fungi open up new voids in the cell matrix, which results in better permeability [48]. One possible explanation for increased electrical conductivity (hence, increased MC) could be the consequence of fungal colonisation, due to the presence of electrolytes excreted by the fungi. However, recent results clearly indicate that the increased moisture content of decayed wood cannot be ascribed to the changed relationship between electrical resistance and MC, as reported by Brischke and coworkers [49].

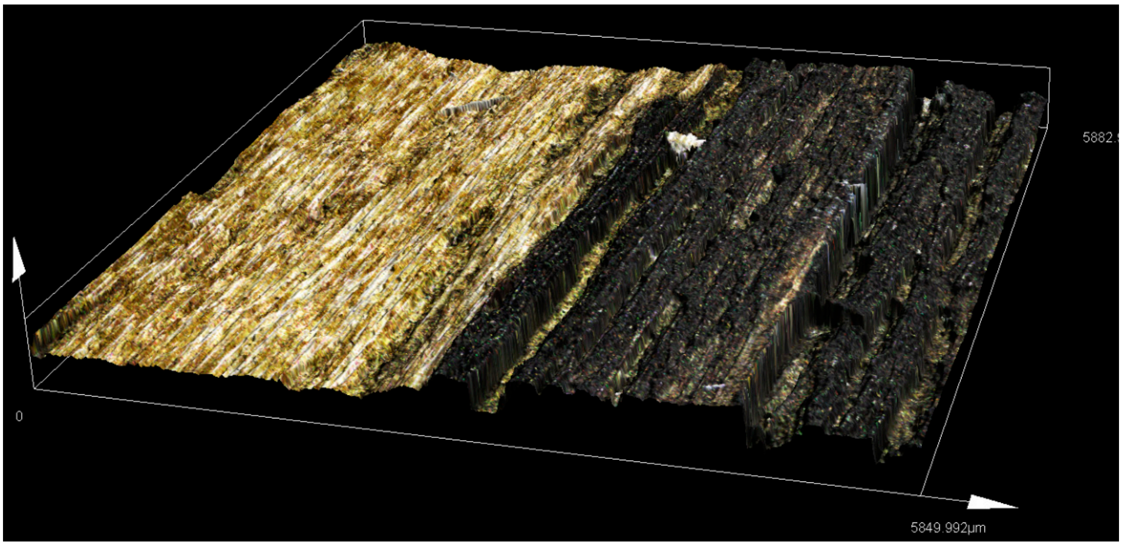

Figure 5. Laser confocal image of the surface of the spruce wood coated with an acrylic coating after five years of exposure. The remaining coating on the decking element is brown, while parts where the coating was removed remain lighter. The surface was severely damaged. Field of view 5850 × 5882 µm.

In addition to the median MC, the number of measurements with MC equal to or higher than 25% is important, since it accounts for the time component (time of wetness). This value provides information about the MC of wood for which conditions are suitable for fungal decay. However, it should be noted that, although the 25% threshold might be suitable for nonmodified wood, recent studies have indicated that the minimum MC required for the decay of thermally modified wood is lower than that of untreated wood [50].

3.3. Decay Rate in the Decking of the Model House

During the first year of exposure, there was no decay to the decking of the model house in Ljubljana. In the second year, the first signs of decay developed on Norway spruce (PA), beech (FS) and Scots pine sapwood (PS). This is in line with findings from previous studies [13,51]. One of the possible reasons for the lesser decay of Scots pine sapwood could be associated with pinosylvin. This extract in pine sapwood causes a delay in spore germination [52]. Decay occurred in the third year. In addition, decay developed on coated Norway spruce (PA–AC), Scots pine heartwood (PH), Ash (FE), wax-treated Norway spruce (PA–NW) and larch (LD). In the fourth year, the first signs of decay also appeared on oak (Q). After four years of exposure, only sweet chestnut (CS), copper-treated spruce (PA–CE; PA–CE–NW) and thermally modified wood remained without visible signs of decay (Table 5). After five years of exposure, Norway spruce wood was completely degraded, followed by beech and

Scots pine sapwood. Fairly prominent decay was noted on Norway spruce coated with acrylic coatings. It must be noted that the acrylic coating was not maintained, so its initially positive effect turned negative, as previously reported by Isaksson et al. [53]. Coating limited liquid penetration in the first stages, but later on when cracks form coatings limit the drying of the wood, which enables fungal development below the acrylic coating. First, cracks formed; later, flakes of coating appeared as well (Figure 5). Brown rot fungi caused the majority of decay on softwood species, e.g., fruiting bodies of *Gloeophyllum* sp. were found. On hardwoods, white rot was more dominant. Fruiting bodies of *Trametes versicolor* were frequently found.

Table 5. Decay rating of the decking elements determined according to EN 252 [24].

Material	Average Decay Rating of the Decking Elements				
	2014	**2015**	**2016**	**2017**	**2018**
PA	0.0	1.0	2.4	3.7	4.0
PA–NW	0.0	0.0	0.2	1.1	1.9
PA–AC	0.0	0.0	0.8	1.6	2.8
PA–CE	0.0	0.0	0.0	0.0	0.0
PA–CE–NW	0.0	0.0	0.0	0.0	0.0
PA–TM	0.0	0.0	0.0	0.0	0.0
PA–TM–NW	0.0	0.0	0.0	0.0	0.0
PA–TM–CE	0.0	0.0	0.0	0.0	0.2
PS	0.0	0.6	1.2	2.2	3.1
PH	0.0	0.0	0.6	1.5	2.3
LD	0.0	0.0	0.6	1.3	1.6
LD–TM	0.0	0.0	0.0	0.0	0.1
FE	0.0	0.0	1.0	1.4	2.1
FE–TM	0.0	0.0	0.0	0.0	0.0
FS	0.0	1.0	2.2	3.1	3.7
FS–TM	0.0	0.0	0.0	0.0	0.0
FS–TM–NW	0.0	0.0	0.0	0.0	0.0
CS	0.0	0.0	0.0	0.0	0.0
Q	0.0	0.0	0.0	0.5	0.9

3.4. Modelling Decay Rates of Treated and Modified Wood

A new concept for characterizing the durability of wood-based materials and predicting the service life of wood was recently proposed by Meyer-Veltrup et al. [13,14], based on the material-inherent protective properties, the moisture performance and the climate- and design-induced exposure dose of wooden structures. This approach has been successfully applied to untreated wood [15–17] and was validated on historical objects from WWII made of spruce wood [54].

The main objective of this study was to validate the model approach of Meyer-Veltrup et al. [13], which has been developed and validated for untreated wood of numerous different species. The need to consider both the inherent protective properties and the wetting ability of a wood-based material for service life prediction becomes evident from Figure 6, in which the relationship between the total (moisture- and temperature-induced) exposure dose and the decay rate of the various decking materials is shown. The two parameters were not well correlated, because the effect of the material-inherent properties of the different materials remained unconsidered.

In contrast, the material resistance dose D_{Rd} correlated well with the decay rates of the decking, as shown in Figure 7. By also applying the effect of inherent protective properties, e.g., due to active ingredients of wood preservatives, the material resistance is represented in a more comprehensive manner compared to solely using temperature and MC data for establishing an exposure dose. Furthermore, the positive effect of thermal modification and water-repellent treatments on the outdoor performance of the examined materials is considered, as well as the most likely synergistic effects between moisture performance and inherent durability.

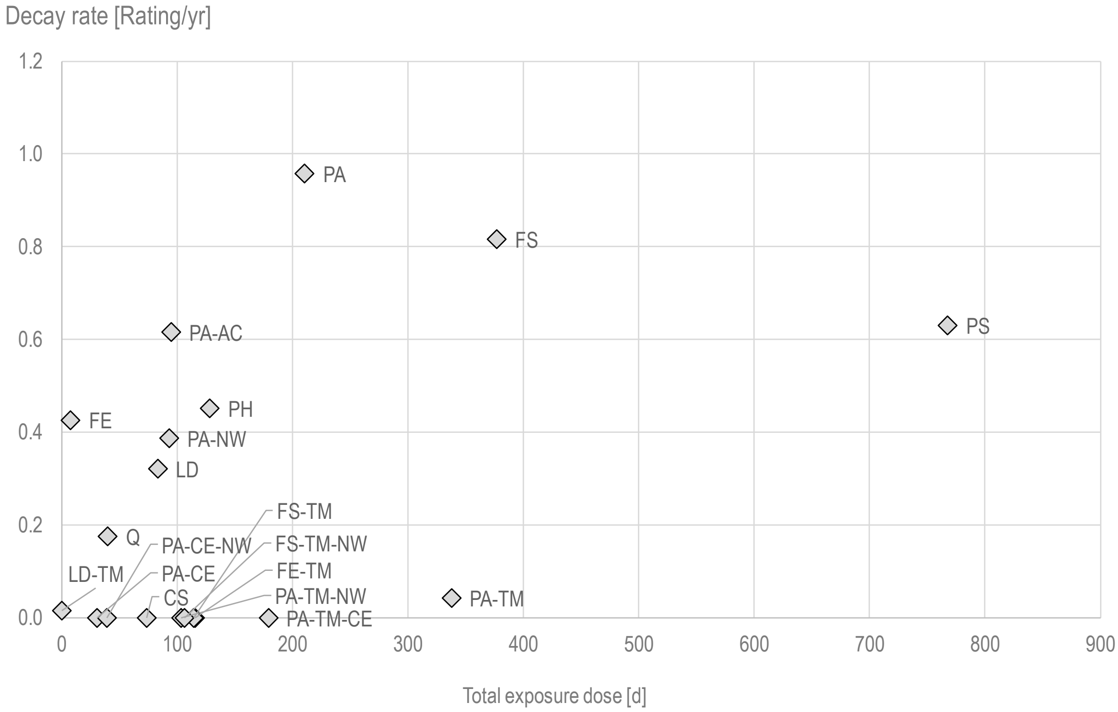

Figure 6. Mean decay rate of decking at the model house in Ljubljana versus the total exposure dose.

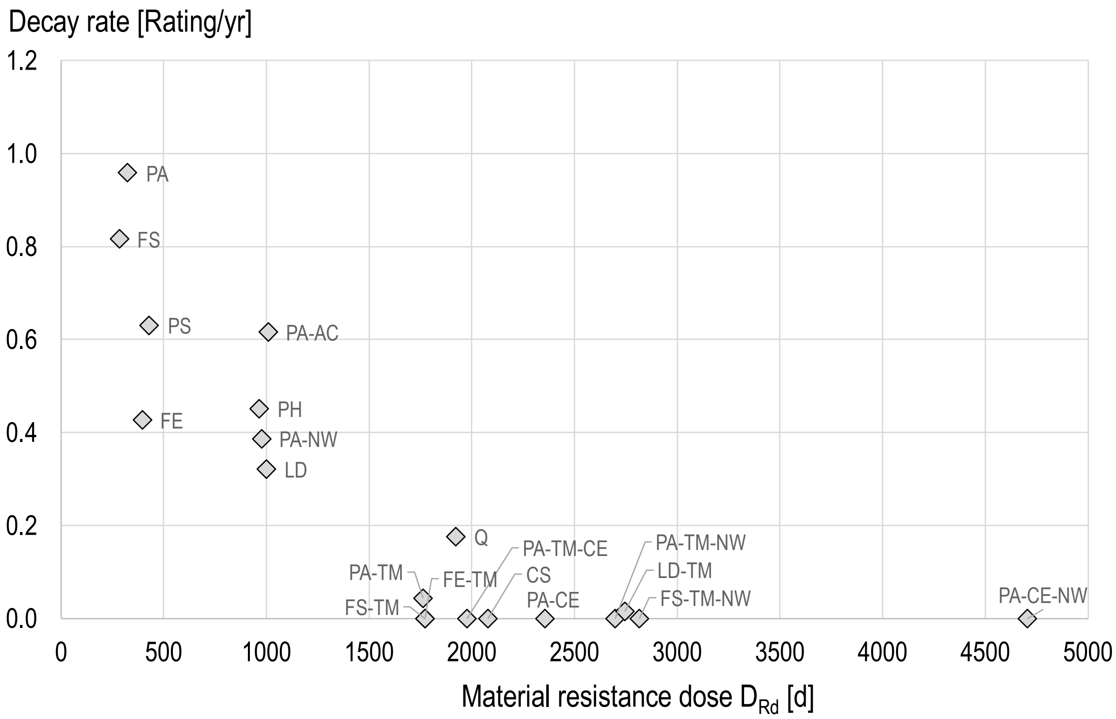

Figure 7. Mean decay rate of the decking at the model house unit in Ljubljana versus the material resistance dose D_{Rd}.

Although the preservative-treated decking, in particular, shows no decay yet, the model fits the decay rates well in general. However, to better distinguish between different highly durable materials, it might be necessary to collect further long-term data (i.e., field test data for an exposure time of several decades) of the latter.

4. Conclusions

The results clearly show that the dose D_{Rd} was well correlated with the decay rates of the decking of the model house. The model approach, taking into account the material-inherent protective properties, the moisture performance and the climate- and design-induced exposure dose of wooden structures, also proved to be accurate for assessing modified and preservative-treated wood. Furthermore, the positive effect of thermal modification and water-repellent treatments on the outdoor performance of the examined materials was evident, as well as a synergistic effect between moisture performance and inherent durability.

Since the number of long-term field tests for which corresponding lab decay and moisture dynamic tests has been performed is scarce, it might be meaningful to sample from longer-running tests for further subsequent validation of the model approach. This might also work for structures in service, with a known service life, that show the first signs of decay.

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