Quantitative design guideline for wood in outdoor above ground applications

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Section 2 **Test methodology and assessment**

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ABSTRACT

This paper describes the background and principles behind an engineering design guideline for wood in outdoors above ground applications, i.e. use class 3 according to EN 355 (1992). The guideline has been developed in the European research project Woodexter and can be seen as a first prototype for a quantitative design tool in the area of wood durability. It is based on a defined limit state for onset of decay under a reference service life of 30 years. Onset of decay is defined as a state of fungal attack according to rating 1 in EN 252 (1989). The approach is to determine the climate exposure as a function of geographical location, local exposure conditions, sheltering, ground distance and detail solution. The exposure is then compared with the material resistance defined in five classes and the design output is either OK or NOT OK. The present version of the guideline only covers applications for decking and cladding. The data included in the guideline have partly been estimated with the help of a dose-response model for decay, which here was used to derive relative measures of decay risk between different locations and between different detail solutions. Some other elements have however been estimated in a semi-subjective manner based on expert opinions as well as experience from field testing. The guideline has been verified by a number of reality checks, which show that the output from the tool agrees reasonably well with documented experience from practice. The guideline has also been presented in a computerized Excel format, which makes practical use convenient. It is believed that many building professionals will appreciate a tool within the area of wood durability which has an approach similar to other design tasks in building projects. An advantage is that in applying the method the designer will go through a check list where he/she becomes aware of the importance of appropriate detailing solutions. In addition the user will have to think about the target service life as well as the consequences of non-performance in the design of a facility.

Keywords: Service life design, limit state, exposure, resistance, reality checks

1. INTRODUCTION

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.

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 (2000). 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.

Empirical type service life design models for wood have been developed in a national research program in Australia, see e.g. Wang et al (2007). It is mainly based on a large field testing program at different sites in Australia with wood species typical for Australia. Methods for performance based durability design are much more developed for e.g. concrete with a firm foundation in physical models; see e.g. Sarja & Vesikari (1996).

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.

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 related to a prescribed limit state, which for the present application could be onset of fungal decay, alternatively a specified acceptable degree of decay. The performance requirement in a certain situation could e.g. be that 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 this approach is that exposure can be described as a function of global and local 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.

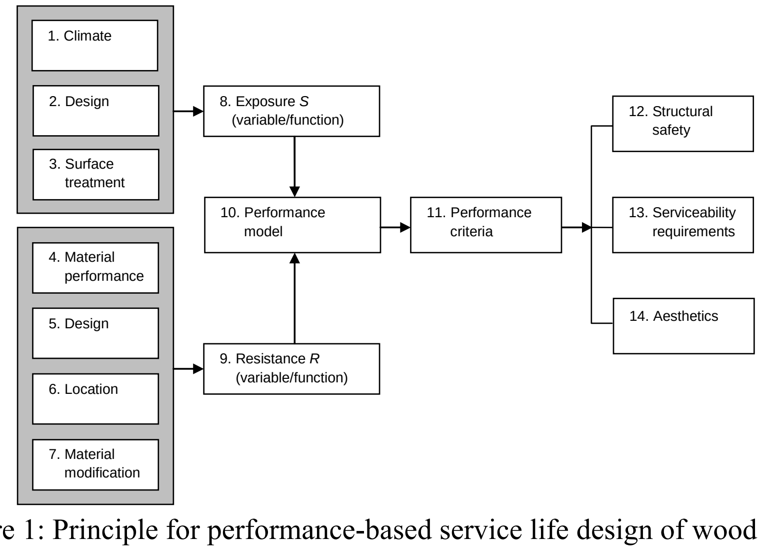


Figure 1: Principle for performance-based service life design of wood elements.

As illustrated in Fig. 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. Various types of limit states may be derived from this. A key element is the performance model, which must be available if a quantitative evaluation shall be possible.

The present paper describes a newly developed service life design tool based on these principles for wood in exterior applications above ground (use class 3 according to EN 335, 1992). The design tool will be presented to users in the form of a simple guideline, Thelandersson et al (2011). The principles behind the guideline and its basic features are described in the present paper.

2. BASIC PRINCIPLES FOR THE GUIDELINE

The present version of the design tool can be seen as a prototype, developed in a Pan-European context, and it may have to be adapted or developed further on a regional or national level, considering e.g. special climate conditions and building traditions. The design tool is mainly focussed on two special applications, cladding and decking. The degradation mechanism considered is the risk for fungal decay.

The design is based on a defined limit state, corresponding to onset of decay, under a reference service life assumed to be 30 years. Onset of decay is defined as a state of fungal attack according to rating 1 ("slight attack") in EN 252 (1989).

According to the principles illustrated in Fig. 1 the design condition on the engineering level is quantitatively formulated in the following way

$$I_{Sd} = I_{Sk}\gamma_d \leq I_{Rd} \qquad (1)$$

where I_{Sk} is a characteristic exposure index, I_{Rd} is a design resistance index and γ_d depends on consequence class. The consequence class refers to the expected consequences if the limit state is violated. If the condition in Eq. 1 is fulfilled, then the design is accepted, otherwise it is not accepted.

The definitions of I_{Sk} and I_{Rd} are related to the following reference situations

- Exposure situation: The exposure to outdoor temperature, relative humidity and rain of a horizontal member with no moisture traps, is used to define a basic exposure index depending on geographical location.
- Material: Norway spruce (*Picea abies*), uncoated, corresponds to I_{Rd} = 1,0
- Consequence class 3 (most severe) corresponds to γ_d = 1,0

Since the reference exposure is a favourable design condition for avoiding decay, things normally get worse when accounting for moisture traps and various design details. This is considered by various exposure factors described below.

The consequence class depends on the severity of consequences in case of non-performance and is described by the factor γ_d as shown in Table 1. The idea is that the user shall consider the consequences and select a level according to the particular situation at hand.

Table 1. Safety factor γ_d as a function of consequence class

Consequence class	γ_d
1 Small (e.g. cases where it may be acceptable to replace a limited number of wood elements in a structure if decay occurs)	0,8
2 Medium (e.g. cases where the expected consequences are of essential economic and practical nature)	0,9
3 High (e.g. wood elements in load-bearing structures where failure may imply risk for humans)	1

3. PERFORMANCE MODEL

A performance model is needed to evaluate whether the limit state is reached or not under a given micro-climate exposure. For this purpose a dose-response model is used, where the dose is given as a function of wood moisture content and temperature. Starting with a time series of interconnected daily average values of moisture content u_i and temperature T_i for day *i* the accumulated dose D_N for *N* days can be calculated from

$$D_N = \sum_{i=1}^{N} D_u(u_i) \cdot D_T(T_i) \tag{2}$$

where

$D_u(u_i)$ is the dose related to moisture content (kg/kg) and

$D_T(T_i)$ is the dose related to temperature (°C) given by

$$D_u(u_i) = \begin{cases} (u_i / 0.3)^2 & \text{for } u_i \leq 0.30 \\ 1 & \text{for } u_i > 0.30 \end{cases} \tag{3a}$$

$$D_T(T_i) = \begin{cases} 0 & \text{for } T_i < 0 \\ T_i / 30 & \text{for } 0 \leq T_i \leq 30 \\ 1 & \text{for } T_i > 30 \end{cases} \tag{3b}$$

These relations are illustrated graphically in Fig. 2. The formulation is a simplified and modified version of the dose-response model proposed by Brischke & Rapp (2008), which was developed on the basis of results from double layer field tests performed at a number of different sites all over Europe, Brischke (2007). The materials used in these tests were Pine sapwood as well as Douglas fir heartwood. The duration of the tests was of the order 8 years with continuous measurements of moisture content and temperature at each site during the whole test period. The test specimens were regularly evaluated with respect to decay according to EN252 (1989). The tests show that the time in calendar days until onset of decay is of the order three times longer for Douglas Fir than for Pine sapwood. One of the main reasons for this is that Douglas fir heartwood is much more resistant to moisture uptake than pine sapwood.

The performance model is based on the simple fact that the fungi spores need favourable moisture and temperature conditions during a sufficiently long period of time in order to germinate and grow. It is therefore reasonable to assume that variable moisture and temperature conditions which occur in practical situations should to some degree have an inhibiting effect on the biological process.

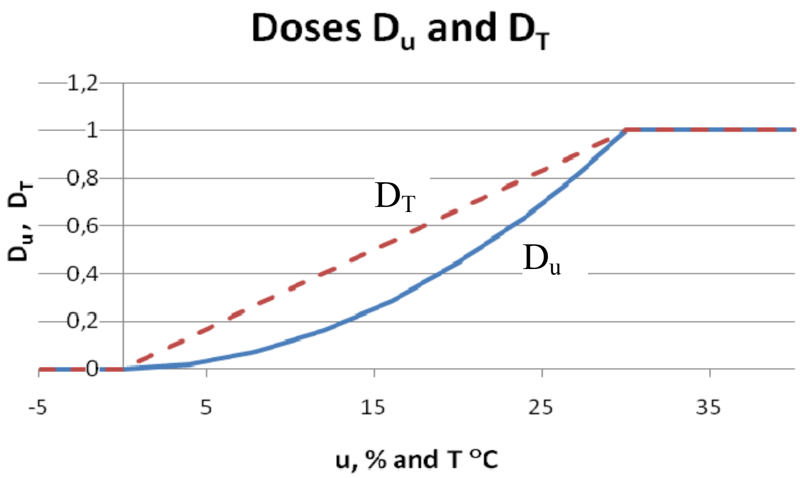


Figure 2. Illustration of the dose-response model described by Eqs. 2 and 3.

For instance, if the organisms are subjected to periods of dry and cold conditions the biological development will stop and may also be reversed. Such a plausible "restraint mechanism" is so far not included in the performance model, due to lack of data to quantify the effect. This must be borne in mind when interpreting the results from the model. This "restraint" effect is probably one of the reasons why the resistance for Douglas fir mentioned above is significantly larger than for Pine sapwood. In the double layer tests, the pine specimens were more or less above the fibre saturation point during the whole test period, while the Douglas Fir specimens oscillated regularly between wet and dry conditions.

The performance model proposed above and illustrated in Fig. 2, is greatly simplified and somewhat unrealistic since the dose should be zero for moisture contents lower than 20-25 %. The present formulation is however chosen to give a non-zero measure also for dry situations so that the margin to critical states can be estimated with the model. For this reason and due to other uncertainties mentioned above, the model in its present version should only be used in a relative sense, i.e. to compare different exposure situations with each other. This is how it has been utilized to derive the data included in the present version of the guideline. Further information about the performance model and comparisons with other models concerning relative decay hazard can be found in Brischke et.al. (2011).

4. CHARACTERISATION OF EXPOSURE

4.1 General

The exposure index I_{sk} can be conceived as a “characteristic (safe) value” accounting for uncertainties. The exposure index is assumed to depend on

- Geographical location determining global climate
- Local climate conditions
- The degree of sheltering
- Distance from the ground
- Detailed design of the wood component
- Use and maintenance of coatings

The exposure index is determined in the guideline from

$I_{sk} = k_{s1} \cdot k_{s2} \cdot k_{s3} \cdot k_{s4} \cdot I_{so} \cdot c_a$ (4)

where

I_{so} = basic exposure index depending on geographical location/global climate

k_{s1}= factor describing the effect of local climate conditions (meso-climate)

k_{s2}=factor describing the effect of sheltering

k_{s3}=factor describing the effect of distance from ground

k_{s4}=factor describing the effect of detailed design

c_a = calibration factor to be determined by reality checks and expert estimates

The exposure index intends to describe the severity in terms of combined moisture and temperature conditions favourable for development of decay fungi.

4.2 Characterisation of basic exposure

The effect of climate variability on risk for decay of wood exposed outdoors was investigated using the performance model described in Section 3. The climate data used was obtained with the program Meteonorm (www.meteonorm.com), Remund & Kunz (1995). 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 modelled by interpolation between different stations. For the present purpose, hourly values of temperature, relative humidity and rain were chosen as output values. In the performance model, however, daily values are used. Therefore, hourly values of temperature and relative humidity are averaged and hourly rain is accumulated to daily values.

For application of the performance model, wood moisture content is calculated from the global climate data. Moisture content depends on the relative humidity ϕ and is calculated as, see Tveit (1966):

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

$$u_{01}(t_i) = u\left[\bar{\phi}(t_i)\right] \quad (5b)$$

$$\bar{\phi}(t_i) = \frac{\phi_1(t_{i-1}) + \phi_1(t_i)}{2} \quad (5c)$$

The daily average moisture content $u_{01}(t_i)$ in equilibrium with relative humidity is estimated on the basis of the average value of relative humidity ϕ for two full days (Eqs. 5b and c). This is assumed to account for a certain delay corresponding to diffusion into the wood.

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 Van den Bulcke et al. (2009) it 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.

For each day i with rain, the daily average moisture content $u_1(t_i)$ is calculated according to Eq. 6 where k_r is the relative increase of moisture content due to rain. According to data in Van den Bulcke et al. (2009), k_r is in the range of 0.6 to 1.0, and the value 0.8 is used here.

$$u_1(t_i) = u_{01}(t_i)[1 + k_r] \tag{6}$$

At the end of each rain period, the parameters t_r and $t_d = a \cdot t_r$ are determined as well as the difference Δu_{1r} between the total moisture content (Eq. 6) and the relative humidity-induced moisture content (Eq. 5), i.e.

$$\Delta u_{1r} = u_1(t_e) - u_{01}(t_e) = k_r \cdot u_{01}(t_e) \tag{7}$$

where t_e denotes the last day of the rain period. For day k after a rain period the moisture content is determined by:

$$u_1(t_k) = \max[(u_1(t_{k-1}) - \frac{k}{t_d}\Delta u_{1r}), u_{01}(t_k)] \tag{8}$$

Note that as soon as a new day with rain occurs the moisture content is again determined by Eq. 6. It is further assumed that the daily average wood temperature T_1 is equal to the daily average surrounding (global) temperature given by Meteonorm. Having interconnected values of daily average moisture content u_1 and temperature T_1 for one year the daily dose can be calculated according to Eqs. 2 and 3.

By calculating the daily dose and accumulating the dose for one year a measure of the risk of decay is obtained. This is made for several sites, and the result in terms of dosedays can be compared between the different sites. To be able to compare different sites, the dose was transferred to a relative dose by dividing it by the dose for the "base-station" Helsinki.

By this methodology, basic exposure indices I_{so} were calculated for various geographical locations. Fig. 3 shows calculated values for a number of European sites. Due to the variation of climate across Europe, relative doses between 0.6 (northern Scandinavia) and 2.1 (Atlantic coast in Southern Europe) were obtained. For sites not shown in Fig. 3 the (relative) base value of the exposure can be estimated with the help of the methods described above based on climate data from Meteoronorm. Note that the values describe the relative climate effect on a horizontal board of spruce sapwood (exposed to rain but without moisture traps). The results have been partly verified against another type of model; see e.g. Viitanen et al (2010). However, it should be kept in mind that local variation of climate conditions may lead to different relative doses than shown in the map. Examples could be sites near large lakes – experiencing higher relative humidity, sites at high altitude with lower temperature or with extremely high relative humidity and large rainfalls.

A detailed climate characterization for the whole Europe is very difficult to make and would be very rough and uncertain. A more detailed mapping on the regional level can however be made with the same methodology. As an example, a map over Sweden showing the relative doses for 34 sites is shown in Fig. 4. The map shows relative doses between 0.45 and 1.6. Border lines for different climate zones can be drawn according to the relative doses. Highest risk for decay is in climate zone 1 – the coastal region in the south of Sweden, lowest risk in climate zone 5 – the inner parts of Northern Sweden; see Table 2. These climate zones match to some extent a similar mapping previously made for Sweden to describe risk for mould growth, see Häglund et al. (2010).

Figure 3. Climate zones in Europe. Numbers shown indicate relative risk of fungal decay.

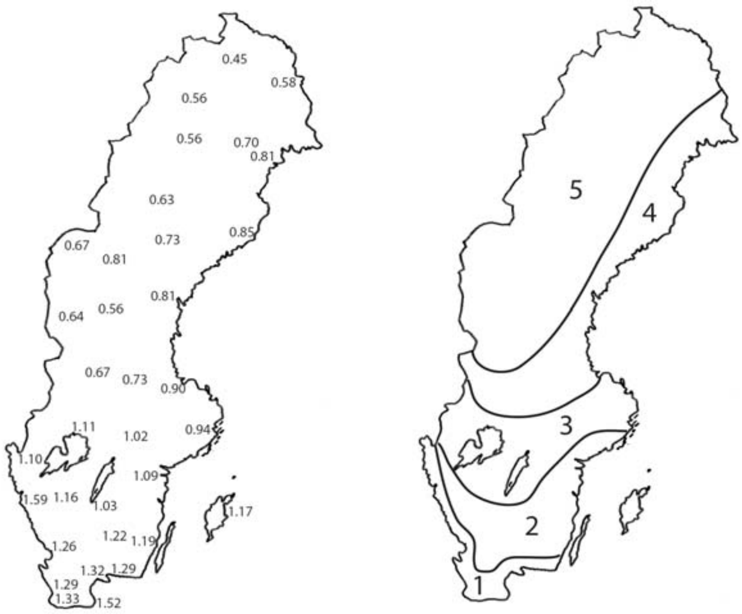


Figure 4. Relative doses for 34 Swedish sites (left) and proposed climate zones (right). Reference value =1,0 valid for Helsinki.

Table 2. Relative dose values for Swedish climate zones according to Figure 4.

Climate zone	Relative dose
1	1.6
2	1.25
3	1.1
4	0.9
5	0.7

4.3 Effect of local conditions

The local exposure for a building at a given geographical site is assumed to be affected by land topography, adjacent buildings and distance from the sea. The local conditions are described in terms of four classes as exemplified in Table 3. The factor k_{s1} is valid for wood facing the dominating wind direction, since this case gives the most severe exposure. Adjustments for less exposed directions are not made, because the design of e.g. cladding normally does not vary between different walls for the same building. The categorization in Table 3 is entirely based on subjective expert judgment.

Table 3. Effect of local conditions

Rating	**Description**	k_{s1}
Light	Local conditions have little impact on performance as the three features all offer sheltering (i) land topography (ii) local buildings (iii) >5km from the sea (so no maritime effect).*	0,8
Medium	Local conditions have some impact on performance as one of the three features does not offer sheltering (i) land topography (ii) local buildings (iii) >5km from the sea (so no maritime effect).	1,0
Heavy	Local conditions have an impact on performance as two of the three features do not offer sheltering (i) land topography (ii) local buildings (iii) >5km from the sea (so no maritime effect).	1,2
Severe	Local conditions have a significant impact on performance as the three features do not offer sheltering (i) land topography (ii) local buildings (iii) >5km from the sea (so no maritime effect).**	1,4

* e.g. building is sheltered by hills and neighbouring buildings and is inland.
** e.g. building is on a flat plain, with no nearby buildings and less than 1km from the sea.

4.4 Degree of sheltering and distance from ground

The sheltering from eaves is described by the factor k_{s2}, see Eq. 4. It is assumed to be a function of the ratio of eave overhang *e* relative the position *d* of the detail under consideration, see Fig. 5. The sheltering effect can be used for both decking and cladding. Similarly, the effect of distance from ground is described by a factor k_{s3}, see Fig. 5. Values for coefficients k_{s2} and k_{s3} are given in Tables 4 and 5, which is based on expert opinions and investigations of existing guidelines for best practice.

Table 4. Effect of sheltering from eave overhang.

Sheltering: eave to detail position ratio e/d (see Fig. 5)	k_{s2}
e>0.5d	0,7
e= 0.15d-0.5d	0,85
e<0.15 d(directly exposed to rain)	1,0

Table 5. Effect of distance from the ground.

Distance from ground (see Fig. 5)	k_{s3}
> 300 mm	1,0
100 – 300 mm	1,5
< 100 mm	2,0

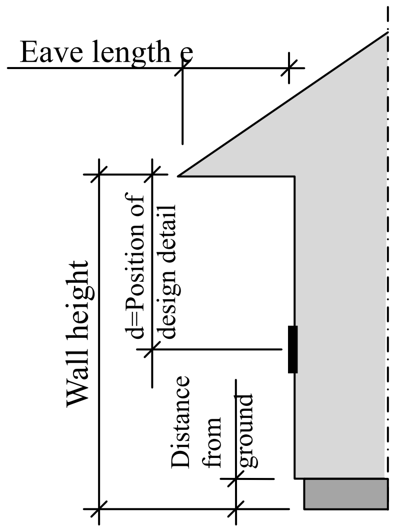


Figure 5. Illustration of effect of eave overhang and definition of distance from ground.

4.5 Effect of detail design

4.5.1 General

The effect of microclimate conditions as influenced by the detailed design is described by the factor k_{s4} in Eq. 4. In general, different details are assumed to be allocated to 5 different ratings according to Table 6. This table describes the rating in generic terms, and for practical application it will be illustrated below with separate interpretations for decking and cladding respectively.

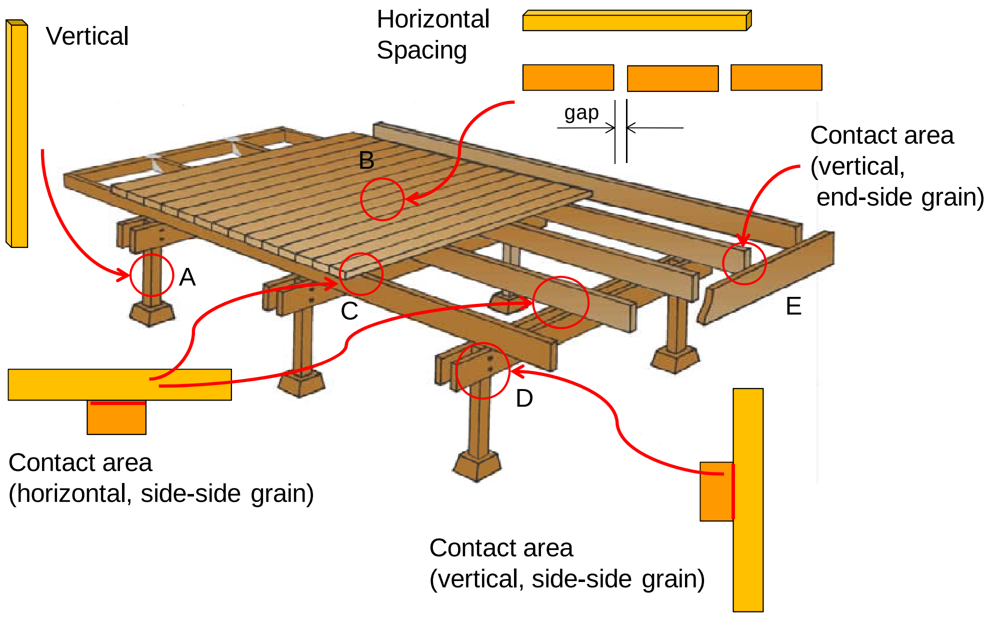
Table 6. General rating of design details.

Rating	**Description**
1. Excellent	Excellent design with features to maximize water shedding and ability to dry when wet
2. Good	Good design with features to provide water shedding and ability to dry when wet (corresponds to the reference of a horizontal board without possibility of moisture trapping)
3. Medium	Design with a limited probability of water trapping and with some ability to dry when wet
4. Fair	Design with medium probability of water trapping and limited ability to dry when wet
5. Poor	Design with high risk of water trapping and very limited ability to dry when wet

4.5.2 Rating of details for decking

Typical details for decking are illustrated in Fig. 6. As an aid to determine the rating, descriptions related to decking are given in Table 7, together with values for the factor k_{s4}. Conventional coating systems used for decking (e.g. oil systems) do not affect risk of decay significantly. Therefore, coating is not assumed relevant for rating of detail design in deckings.

The data given in Table 7 are based on a comparative experimental investigation of exposure in different type details, where the moisture content was monitored continuously during a period of 5 months. A variety of type details were tested and compared with a reference detail, which was a horizontal board (22 by 95 mm^2) of spruce (Picea abies) free in the air without moisture traps and exposed outdoors without protection from rain, see Fig. 7. The moisture content was measured at mid thickness of the board by resistive moisture gauges.



Figur 6. Typical details in decking construction. Courtesy: Timber Decking Association, UK.

Table 7. Ratings of details common for decking. (Example details from Fig. 6 are given)

Rating	**Details**	k_{s4}
1. Excellent	Vertical wood element free to dry on all sides (e.g. detail A)	0,9
2. Good	Horizontal board free to dry on all sides (e.g. with sufficient gaps* between boards in a decking, e.g. B)	1,0
3. Medium	Contact area side grain to side grain with sufficient gap if clean from dirt*	1,2
4. Fair	Horizontal and vertical contact area side grain to side grain without designed gap or with too narrow gap* (e.g. C and D) Horizontal boards near end grain	1,4
5. Poor	Horizontal and vertical contact area end grain to side grain as well as contact end grain to end grain (e.g. E)	1,6

* A safe gap size would be 5-8 mm.

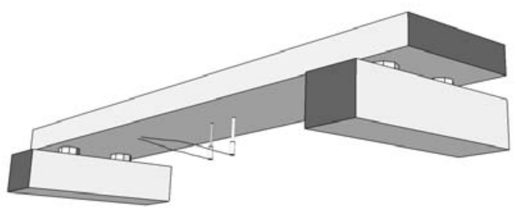


Figure 7. Test set up for reference detail of spruce board (cross section 22x95 mm^2)

A number of other details and designs were tested under the same climate exposure to investigate the relative effect depending on the type of detail. Variables investigated were compass orientation for vertical boards, inclination of horizontal boards, cross section dimensions, vertical and horizontal contact with different sizes for the contact areas and size of designed gaps. Examples of tested contact zones with moisture traps are shown in Fig. 8. Further details about the tests can be found in Hoeft (2010).

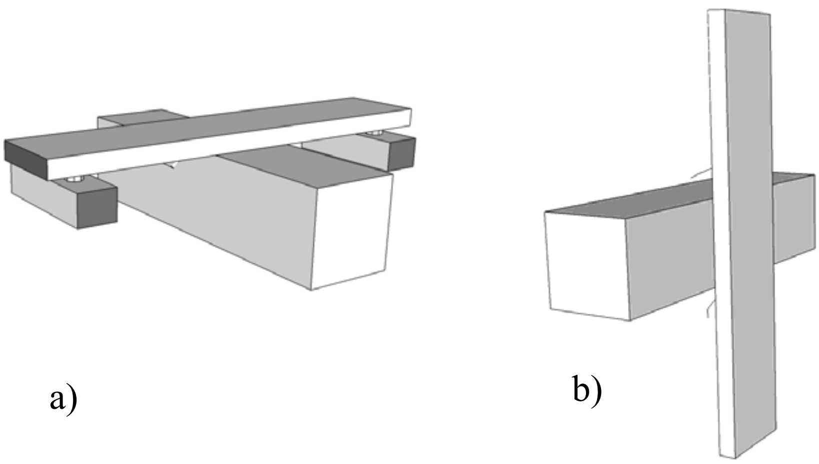


Figure 8. Examples of tested details with horizontal (a) and vertical (b) contact zones (moisture traps)

Typical results from the tests are shown in Fig. 9, where the curve at the top shows the variation in moisture content in the reference board and the rest of the curves show the increase of moisture content relative to the reference board (vertical co-ordinate axis at the right side) for horizontal and vertical contact zones with different contact areas A=45x95 mm^2 and 2A = 95x95 mm^2.

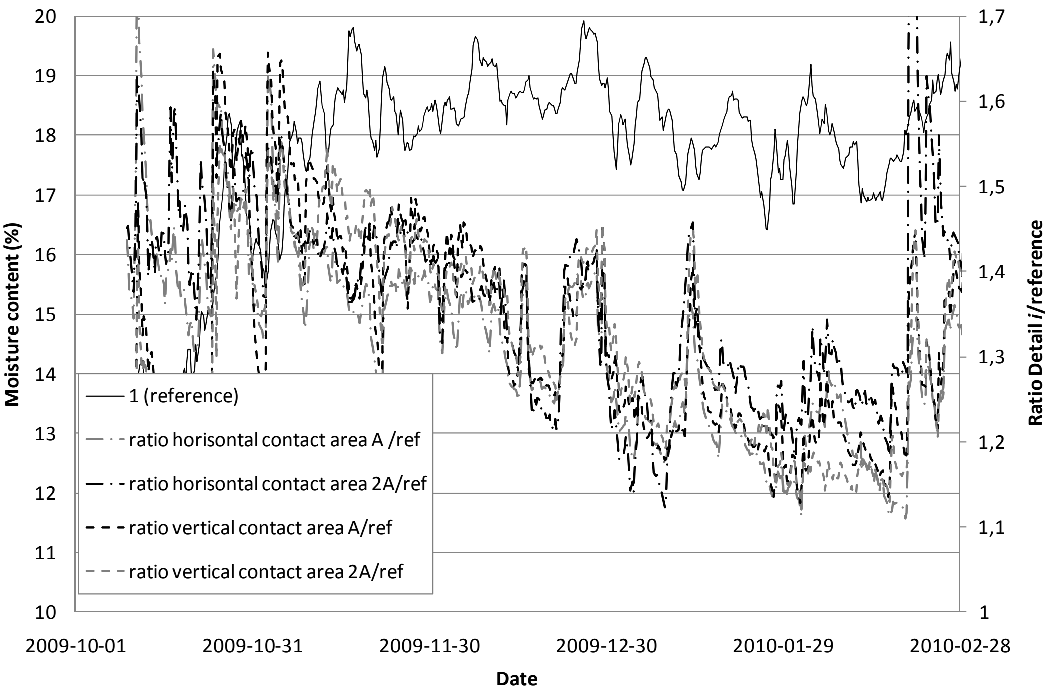


Figure 9. Moisture content for the reference detail (top curve) shown together with the ratios between details with different size and orientation of contact area (side to side grain).

During the first three months of the test period rain occurred frequently and the temperature was between 0 and 10 °C, while the temperature during the last two months was almost always below zero with no precipitation. Figure 9 shows that the moisture content in the contact areas area are of the order 40 % higher than in the reference board during the rainy period. Furthermore, no significant influence could be found for orientation or size of the contact zone. For contact zones with end grain/side grain the moisture content was slightly larger, but no effect of orientation was found.

To evaluate the relative influence of detail design in terms of decay risk, the test data has been fed into the dose-response model described in section 3. Selected results from this can be seen in Table 8. It is seen that orientation and size of contact areas have no significant effect. But for vertical contact zones a designed gap has a clearly positive effect. For contact zones between side grain and end grain the moisture content was monitored on both sides of the contact surface. The exposure in the wood part with side grain is somewhat more severe than in the wood with end grain facing the contact surface; see Table 8. The reason for this is not known. Data of the type shown in Table 8 has been used as a basis to estimate the coefficients selected in Table 7.

Table 8. Effect of detail design evaluated by the dose-response model, see Section 3.

Detail	Type	Monitoring position	Dose, see Section 3	Dose relative reference detail
0	Reference, horizontal board	-	8,89	1,0
B	Under shelter, horizontal board	-	7,14	0,81
C	Horizontal contact area A, side to side grain	side grain	14,28	1,61
D	Horizontal contact area 2A, side to side grain	side grain	14,39	1,62
E	Vertical contact area A, side to side grain	side grain	13,25	1,49
F	Vertical contact area 2A, side to side grain	side grain	12,38	1,39
G	Horizontal contact area A, side to end grain	side grain	14,18	1,60
		end grain	11,09	1,25
H	Vertical contact area A, side to end grain	side grain	13,14	1,48
		end grain	12,61	1,42
I	Vertical contact area A, side to side grain, gap 3 mm	side grain	8,72	1,07
J	Vertical contact area A, side to side grain, gap 6 mm	side grain	11,50	1,29

4.5.3 Ratings related to cladding

For design related to cladding, ratings are described in Table 9. The classification is based either on ventilation of the back of the cladding or the degree of protection of wood end grain. The worst classification determined from either of these two features is decisive for choosing the detail design factor.

Ventilation of the back of the cladding depends on design of the exterior wall layers with four categories included in Table 9. Full ventilation is valid when ventilation gaps are present at the bottom and the top of the cladding whereas the absence of ventilation gaps reduces the ventilation of the back side. For non-ventilated cladding the presence of an air space between the cladding and the outermost wall material (e.g. heat insulation) is decisive to distinguish the two lowest categories. For the quality of end grain protection it is decisive if the end grain is covered by construction elements or if it is open, whether or not a gap (> 1cm) is constructed at the end grain of panels and whether or not the end grain is sealed with low permeable sealing materials.

Back side ventilation and end grain protection are the two major factors influencing durability. Further recommendations of best practice guidance documents should be respected but they usually have less dominant impact on the risk of decay. Coating is expected to have a positive effect to reduce the exposure of the wood provided that the coating system is checked and maintained regularly. Further details about this are given in the guideline. The data given in Table 9 has been estimated on the basis of expert opinions but is also partly based on results from comparative measurements of moisture content in coated as well as uncoated wood in field tests; see Grüll et al (2010).

Table 9. Ratings of details for cladding (vertical wood members) depending on a) backside ventilation or b) end grain protection. The most unfavourable of (a) and (b) determines the rating.

Rating	a) Back side ventilation	b) End grain protection	Uncoated	Coated
			k_{s4}	k_{s4}
1. Excellent	fully ventilated	with gap and sealed or end grain covered	0,8	0,5
2. Good	limited ventilation	with gap unsealed	0,9	0,6
3. Medium	not ventilated, with air space		1,1	0,9
4. Fair		without gap but sealed	1,3	1,1
5. Poor	not ventilated without air space	without gap and unsealed	1,5	1,5

5. RESISTANCE OF WOOD MATERIALS AGAINST DECAY

The design resistance index I_{Rd} for selected wood materials is determined on the basis of resistance class according to Table 10. This is a simplified first step for a material resistance classification based on a balanced *expert judgment of moisture dynamics and durability class*. The resistance class is based on a combination of durability class data according to EN 350-2 (1994), test data, practical experience of treatability and permeability for wood species as well as experience from use in practice.

Biological durability is the key factor determining performance for wood in different use classes. The robust laboratory and field test methods that exist make it possible to assign a durability rating to timber linked to the intended use class according to EN 335 (1992), assuming a worst case scenario. Other factors, see Section 4, determine the likelihood of the worst case scenario occurring in practice.

The natural durability of wood is classified into durability classes as described in EN 350-1 (1994) and presented as durability classes for heartwood of timber species in EN 350-2 (1994). Durability class is a classification on five levels from non-durable to very durable. This is based on decades of data from ground contact field trials for use class 4 (ground contact). The natural durability for a wood species can vary widely.

Table 10. Resistance rating of selected wood materials and corresponding design resistance index I_{Rd}.

Material resistance class	**Examples of wood materials***	I_{Rd}
A	Heartwood of very durable tropical hardwoods, e.g. Afzelia, Robinia (durability class 1) Preservative-treated sapwood, industrially processed to meet requirements of use class 3.	10,0
B	Heartwood of durable wood species e.g. Sweet Chestnut and Western Red Cedar (durability class 2)	5,0
C	Heartwood of moderately and slightly durable wood species e.g. Douglas Fir, larch and Scots pine (durability class 3 and 4,)	2,0
D	Slightly durable wood species having low water permeability (e.g. Norway spruce)	1,0
E	Sapwood of all wood species (and where sapwood content in the untreated product is high)	0,7

*For the majority of wood materials there is variability in material resistance. The material resistance classification should defer to local knowledge based on experience of performance of cladding and decking and where this is not available field test data and then laboratory test data. It is possible that a classification with different design resistance indices may need to be adopted for specific regions or countries, based on practical experience e.g. from the use of a material in that region.

For out of ground contact (e.g. exterior wood cladding) the challenge is to translate durability class from use class 4 to use class 3. In EN 350-1 (1994), the term “markedly different” is used to describe the additional benefits of low permeability on the performance of wood out of ground contact. Expert advice is recommended for assigning the material resistance class for wood materials such as:

Preservative treated wood is often a combination of mixed treated heartwood and sapwood. The treated sapwood should be thoroughly treated and enhanced to durability class 1 according to EN 350. The heartwood is more resistant to treatment and the enhancement of the heartwood can be considered to be slightly higher than the natural durability class of the heartwood for the species according to EN 350, part 2. Therefore, for preservative treated decking it may be more sensible to take a mid-point between the resistance class of the treated sapwood and the treated heartwood. E.g. for pine heartwood treated (resistance class C) and pine sapwood treated (resistance class A) the overall batch of preservative treated wood should then be classified as resistance class B.

For untreated wood if there is a mixture of heartwood and sapwood present in the wood species then the material resistance can either be classified as the mid-point between the class of the heartwood (resistance class A to D) and the sapwood (resistance class E). If this risk is not acceptable then the material resistance class should be taken as the worse case (E), the least resistant competent of the overall material.

The durability of modified wood, e.g. acetylated, furfurylated and thermally modified, is specific to the technologies employed and may vary between specifications for the different materials. Expert advice is also recommended for assigning the material resistance class for modified wood.

6. VERIFICATION BY REALITY CHECKS

All elements in the design system are so far only expressed in relative terms. The calibration factor c_a has to be determined to produce a reasonable safety level against non-performance. The only possible approach at the present level knowledge is to check if the system will give reasonable results in accordance with generally accepted experience. For this reason verifications of the guideline against a number of reality checks have been made. Each reality check consists of a case from practice, for which the guideline is applied and where the real service life performance is known. In general the interpretation of the guideline was made of the person providing the information about the particular case (named as source below). Information about each case is summarized in Table 11.

Table 11. Basic information about reality checks

Case	Type	Location	Coating	Material	Source	Actual performance
1	C	Öland, S	*	Spruce	Jöran Jermer	No decay after 60 years
2	C	Stockholm, S	yes	Spruce	"	Decay after 15 years
3	C	Turku, SF	yes	Spruce	Hannu Viitanen	No decay after 20 years
4	C	Helsinki, SF	yes	Spruce	"	Decay after 20 years
5	C	Bordeaux, F	no	Western Red Cedar	Ed Suttie	No decay after 40 years
6	C	Garston, UK	no	"	"	No decay after 15 years
7	D	Helsingborg, S	no	Larch	Jöran Jermer	Severe decay after 5-6 years
8	D	Vienna, A	no	Larch	Peter Schober	Decay after 10 years
9	D	Vienna, A	no	Teak	"	No decay after 6 years
10	D	Vienna, A	no	Oak	"	Decay after 6 years
11	D	Essing, G	no	Azobe	Chr. Brischke	Decay after 16 years
12	D	Germany	no	CCB impregnated pine	C. Welzbacher	Decay after 15 years
13	C	France, NW	no	Western Red Cedar	L. Podgorski	OK after 20 years but some boards replaced after 5 years
14	C	France, NW	no	"	"	Decay after 20 years
15	D	France, SW	no	Robinia	"	Limited decay after 10 years
16	D	France, SW	no	Robinia	"	No decay after 12 years
17	D	France, NE	no	Treated pine	"	Decay after 20 years

*Surface treatment with creosote

The cases listed in Table 11 were evaluated with the guideline and the results are shown in Table 12 assuming that the calibration factor was set to 1,0. The output from the guideline agrees with the reality in the majority of the cases, but did not perform as it should in 4 out of 17 cases. One of the main problems is to rate different materials in a correct manner and to cope with the great variability of wood materials. For three of the cases (10,11 and 15) where the output from the tool did not agree with what happened in reality, the materials used were species with nominally high durability, given that only heartwood is present, which was assumed in the design tool evaluation. Decay occurred however in reality after 6-16 years in these cases. One possible explanation could be that the material contains significant amounts of sapwood, but no information has been available to confirm this. For case 12 with CCB impregnated pine with nominal high durability, the possible presence of non-impregnated heartwood could similarly explain that also this case failed in reality. In general, both heartwood from durable species and treated sapwood involve a risk due to the difficulty to distinguish between heartwood and sapwood in practice, as discussed in section 5.

It should be noted that that the present limited collection of reality checks cannot be seen as representative for practical use of wood in exterior above ground situations. There is probably a bias towards cases where things have gone wrong. The risk of failure, given that the guideline accepts a certain design, can therefore not be evaluated directly on the basis of the reality checks.

If the calibration factor would be chosen to a higher value the reliability would be improved, but the challenge is to find the right balance from the risk point of view. Testing against more reality checks with more detailed background information should be made.

Table 12. Guideline evaluation of cases in Table 10 and comparison with reality

Case	Site I_{so}	Local k_{s1}	Shelt. k_{s2}	Dist. k_{s3}	Detail k_{s4}	I_{sk}	γ_d	$I_{sd} = \gamma_d \cdot I_{sk}$	I_{rd}	$I_{Sd} < I_{Rd}$?	reality
1	1,2	1,0	1,0	1,0	0,9	1,08	0,9	0,97	1,0*	OK	OK
2	1,0	1,0	1,0	1,5	0,9	1,35	0,9	1,21	1,0	NO	NO
3	1,0	1,0	1,0	1,0	0,5	0,5	0,9	0,45	1,0	OK	OK
4	1,0	1,4	1,0	1,5	0,9	1,89	0,9	1,70	1,0	NO	NO
5	2,08	1,0	1,0	1,0	1,1	2,29	0,9	2,64	5,0	OK	OK
6	1,64	1,2	1,0	1,0	0,8	1,57	0,9	1,42	5,0	OK	OK
7	1,5	1,4	1,0	1,0	1,4	2,94	0,9	2,64	2,0	NO	NO
8	1,4	1,2	1,0	2,0	1,4	4,70	0,8	3,76	2,0	NO	NO
9	1,4	1,2	1,0	2,0	1,0	3,36	0,8	2,69	5,0	OK	OK
10	1,4	1,2	1,0	2,0	1,2	4,03	0,8	3,22	5,0	**OK**	**NO**
11	1,4	1,4	1,0	1,5	1,0	2,94	0,9	2,65	5,0	**OK**	**NO**
12	1,4	1,0	1,0	1,5	1,2	2,52	0,9	2,27	10	**OK**	**NO**
13	1,7	1,4	1,0	1,5	0,8	2,86	0,9	2,57	5,0	OK	OK
14	2,0	1,4	1,0	2,0	1,5	8,40	0,9	7,56	5,0	NO	NO
15	2,0	1,2	1,0	1,5	1,2	4,32	0,9	3,89	10	**OK**	**NO**
16	2,0	0,8	0,7	1,0	1,2	1,34	0,9	1,21	10	OK	OK
17	1,4	1,2	1,0	1,5	1,6	4,03	0,9	3,63	2,5*	NO	NO

*This has been assigned a value slightly better than pine heartwood, since untreated heartwood probably was present

7. SUMMARY AND CONCLUSIONS

The background and principles for an engineering design guideline for wood in outdoors above ground applications, i.e. use class 3 according to EN 355 (1992), has been presented in this paper. It has been developed in the European research project Woodexter and can be seen as a first prototype for a quantitative design tool for wood durability focused on decking and cladding applications. It is based on a limit state for onset of decay, defined as a state of fungal attack according to rating 1 in EN 252 (1989) under a reference service life of 30 years. The approach is to determine climate exposure as a function of geographical location, local exposure conditions, sheltering, distance to ground and detail solution to be compared with the material resistance for various wood species and products. The design output is either OK or NOT OK, related to the specified limit state.

The quantification of the design tool is partly based on experimental data and physical models. Where necessary, input based on experience and expert opinions has been used for some of the elements in the design guideline and it could be continuously improved in the future when new research results and data become available.

The relative exposure for a reference situation (exposed horizontal board free from moisture traps) can be estimated with reasonable reliability by using time series of climate data at different geographical locations together with a simplified performance model for onset of decay. A simple model for transformation of global climate data to moisture content variation in the reference board was also used for this purpose. Likewise, the relative effect of detail design can be evaluated on the basis of results from continuous monitoring of moisture content comparing the performance of different detail solutions with the reference situation. The effect of potential moisture traps on risk of decay was also evaluated with the proposed performance model.

One of the major difficulties is to quantify the material resistance due to the large variability of wood materials and due to the difficulty to distinguish between heartwood and sapwood in practical situations. The material resistance has been described in five classes A-E, based on a combination of durability class data according to EN 350-2 (1994), test data, practical experience of treatability and permeability for wood species as well as experience from use in practice.

The design system as a whole was tested against a number of "reality checks", to see if the output from the design method agrees with known experience and results from practice. The results from this validation led to the following conclusions

- The output from the design tool agrees reasonably well with experience from the practice.
- The quantification of exposure seems to provide reasonable results
- The quantification of resistance is difficult on the basis of the limited information normally available in practice.
- More carefully documented reality checks are needed to fully validate the design tool.
- A main challenge is to find the right balance from the risk point of view accounting for variability in material response but also variation in exposure.

However, the use of the design tool can give the following advantages compared to current practice, since the designer will

- have a method to consider climate conditions at the actual geographical site and also to some extent local exposure conditions.
- have a simplified way to account for the effect of coatings on exposure
- have to think about the consequences of violation of the limit state.
- have to go through a check list where he/she becomes aware of the importance of appropriate detailing solutions.

Even if the factors describing material resistance, effects of detailing, contact zones, coating systems and maintenance are difficult to quantify in a reliable way the use of the method can generally be expected to lead to better solutions. Many users have limited understanding of the concept durability by design. Direct descriptions of so called best practice solutions are quite difficult to use because the designer does not understand what happens if the solution is modified, which is most often necessary. It is believed that many building professionals will appreciate a tool within the area of wood durability which is structured in a similar way as other design tools they are using.

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