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Service life of wood in outdoor above ground applications:
Engineering design guideline

Background document

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PREFACE

This report gives background information to an engineering service life design guideline for wood in outdoor above ground applications (use class 3 according to EN 335). The guideline was developed within the European project WoodExter (Service life and performance of exterior wood above ground) during 2008-2011.

The WoodExter project had the following R&D partners:

SP Technical Research Institute of Sweden (co-ordinator)
LTH - Lund University, Sweden
BRE - Building Research Establishment, United Kingdom
VTT, Finland
FCBA, France
HFA - Holzforschung Austria
TUW – Technische Universität Wien, Austria
NFLI – Norwegian Forest and Landscape Institute
UGOE – Universität Göttingen, Germany
UG – Universiteit Gent, Belgium

Industrial partners were:

CEI-Bois (major industrial partner)
Swedish Wood Preservation Institute
Södra Timber AB, Sweden
Bergs Timber Bitus AB, Sweden
Kebony ASA, Norway
Fachverband der Holzindustrie Österreichs, Austria
Synthesa GmbH, Austria
Adler-Werk Lackfabrik, Austria

The guideline and the present background document has been written jointly by the WoodExter partners and the following persons have directly contributed:

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ABSTRACT

This report describes the background and principles behind an engineering design guideline for wood in outdoor above ground applications, i.e. use class 3 according to EN 335 (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 for durability and wood product performance. 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, distance to ground and design of details. 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 mainly 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 was used to derive relative measures of decay risk between different locations and between different detail solutions. Some other elements in the guideline have been estimated in a semi-subjective manner based on expert opinions as well as from review of 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 an Excel format, which makes practical use more 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. The guideline, the excel tool and the present background document can be downloaded for free at www.kstr.lth.se.

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

The objective with this report is to describe the background and principles behind an engineering design guideline for wood in outdoor above ground applications, i.e. use class 3 according to EN 335 (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 field of wood performance, Thelandersson et al (2011a). An Excel tool based on the guideline is available to facilitate convenient evaluation.

1.1. Performance based service life design

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). A recent overview of service life prediction methods can be found in Isaksson (2008).

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 Fig. 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 is onset of fungal decay. Alternatively, a specified acceptable degree of decay could be defined as a limit state. The performance requirement in a certain situation could e.g. be that decay is not accepted during a specified service life. Since most factors and parameters 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 and standardized micro-climate conditions independent of practical design situations.

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.

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

In the Wood Wisdom project WoodExter a quantitative design tool has been developed in the form of a simple engineering type guideline, see Thelandersson et al (2011a and 2011b). The purpose is to give the user a tool to evaluate the durability of wood based commodities in outdoor conditions above ground (use class 3 according to EN 335, 1992). The present report describes the principles and background scientific knowledge behind the proposed guideline.

1.2. Basic principles and limitations 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 system is open for future implementation of new knowledge and information, which may increase the reliability in predictions made by the system. The design tool in its present form is mainly focussed on two applications, cladding and decking. The degradation mechanism considered is limited to 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). The concept of limit state is fundamental in the approach used here, and in practical application of the guideline the result will be either that the limit state will not be reached (design is OK) or that the limit state is
violated (design is NOT OK). This approach is familiar to engineers and building professionals since it is similar to the approach used in design of load-bearing structures for buildings, bridges and other infrastructural facilities.

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

\[ I_{Sd} = I_{Sk} \gamma_d \leq I_{Rd} \]  

where \( I_{Sk} \) is a characteristic exposure index, \( I_{Rd} \) is a design resistance index and \( \gamma_d \) 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 (OK), otherwise it is not accepted (NOT OK).

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 \( \gamma_d = 1,0 \)

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 in section 3.

1.3. Performance model

According to Fig. 1, 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 \( u \) and temperature \( T \). 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

\[ D_N = \sum_{i=1}^{N} D_u(u_i) \cdot D_T(T_i) \]  

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)

The above introduced dose functions are given by

\[ D_u(u_i) = \begin{cases} (u_i / 0.3)^2 & \text{for } u_i \leq 0.30 \\ 1 & \text{for } u_i > 0.30 \end{cases} \]  

\[ D_T(T_i) = \begin{cases} 0 & \text{for } T_i < 0 \\ T_i / 30 & \text{for } 0 \leq T_i \leq 30 \\ 1 & \text{for } T_i > 30 \end{cases} \]
The model rests on the assumption that onset of decay occurs when the accumulated dose reaches a critical value $D_{\text{crit}}$ which may be different for different wooden materials depending on their resistance to decay.

Eqs. (3a-b) 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 EN 252 (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.

![Figure 2. Illustration of the dose-response model described by Eqs. 3a-b.](image)

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.

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 time to decay for Douglas fir mentioned above is significantly longer 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 (2011a).

Another type of performance model has also been proposed by Viitanen et al (2010). This is based on a combination of relative humidity and temperature and calibrated against laboratory tests performed by Viitanen (1997). This model will be described briefly in Section 3 and the result from that model will be compared to those from the model described above concerning effect of geographical location.
2. Consequence class

The consequence class depends on the severity of consequences in case of non-performance and is described by the factor $\gamma_d$ 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 $\gamma_d$ as a function of consequence class

<table>
<thead>
<tr>
<th>Consequence class</th>
<th>$\gamma_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Small (e.g. cases where it is cost-effective and simple to replace wooden elements in a structure if decay occurs)</td>
<td>0.8</td>
</tr>
<tr>
<td>2 Medium (e.g. cases where it is costly and difficult to replace wooden elements in a structure if decay occurs)</td>
<td>0.9</td>
</tr>
<tr>
<td>3 High (e.g. wood elements in load-bearing structures where failure may imply risk for humans)</td>
<td>1</td>
</tr>
</tbody>
</table>

The values of $\gamma_d$ have been chosen in accordance with the corresponding values used to distinguish consequence classes in structural design. Ideally, these values should be chosen so that they could be related to acceptable values for the probability of violation of the limit state, but this is not possible at the present state of knowledge.

The highest consequence class corresponds to cases where decay might lead to failure in structural elements or elements falling off structures, with potential risk for humans. The smallest consequence class refers to cases with only minor damages which can be repaired with moderate efforts and costs.
3. Exposure index $I_{sk}$

3.1. General

The exposure index $I_{sk}$ shall be seen as a “characteristic value”, including safety margins 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

In the guideline the exposure index is determined as

$$I_{sk} = k_{s1} \cdot k_{s2} \cdot k_{s3} \cdot k_{s4} \cdot I_{so} \cdot c_a$$  \hspace{1cm} (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

How all these factors are determined is described below in separate sections. The exposure index intends to describe the severity in terms of combined moisture and temperature conditions favourable for development of decay fungi. It is assumed that it can be derived with the aid of the performance model described in section 1.3.

3.2. Basic exposure index $I_{so}$

3.2.1. Approach used for the guideline

The effect of climate variability on risk for decay of wood exposed outdoors was investigated using the performance model described in Section 1.3. The climate data used was obtained with the software 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. The moisture content $u$ depends on the relative humidity $\phi$ and is calculated as:

$$u(\phi) = 0.7\phi^3 - 0.8\phi^2 + 0.42\phi + 0.0077$$

(5a)

$$u_{01}(t_i) = u[\bar{\phi}(t_i)]$$

(5b)

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

(5c)

Expression (5a) is derived from Tveit (1966). 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 $\phi$ for two full days (Eqs. 5b and c). This is assumed to account for a certain delay corresponding to diffusion into the wood. This approximation is rather crude, since it does not account for e.g. size of the wood element. But the moisture content of interest for defining conditions for the fungi is not necessarily the average within the wood element. At the present state of knowledge it is therefore pointless to describe the moisture dynamics in the wood in more detail.

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 Bulcke et al. (2009) it can be estimated as $t_d = a \cdot t_r$, 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 Bulcke et al. (2009), $k_r$ is in the range of 0.6 to 1.0, and the value 0.8 is used here.

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

(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 $\Delta u_{1r}$ between the total moisture content (Eq. 6) and the relative humidity-induced moisture content (Eq. 5), i.e.

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

(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:

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

(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 $T_i$ 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 Meteonorm. Note that the values describe the relative climate effect on a horizontal board of spruce sapwood (exposed to rain but without moisture traps). In section 3.2.2 these relative results are compared against a different type of model; see 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 heavy rainfalls.

A detailed climate characterization for the whole Europe is very difficult to make and would be crude 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.

Rain included
Meteon...... a
See [2].
Figure 4. Relative doses for 34 Swedish sites (left) and proposed climate zones (right). Reference value = 1.0 is valid for Helsinki.

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

<table>
<thead>
<tr>
<th>Climate zone</th>
<th>Relative dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.6</td>
</tr>
<tr>
<td>2</td>
<td>1.25</td>
</tr>
<tr>
<td>3</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>0.9</td>
</tr>
<tr>
<td>5</td>
<td>0.7</td>
</tr>
</tbody>
</table>

3.2.2. Exposure index estimated from performance model developed by VTT

A model to determine the decay growth in wood based on relative humidity and temperature conditions was developed at VTT in Finland. This model is based on the previous experimental studies of Viitanen and Ritschkoff (1991), Viitanen (1996), and Viitanen (1997). In these references, the decay growth of brown rot in spruce and pine sapwood was experimentally studied in different constant relative humidity and temperature conditions. In the present model, only the data of pine sapwood are considered.

This model is a time stepping scheme and the climate conditions may be variable. A more complete description can be found in reference Viitanen et al (2010). The development of decay is modelled as two consecutive processes:

a) Activation process:

This is defined using a parameter $\alpha$, which is initially 0 and gradually grows depending on the air humidity and temperature to a limit value of 1. This process is assumed to recover at a given rate under favourable conditions (dry air) (although no experimental evidence of recovery is available).

b) Mass loss process:
This occurs when the activation process has fully developed \((\alpha=1)\) otherwise it does not occur. This process is naturally irrecoverable.

In the model, these two processes only occur when the temperature is above \(0 \, ^\circ\text{C}\) and the relative humidity is 95% or above. Outside these condition bounds, the activation process may recover, but the mass loss process is simply stopped.

For the activation process the development of the function \(\alpha(t)\) is determined by

\[
\alpha(t) = \int_0^t d\alpha \approx \sum_0^t (\Delta\alpha)
\]  

(9)

where \(\Delta\alpha\) is the change in \(\alpha\) during a time step \(\Delta t\), determined by

\[
\Delta\alpha = \begin{cases} 
\frac{\Delta t}{t_{\text{crit}}(\phi, T)} & \text{under conditions favourable for decay} \\
-\frac{\Delta t}{t_{\text{rec}}} & \text{under conditions unfavourable for decay}
\end{cases}
\]

The function \(t_{\text{crit}}(\phi, T)\) was estimated from test results as

\[
t_{\text{crit}}(\phi, T) = \left[\frac{2.3T + 0.35\phi - 0.024\phi T}{-42.0 + 0.14T + 0.45\phi}\right] \cdot 30 \cdot 24 \quad \text{[hours]}
\]

(10)

The recovery time \(t_{\text{rec}}\) (i.e. the time needed for \(\alpha\) to recover from a value of 1 back to 0) is assumed to be 17520 hours (2 years). Recovery takes place when the conditions are outside the bounds of the decay growth, i.e. if \(\phi < 95\%\) or \(T < 0 \, ^\circ\text{C}\).

The mass loss process proceeds the activation process, when \(\alpha\) has reached 1 in Eq. (9). The mass loss \(ML(t')\) as a function of time \(t'\) is obtained from

\[
ML(t') = \int_{t_a}^t \frac{dML(\phi, T)}{dt} dt = \sum_{t_a}^{t'} \frac{dML(\phi, T)}{dt} \Delta t
\]

(11)

where \(t_a\) is the time when activation is completed (when \(\alpha=1\)).

The rate of mass loss is estimated from test results to

\[
\frac{dML(\phi, T)}{dt} = -5.96 \cdot 10^{-2} + 1.96 \cdot 10^{-4} T + 6.25 \cdot 10^{-4} \phi
\]

(12)

In Eqs. 9-12 the following dimensions should be used
\(\phi = \text{relative humidity [\%]}\)
\(T = \text{temperature} \, ^\circ\text{C}\)

This wood decay model was applied using the same Meteonorm data as in Section 3.2.1 for some cities of Europe for air temperature, relative humidity and precipitation at 1 hour intervals. These data were available for a single year which can be considered as normal. This year was run identically for consecutive years during the simulation. The precipitation information was utilized simply to set the relative humidity value to 100% when it rains. This is assumed to reflect the situation on wood surfaces which are exposed to rain.
The results of the model are given in Fig. 5 as relative values for the activation rate up to onset of decay ($\alpha=1$), to occur in the European climates. The values here are normalised against Helsinki, which has a value of 1.00. For instance, it is seen that the decay occurs 1.54 times faster in Lisbon than in Helsinki.

Figure 5. Relative activation rates for initiation of decay at different locations in Europe based on the VTT model, Viitanen et.al. (2010).

A comparison between the maps in Figs. 3 and 5 shows that the same climate zone pattern is found with both models, although the two models are very different. The relative values differ, however, due to the fact that the two models generate different output quantities. Hence the relative values shown in the maps will be scaled differently.
3.3. Local conditions

The local exposure for a building at a given geographical site is assumed to be a function of three distinct factors: land topography, presence of adjacent buildings and distance from the sea. The local conditions are described in terms of four classes as shown 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.

Table 3. Effect of local conditions

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
<th>$k_{s1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Local conditions have little impact on performance as the three features all offer sheltering (i) land topography (ii) local buildings (iii) &gt;5km from the sea (so no maritime effect).*</td>
<td>0.8</td>
</tr>
<tr>
<td>Medium</td>
<td>Local conditions have some impact on performance as one of the three features does not offer sheltering (i) land topography (ii) local buildings (iii) &gt;5km from the sea (so no maritime effect).</td>
<td>1.0</td>
</tr>
<tr>
<td>Heavy</td>
<td>Local conditions have an impact on performance as two of the three features do not offer sheltering (i) land topography (ii) local buildings (iii) &gt;5km from the sea (so no maritime effect).</td>
<td>1.2</td>
</tr>
<tr>
<td>Severe</td>
<td>Local conditions have a significant impact on performance as the three features do not offer sheltering (i) land topography (ii) local buildings (iii) &gt;5km from the sea (so no maritime effect)**</td>
<td>1.4</td>
</tr>
</tbody>
</table>

* 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.

The categorization in Table 3 is based on the classification developed in WoodExter WP2 "Durability indicators", in connection with inspections of exterior wood cladding and decking, see Suttie et al (2011). The rating of local conditions was used there as a durability indicator. The categories in Table 3 also resembles the classification in terrain classes used in many structural codes to estimate wind loads on structures, see e.g. EN 1991-1-4 (2005). The values for the parameter $k_{s1}$ have been estimated by expert judgement.

3.4. 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, based on expert opinions and information from existing guidelines for best practice.
Table 4. Effect of sheltering from eave overhang.

<table>
<thead>
<tr>
<th>Sheltering: eave to detail position ratio e/d (see Fig. 5)</th>
<th>$k_{s2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>e &gt; 0.5d</td>
<td>0.7</td>
</tr>
<tr>
<td>e = 0.15d - 0.5d</td>
<td>0.85</td>
</tr>
<tr>
<td>e &lt; 0.15d (directly exposed to rain)</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 5. Effect of distance from the ground.

<table>
<thead>
<tr>
<th>Distance from ground (see Fig. 5)</th>
<th>$k_{s3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 300 mm</td>
<td>1.0</td>
</tr>
<tr>
<td>100 – 300 mm</td>
<td>1.5</td>
</tr>
<tr>
<td>&lt; 100 mm</td>
<td>2.0</td>
</tr>
</tbody>
</table>

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

### 3.5. Detail design

#### 3.5.1. General

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

This general classification in Table 6 was developed in WoodExter WP2 "Durability indicators", and was also used as a tool for inspection of exterior wood decking, see Suttie et al (2011).
Table 6. General rating of design details.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Excellent</td>
<td>Excellent design with features to maximize water shedding and ability to dry when wet</td>
</tr>
<tr>
<td>2. Good</td>
<td>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)</td>
</tr>
<tr>
<td>3. Medium</td>
<td>Design with a limited probability of water trapping and with some ability to dry when wet</td>
</tr>
<tr>
<td>4. Fair</td>
<td>Design with medium probability of water trapping and limited ability to dry when wet</td>
</tr>
<tr>
<td>5. Poor</td>
<td>Design with high risk of water trapping and very limited ability to dry when wet</td>
</tr>
</tbody>
</table>

3.5.2. 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 $k_{sd}$. Conventional coating systems used for decking (e.g. oil systems) do not affect risk of decay significantly. Therefore, coating is not assumed relevant to rate detail design of decking.

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.

![Diagram of decking construction](image_url)

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

<table>
<thead>
<tr>
<th>Rating</th>
<th>Details</th>
<th>$k_{sd}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Excellent</td>
<td>Vertical wood element free to dry on all sides (e.g. detail A)</td>
<td>0.9</td>
</tr>
<tr>
<td>2. Good</td>
<td>Horizontal board free to dry on all sides (e.g. with sufficient gaps* between boards in a decking, e.g. B)</td>
<td>1.0</td>
</tr>
<tr>
<td>3. Medium</td>
<td>Contact area side grain to side grain with sufficient gap if clean from dirt*</td>
<td>1.2</td>
</tr>
<tr>
<td>4. Fair</td>
<td>Horizontal and vertical contact area side grain to side grain without designed gap or with too narrow gap* (e.g. C and D)</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>Horizontal boards near end grain</td>
<td></td>
</tr>
<tr>
<td>5. Poor</td>
<td>Horizontal and vertical contact area end grain to side grain as well as contact end grain to end grain (e.g. E)</td>
<td>1.6</td>
</tr>
</tbody>
</table>

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

Figure 7. Test set up for reference detail of spruce board (cross section 22x95 mm²)

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 different sizes 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 remaining curves show the
relative increase of moisture content compared to the reference board (vertical co-ordinate axis to the right) for horizontal and vertical contact zones with different contact areas $A=45\times95 \text{ mm}^2$ and $2A = 95\times95 \text{ mm}^2$.

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 40-60 % 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 were fed into the dose-response model described in section 1.3. 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 1.3.

<table>
<thead>
<tr>
<th>Detail</th>
<th>Type</th>
<th>Monitoring position</th>
<th>Dose (days)</th>
<th>Dose relative reference detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Reference, horizontal board</td>
<td>-</td>
<td>8.89</td>
<td>1.0</td>
</tr>
<tr>
<td>B</td>
<td>Under shelter, horizontal board</td>
<td>-</td>
<td>7.14</td>
<td>0.81</td>
</tr>
<tr>
<td>C</td>
<td>Horizontal contact area A, side to side grain</td>
<td>side grain</td>
<td>14.28</td>
<td>1.61</td>
</tr>
<tr>
<td>D</td>
<td>Horizontal contact area 2A, side to side grain</td>
<td>side grain</td>
<td>14.39</td>
<td>1.62</td>
</tr>
<tr>
<td>E</td>
<td>Vertical contact area A, side to side grain</td>
<td>side grain</td>
<td>13.25</td>
<td>1.49</td>
</tr>
<tr>
<td>F</td>
<td>Vertical contact area 2A, side to side grain</td>
<td>side grain</td>
<td>12.38</td>
<td>1.39</td>
</tr>
<tr>
<td>G</td>
<td>Horizontal contact area A, side to end grain</td>
<td>side grain</td>
<td>14.18</td>
<td>1.60</td>
</tr>
<tr>
<td>H</td>
<td>Vertical contact area A, side to end grain</td>
<td>side grain</td>
<td>13.14</td>
<td>1.48</td>
</tr>
<tr>
<td>I</td>
<td>Vertical contact area A, side to side grain, gap 3 mm</td>
<td>side grain</td>
<td>8.72</td>
<td>1.07</td>
</tr>
<tr>
<td>J</td>
<td>Vertical contact area A, side to side grain, gap 6 mm</td>
<td>side grain</td>
<td>11.50</td>
<td>1.29</td>
</tr>
</tbody>
</table>

3.5.3. Rating of details for cladding

For design detailing 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.

Table 9. Ratings of details for cladding boards and panels depending on ventilation (a) or end grain protection (b). The worst rating of (a) and (b) determines the overall rating.

<table>
<thead>
<tr>
<th>Rating</th>
<th>a) Ventilation</th>
<th>b) End grain protection</th>
<th>Uncoated $k_{sd}$</th>
<th>Coated $k_{sd}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Excellent</td>
<td>fully ventilated</td>
<td>with gap and sealed or end grain covered</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>2. Good</td>
<td>limited ventilation</td>
<td>with gap unsealed</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>3. Medium</td>
<td>not ventilated, with air space</td>
<td></td>
<td>1.1</td>
<td>0.9</td>
</tr>
<tr>
<td>4. Fair</td>
<td>without gap but sealed</td>
<td></td>
<td>1.3</td>
<td>1.1</td>
</tr>
<tr>
<td>5. Poor</td>
<td>not ventilated without air space</td>
<td>without gap and unsealed</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

In the construction of cladding a number of details must be considered for durable design. Choice of material, distance from the ground and other water spray risk areas, corner joints, horizontal and vertical joints of boards or panels, connections to roof, windows and doors as well as ventilation are critical regions where care must be taken to minimize water ingress.
into the material and to allow moisture to dry out rapidly. Englund (2010) collected the recommendations in different national guidelines and other information sources and identified agreements and differing views. Individual design of buildings, in particular in modern architecture, often requires individual solutions in correspondence with basic principles of construction as described in various national best practice guidelines.

Besides other construction details, ventilation of the back of the cladding and protection of wood end grain are two major factors influencing durability with most dominant impact on the risk of decay. Therefore, these features were chosen to rate detail design of cladding in the guideline for a very basic assessment that can easily be applied in any case. Schober et al (2007) carried out detailed investigations on the influence of ventilation at the back of the cladding on hygrothermal behaviour (heat transmission, moisture balance) of cladding on test houses under natural weathering and with non-steady state computer modelling. Based on their results they described the four types of ventilation of the back of the cladding shown in Fig. 10 and they created a matrix to judge whether a construction is critical and must be assessed by detailed calculations or if it is acceptable (Fitl et al. 2007, Schober et al. 2010). Fully ventilated claddings turned out to be beneficial and hence they can be considered as the safest type of construction to avoid decay risk of the wood whereas lower degrees of ventilation can lead to critical situations and must be considered by careful planning. These conclusions were confirmed in an independent study by Kehl & Hauswirth (2009).

![Figure 10. Categories of ventilation of the back of the cladding, Schober et al. (2007).](image)

Due to the capillary structure of wood the end grain can soak up and transport water easily, which makes end grain surfaces of panels and boards sensitive to moisture ingress which may induce decay by wood destroying fungi. Many defects caused by rot fungi occur in the proximity of wood end grain, see e.g. Suttie et al (2011), and therefore its protection is of utmost importance for durable design. End grain is preferably covered by other elements and its moisture uptake can be significantly reduced by special sealants applied in a few layers (Boxall et al. 1992). Gaps of sufficient size (> 1 cm) are beneficial for good ventilation, rapid drying and possible maintenance of sealants. Butted end joints (with a small or no gap for ventilation) are extremely vulnerable and should be avoided. They can be acceptable, but only with rigorous sealing of the end grain, Englund (2010).

Coating systems are able to protect wood against moisture ingress and they influence moisture release depending on their permeability for liquid water and water vapour (Ekstedt 2002, 2012).
Fig 11, from Grüll et al. (2010a), shows the effect of intact coating systems on wood moisture content measured in naturally weathered panels during 18 months. The moisture level and moisture fluctuations for panels with coatings are clearly reduced compared with untreated panels (labelled U in Fig. 11). The investigated coating systems in Fig. 11 are ICP (Internal Comparison Product applied in 1, 2 or 3 layers), P (light brown acrylic stain semi transparent (+ primer) and with top coat film thicknesses <20, 50 or 80 µm) or W (white acrylic paint opaque (+primer) with top coat film thicknesses 50 or 100 µm). Wood moisture content is influenced by the type of binder, the film thickness and the colour of the coating systems. The first two are major factors to determine coating permeability, Janotta (1973), Ekstedt (2002). The light colour of white opaque paints leads to higher levels of wood moisture content in cladding panels compared to darker stains, in particular in summer periods, Janotta (1979), Fitl et al. (2007), Grüll et al. (2010a). This can be explained by less energy absorption of sunlight for these panels. Engelund et al. (2009) conducted moisture measurements on cladding elements exposed vertically, showing the influence of butt joints and open end grain. They concluded on service life prediction and maintenance periods of coatings as well as the risk of biological decay. Grüll et al. (2011) carried out a similar experiment on a cladding with ventilated back side and various coating systems. They found reduced moisture fluctuations on panels coated with less permeable systems and in particular with light colour, see Fig. 12. Critical limits of wood moisture content were not reached in their experiment which underpins the higher safety of fully ventilated cladding. A summarized conclusion of these studies is that coatings reduce decay risk of cladding boards as long as they are in good condition without significant degradation due to weathering provided that construction details of the cladding are according to the above mentioned construction principles to avoid moisture traps. Schober et. al. (2010) recommend coating systems with sd-values < 1m (diffusion equivalent air layer thickness according to EN ISO 12572, dry cup method) to reduce the risk of moisture trapping by the coating. This recommendation was based on experiments described in Schober et. al. (2007).

The durability and protective properties of coatings on exterior wood are limited in time which results in a service life of the coating that usually is different from the service life of the wood component. The durability of wood coatings has been investigated in numerous studies. It is influenced by a variety of factors, where coating formulation, film thickness, pigmentation, use of light stabilizers, substrate properties and design as well as exposure conditions play the most important roles (Sell 2003, Ekstedt 2002, de Meijer 2002, Richter 2006, Schober et al. 2006). Degradation of coated wood surfaces leads to decreasing moisture protection of the coating and hence, increasing moisture fluctuations in the wood. The results of Grüll et al. (2010a) confirm that the occurrence of cracks indicates a limit state of the coated element when maintenance is required. Various types of limit states for coatings based on experiences with maintenance procedures were proposed by Grüll et al. (2010b). These limit states are shown in Table 10. Hence, regular checking and maintenance of coated surfaces is important to ensure the protective function of a coating as well as the aesthetic aspects of a building.

Coating application on wood for cladding requires suitable profiles where edges are rounded. The reason for this is that an uneven and very low film thickness would occur at sharp edges due to the surface tension of the wet coating material when it is applied to the wood, see Fig. 13. Coating application on freshly machined wood surfaces promotes adhesion of coatings and previous ageing or weathering should therefore be avoided.
Figure 11. Wood moisture content (smoothed by weekly average) of coated wood panels (coating systems 1x ICP, 2x ICP, 3x ICP, P20, P50, P80, W50, W100, U uncoated reference) during 18 month natural weathering 45° south in Vienna (Grill et al. 2010a)
Figure 12. Comparison of wood moisture content in boards of a fully ventilated cladding; uncoated (U), low build water borne brown stain (4w); high build opaque brown solvent born coating system (10s), Grüll et al. (2011).

Table 10. Definition of limit states for wood coating systems (Grüll et al. 2010b)

<table>
<thead>
<tr>
<th>Limit state</th>
<th>Film forming coatings</th>
<th>Non film forming coatings</th>
<th>State of coating</th>
<th>Defects</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-E</td>
<td>Aesthetical limit, optical deficiency</td>
<td>Aesthetical limit, optical deficiency</td>
<td>only optical alterations</td>
<td>change of gloss, change of colour, growth of algae</td>
</tr>
<tr>
<td>L-D1</td>
<td>Maintenance interval</td>
<td>Maintenance interval = Renovation interval</td>
<td>minor defects that do not require removal of original coating</td>
<td>reduction of film thickness &gt; 50%, intensive chalking, cracks in coating film (without discolouration), flaking in single areas (&lt; 5mm², without discolouration), superficial mould growth/blue stain</td>
</tr>
<tr>
<td>L-D2</td>
<td>Renovation interval</td>
<td></td>
<td>coating degradation</td>
<td>cracking, blistering, flaking, hail damage, discolouration around cracks, penetrating mould growth/blue stain</td>
</tr>
<tr>
<td>L-D3</td>
<td>Decay of wood</td>
<td>Decay of wood</td>
<td>onset of decay in wood</td>
<td>brown rot fungi, white rot fungi, wood boring insects</td>
</tr>
</tbody>
</table>

Figure 13. Film formation at sharp and round edges, Schober et al. (2010).
4. Design value $I_{Rd}$ for resistance depending on material

Biological durability is the key factor determining performance for wood materials in different use classes. The robust laboratory and field test methods that exist make it possible to assign a durability and decay resistance rating to timber linked to the intended use class according to EN 335 (1992), assuming a worst case scenario.

The biological natural durability of wood is complex and is linked to the structure of the wood, the chemical composition, the position of the wood in the tree, the age and maturity of the tree, the forest management system employed and the growth region. The European standard test methods and classification system manages a degree of this variability and complexity. For general evaluation, wood species are classified into durability classes as described in EN 350-1 (2004) and presented as durability classes for heartwood of timber species in EN 350-2 (Table 11). Durability class is a classification on five levels from not durable to very durable. This is based on decades of data from European ground contact field trials for use class 4. The natural durability for a wood species can vary widely and even within the same species, especially when considering different regions of origin.

Table 11. Durability class of some timber species according to EN 350-2. Mainly valid for wood in ground contact.

<table>
<thead>
<tr>
<th>Durability class</th>
<th>Description</th>
<th>Examples of timber species*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very Durable</td>
<td>Heartwood of afzelia, robinia</td>
</tr>
<tr>
<td>2</td>
<td>Durable</td>
<td>Heartwood of western red cedar</td>
</tr>
<tr>
<td>3</td>
<td>Moderately durable</td>
<td>Heartwood of sweet chestnut and larch species</td>
</tr>
<tr>
<td>4</td>
<td>Slightly durable</td>
<td>Heartwood of Douglas fir, Scots pine, Norway and Sitka spruce</td>
</tr>
<tr>
<td>5</td>
<td>Not durable</td>
<td>Heartwood of European beech and sycamore. Sapwood of all wood species.</td>
</tr>
</tbody>
</table>

*For the majority of timber species there is variability in natural durability associated with the provenance, growth region and whether sourced from plantation grown timber. A review of EN 350-2 is underway in CEN/TC38 to capture new durability information and to address some of these variables. The material durability classification should defer to local knowledge based on field test data and laboratory test data from independent experts.

National timber and wood science research organizations often manage test fields for in ground and out of ground contact trials. These provide up-to-date data and information on the durability of commercial wood species. These are published in technical reports see e.g. BRE (1998), BRE (2001), Edlund and Bergman (2000), Bergman and Terziev (2007), Edlund and Jermer (2007) and Flæte et al (2011).

The durability class is one component of resistance class and the other is the permeability of the wood to water which in practical terms of wood treatment is presented as treatability - the ease with which a wood preservative treatment can be achieved with the species, see Table 12.
Table 12. Treatability classifications according to EN 350-2.

<table>
<thead>
<tr>
<th>Treatability class</th>
<th>Class description</th>
<th>Examples of timber species</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Easy to treat</td>
<td>Heartwood of European beech, sapwood of pine species</td>
</tr>
<tr>
<td>2</td>
<td>Moderately easy to treat</td>
<td>Heartwood of Scots pine, sapwood of larch species</td>
</tr>
<tr>
<td>3</td>
<td>Difficult to treat</td>
<td>Heartwood of larch and spruce species, western red cedar</td>
</tr>
<tr>
<td>4</td>
<td>Extremely difficult to treat</td>
<td>Heartwood of afzelia, robinia, sweet chestnut</td>
</tr>
</tbody>
</table>

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 the term “markedly different” is used to describe the additional benefits of low permeability on the performance of wood out of ground contact. Although long term field trials above ground are not so common with wood species frequently used in different parts of Europe for exterior end uses, recent trials indicate that the ranking will be roughly the same as for ground contact trials, see e.g. Flæte et al (2011), Edlund and Jermer (2007) and Edlund et al (2006).

The design resistance index $I_{Rd}$ for selected wood materials is determined on the basis of resistance class, see Table 13. 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 term is based on a combination of durability class data according to EN 350-2, test data, practical experience of treatability and permeability for wood species as well as experience from use in practice. One can always argue that the classification should be different from that presented in Table 13 and indeed this will need refining in future. However, it is believed that the classification reflects reality reasonable well.

Norway spruce ($Picea abies$) is chosen as reference material and assigned $I_{Rd} = 1.0$. Although field tests in ground contact, e.g. Edlund et al (2006), Bergman and Terziev (2007), and above ground, e.g. Flæte et al (2011) indicate similar durability for spruce as for pine sapwood, pine sapwood and sapwood of other wood species have been assigned a slightly lower $I_{Rd} = 0.7$. This difference is justified by the fact that the permeability (water uptake) of spruce is lower than for pine heartwood, see e.g. Viitanen et al (2006), Edlund (1992), Blom et al (2010). This property, in particular for vertical timbers, Lindegaard and Morsing (2003), is probably the reason why spruce traditionally has been used for external cladding in the Nordic countries.

The resistance class is maximized (class A) for wood species or treatments where the durability class is very durable (class 1) and the treatability class (permeability) is extremely difficult to treat (class 4). It is accepted that if a material of high resistance class is selected then this may deliver a satisfactory service life for the cladding irrespective of the exposure aspects and moisture risk. Hence the high index $I_{Rd}$ value of 10 for the highest resistance class.

If there is difficulty in deciding how to classify a wood substrate within resistance class then advice should be sought from national experts. It is for example 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. This should be verified by independent national experts.
Table 13. Resistance rating of selected wood materials and corresponding design resistance index $I_{Rd}$.

<table>
<thead>
<tr>
<th>Material resistance class</th>
<th>Examples of wood materials*</th>
<th>$I_{Rd}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Heartwood of very durable hardwoods, e.g. afzelia, robinia (durability class 1) Preservative-treated sapwood, industrially processed to meet requirements of use class 3</td>
<td>10,0</td>
</tr>
<tr>
<td>B</td>
<td>Heartwood of durable wood species e.g. sweet chestnut and western red cedar (durability class 2)</td>
<td>5,0</td>
</tr>
<tr>
<td>C</td>
<td>Heartwood of moderately and slightly durable wood species e.g. douglas fir, larch and Scots pine (durability classes 3 and 4)</td>
<td>2,0</td>
</tr>
<tr>
<td>D</td>
<td>Slightly durable wood species having low water permeability (e.g. Norway spruce)</td>
<td>1,0</td>
</tr>
<tr>
<td>E</td>
<td>Sapwood of all wood species (and where sapwood content in the untreated product is high)</td>
<td>0,7</td>
</tr>
</tbody>
</table>

*For the majority of wood materials there is variability in material resistance. The material resistance classification should refer 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.

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. 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 (EN 350-2). 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. Expert advice is recommended for assigning the material resistance class for batches of preservative treated wood.

During the WoodExter project very few studies with treated heartwood have been found. However, Edlund and Bergman (2000) and Bergman and Terziev (2007) report two interesting in ground field trials that are summarized in Tables 14 and 15.
Table 14. Results from stake tests with preservative-treated and untreated heartwood of different wood species after 16 years’ exposure in Ultuna, Sweden (after Edlund and Bergman, 2000).

<table>
<thead>
<tr>
<th>Wood species</th>
<th>Average service life (years)</th>
<th>Rentokil K33*</th>
<th>Cuprinol Tryck**</th>
<th>Untreated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red silver fir</td>
<td>7,5</td>
<td>14</td>
<td>2,6</td>
<td></td>
</tr>
<tr>
<td>Lodgepole pine</td>
<td>6,1</td>
<td>9,5</td>
<td>1,8</td>
<td></td>
</tr>
<tr>
<td>Douglas fir</td>
<td>4,4</td>
<td>3,3</td>
<td>2,1</td>
<td></td>
</tr>
<tr>
<td>Larch</td>
<td>3</td>
<td>3,2</td>
<td>2,4</td>
<td></td>
</tr>
<tr>
<td>Scots pine</td>
<td>7,8</td>
<td>7,4</td>
<td>3,2</td>
<td></td>
</tr>
<tr>
<td>Western Hemlock</td>
<td>12</td>
<td>13</td>
<td>3,9</td>
<td></td>
</tr>
</tbody>
</table>

*A CCA-type preservative  
** An ammoniacal copper-organics type preservative

Table 15. Stake tests in Ultuna, Sweden, with sapwood and heartwood of Scots pine and Norway spruce, untreated and treated with different wood preservatives

<table>
<thead>
<tr>
<th>Wood species</th>
<th>Average service life</th>
<th>Rentokil K33</th>
<th>Cuprinol Tryck</th>
<th>Creosote</th>
<th>Untreated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scots pine heartwood</td>
<td>8,0</td>
<td>8,5</td>
<td>12</td>
<td>2,7</td>
<td></td>
</tr>
<tr>
<td>Spruce heartwood</td>
<td>4,0</td>
<td>6,6</td>
<td>3,5</td>
<td>1,9</td>
<td></td>
</tr>
</tbody>
</table>

It is clear from this data that the preservative treatment, although with less penetration and retention of preservative, will enhance the durability of the heartwood in ground contact. It is reasonable to assume that this will also be the case for above ground performance.

For untreated wood if there is a mixture of heartwood and sapwood present in the wood species then the material resistance may 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 component of the overall material. Expert advice is recommended for assigning the material resistance class.

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 recommended for assigning the material resistance class for modified wood.
5. Verification of the guideline by reality checks

All elements in the design described so far are only expressed in relative terms. The calibration factor \( c_a \) in Eq. 4 has to be determined to produce a reasonable safety margin against non-performance. The only possible approach at the present level of knowledge is to check if the system will give reasonable results in accordance with generally accepted and known experience. For this reason verification of the guideline against a number of reality checks of decking and building cladding across Europe 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 the reality checks presented below, the interpretation of the guideline was made by the individual named. Information about each case is summarized in Table 16 and further detail can be found in Suttie et al (2011).

Table 16. Basic information about reality checks.

<table>
<thead>
<tr>
<th>Case</th>
<th>Type</th>
<th>Location</th>
<th>Coating</th>
<th>Material</th>
<th>Source</th>
<th>Actual performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C</td>
<td>Öland, SE</td>
<td>*</td>
<td>Pine</td>
<td>Jöran Jermer</td>
<td>No decay after 60 years</td>
</tr>
<tr>
<td>2</td>
<td>C</td>
<td>Stockholm, SE</td>
<td>yes</td>
<td>Spruce</td>
<td>Jöran Jermer</td>
<td>Decay after 15 years</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>Turku, FIN</td>
<td>yes</td>
<td>Spruce</td>
<td>Hannu Viitanen</td>
<td>No decay after 20 years</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>Helsinki, FIN</td>
<td>yes</td>
<td>Spruce</td>
<td>Hannu Viitanen</td>
<td>Decay after 20 years</td>
</tr>
<tr>
<td>5</td>
<td>C</td>
<td>Bordeaux, FR</td>
<td>no</td>
<td>Western Red Cedar</td>
<td>Ed Suttie</td>
<td>No decay after 40 years</td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>Garston, GB</td>
<td>no</td>
<td>Western Red Cedar</td>
<td>Ed Suttie</td>
<td>No decay after 15 years</td>
</tr>
<tr>
<td>7</td>
<td>D</td>
<td>Helsingborg, SE</td>
<td>no</td>
<td>Larch</td>
<td>Jöran Jermer</td>
<td>Severe decay after 5-6 years</td>
</tr>
<tr>
<td>8</td>
<td>D</td>
<td>Vienna, AT</td>
<td>no</td>
<td>Larch</td>
<td>Peter Schober</td>
<td>Decay after 10 years</td>
</tr>
<tr>
<td>9</td>
<td>D</td>
<td>Vienna, AT</td>
<td>no</td>
<td>Teak</td>
<td>Peter Schober</td>
<td>No decay after 6 years</td>
</tr>
<tr>
<td>10</td>
<td>D</td>
<td>Vienna, AT</td>
<td>no</td>
<td>Oak</td>
<td>Peter Schober</td>
<td>Decay after 6 years</td>
</tr>
<tr>
<td>11</td>
<td>D</td>
<td>Essing, DE</td>
<td>no</td>
<td>Azobé</td>
<td>C Brischke</td>
<td>Decay after 16 years</td>
</tr>
<tr>
<td>12</td>
<td>D</td>
<td>Germany</td>
<td>no</td>
<td>CCB-treated pine</td>
<td>C Welzbacher</td>
<td>Decay after 15 years</td>
</tr>
<tr>
<td>13</td>
<td>C</td>
<td>NW France</td>
<td>no</td>
<td>Western Red Cedar</td>
<td>L Podgorsi</td>
<td>OK after 20 years but some boards replaced after 5 years</td>
</tr>
<tr>
<td>14</td>
<td>C</td>
<td>NW France</td>
<td>no</td>
<td>Western Red Cedar</td>
<td>L Podgorsi</td>
<td>Decay after 20 years</td>
</tr>
<tr>
<td>15</td>
<td>D</td>
<td>SW France</td>
<td>no</td>
<td>Robinia</td>
<td>L Podgorsi</td>
<td>Limited decay after 10 years</td>
</tr>
<tr>
<td>16</td>
<td>D</td>
<td>SW France</td>
<td>no</td>
<td>Robinia</td>
<td>L Podgorsi</td>
<td>No decay after 12 years</td>
</tr>
<tr>
<td>17</td>
<td>D</td>
<td>NE France</td>
<td>no</td>
<td>Preservative-treated pine</td>
<td>L Podgorsi</td>
<td>Decay after 20 years</td>
</tr>
</tbody>
</table>

*Surface treatment with creosote, C = cladding, D = decking

The cases listed in Table 16 were evaluated with the guideline and the results are shown in Table 17 assuming that the calibration factor was set to 1.0. The output from the guideline tool agrees with the actual performance on the buildings in the majority of the cases, but did not agree 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 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 natural durability, given that only heartwood
is present, which was assumed in the design tool evaluation. Under this assumption the guideline predicted that the design in these three cases should be acceptable implying a service life up to 30 years. 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-treated 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 4.

It should be noted 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 these reality checks. The research team invites more data to be tested in the guideline tool to improve our understanding.

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

<table>
<thead>
<tr>
<th>Case</th>
<th>Site $I_{sk}$</th>
<th>Local $k_{s1}$</th>
<th>Shelt. $k_{s2}$</th>
<th>Dist. $k_{s3}$</th>
<th>Detail $k_{sd}$</th>
<th>$I_{sd} = \gamma_d I_d$</th>
<th>$I_{sd} &lt; I_{Rd}$?</th>
<th>reality</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.9</td>
<td>1.08</td>
<td>0.9</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.5</td>
<td>0.9</td>
<td>1.35</td>
<td>0.9</td>
<td>1.21</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
<td>0.9</td>
<td>0.45</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>1.4</td>
<td>1.0</td>
<td>1.5</td>
<td>0.9</td>
<td>1.89</td>
<td>0.9</td>
<td>1.70</td>
</tr>
<tr>
<td>5</td>
<td>2.08</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.1</td>
<td>2.29</td>
<td>0.9</td>
<td>2.64</td>
</tr>
<tr>
<td>6</td>
<td>1.64</td>
<td>1.2</td>
<td>1.0</td>
<td>1.0</td>
<td>0.8</td>
<td>1.57</td>
<td>0.9</td>
<td>1.42</td>
</tr>
<tr>
<td>7</td>
<td>1.5</td>
<td>1.4</td>
<td>1.0</td>
<td>1.0</td>
<td>1.4</td>
<td>2.94</td>
<td>0.9</td>
<td>2.64</td>
</tr>
<tr>
<td>8</td>
<td>1.4</td>
<td>1.2</td>
<td>1.0</td>
<td>2.0</td>
<td>1.4</td>
<td>4.70</td>
<td>0.8</td>
<td>3.76</td>
</tr>
<tr>
<td>9</td>
<td>1.4</td>
<td>1.2</td>
<td>1.0</td>
<td>2.0</td>
<td>1.0</td>
<td>3.36</td>
<td>0.8</td>
<td>2.69</td>
</tr>
<tr>
<td>10</td>
<td>1.4</td>
<td>1.2</td>
<td>1.0</td>
<td>2.0</td>
<td>1.2</td>
<td>4.03</td>
<td>0.8</td>
<td>3.22</td>
</tr>
<tr>
<td>11</td>
<td>1.4</td>
<td>1.2</td>
<td>1.0</td>
<td>1.5</td>
<td>1.0</td>
<td>2.94</td>
<td>0.9</td>
<td>2.65</td>
</tr>
<tr>
<td>12</td>
<td>1.4</td>
<td>1.0</td>
<td>1.0</td>
<td>1.5</td>
<td>1.2</td>
<td>2.52</td>
<td>0.9</td>
<td>2.27</td>
</tr>
<tr>
<td>13</td>
<td>1.7</td>
<td>1.4</td>
<td>1.0</td>
<td>1.5</td>
<td>0.8</td>
<td>2.86</td>
<td>0.9</td>
<td>2.57</td>
</tr>
<tr>
<td>14</td>
<td>2.0</td>
<td>1.4</td>
<td>1.0</td>
<td>2.0</td>
<td>1.5</td>
<td>8.40</td>
<td>0.9</td>
<td>7.56</td>
</tr>
<tr>
<td>15</td>
<td>2.0</td>
<td>1.2</td>
<td>1.0</td>
<td>1.5</td>
<td>1.2</td>
<td>4.32</td>
<td>0.9</td>
<td>3.89</td>
</tr>
<tr>
<td>16</td>
<td>2.0</td>
<td>0.8</td>
<td>0.7</td>
<td>1.0</td>
<td>1.2</td>
<td>1.34</td>
<td>0.9</td>
<td>1.21</td>
</tr>
<tr>
<td>17</td>
<td>1.4</td>
<td>1.2</td>
<td>1.0</td>
<td>1.5</td>
<td>1.6</td>
<td>4.03</td>
<td>0.9</td>
<td>3.63</td>
</tr>
</tbody>
</table>

*This has been assigned a value slightly better than pine heartwood, since untreated heartwood probably was present
6. Future research needs

The engineering design guideline described in this report should be seen as a first prototype for a quantitative tool in the area of wood durability and the performance of wood products. Many of the elements in the guideline are still uncertain and crude and are based on expert judgements. To be able to improve the guideline and have a more solid knowledge base for it a number of aspects need to be addressed in future research.

A key element is the performance model which is used to establish the relation between exposure and resistance to decay. This model need to be further developed and verified for a broader range of materials. To accomplish this, more test data is needed where development of decay above ground is studied and where the exposure in terms of moisture content and temperature is recorded during the test period. New laboratory test methods are needed to investigate how the mechanisms behind growth of fungi are affected by moisture and temperature as well as other important factors. A comprehensive overview of future possibilities in this field has recently been presented by Brischke et.al. (2011b).

The effect of global climate exposure should be described with a more detailed mapping based on an improved performance model. Improved models need to be developed, which can predict moisture content variation in wood elements based on time series of available global climate data such as relative humidity, rain and temperature. A significant point is to study the effect of variability between years so that probability of extreme exposure situations can be estimated. An important aspect is the effect of local conditions (meso-climate) which need to be studied so that effects from e.g. driving rain can be predicted in a more reliable way.

As regards micro-climatic exposure, more knowledge is needed about the effect of detailing solutions on risk for adverse moisture exposure. In this report a comparative approach is described where moisture content is measured in sets of type details under the same external exposure so that the relative performance of details can be quantified. More tests of this type should be performed. This can improve the basis for developing sound design solutions of wood commodities exposed outdoors. Modelling of moisture dynamics in typical details will also contribute to improve the basis for developing efficient durability design. Type details for different categories of exterior wood structures should be identified and tested systematically including the effect of wood materials with different water uptake properties.

Research within the framework of the project and previous studies underpin the effect of intact coating systems to reduce moisture in wood elements exposed to weathering. However, consequences of coating degradation, such as cracking and flaking, have not been considered sufficiently and require further research. Basic questions to be addressed are: What is the effect of coating in the vicinity of joints and details? How do coatings contribute to moisture trapping? Also the influence of coating maintenance on moisture conditions in coated wood is of interest, where only limited knowledge is available.

The most important element in durability design of this kind is to quantify the resistance correctly. In spite of decades of field testing of wood species and wood products both in ground and above ground there are large gaps in knowledge due to the complexity of the issue and the long time spans needed to get reliable results. One of the critical issues is the variability of wood also within the same species due to largely varying growth characteristics.
and the dependence on position in the tree. An obvious problem in practice is to distinguish between heartwood and sapwood, which often is crucial for the result. In the future there is a need for more precise and reliable test methods to verify resistance of wood material, both in field tests and in laboratory tests. There is a need for independent above ground use class 3 field test data. Field tests in use class 3 applications should be performed with much better control of exposure and with monitoring of moisture content as proposed by Brischke et al (2011b). It would also be of value if the specimens used in the tests could be tested for permeability and other relevant control properties of the specimens to reduce the variability and obtain a better basis for interpretation of results. The variability in test results should also be monitored and reported.

There is obviously a large need to develop novel research and test methods regarding resistance of wood to decay, such as

- more reliable methods to quantify and measure decay
- fast methods to detect initiation or early growth of decay
- indirect methods to characterize sensitivity to decay in wood materials
- rational methods to distinguish between heartwood and sapwood
7. Summary and conclusions

The background and principles for an engineering design guideline for wood in outdoor above
ground applications, i.e. use class 3 according to EN 335 (1992), have been presented in this
report. 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 design of details 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 in some cases 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 they are made aware of the importance of appropriate detailing solutions on performance

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 and further encourage best practices. Many users have a 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.

Finally the authors of this report invite all readers to use the guideline in practice. Readers are also invited to provide reality checks, i.e. to apply the guideline for existing decking and cladding solutions where the actual long term service life performance is known. Feed-back concerning the results of such exercises can be sent to Sven.Thelandersson@kstr.lth.se. The guideline, the associated Excel tool and the present background document can be downloaded for free at www.kstr.lth.se.
8. Acknowledgements

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**Metconorm**: *Global Meteorological Database for Engineers, Planners and Education.*

http://www.meteonorm.com/ METEOTEST.


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Service life of wood in outdoor above ground applications: Engineering design guideline

Background document

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Lund 2011