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Durability and outdoor performance of wood products - Towards a comprehensive methodology for service life prediction

Durability and outdoor performance of wood products – Towards a comprehensive methodology for service life prediction

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CONTENT

ABSTRACT

The building sector is strongly requested to provide reliable data on the performance of building materials and products, in particular for highly demanded renewable materials from sustainably managed production. In this respect wood and wood-based products can play a key role. Wood has numerous advantages compared to other building materials such as a high strength-weight ratio, good thermal insulation, and appealing aesthetics. However, its durability against different biological agents is limited and requires consideration when wood is exposed to moisture and thus favourable conditions for decay. Performance prediction of wooden structures and components therefore requires particular tools and instruments allowing for consideration of biotic degradation agents.

The overall objective of this thesis was to develop a system of methods and models for classifying the durability and outdoor performance of wood products. The system should allow for discrete quantification of durability and performance related parameters, service life prediction, and considering moisture induced risk as well as potential decay organisms. It should be applicable to all relevant wood-based materials, transferable to various use and exposure conditions, and utilisable in field durability testing.

Therefore, various laboratory and field test methods as well as long-term monitoring of real timber structures in service were applied to a wide range of wood-based materials. The data obtained were used for developing decay models to describe the effect of macro and micro climate on the material climate, and thus on the moisture and temperature induced risk for decay in wooden structures. Different approaches were followed to achieve i.) precise service life prediction, ii.) quantification of decay influencing factors (factorisation), and iii.) a performance classification system considering material resistance and moisture dynamics of wood-based products.

From the various surveys and experimental studies regarded in this thesis it became obvious that instruments are needed to break up the rigid traditional ways of durability and efficacy testing as manifested in European standards today. To pave the way for performance based building and design, durability testing needs to get linked with service life prediction as well as life cycle analysis and life cycle costing. Well-functioning performance models, transparent test data, and a universally applicable set of instruments are needed to deliver reliable wood-based components of controlled durability with minimum maintenance needs and life-cycle costs. However, a tool that is considered universal on the one hand, should be specific for certain applications on the other hand. For instance, a dose-response approach is

universally applicable, but allows consideration of a dosage only for specific agents.
The set of models developed in this thesis are in principle able to predict service lives as absolute numbers in years, and allow discrete quantification of decay influencing factors as relative values. This factorisation approach can be easily implemented in design guidance as well as for performance prediction. Nevertheless, the models developed on the base of field test results so far turned out to be decay type specific. Therefore, further validation and modification of the models where required will be a task for the future.
Information about regional peculiarities and markets become increasingly important in a globalised world. Setting thresholds and defining safety margins might be operated on national level. Guidance on how to treat climatic differences within and beyond Europe should be provided on a European or even international level. For a better handling of differences in climate induced hazards it will be beneficial to develop more precise and more reliable climate models that can be linked to performance prediction on macro, meso or even local level.
With respect to the intensive discussion about climate change impacts on human beings and their environment, the question to what extent the moisture induced risk for decay and the resulting performance of wood are affected was addressed. The partly drastic effects of climate change on the durability of wood became evident. However, their quantity will strongly depend on the geographical position and the prevailing climate.

ZUSAMMENFASSUNG

Der Baubereich steht unter dem zunehmenden Druck, verlässliche Daten über die Performance von Baumaterialien und –produkten zu liefern. Dies gilt insbesondere für stark nachgefragte nachwachsende Rohstoffe aus nachhaltiger Produktion. In diesem Zusammenhang können Holz und holzbasierte Produkte eine Schlüsselrolle einnehmen. Holz hat zahlreiche Vorteile im Vergleich zu anderen Baumaterialien wie beispielsweise ein hohes Festigkeits-Masse-Verhältnis, gute Dämmeigenschaften sowie ein ansprechendes Erscheinungsbild. Die Dauerhaftigkeit von Holz gegenüber unterschiedlichen Organismen ist allerdings begrenzt und erfordert besondere Beachtung, wenn Holz Feuchtigkeit und somit fäulnisbegünstigenden Bedingungen ausgesetzt ist. Die Vorhersage der Performance von Holz bedarf deshalb eines umfassenden Instrumentariums zur Berücksichtigung biologischer Abbauagenzien.

Das übergeordnete Ziel dieser Arbeit war es, ein System aus Prüfmethoden und Modellen zur Klassifizierung der Dauerhaftigkeit und Performance von Holzbauteilen zu entwickeln. Folgende Anforderungen wurden an ein solches System gestellt: diskrete Quantifizierung der Dauerhaftigkeit und weiterer Performance-Parameter, Vorhersage der Gebrauchsdauer von Bauteilen, Anwendbarkeit auf alle holz-basierten Materialien, Berücksichtigung von Feuchteverhalten und potentiellen Abbauorganismen, Übertragbarkeit auf unterschiedliche Gebrauchsbedingungen sowie die Einsetzbarkeit in Dauerhaftigkeitsprüfungen im Freiland.

Es kamen hierzu verschiedene Labor- und Freilandprüfmethoden sowie ein Langzeit-Monitoring an realen Holzkonstruktionen im Gebrauch an einer großen Vielzahl holz-basierter Materialien zum Einsatz. Die gewonnenen Daten wurden zur Entwicklung von Modellen verwendet, die den Effekt von Makro- und Mikroklima auf das Materialklima und somit auch auf das resultierende feuchte- und temperaturinduzierte Befallsrisiko beschreiben. Unterschiedliche Ansätze wurden verfolgt, um i.) eine präzise Gebrauchsdauervorhersage, ii.) die Quantifizierung abbaubestimmender Faktoren (Faktorisierung) und iii.) ein System zur Klassifizierung der Performance von Holzprodukten auf Basis von Feuchteverhalten und Materialresistenz zu erzielen.

Performance-basiertes Bauen ist eine Aufgabe für zahlreiche Forschungsgebiete wie beispielsweise die Materialwissenschaften, die Biologie, die Bauphysik und das Bauingenieurwesen, weshalb hierzu ein interdisziplinärer Ansatz unbedingt zu bevorzugen ist. Aus den zahlreichen Studien und experimentellen Untersuchungen, die im Rahmen dieser Habilitationsschrift Berücksichtigung fanden, wurde deutlich, dass

Instrumente benötigt werden, die die starre traditionelle Weise der Dauerhaftigkeits- und Wirksamkeitsprüfung, wie sie in europäischen Standards verankert ist, aufzubrechen vermag. Um den Weg für Performance-basiertes Bauen zu ebnen, ist es notwendig, die Prüfung der Dauerhaftigkeit mit Gebrauchsdauervorhersagen, Lebenszyklusanalysen sowie Lebenszykluskosten-Berechnungen zu verbinden. Funktionierende Performance-Modelle, transparente Prüfdaten und ein universell einsetzbares Instrumentarium sind nötig, um verlässliche Holzprodukte mit kontrollierter Dauerhaftigkeit, minimalem Wartungsaufwand und geringen Lebenszykluskosten bereitzustellen. Ein solches als universell betrachtetes Instrument sollte zugleich spezifisch für bestimmte Anwendungen sein. Ein Dosis-Wirkungs-Ansatz mag beispielsweise universell einsetzbar sein, ermöglicht aber zugleich die Berücksichtigung einer Dosis nur für bestimmte Abbauagenzien.

Die im Rahmen dieser Arbeit entwickelten Modelle erlauben es einerseits, Gebrauchsdauern als absolute Größe in Jahren vorherzusagen, andererseits lassen sich aber auch abbaubestimmende Faktoren durch Relativwerte diskret quantifizieren. Dieser Faktorisierungsansatz lässt sich wiederum einfach in Design-Richtlinien implementieren und somit ebenfalls für die Performance-Vorhersage nutzen. Nichtsdestotrotz scheinen die bislang entwickelten Modelle in gewisser Weise spezifisch für bestimmte Befallstypen zu sein. Eine weitere Validierung und ggf. Modifizierung der Modelle bleibt somit eine Aufgabe für die Zukunft.

Informationen über regionale Besonderheiten und Märkte gewinnen in einer globalisierten Welt weiter an Bedeutung. Dennoch ist es aktuell die Aufgabe nationaler Behörden, internationale Standards auf die landestypischen Bedürfnisse anzupassen. Die Festlegung von Grenzwerten und Sicherheitszuschlägen mag hierbei problemlos auf nationaler Ebene erfolgen, Richtlinien zum Umgang mit Klimaeinflüssen auf die zu erwartende Performance von Konstruktionen innerhalb Europas und darüber hinaus sollten allerdings auf europäischer oder gar internationaler Ebene bereitgestellt werden. Um zukünftig mit klimainduzierten Gefährdungen für Bauteile besser umgehen zu können, werden präzisere und verlässlichere Klimamodelle benötigt, die sich darüber hinaus für die Performance-Vorhersage auf Makro-, Meso- und auch lokaler Ebene verbinden lassen.

Im Hinblick auf die intensive Diskussion über die Auswirkungen des Klimawandels auf den Menschen und seine Umwelt wurde auch die Frage, in welchem Maße das feuchteinduzierte Befallsrisiko und die daraus resultierende Performance von Holzbauteilen betroffen sind, betrachtet. Es wurden teilweise drastische Auswirkungen auf die zu erwartende Gebrauchsdauer von Holz offensichtlich. Die Quantität solcher klimawandelbedingten Einschränkungen ist aber stark abhängig von der geographischen Lage und den dort derzeit herrschenden klimatischen Bedingungen.

1 INTRODUCTION

1.1 Background

1.1.1 European standards on durability and performance of wood products – current situation and future needs

The building sector is strongly requested to improve its quality, energy efficiency, environmental performance and cost effectiveness. At the same time the use of non-renewable resources needs to be reduced. In this respect wood and wood-based products can play a key role since they are generally low in embodied CO_2 and can be gained from sustainable forest resources. Wood has numerous further advantages compared to other building materials such as a high strength-weight ratio, good thermal insulation, and appealing aesthetics. However, its durability against different biological agents is limited and requires consideration when wood is exposed to moisture and thus favourable conditions for decay.

There is an increasing need for consideration of performance classification for wood products in construction, as evidenced by the European Construction Products Regulation (CPR 2011), warranty providers and end user demands for information. A key issue for the competitiveness of wood is the delivery of reliable components of controlled durability with minimum maintenance needs and life-cycle costs. The development of performance-based design methods for durability requires that models are available to predict performance in a quantitative and probabilistic format. The relationship between durability during laboratory and field testing and the performance under in-service conditions needs to be quantified in statistical terms and the resulting prediction models need verification and adaptation according to the performance of different wood-based materials in real life.

Standardisation work in the field of wood durability, wood preservation, wood protection, and performance of wood products is managed, at the European level, by the European Committee for Standardisation technical committee (CEN/TC 38) ‘Durability of wood and wood-based products’. **Publication 6.1** provides an overview of the current situation of standardisation within this field and summarises shortcomings, future needs and challenges as well as recent movements towards a more performance oriented standardisation concept for wood-based building materials.

The overall goal of CEN/TC 38 is to elaborate standards for wood preservatives and preservative treated, modified, and untreated wood, developing terminology, analytical and biological test methods as well as classification and specification schemes in accordance with the market needs and European regulations.

Tab. 1 gives an overview of classification schedules related to wood durability and the performance of wood products. Durability, treatability, and preservative penetration classes aim to characterise the properties of the material. In contrast, use and service classes describe the environment the wooden components are exposed to. Hereby, the service classification according to EN 1995-1-1 (2010-12) has been introduced to consider the effects of temperature, humidity, weathering, and resulting wood moisture content for design of timber structures. Service classes and use classes according to EN 335 (2013) are partly overlapping. However, the most severe service class 3 is only characterised by climatic conditions leading to higher moisture contents than one can expect at 20 °C/ 85 % RH for a few weeks per year, *i.e.* moisture contents higher than 20 % for softwoods. A more detailed characterisation of such critical exposure conditions is given by EN 335 (2013), where use classes (UC) are defined according to the respective moisture conditions and potentially occurring decay organisms, such as brown, white and soft rot fungi, beetle larvae, termites, and marine borers. Finally, the European standard EN 460 (1994), which is currently approaching its first revision after more than 20 years, may be seen as the linking element between the durability and the exposure related classification concepts. The material-inherent durability is opposed to the exposure conditions to identify if preservative treatment is required in order to deliver a product that is fit for purpose. However, none of these standards provide information about the expected service life or performance. Performance classes do not exist yet, but have been suggested to be implemented in a revised EN 460 standard in order to consider material resistance alongside an exposure dose (see **publication 6.1**).

Tab. 1. Classification systems related to the durability of wood and wood products.

Classification	Standard / Reference document	Committee / Organisation
Durability classes	EN 350-1 and -2 (1994)	CEN/TC 38
Treatability classes	EN 350-2 (1994)	CEN/TC 38
Penetration classes	EN 351-1 (2007)	CEN/TC 38
Use classes	EN 335 (2013)	CEN/TC 38
Gebrauchsklassen [Use classes]	DIN 68800-1 (2011)	NA 042-03-01 AA / Normenausschuss Holzwirtschaft und Möbel (NHM)
Service classes	EN 1995-1-1 (2010-12)	CEN/TC 250

The European landscape of wood protection has changed during the past two decades. Wood-based products from non-biocidal processes entered the market such as wood modification and treatments with water repellents (Hill 2007, Scheiding and Welzbacher 2012). Furthermore, users and manufacturers are encouraged to use home-grown untreated timber, e. g. through off-setting low durability through optimised design (e. g. Thelandersson *et al.* 2011, Isaksson *et al.* 2014). European regulations, not at least the Construction Products Regulation (CPR, EC 2011) also encourage the development of products, which are more efficient and less harmful for the environment and human health, and whose performance takes into account end-user expectations. The latter particularly deviate between countries as well as between product groups as shown in a Europe-wide survey by Englund (2013).
As a consequence one can observe a gradual shift in the global approach from traditional ‘wood preservation’ to ‘wood protection’, which is a more general concept. Besides the inherent characteristics of the material the concept takes into account interactions with its environment, *i. e.* design, maintenance, workmanship, exposure, and moisture risks. In this respect validation tools are needed to ensure the reliability of new products, processes and construction rules. Several issues crucial for the future improvement of such instruments and corresponding standards were addressed in **publication 6.1**.
For historical reasons the majority of current standards is meant for the assessment of the efficacy of wood preservatives and the inherent resistance of wood species respectively, but they are typically inadequate for qualification of new products such as wood polymer composites and modified wood. The suggested test protocols of resistance tests against basidiomycetes (e. g. EN 113, 1996, CEN/TS 15083-1, 2005) do not reflect the divergent modes of protective action of preservative treated, modified, and untreated wood, since it is invalidated by forced moistening. In analogy, durability of wood-based materials may vary between different outdoor exposures. For instance, thermally modified wood is suffering from permanent wetting when it is exposed to ground contact, but performs fairly well if re-drying is possible as in above ground exposures (Welzbacher and Rapp 2007, Metsä-Kortelainen *et al.* 2011).
Durability is usually expressed as relative measure, e. g. as factor or related durability class (EN 350-1, 1994). This allows comparison between test results obtained at different test sites and makes this property independent of geographical locations and respective climatic conditions. However, transferability of durability data from one exposure situation to the other is restricted, since moisture risks as well as the society of decay organisms

present can significantly differ, e. g. between tropical and moderate climates (**publication 6.2**), or between in-ground and above ground exposures. This phenomenon can be observed not only with modified timber, but also with untreated timber as shown for European oak (*Quercus robur* L. and *Q. petraea* Liebl.) in **publication 6.12**.

A first step towards a more comprehensive view on durability will be made within the actual revision of EN 350-1 and -2 (1994), which will be combined to one single standard in the future. Besides the inherent resistance of wood due to inhibiting or toxic ingredients, its permeability to water will be considered having an impact on durability and thus on performance of wood and wood based products. However, up to now no standardised test protocol exists and neither water permeability nor the susceptibility of wood to get and stay wet (wetting ability) is considered for durability evaluation in a quantitative manner. In contrast, the prominent role of wood moisture content for the decay risk is commonly accepted and considered in many studies by so-called 'time of wetness (tow)' concepts (Norberg 1999, Leicester 2001, Van den Bulcke *et al.* 2009, 2011, Viitanen *et al.* 2010b). For determining the moisture-induced risk of wooden components various measures are believed to have a significant effect, but are still not fully understood. Short, medium, and long term uptake of liquid water and water vapour require consideration as well as water release, both in dependence of the different anatomical directions of wood (Fredriksson *et al.* 2013a, 2013b, Brischke *et al.* 2014a, 2015).

Usually, standard durability tests in the field do not require moisture monitoring, even though a Europe-wide survey has shown that many research institutions would appreciate this for several reasons (Brischke *et al.* 2014c): Firstly, the protective action of many recently developed products is based on water exclusion (Humar and Lesar 2013, Thybring 2013) and their effectiveness might be approved through moisture monitoring faster and more efficiently than through long-term decay monitoring alone. Secondly, it is of great interest to quantify the moisture regime for comparing test results between climatically different test locations and to evaluate the transferability of laboratory test results to field and in-service conditions.

Wood moisture content recording is increasingly used within research, restoration and structural health monitoring projects (e. g. Fredriksson 2010, Fortino *et al.* 2013, Hasan *et al.* 2013, Cavalli and Togni 2014, Dietsch *et al.* 2014 a & b, Franke *et al.* 2014, Lanata 2015, Olsson 2014). Consequently, the amount of available data for comparative analysis of data from field tests and in-service is constantly increasing and may be used for improving future service life and performance models (see **publication 6.3**).

Differences between laboratory and field test set-ups are not exclusively related to moisture and temperature conditions; frequently they do also not involve the same decay organisms. Laboratory tests usually include a limited number of strains of white and brown rot fungi that are carefully referenced and maintained; in field tests the fungal species are 1.) almost never identified, 2.) therefore largely unknown, and 3.) not occurring as monoculture, but associated with other organisms, either simultaneously or in a succession (Råberg *et al.* 2007, Matthieu *et al.* 2013, Plaschkies *et al.* 2014, Meyer *et al.* 2015). Restricting laboratory decay tests to a certain set of fungi involves therefore the risk of over- or underestimating the resistance of the material in question. Depending on the choice of test fungi differences in durability can be obtained up to several durability classes (e.g. Welzbacher and Rapp 2007, Meyer *et al.* 2014). In particular the susceptibility of certain materials, for instance the white rot sensitivity of thermally modified timber (TMT) or the copper tolerance of some brown rot causing basidiomycetes, is difficult to tackle with standard laboratory test protocols. More detailed consideration of the different groups of decay organisms is obviously needed and shall be considered as an additional aspect for a performance classification concept.

1.1.2 Availability and usability of durability data

Service life and performance prediction of wood products requires reliable test data. Hereby, the material-inherent resistance of wood is one of the most important qualities influencing the durability of timber. In addition, design details and climatic conditions determine durability and make it impossible to treat wood durability as an absolute value. Moreover, the reference magnitude varies between locations because of climatic differences (Francis and Norton 2005, Brischke and Rapp 2008, Flæte *et al.* 2011), wherefore any durability classification is based on comparing a certain performance indicator between the timber in question and a reference timber. Finally, the relative values (factors) are grouped and related to durability classes, which can refer to a high range of service lives for a certain location.
The insufficient comparability of such durability records (e. g. Willeitner and Peek 1997) has turned out to be a major challenge for service life prediction of timber structures. Therefore, a global inventory of literature data was conducted directly based on service life measures, not masked by a durability classification schedule (**publication 6.2**). In addition, the author team provided their own test data from terminated and still ongoing tests. The focus of the survey was clearly on natural durability of timber tested in the field under above-ground conditions. In total, 395 durability recordings from

31 different test sites worldwide and based on ten different test methods were collected and used for calculating resistance factors: 190 for hardwoods and 205 for softwoods.
The computation of resistance factors with either Scots pine (*Pinus sylvestris* L.) sapwood or Radiata pine (*Pinus radiata* D. Don.) sapwood as reference species allowed the wide range of previous and ongoing tests to be compared, irrespective of test configurations and assessment methods. However, a remarkable variation was found even for the relative values (resistance factors) which were expected to be less affected by climatic and further set-up related differences. The variation and how it can be related to durability classes is shown in Figure 1. The importance of this variation becomes even more obvious when calculating the expected service life: Based on the mean service life of the reference species Scots pine sapwood of 6.5 years one might expect a service life of Douglas fir (*Pseudotsuga menziesii* Franco.) between 7.4 and 29.5 years. The predicted service life of Spotted gum (*Corymbia* spp.) scattered even more between 18.7 and 473.3 years.

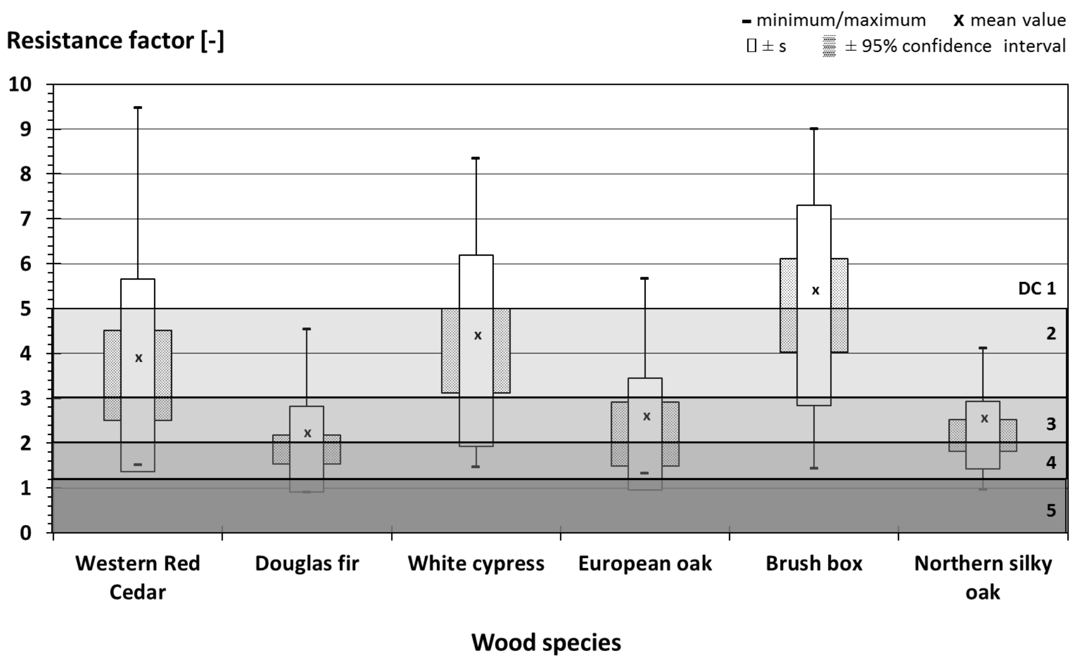

Figure 1. Variation of resistance factors of six selected wood species and corresponding durability classes (DC) according to EN 350-1 (1994), taken from: Brischke *et al.* (2013), publication 6.2.

These findings highlight the need for service life modelling to greatly increase the accuracy and relevance of information available regarding the expected durability of timber used at climatically different locations. From this survey it

was concluded that resistance factors, and hence the relative durability of different species is not necessarily the same at climatically different places. Furthermore, test and assessment methods, prevailing decay types, and detoxifying agents at the respective sites are affecting the resulting durability.
Many durability studies are known to exist around the world, but respective data are not freely available. This lack was strongly indicated through the fact that 80 % of the durability records used for the study was unpublished data. Furthermore, many data sets were incomplete or information was too condensed for further analysis. In summary, an open platform for scientific exchange was found necessary to increase the amount of available service life related data and a proposal for an open source data base has been made (Brischke *et al.* 2012) and afterwards realised in the frame of the Durability Database of the International Research Group on Wood Protection (www.irg-wp.com). Reliable and uncodified durability data were identified as key prerequisite for the development of performance models for wood in outdoor use.

1.2 Modelling the outdoor performance of wood products

1.2.1 Model types

Service life planning and performance classification require well-functioning ‘performance models’. **Publication 6.3** contains a comprehensive literature review on different approaches to adequately reflect the influence of biotic and abiotic factors on the performance of wood. The focus of the review was clearly on moisture performance and durability against fungal decay as it is the focus of this thesis.
The term ‘performance model’ is to some extent ambiguous in a double sense: On the one hand ‘performance’ can be understood differently depending on the respective material, product, commodity, and its application. On the other hand, the general meaning of ‘model’ is the ‘schematic description of a system, theory, or phenomenon that accounts for its known or inferred properties and may be used for further study of its characteristics’, but it is not settled which factors will describe the command variable. In particular for bio-based building materials biological agents need consideration for service life modelling.
As shown for the UC concept according to EN 335 (2013) the exposure conditions of wooden structures can be categorised either according to the respective moisture regime, to the likelihood that certain decay organisms occur, or both. In particular above-ground situations are characterised through the respective moisture conditions, whereby UC 4 (‘ground contact’) is considered to be permanently wet. Consequently, developing performance

models with respect to fungal decay above ground covers a wide range of exposure conditions and it appears reasonable that one general model cannot display the whole diversity of exposure conditions; rather a set of models is needed each considering a particular exposure range and group of potentially occurring organisms.

Mathematical models are widely used in natural sciences to handle different variables. Depending on the system to be analysed the type and structure of the most suitable model might significantly differ, and so do the preferences of scientists. Engineering models frequently work with limit states (Limit state design LSD, see EN 1995-1-1, 2010-12), which seems to stand in contrast with biological approaches aiming on displaying the full process of degradation and thus the full service life span. Therefore, dose-response functions are preferential instruments for biologists, because they describe the change in effect on an organism caused by differing levels of exposure (or dosage) to a stressor after a certain exposure time. The development of different dose-response based performance models is described in **publication 6.4** and will be further discussed in section 3.1. Furthermore, possibilities to implement logistic dosimeter approaches into limit state based engineering design guidelines will be highlighted (e. g. Isaksson *et al.* 2014).

To quantify the impact of a certain construction detail on the service life of a whole structure, many engineering tools work with factorisation and normalisation of the impact variables (e. g. Svensson *et al.* 1999, Smith and Foliente 2002, Isaksson and Thelandersson 2013). Also, this aspect does not necessarily stand in contrast with the dose-response approach, since the often dimensionless dose can be used as measure for factorisation. Arbitrary deviations from a carefully defined reference situation can thus be quantified on the basis of accurately determined biological processes such as fungal degradation (Brischke *et al.* 2014b, Isaksson *et al.* 2014). Finally, this approach is in line with recommendations given in the ISO 15686 standard series on service life planning, namely through the ‘factor method’ (ISO 15686-1, 2011).

Depending on how much *a priori* information is available for a system one can distinguish between black box models and white box models, whereby these terms do only describe extremes and usually a mathematical model is located somewhere in between. It appears trivial that using as much *a priori* information as possible increases the accuracy of a model, but nevertheless for certain applications it is worth to consider also black box models. For service life prediction computer systems would be eligible that utilise pre-programmed logic to return output to the user, but the ‘black box’ portion of such systems contains algorithms that the user does not see and does not need to know to use the system. However, for modelling biological processes

this can cause severe problems, which is why 'white-box' models are usually preferable. A multitude of materials, potential data sources, design details, exposure conditions, and abiotic and biotic agents come into consideration for service life prediction of wooden components. The existing knowledge about many of the relevant decay influencing factors can be utilised only in white box models as illustrated in **publication 6.3** with several examples (Gierlinger *et al.* 2004, Kokutse *et al.* 2006, Welzbacher *et al.* 2007, 2009).
Ideally, a performance model should therefore be transparent with traceable functional relationships to enable continual adjustment and implementing a steadily increasing amount of input data. Moreover, it needs to allow usage of data from different sources such as lab and field tests, in-situ moisture recordings, commodity and in-service performance tests, surveys, questionings and case studies. Finally, the model should allow defining different limit states as well as target performance.

1.2.2 Model approaches and applications

Different climate indices have been developed to estimate the decay hazard in dependence of the climatic conditions at a certain location. The first and still most frequently used index of its kind is the Scheffer Index for estimating the relative decay hazard of a geographical site (Scheffer 1971, Equation 1):

Equation 1. Climate Index according to Scheffer (1971).

$$Climate\ index = \frac{\sum_{Jan}^{Dec}[(T-35)(D-3)]}{30}$$

T = mean day temperature of the month [°F]
D = mean number of days with more than 0.001 inch of rain per month [-]

Initially developed to characterise the relative site-specific decay hazard for wood in above ground applications in the USA, the Scheffer Index was later applied to many different regions around the globe, e. g. Canada (Setliff 1986), North America (Morris *et al.* 2008), China (Wang *et al.* 2007), Japan (Kiguchi *et al.* 2001, Momohara *et al.* 2013), South Korea (Kim and Ra 2013), Australia (Wang *et al.* 2008), Norway (Lisø *et al.* 2006), and Europe (Brischke *et al.* 2011).
Further climate indices were developed and considered for service life planning, but mostly they lacked sufficient fit between macro climatic data and corresponding decay rates, because further influences on wood decay request consideration such as design details impacting on the microclimate. A far more comprehensive approach has been followed within the Australian

TimberLife project (Foliente *et al.* 2002, MacKenzie *et al.* 2007). Results from large field trials and country-wide surveys on timber structures were used to develop a series of probabilistic performance models covering various decay organisms such as fungi, termites, and marine borers as well as physical agents impacting on the risk for corrosion of fasteners. The basic model for above ground decay (Wang *et al.* 2008) was established on the base of field test results and is expressed as decay depth over time. Following the factor method approach according to ISO 15686-1 (2011), the rate of decay was multiplied with a number of factors accounting for different material and design parameters (k-factors). In addition a lag phase (before onset of decay) was determined and considered for modelling the full life span of a component. The outcome of the 10 years' TimberLife project flew into a series of manuals and numerous scientific publications (see **publication 6.3**).

Different decay models were developed on the base of dose-response functions in Europe. Viitanen *et al.* (2010b) used laboratory test data (Viitanen 1996) to establish a relationship between temperature, relative humidity and exposure time on the one hand and mass loss by fungal decay on the other hand. Furthermore, they modelled decay development as two processes: an activation process and a mass loss process. The idea of assuming an activation stage in the fungal degradation process coincides with earlier models based on field test data in Australia (Wang *et al.* 2008) as well as more current studies by Francis and Norton (2006), Brischke and Rapp (2008), Hansson *et al.* (2013), and the model approaches presented in **publications 6.4** and **6.7**. Further model approaches either based on laboratory or field test data are described and discussed in **publication 6.3.** The various models differ with respect to the boundary conditions (e. g. providing or lacking an external moisture source for the fungi) and the way of considering the different environmental input factors. While for instance Viitanen *et al.* (2010b) considered days with rain events as days with a relative humidity (*RH*) equal to 100%, Brischke and Rapp (2008) used the direct factor 'wood moisture content' as input variable and allowed the latter to be above fibre saturation as a consequence of rain events.

The use of decay and performance models as described in **publication 6.3** can be multifaceted: Models were used for mapping the moisture induced risk of decay (Viitanen *et al.* 2010a, Frühwald Hansson *et al.* 2012), for service life prediction of wooden components and commodities (MacKenzie *et al.* 2007, **publication 6.9** and **6.10**), for the quantitative evaluation of design options in guidelines (Thelandersson *et al.* 2011, Isaksson *et al.* 2014), and finally to estimate the effect of climate changes on performance and service life of wood (**publication 6.17**).

Figure 2 shows the relative decay potential for wood above ground in Europe based on the performance model by Brischke and Rapp (2008) and an additional ‘climate model’ describing the relationship between the weather parameters *RH*, temperature and precipitation on the one hand and the material climatic parameters wood moisture content and temperature on the other hand (*cf.* Thelandersson *et al.* 2011). Accordingly, the highest decay hazard was estimated for the West coast of the continent as well as for Western Ireland, Scotland and Norway where the Gulf Stream hits Europe. Comparatively little risk for decay was determined for cold regions in the Nordic countries and dry areas in the Mediterranean countries.

For service life prediction of wooden components a series of further factors needs to be considered in addition to macroclimatic data. Guidance on service life planning is provided by the ISO 15686 standard series with the factor method as key element (Equation 2, ISO 15686-1, 2011).

The multiplicative character of this approach was discussed controversially, in particular with respect to the high risk of error propagation. However, the idea of considering the full spectrum of potential impact factors is beyond controversy and can be reflected by a more general formulation (Equation 3).

Equation 2. Service life estimation according to the factor method (ISO 15686-1, 2011) – multiplicative approach.

$$ESL = RSL \times A \times B \times C \times D \times E \times F \times G$$

ESL = estimated service life [a]
RSL = reference service life [a]
A, B, C, D, E, F, G = modifying factors

Equation 3. Service life estimation according to the factor method (ISO 15686-1, 2011) – general approach.

$$ESL = f(RSL, A, B, C, D, E, F, G)$$

Results from experimental studies with continuous *MC* and temperature monitoring on different wooden commodities were used for service life prediction either on the basis of dosimeter models (**publications 6.9** and **6.10**) or in terms of factorisation referring to a clearly defined reference object under reference conditions (Isaksson and Thelandersson 2013). The latter can easily be adapted and applied for design guidelines as for instance shown by Isaksson *et al.* (2014). Besides material-specific resistance and climatic conditions at a certain location, the effect of design of an arbitrary detail on the microclimate and thus on the material climate can be quantified in terms of factors (values relative to a reference component, in this study a horizontal 20 mm thick Norway spruce board).

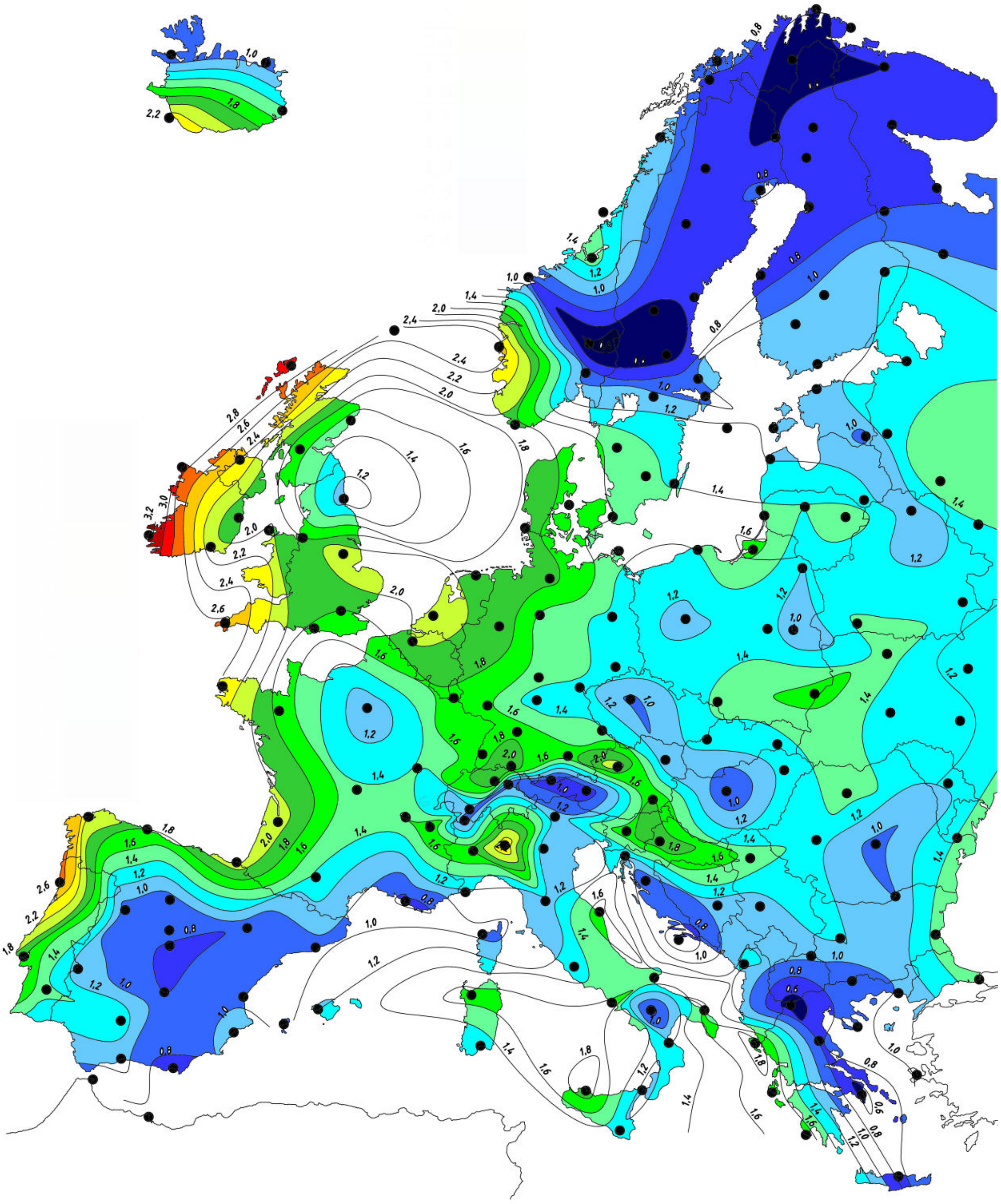

Figure 2. Relative decay potential for Europe indicated as relative doses for 206 European sites (circles) based on Meteonorm climate data. Relative dose compared to Uppsala, Sweden; modified after Frühwald Hansson *et al.* (2012).

A first technical guideline in Europe for the design of wooden constructions with respect to durability and service life has been produced within the European research project 'WoodExter' (Thelandersson *et al.* 2011). It is based on a limit state described as ‘onset of decay’. Later on this guideline was further developed and modified in a way that the design condition on engineering level is formulated as follows:

Equation 4. Design condition according to Isaksson *et al.* (2014).

$$D_{Ed} = D_{Ek}\gamma_d \leq D_{Rd}$$

D_{Ed} = exposure [d]
D_{Ek} = characteristic exposure, e.g. the annual exposure dose [d]
γ_d = consequence factor
D_{Rd} = resistance dose [d]

The resistance dose D_{Rd} is considered to be the product of a critical dose D_{crit}, which is specific for an arbitrary limit state (here: decay rating 1, *i.e.* slight attck) and two modifying factors taking into account the wetting ability of wood (k_{wa}) and its inherent durability (k_{inh}) as given by the following equation according to Isaksson *et al.* (2014):

Equation 5. Resistance dose according to Isaksson *et al.* (2014).

$$D_{Rd} = D_{crit}k_{wa}k_{inh} \quad \text{[d]}$$

D_{Rd} = resistance dose [d]
D_{crit} = critical dose corresponding to decay rating 1 according to EN 252 [d]
k_{wa} = factor accounting for the wetting ability of the material
k_{inh} = factor accounting for the inherent protective properties of the material against decay

The resistance dose goes alongside with the annual exposure dose which is determined as follows:

Equation 6. Annual exposure dose according to Isaksson *et al.* (2014).

$$D_{Ek} = D_{E0}k_{E1}k_{E2}k_{E3}k_{E4}k_{E5}c_a$$

D_{Ek} = annual exposure dose [d]
D_{E0} = annual exposure dose depending on geographical location/global climate [d]
k_{E1} = factor describing the effect of driving rain on vertical surfaces
k_{E2} = factor describing the effect of local climate conditions (meso-climate)
k_{E3} = factor describing the effect of sheltering
k_{E4} = factor describing the effect of distance from ground
k_{E5} = factor describing the effect of detail design (risk of trapping water)
c_a = calibration factor to be determined by reality checks and expert estimates

With this approach the apparent conflict between engineering limit state design and biological dose-response modelling of full life spectra has been overcome. While the impact of single influence factors is considered in a factorisation approach within the guideline, every single parameter can be quantified with the help of experimental data applied to a dosimeter model (Isaksson *et al.* 2014, Brischke *et al.* 2015).

1.3 Objectives

The overall objective of this thesis was to develop a system of test methods and models for classifying the durability and outdoor performance of wood products. The system should fulfil the following requirements:

- Discrete quantification of durability and performance related parameters,
- Concrete service life prediction,
- Applicability to all relevant wood-based materials,
- Consideration of both, moisture induced risk and potential decay organisms,
- Transferability to various use and exposure conditions,
- Applicability in field durability testing.

A set of suitable methods and calculation models was sought rather than a single universal instrument. For achieving this, the comparability of results obtained with different test methods should be increased through factorisation instead of defining classes (**publication 6.2**). Moisture and weather monitoring should be implemented in field tests and in-service studies for quantifying the moisture induced risk and comparing it between materials, methods, design options, and test locations (**publications 6.8, 6.9, 6.10,** and **6.11**). The presence of decay organisms should be considered for interpretation of test results and designing laboratory durability tests under various scenarios. Test results should be re-interpreted with respect to the prevailing decay types and organisms to identify worst case scenarios (**publications 6.4** and **6.7**). Finally, compatibility of the performance classification system with design guidelines was requested and had to be assured through generating test results in a feasible format.
Hereby the focus was on the durability of wood against decay fungi under various exposure situations in and above ground. Other potential wood-destroying organisms such as beetles, termites or marine borers were only marginally considered (**publication 6.1**). The performance of wood under laboratory, field, and in-service conditions should be compared exemplarily

for European oak (*Quercus* sp.) (**publications 6.12, 6.14,** and **6.16**), whose durability had recently been discussed controversially.

With respect to the intensive discussion about climate change impacts on human beings and their environment, the question to what extent the moisture induced risk for decay and the resulting performance of bio-based building materials might be affected is of high interest and should be highlighted (**publication 6.17**).

2 MATERIAL AND METHODS

2.1 Durability tests

2.1.1 Laboratory tests

2.1.1.1 Laboratory tests with basidiomycete monocultures

The resistance to basidiomycetes was tested exemplarily of European oak, (*Quercus robur* L. and *Q. petraea* Liebl.), according to EN 113 (1996) and CEN/TS 15083-1 (2005). Test specimens were exposed to pure cultures of *Coniophora puteana*, *Poria placenta*, *Trametes versicolor*, and *Donkioporia expansa*. The specimens were either 15 x 25 x 50 mm³ according to EN 113 (1996) or in mini block format (40 x 10 x 10 mm³) (**publication 6.12**). In addition, drilling core samples (10 mm diameter, 30 mm length) were taken from oak bridges and used for resistance tests (**publication 6.14**). After 8 weeks (drilling cores), 12 weeks (mini blocks), or 16 weeks (EN 113 standard specimens) the mass loss due to fungal degradation was determined and used for durability classification.

2.1.1.2 Laboratory tests with terrestrial microcosms

Furthermore, the resistance of European oak to soft rotting micro-fungi and other soil-inhabiting micro-organisms was determined in soil box tests (terrestrial microcosms, TMC) either according to ENV 807 (2001, **publication 6.12**) or CEN/TS 15083-2 (2005, **publication 6.14**). Natural top soil from different test sites and compost soil made from horticultural waste was used for the tests. In addition to standard specimens (10 x 5 x 100 mm³), drilling cores (10 mm ø x 30 mm) taken from bridge components were used. The incubation time of the tests with drilling cores was 24 weeks; standard specimens were incubated for 32 or 37 weeks. Mass loss due to fungal degradation was determined and used for durability classification.

2.1.2 Field tests

2.1.2.1 Test sites

Different field test studies and monitoring of components and structures in service were performed at various locations in Europe. Furthermore, data obtained from previous European and Australian projects were used for further analysis and modelling. All test sites are shown in Figure 3 and Figure 4; the respective publications are indicated in Tab. 2.

Tab. 2. Test sites and reference to publications.

Location	Publication No.												
	II	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII
Hannover, DE	x		x	x	x	x	x			x	x	x	
Hamburg, DE	x	x	x	x				x					
Reulbach, DE	x	x		x				x					
Freiburg, DE	x	x	x	x				x					x
Stuttgart, DE	x	x	x	x				x					
Bühlertal, DE	x	x		x									
Hinterzarten, DE	x	x		x									
Oberrottweil, DE		x											
Feldberg, DE		x											
Hornisgrinde, DE		x											
Schömberg, DE		x											
Heilbronn/ Heidelberg, DE		x											
Dobel, DE		x											
St. Märgen, DE		x											
Versmold-Bockhorst, DE									x				
Werther-Rotingdorf, DE									x				
Ghent, BE	x	x											
Ljubljana, SI	x	x	x	x									
Zagreb, HR	x	x	x	x									x
Bordeaux, FR		x	x										x
Uppsala, SE		x											x
Borås, SE	x												
Tåstrup, DK					x								
Ås, NO	x					x							
Oslo, NO	x	x											
Bergen, NO	x												
Portsmouth, UK	x	x		x									x
Garston, UK	x	x	x	x									
London, UK		x											
Beerburrum, AUS	x												
Dalby,AUS	x												
Frankston, AUS	x												
Pennant Hills, AUS	x												
Rockhampton, AUS	x												
South Johnstone, AUS	x												
Toowoomba, AUS	x												
Yarralumla, AUS	x												
Mount Isa, AUS	x												
Townsville, AUS	x												

Figure 3. Location of test sites in Europe.

Figure 4. Location of test sites in Australia, data from field trials used for publication 6.2.

2.1.2.2 In-ground field tests

Durability field tests with ground contact were performed according to EN 252 (1989) in Hamburg, Reulbach, Stuttgart, Freiburg, and Hannover. Therefore, specimens of 500 x 50 x 25 mm³ were buried to half of their length in the soil of the different test sites with a distance of 30 cm between each other (**publications 6.12, 6.15** and **6.16**). In Hamburg and Hannover additional mini-stake specimens (200 x 20 x 8 mm³) were exposed and therefore buried to 4/5 of their length (**publications 6.12** and **6.16**). In Hannover and Hamburg in ground tests were also performed with different substrates, *i. e.* field soil, compost, fertilised soil, mulch, turf-soil mix, sand, sand-soil mix, gravel, and concrete. All specimens were evaluated regularly regarding the onset and progress of decay in intervals between 3 and 12 months.

2.1.2.3 Above ground field tests

Durability field tests above ground were performed according to different standardised and non-standardised methods. Horizontal double layer tests were carried out in the frame of different studies as described in **publication**

6.2, 6.6, 6.7, 6.8, 6.12, and **6.17**. Specimens of 25 x 50 x 500 mm³ were placed horizontally in double layers with the upper layer displaced laterally by 25 mm to the lower layer. Supports were 25 cm above ground and made either from aluminium profiles or preservative treated wood covered with bitumen foil.

Horizontal lap-joint tests were conducted according to CEN/TS 12037 (2003). Specimens (38 x 85 x 300 mm³) forming a lap-joint were prepared, end-grain sealed, and exposed on aluminium profiles 1 m above ground (**publication 6.2** and **6.8**). Sandwich tests were performed with segmented specimens consisting of one base member (25 x 100 x 200 mm³) and two top members (25 x 50 x 200 mm³) exposed on rigs 1 m above ground (**publication 6.8**).

The data sets used for the literature review on above ground field test data (**publication 6.2**) were obtained from further test methods, such as cross brace tests according to Highley (1995), painted and unpainted L-joint tests according to EN 330 (1993), accelerated L-joint tests according to Van Acker and Stevens (2003), ground proximity multiple layer tests according to Edlund (2004), and various bundle tests using several stake shaped specimens stripped together and thus forming water traps.

Moisture monitoring was performed on combined façade-deck-elements consisting of horizontal decking boards as well as south and north oriented cladding boards (Bornemann *et al.* 2012). Each board was 25 x 100 x 500 mm³; the decking boards were exposed as single layer on two support beams, the façade was carried out as board-on-board cladding (**publications 6.8** and **6.10**). All specimens were evaluated regarding the onset and progress of decay in intervals between 6 and 12 months.

2.1.2.4 Commodity tests and case studies

The durability and performance of wooden components was furthermore studied on objects in service. Therefore commodity tests with terrace decking, fence posts, and claddings (**publications 6.8** and **6.9**) were performed including continuous moisture monitoring as well as studies on real life structures such as double split fence posts (**publication 6.13**), wooden claddings (**publication 6.9**), and timber bridges (**publication 6.14**). In addition to the material durability, the effect of microclimate, design details, and further constructive protection measures was studied. Besides decay related damages, the formation of cracks and superficial growth of algae, lichen, and mosses was documented on timber bridge components.

2.1.2.5 Decay assessment in the field

The distribution and maximum degradation depths of fungal decay were assessed using a pick test. A pointed knife was pricked into the specimen or wooden component and backed out again. The fracture characteristics of the splinters as well as depth and appearance was assessed visually, referred to the different decay types and evaluated according to the 5-step rating scheme according to EN 252 (1989) as sound (0), slight attack (1), moderate attack (2), severe attack (3) or failure (4).
Specimens with cross sections deviating from the EN 252 standard format were assessed using a modified rating scheme based on the minimum remaining cross section (**publications 6.11, 6.12**, and **6.16**). Similarly, fence posts in service made from European oak were assessed with respect to their minimum remaining cross section (**publication 6.13**) and rated according to the EN 252 scheme.

2.1.3 Durability classification

To assess the durability in the laboratory tests the relative durability was calculated as the quotient of mass loss of the tested wood and Scots pine sapwood references (*x*-value, EN 350-2, 1994). The results of the decay ratings from the various field tests were used to determine the durability of the tested materials. According to EN 350-1 (1994) *x*-values were calculated on the base of the mean service life of the specimens according to Equation 7.

Equation 7. Calculation of *x*-values based on mean service life according to EN 350-1 (1994).

$$durability\ x - value = \frac{SL_{mean,\ tested\ specimens}}{SL_{mean,\ references}} \qquad [\text{-}]$$

SL_{mean} = mean service life of specimens [a]

Since the mean service life of the specimens was not yet obtained for all tested materials the durability was alternatively calculated either on the basis of median service life SL_{median} (Equation 8), the 25th percentile of service life SL_{25perc} (Equation 9) or as quotient of the decay rate v of the reference and the decay rate of the material tested (durability factor f, Equation 10 and Equation 11), where necessary.

Equation 8. Calculation of median service life of specimens.

$$SL_{median}\begin{cases} SL_{\frac{n+1}{2}} & ; if\ n\ is\ uneven \\ \frac{1}{2}\left(SL_{\frac{n}{2}} + SL_{\frac{n}{2}+1}\right) & ; if\ n\ is\ even \end{cases}$$

SL_{median} = median service life of specimens [a]
n = number of replicate specimens

Equation 9. Calculation of 25th percentile of the service life of specimens.

$$SL_{25\,perc}\begin{cases} SL_{\frac{n+1}{4}} & ; if\ n\ is\ uneven \\ \frac{1}{2}\left(SL_{\frac{n}{4}} + SL_{\frac{n}{4}+1}\right) & ; if\ n\ is\ even \end{cases}$$

$SL_{25\,perc}$ = 25th percentile of service life of specimens [a]
n = number of replicate specimens

Equation 10. Calculation of the mean decay rate v_{mean}.

$$v_{mean} = \frac{\sum_i^n v_i}{n} = \frac{\sum_i^n \frac{DR}{t}}{n}$$

v_{mean} = mean decay rate of specimens [a^{-1}]
v_i = decay rate of single specimen [a^{-1}]
DR = rating, e.g. according to EN 252 (CEN 1989)
t = exposure time [a]
n = number of replicate specimens

Equation 11. Calculation of durability factors.

$$durability\ factor\ f = \frac{v_{mean,\ references}}{v_{mean,\ tested\ specimens}} \qquad [\text{ - }]$$

Durability classes (DC) were derived from *x*- and *f*-values according to the scheme shown in Tab. 3

Tab. 3. Classes of natural durability (DC) based on calculated *x*-values according to EN 350-1 (1994), using results from laboratory tests, and adapted classification using durability factors *f* from field tests.

DC	Definition	Classification based on EN 350-1 (1994) Laboratory tests	Classification based on EN 350-1 (1994) Field tests	Classification adapted to EN 350-1 (1994) Field tests
1	Very durable	$x \leq 0.15$	$x > 5$	$f > 5$
2	Durable	$0.15 < x \leq 0.30$	$3 < x \leq 5$	$3 < f \leq 5$
3	Moderately durable	$0.30 < x \leq 0.60$	$2 < x \leq 3$	$2 < f \leq 3$
4	Slightly durable	$0.60 < x \leq 0.90$	$1.2 < x \leq 2$	$1.2 < f \leq 2$
5	Not durable	$x > 0.90$	$x \leq 1.2$	$f \leq 1.2$

2.2 Moisture monitoring

Automated moisture content and temperature recordings were applied on numerous field test specimens, commodity test set ups and monitoring objects in service (**publications 6.6, 6.8, 6.9, 6.10, 6.11,** and **6.17**). Therefore, a resistance based measurement system was applied as described in an earlier publication (Brischke *et al.* 2008). The system can be summarised in brief as follows: electrodes of polyamide coated stainless steel cables were conductively glued in the specimens. The electrodes were connected to a small data logger that recorded the electrical resistance of the wood. The data loggers were calibrated in a range between 12 and 50 % *MC* and species-specific resistance characteristics were developed (Brischke *et al.* 2008, **publication 6.4**). In general the measurement points were placed in the centre of the specimens. However, in particular for measurements on different design details and components the electrodes were positioned by purpose close to contact faces, end-grain areas, or covered and sheltered parts of the structure (details can be seen in **publications 6.9, 6.10**, and **6.11**). As shown in **publication 6.4** the measurement system was found to be applicable for a variety of different wood species and wood-based materials including chemically and thermally modified wood as well as preservative treated wood. Most precise *MC* estimation was found for salt treated timber (± 2.5 %), followed by untreated timber (± 3.5 %) and modified wood (± 7 %) in the hygroscopic range (Figure 5). As expected, preciseness decreased above fibre saturation.

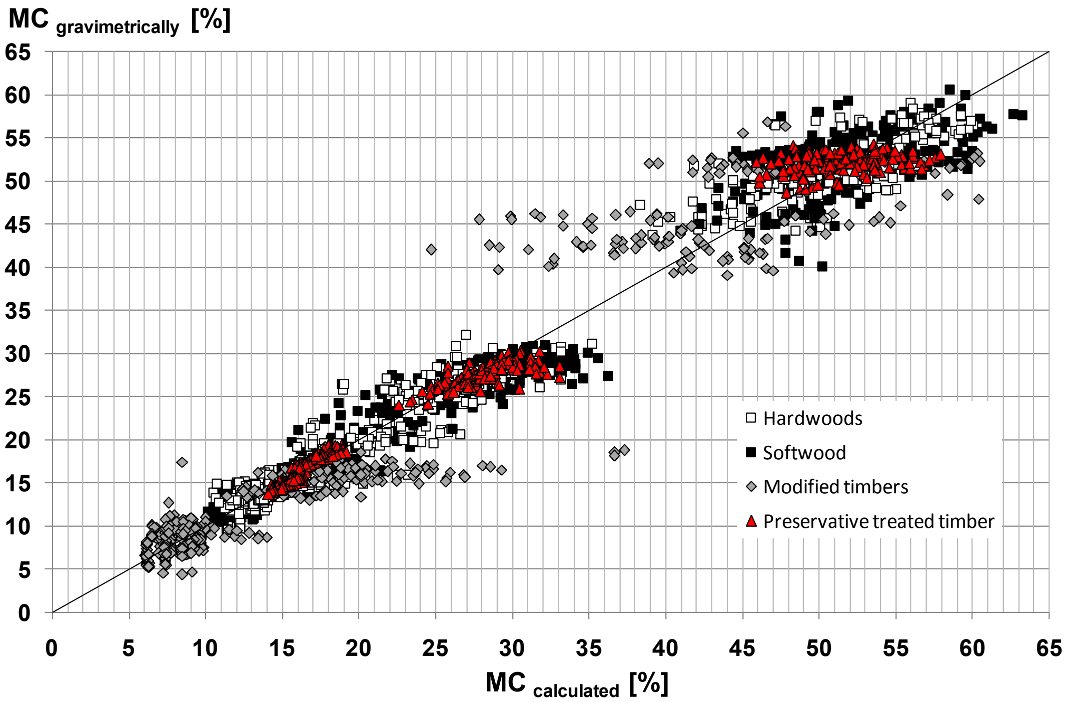

Figure 5. Calculated moisture content (*MC*) compared with gravimetrically measured *MC* of in total 27 different wood-based materials (taken from Meyer *et al.* 2012).

The material-specific resistance characteristics for modified timber need to be established strongly dependent on the respective modification level, *i.e.* weight percent gain of furfurylated or acetylated wood and heat-induced decrease in mass of thermally modified timber (TMT). Therefore, in a separate study (**publication 6.5**) the influence of thermal modification on the electrical conductivity of wood was modelled. The model allowed to calculate the moisture content of TMT through the parameters electrical resistance *R*, wood temperature *T*, and *CIE L*a*b** colour data, which correlate well with the intensity of a heat treatment (Brischke *et al.* 2007). The model was based on comparative gravimetric moisture measurements and electric resistance measurements of Norway spruce and beech sample sets heat treated at eleven different intensities. To validate the model afterwards, colour values of 15 different arbitrarily heat-treated TMT were calculated with an accuracy of ± 3.5 % within the hygroscopic range. The material-specific resistance characteristics based on experimental data led to an accuracy of ± 2.5 %.

2.3 Moisture uptake measurements

Moisture uptake measurements were conducted on small clear specimens (5 x 10 x 100 mm³ and 4 x 10 x 100 mm³) made from the same material used for *MC* monitoring in **publication 6.8**. Therefore, the dimensions of the respective field test specimens were scaled down to one fifth. The specimens were oven dried and afterwards exposed to either liquid water (24 h submersion test) or water saturated atmosphere (24 h vapour test). Moisture uptake was determined according to Equation 12. Moisture uptake tests were performed before and after 6 months above ground outdoor weathering.

Equation 12. Calculation of moisture uptake.

$$moisture\ uptake = \frac{(m_w - m_0)}{m_0} \times 100 \qquad [\%]$$

m_w mass after water uptake [g]

m_0 oven-dry mass [g]

3 RESULTS AND DISCUSSION

3.1 Performance models

Performance models were developed based on results from long term field tests at various climatically different locations in Europe. In a first step, a logistic dose-response model was achieved based on moisture, temperature and decay data from horizontal double layer tests with Scots pine sapwood and Douglas fir heartwood (Brischke 2007, **publication 6.6**). The majority of data sets used for this model were dominated by white and soft rot decay. Only at a few test sites, e. g. Ljubljana, Freiburg, and Zagreb, the specimens were decayed by brown rot fungi. Therefore at a later stage the obtained model was adjusted for brown rot as described in **publication 6.7** using further data sets from new tests dominated by brown rot decay.
The performance model should fulfil the following requirement characteristics:

- Model based on hard data obtained under real life conditions in the field
- Dosimeter approach considering climate based input variables
- Response referring to discrete limit states
- Open approach allowing continuous adaptation through including new test data
- Input and output variables (= dose and response) that can be normalised for factorisation in performance based design
- Potential for precise service life prediction

To achieve the above formulated requirements material climate data, *i.e.* wood moisture content and temperature, were used as dose parameters. Both measures can basically be derived from macro and meso climatic parameters (Van den Bulcke *et al.* 2009, Viitanen *et al.* 2010a, Frühwald Hansson *et al.* 2012), but on a smaller scale also depend on design detailing and surrounding environment (micro climate). To quantify onset and progress of decay the 5-step rating scheme according to EN 252 (1989) was used, whereby the four steps between 'slight attack' (equivalent to onset of decay) and 'failure' may be considered as limit states for the model.
As described in **publication 6.6** different models were proposed on the basis of results from white and soft rot dominated field tests, *i.e.* a logistic dose-response (LDR) model (Figure 6), a simplified LDR model, a set-back dose-response model, and a two-step dose-response model. The different models were evaluated for predicting onset and progress of decay.

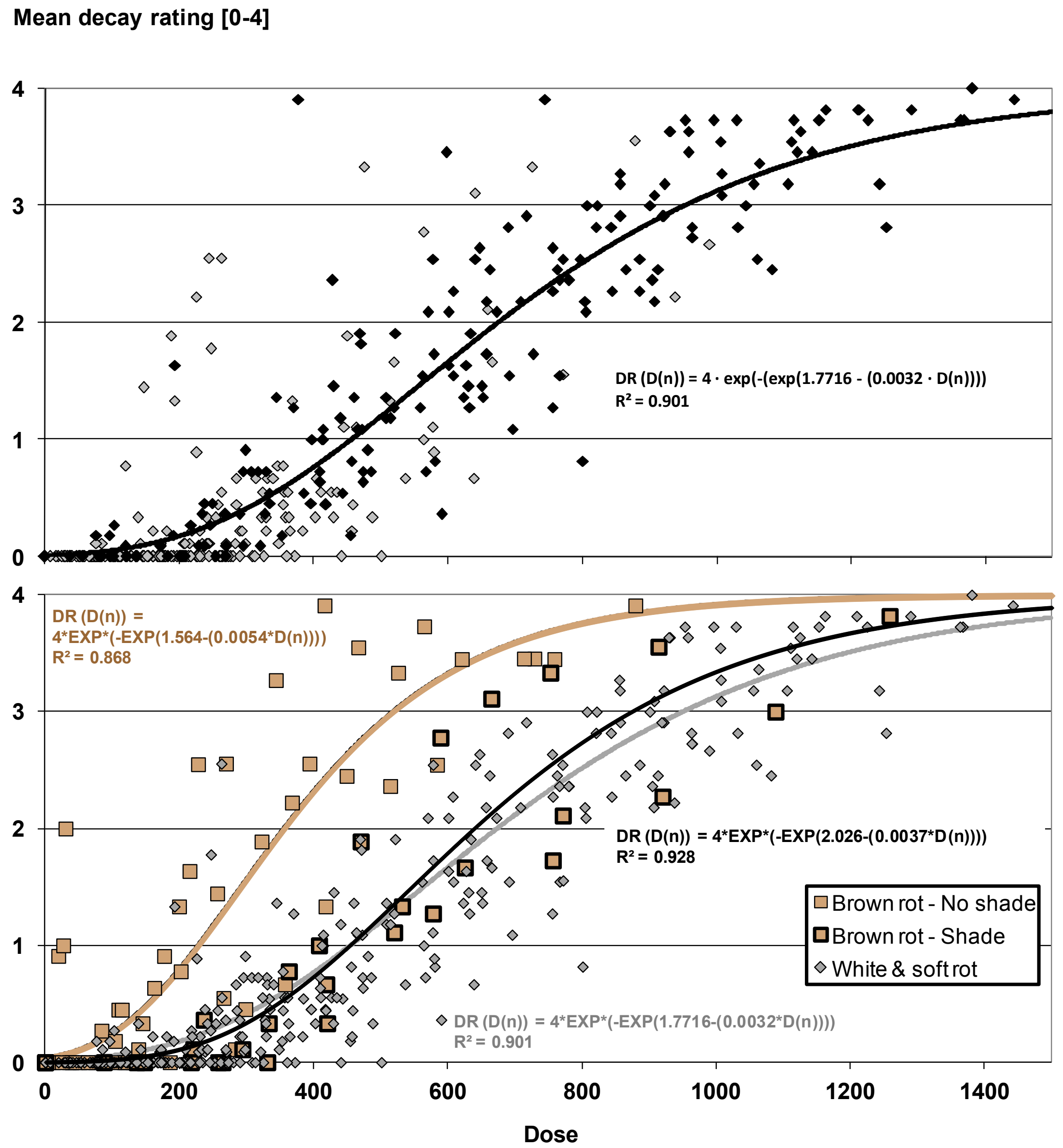

Figure 6. Relationship between dose and mean decay rating according to EN 252 (1989). Top: based on Scots pine sapwood (black) and Douglas fir heartwood (grey) exposed at different field test sites using a logistic dose-response model. Bottom: based on different softwood species dominated either by brown rot decay and exposed shaded or non-shaded or dominated by white and soft rot decay at different field test sites using a logistic dose-response model (each dot represents the mean decay rating at one exposure site at a certain time of exposure).

From a biological viewpoint it seemed reasonable to consider that dry and cold conditions do not only inhibit initiation of fungal decay, but do also cause 'damage' to it depending on the duration of such adverse conditions. Therefore, the authors tried to establish an activation process as well as a possible set back of the model similar to previous approaches reported by

Viitanen *et al.* (2010a). However, several attempts of modelling the set-back did not improve the accuracy of the model when tested against the data from double layer field tests. At the time, highest accuracy was achieved with the LDR model without set-back. For estimating the decay risk of less severe exposed components than the water trapping double layer the simplified LDR model as well as a two-step model are expected to be more powerful to describe the moisture induced risk. From an engineering viewpoint additional tools are needed to describe the level of moisture protection, *i.e.* the distance from conditions which are favourable for decay (publication 6.6 and Isaksson et al. 2014).

The LDR model considers the impact of a general time variation of moisture content *MC* and temperature *T* on the potential for decay. The total daily dose *D* is a function of two components, D_{MC} dependent on daily average of *MC*, and D_T dependent on the daily average of *T* (Equation **13** and Equation 14).

Equation 13. Total daily dose *D*.

$$D = f\left(D_T(T), D_{MC}(MC)\right)$$

Equation 14. Total daily dose *D* for *n* days.

$$D(n) = \sum_1^n D_i = \sum_1^n \left(f\left(D_T(T_i), D_{MC}(MC_i)\right)\right)$$

D = Total daily dose [-]
D_T *= temperature induced dose component [-]*
D_{MC} *= moisture induced dose component [-]*
MC = average moisture content [%]
T = average temperature [°C]
$D(n)$ *= total dose for n days of exposure*

Decay is initiated when the accumulated dose reaches a critical dose. As described in detail by Brischke and Rapp (2008) the cardinal points of the parameters wood temperature and moisture content for fungal growth and decay activity were sought and used to set up polynomial base functions for both dose components (Equation 15 and Equation 16). The total dose *D* is calculated as a function of D_{MC} and D_T according to Equation 17, where D_T was weighted by a factor *a*.

Equation 15. Moisture induced dose component D_{MC}.

$$D_{MC}(MC) = \begin{cases} 0 & if MC < 25\% \\ e \cdot MC^5 - f \cdot MC^4 + g \cdot MC^3 - h \cdot MC^2 + i \cdot MC - j & if MC \geq 25\% \end{cases}$$

Equation 16. Temperature induced dose component D_T.

$$D_T(T) = \begin{cases} 0 & if\ T_{min} < 0°C\ or\ if\ T_{max} > 40°C \\ k \cdot T^4 + l \cdot T^3 - m \cdot T^2 + n \cdot T & if\ T_{min} \geq 0°C\ or\ if\ T_{max} < 40°C \end{cases}$$

Equation 17. Total daily dose *D*.

$$D = (a \cdot D_T[T] + D_{MC}[MC]) \cdot (a+1)^{-1} if D_{MC} > 0\ and D_T > 0$$

D = Total daily dose [d]
D_T = temperature induced dose component [-]
D_{MC} = moisture induced dose component [d]
MC = daily average moisture content [%]
T = daily average wood temperature [°C]
T_{min} = minimum wood temperature for the day considered[°C]
T_{max} = maximum wood temperature for the day considered[°C]
a = temperature weighting factor
e, f, g, h, i, j, k, l, m, n = variables

The best fit for this model against the available data (Brischke and Rapp 2010) was obtained with the following parameters and the final logistic model function according to Equation 18.

Tab. 4. Parameters representing best fit of logistic dose-response model according to Equation 18.

$a = 3.2$	$h = 7.22 \cdot 10^{-3}$	$l = 9.57 \cdot 10^{-5}$
$e = 6.75 \cdot 10^{-10}$	$i = 0.34$	$m = 1.55 \cdot 10^{-3}$
$f = 3.50 \cdot 10^{-7}$	$j = 4.98$	$n = 4.17$
$g = 7.18 \cdot 10^{-5}$	$k = 1.8 \cdot 10^{-6}$	

The total dose over a certain time period is given by Equation 14 and the decay rating is given by a dose-response function according to Equation 18.

Equation 18. Dose-response function.

$$DR(D(n)) = 4 \cdot \exp\left(-\exp\left(1.7716 - \left(0.0032 \cdot D(n)\right)\right)\right)$$

DR = decay rating according to EN 252 (1989)

An arbitrary decay rating *DR* can be defined as limit state and the critical dose D_{crit} can be calculated as a function of the total dose for n days according to Equation 19.

Equation 19. Critical dose D_{crit}.

$$D_{crit} = f_{DR}(D(n))$$

D_{crit} = *critical dose [d]*

Brown rot fungi attacked the specimens only at a few sites, but here decay proceeded faster compared to white and soft rot decay at a given dosage. Thus, there were different outliers, where decay developed faster than predicted from the accumulated dose (*cf.* Figure 6). Consequently, the model was later on applied to a larger set of data from field tests, where brown rot was the dominating decay type (**publication 6.7**). Based on results from double layer, lap-joint, and sandwich tests with various softwoods the basic model was evaluated against brown rot decay. The moisture and temperature induced dosage was again calculated on the basis of Equation 15 and Equation 16. Solely, the response in terms of decay ratings according to EN 252 (1989) was different.

In analogy to the first LDR model (**publication 6.6**) the moisture and temperature induced dose was clearly correlated with the intensity of fungal decay (Figure 6). Obviously, exposure to shade led to both, a prolonged time lag between exposure and onset of decay and a slower progress of the brown rot degradation itself. Potential reasons for this delay are superficial growth of algae and other non-decaying organisms on the specimens exposed to shade and lowered ventilation.

Residual scattering of the dose-response relationship is likely related to the various wood-destroying organisms themselves, *i. e.* the specific fungal flora established on a particular wooden substrate. Consequently, the most decisive process for service life prediction of wooden structures is the establishment of fungi representing a certain decay type. This may happen from very incipient stages of decay or in the frame of a succession, but remains an almost unpredictable mechanism.

From an engineering viewpoint the most critical hazard needs to be considered for design and service life planning of timber structures. Hence, differences in time till colonisation, onset of decay and subsequent decay progress between various fungi or corresponding rot types need to be analysed separately. Brown rot decay on wood exposed to sun turned out to be initiated earlier and preceded faster compared to white and soft rot decay at a given dose, even though brown rot fungi do not necessarily demand less moisture and temperature. The dosage needed to reach a certain limit state (*i.e.* decay rating) was up to two times higher for white and soft rot compared to brown rot decay. Accordingly, establishment of a certain decay type on a wooden component can influence its service life by up to factor 2.

3.2 Service life prediction

The service life of various wooden commodities has been estimated on the basis of long-term monitoring data using the LDR model described through Equation 18. Therefore, daily measurements of wood temperature and moisture content were conducted on wooden claddings, terrace decks, and fence elements **(publication 6.9)**. Service lives of the different commodities were prognosticated for different limit states, *i.e.* different levels of decay progress. As expected the predicted service lives differed between wood species (e. g. Norway spruce, Scots pine sapwood and Douglas fir heartwood), between different commodities and different design details. For instance, the lowest moisture induced dose on fence elements was found on free ventilated pickets followed by posts, the contact areas between post and picket where water is trapped, and the ground line area of the posts. Similarly, the free ventilated terrace decking boards showed the least moisture induced dosage compared to bearings and contact areas.

The predicted service life of cladding boards turned out to be dependent on the respective roof overhangs and the distance to ground, which determines the amount of wind driven rain and splash water on the wall. However, these effects were partly superposed by the orientation of the walls, which affects wind driven rain and the re-drying potential in terms of wind and direct solar radiation, confirming earlier findings by Nore *et al.* (2007) and Ge and Krpan (2009).

Besides the reliability of the performance model applied, it became obvious that the service life prediction accuracy strongly depends on the respective time period wherefore a span of several years is needed to adequately consider the climatic variations between years. Even the use of factors expressing the service life relative to a reference turned out to be significantly affected by climatic differences between years.

The studies referred to in **publication 6.9** used the model based on soft and white rot decay exclusively. For a more conservative prediction approach a model based on brown rot decay is needed instead in particular for softwood species and exposure situations where brown rot frequently occurs (**publication 6.7**).

3.3 Quantification of decay influencing factors

Performance based design requires quantification of decay influencing factors even more than prediction of absolute service lives in years. As expressed through the factor method according to ISO 15686-1 (2011) a global approach is needed to quantitatively consider all internal and external factors that might affect the performance of a commodity or structure. Factorisation based on a reference commodity exposed to reference conditions has therefore become a preferential method for design and planning (MacKenzie *et al.* 2007, Thelandersson *et al.* 2011, Isaksson and Thelandersson 2013, Isaksson *et al.* 2014). Nevertheless, factorisation can also be considered as a probabilistic process (*cf.* Equation 6) and accurate models are needed to determine factors for specific parameters. The quantification of various decay influencing factors has therefore been addressed in several studies described in **publication 6.9, 6.10, 6.11,** and **6.14** and is shown exemplarily in the following.

Ideally, the effect of a certain parameter on the resulting service life of a wooden structure should be determined. This is to some extent intended by different standard durability test methods (e. g. EN 252, 1989), when for example the service lives of test specimens exposed in ground are determined and compared with those of reference materials, such as non-durable sapwood controls. However, for more durable materials or if the material is exposed to a less severe environment, the determination of service lives can take many years or even decades. Alternatively, the dose needed before decay occurs and thus leading to a certain lifetime can serve as alternative measure for quantitative factorisation of service life affecting influences. Different measures describing the effect of decay factors such as the number of wet days, temperature and moisture induced dose, and the resulting predicted service life were therefore compared. After at least three years of outdoor exposure the moisture risk was assessed for different test specimens (**publication 6.8**), combined façade-deck elements exposed to South and North, fence and terrace elements as well as fence posts with differently detailed post caps and bearings (**publication 6.10**).

In summary, the prediction model showed high potential to save time when monitoring timber products exposed outdoors, in particular under less severe conditions such as vertically mounted cladding. Differences between wood species as well as between design details became apparent. More simple measures such as the number of wet days (here defined as days with *MC* > 25 %) did not meet the expectation to the same extent, but can still be considered as useful alternative indicators. The results of both studies recommend taking more advantage of the additional information provided by continuous *MC* measurements, in particular for service life and performance prediction. Similar perceptions have been observed by Brischke *et al.* (2014c) in a survey among European scientists working in the field of wood protection and technology.

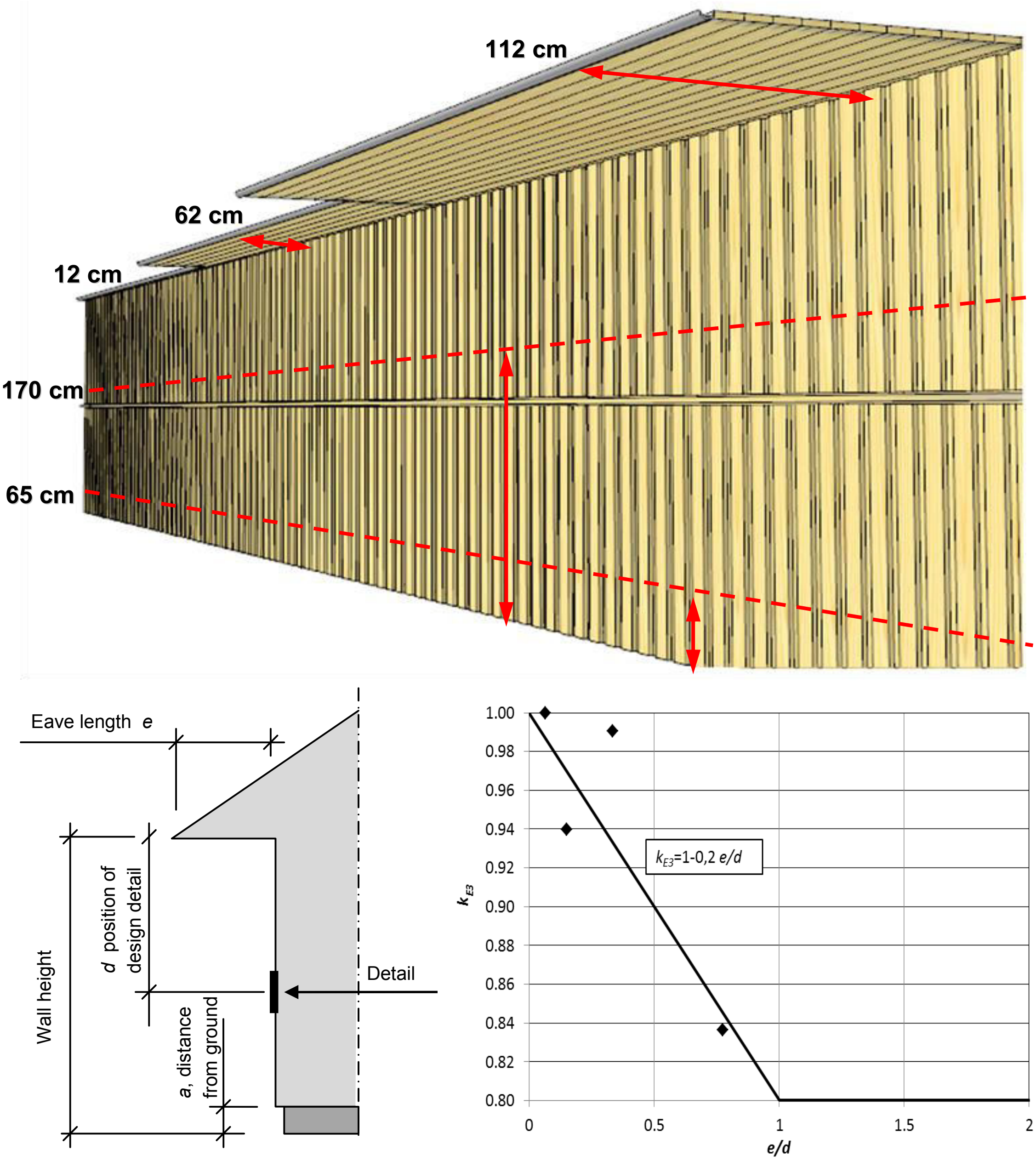

Figure 7. Quantifying the effect of eaves on the moisture-induced decay risk. Top: Board-on-board cladding with different eaves monitored for several years in Tåstrup, Denmark. Bottom: Relation between the ratio *e/d* and the total dose based on measured *T* and *MC* expressed as factor k_{E3} according to Isaksson *et al.* (2014).

Exemplarily, the quantification of **sheltering effects** through roof overhangs is illustrated in Figure 7. Based on long-term measurements the moisture induced risk was assessed for three different eaves at different heights on a

Norway spruce cladding in Tåstrup, Denmark. For simple utilization in performance based design one can estimate the expected dose from the ratio between eave and distance to the roof edge.

The effect of **component dimension** on moisture risk and resulting decay development in timber elements has been studied on Norway spruce and Scots pine sapwood (**publication 6.11**). However, from the results obtained during five years of outdoor exposure no clear effect of the size of the cross section became evident. The specimen dimension was neither correlated with wood *MC* nor with the decay development. Regarding onset and further development of decay cracks as well as contact faces turned out to be weak points, but interior rot was observed as well. Brown rot, which occurred predominantly in the specimens, was partly difficult or even impossible to detect from outside. Likely due to deviating ways of infection brown rot fungi were able to cause severe degradation also in small-dimensioned samples.

A further study focused on the effect of the **material inherent resistance** on the performance of timber bridges made from English oak (**publication 6.14**). In total, elements from six different bridges in the city area of Hannover, Germany, were studied and drilling cores were sampled for comparative laboratory resistance tests against brown, white and soft rot causing fungi. Keeping all factors, such as site, wood species, and bridge element constant allowed identifying differences in the inherent resistance within one species and their potential effect on the outdoor performance of the respective timber structure. Nevertheless, many other factors, in particular the microclimate at the different bridge details, were superposing the effects of material-inherent resistance and larger sampling size would be needed to establish correlations in a sufficient quantitative manner.
Factorisation turned out as a feasible and simple way of quantifying the effect of various agents on performance and service life of wood products. Furthermore, the efficiency of **protective design measures**, such as sheltering, drainage, or coatings, can be quantitatively described through factors. However, all these factors that will be used subsequently for performance modelling and service life prediction need to be established on the basis of hard experimental data rather than on expert opinion and guesses.
Therefore, a dosimeter model considering direct key factors such as wood moisture content and temperature is proposed, since it allows for describing various indirect influences. To some extent it can also be used to quantify the effect of the material-inherent resistance of wood, which is basically determined by two parameters, wood ingredients and moisture dynamics.

Since the latter directly affects the moisture induced risk for fungal decay of wood, its effect can be described by a dosimeter model as well.

3.4 Durability testing

3.4.1 Variability factors

Traditionally, the durability of wood is determined in laboratory decay tests or field tests with ground contact, even though it is commonly accepted that results from those tests cannot be transferred directly to less severe exposure situations, for instance when timber is exposed above ground. The durability and performance of wood was exemplarily studied on European oak (*Quercus robur* and *Q. petraea*). The durability of oak wood is one of the most controversially discussed and was therefore of particular interest. According to EN 350-2 (1994) European oak is classified as 'durable' (durability class DC 2). Results from laboratory tests against different fungi confirmed or even exceeded this durability classification. However, further results indicated an intra-specific variability of European oak wood with remarkable percentages of less durable timber (e. g. Aloui *et al.* 2004, Humar *et al.* 2008, Meyer *et al.* 2014, Plaschkies *et al.* 2014).
Laboratory decay tests with brown, white and soft rot fungi as well as in-ground and above ground tests at different sites were conducted and compared with respect to the durability classification obtained (**publication 6.12**). Furthermore, fence posts and bridge structures made from English oak, which had been in service for different time periods were investigated (**publications 6.13** and **6.14**). The comparative laboratory and field studies revealed significant discrepancies between the different tests and compared to the current European normative durability classification. The full spectrum between DC 1 (laboratory decay tests with basidiomycete monocultures) and DC 5 (laboratory and field tests with soil contact) was obtained.
Besides differences in durability caused by test methodology, the results from this study as well as many further reports indicate a remarkable intra-species variation of resistance. This was further supported by the findings from a case study on split fence posts which had been in service between 5 and 60 years (**publication 6.13**). The durability of the oak posts was affected by high variation. Posts prematurely failing after only 5 years were found as well as posts still serviceable after 60 years. Similarly, the resistance of oak samples taken from six different timber bridges turned out to vary significantly in laboratory decay tests with basidiomycetes and in unsterile soil (**publication 6.14**) and it was in most cases attributed to varying performance of the entire components in service.

In summary, the results strongly recommended to define durability separately for different in-use conditions (e. g. for different use classes or organism groups occurring under different exposure conditions). Furthermore, intra-specific variations in material resistance need to be considered for service life planning to avoid unexpected premature failures.

3.4.2 Variation in ground

The durability of wood, in absolute as well as relative matters, is itself affected by the exposure conditions. This has been shown for above ground test results from test sites all around the globe in **publication 6.2**. The same is expected for in-ground exposures as well. **Publication 6.15** and **6.16** are focusing on in-ground durability with respect to variations of the soil substrate. Comparative field trials with different soil substrates showed that decay rates differed significantly between field soil containing substrates and those containing no natural soil, such as sand, gravel, and concrete. The effect of adding fertiliser, turf, and bark mulch to the field soil was negligibly small. Less fertile substrates such as sand and concrete delayed the onset of decay (lag phase), but did not reduce the rate of decay once it had started.
In a second study (**publication 6.15**) the variability of fungal decay was examined within one test field. Distribution of decay types and intensity were exemplarily examined on 666 specimens in total in the field in Hannover-Herrenhausen, and related to different soil parameters. All three main types of fungal decay, white, brown, and soft rot, were found in the field, but varied significantly in frequency and spatial distribution. The field was clearly dominated by white and soft rot decay, but showed some spots with aggressive brown rot often caused by *Leucogyrophana pinastri*. The assessments showed that small areas with high decay activity of a certain type can easily be included or excluded.
In reverse, this might also explain extreme variations in service life when it comes to real structures. Premature failures likely occur when a wooden component is exposed to a 'hot spot' with well-established and active decay of a certain kind. Consequently, randomised distribution of test specimens needs to be assured even on relatively small in-ground test sites.

3.4.3 Alternative durability measures for above ground exposures

In particular in above ground situations the durability and performance of wooden components is affected by the moisture-induced risk. While wood in ground contact is assumed to be constantly wet – or at least wet enough to facilitate fungal decay – the moisture regime above ground is varying a lot and is additionally influenced by the moisture dynamics of the wood material itself. **Publication 6.8** focuses therefore on assessing alternative durability measures related to the moisture performance of wood. Results from above-ground tests including continuous wood moisture content monitoring were analysed. Decay ratings from horizontal double layer tests were compared with different moisture related indicators. In addition, façade-deck elements, sandwich and lap-joint specimens were monitored. Both, time of wetness (here: days > 25 % *MC*) and the total dose *D* (see Equation 18) turned out to be useful indicators for the moisture performance of most wood species tested under different exposure conditions. Furthermore, it became obvious that the moisture performance of timber also strongly depends on the exposure situation. With increasing severity of exposure, durability decreased for most species.

For predicting the outdoor moisture performance of wood-based materials different laboratory water uptake tests were conducted. With rising water uptake during 24 h submersion or exposure at 20 °C/ 100 % *RH* the total dose determined on horizontal double layer specimens in the field increased. However, as subsequently shown by Brischke *et al.* (2015) desorption and capillary water uptake are needed to obtain a more pronounced correlation between laboratory indicator and outdoor moisture performance. This approach is thus proposed as an alternative or additional tool to previously reported indicators (Rapp *et al.* 2000, Van Acker *et al.* 2014).

3.5 Performance based design

Up to date the building sector still treats durability testing, service life prediction and life cycle analysis (LCA) separately. LCA studies frequently need to deal with assumptions for expected service lives rather than with experimental results (e. g. Ortiz *et al.* 2009, Menzies 2013, Takano *et al.* 2015, Yeh 2014). Integrated approaches are still rare (Miller *et al.* 2015).

The basic principle of performance models is to separate exposure and resistance, *i.e.* the material resistance of wood based products. Performance criteria can be defined by a limit state - in this thesis certain levels of fungal degradation, e. g. onset of decay. This approach has the advantage that the exposure can be expressed as a function of global and micro climate, design level and surface treatment in a general way and independent of the exposed material. In principle, the material resistance can also be expressed in the same way independent of the design situation.

However, since both, material resistance and exposure, depend on the potential deteriorating agents present, dose-response relationships need to be determined separately for different exposure situations. Figure 8 illustrates the concept of performance prediction based on a combination of exposure dose and material resistance for different groups of deteriorating organisms as suggested by Suttie *et al.* (2013).

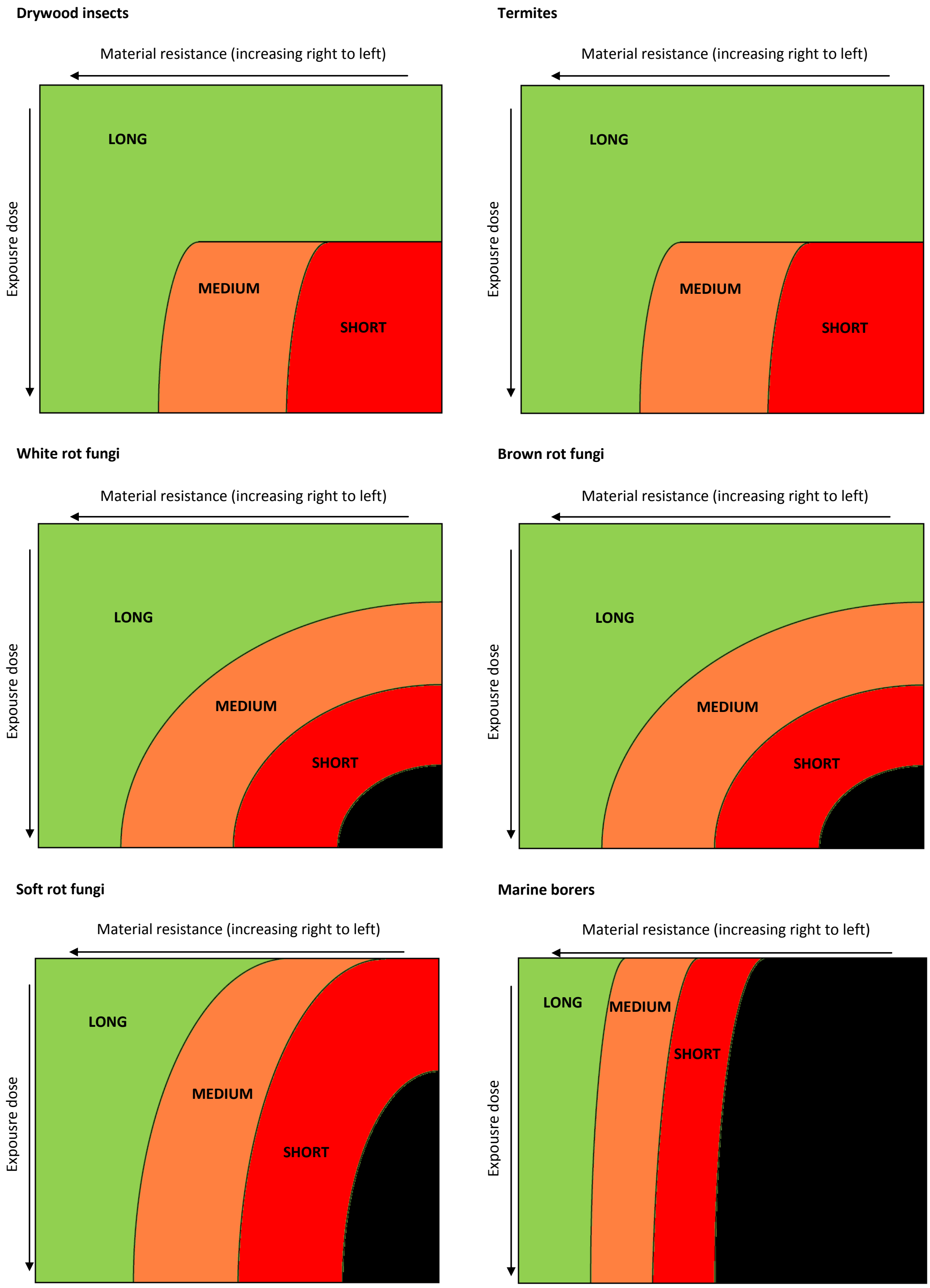

Figure 8. Conceptual charts for classifying performance in terms of service lives for a combination of material and exposure parameters (according to Brischke *et al.* 2014).

A first attempt to utilise performance models and corresponding data for design of wooden constructions was developed within the European research project 'WoodExter' as described in more detail in section 1.2.2. In the frame of the Swedish research program 'WoodBuild' this design guideline was further developed and numerous decay influencing factors were quantified on the basis of experimental data from long-term monitoring using the LDR model (*cf.* Equation 18; Isaksson *et al.* 2014).
Besides the various environmental factors such as global and micro climate, driving rain, sheltering, distance to ground, and detail design also the material resistance was expressed for the first time as dose, *i.e.* the resistance dose D_{Rd} (Equation 5, section 1.2.2). D_{Rd} is hereby determined as the product of a critical dose D_{crit} and two factors representing the wetting ability (k_{wa}) and the inherent protective properties (k_{inh}) of wood. Experimental data for describing the inherent protective properties may be taken from laboratory or field durability tests for many materials. In contrast, data characterising the moisture dynamics of wood are rare. Comparative studies determining factors for both, wetting ability and protective properties, for the same wood-based materials did not exist previously. A first attempt to verify this design concept has therefore been made by Brischke *et al.* (2015):
A comprehensive data set was obtained from laboratory durability tests and ongoing field trials in Norway with 21 different wood species. Supplementary, four different wetting ability tests (24 h submersion, 24 h exposure at 100 % *RH*, 24 h desorption, and capillary water uptake in a tensiometer) were performed with the same material. Based on the dose-response concept decay rates for specimens exposed above ground in horizontal double layer tests were predicted on the base of the different indicating factors. A model was developed and optimised taking into account the resistance of wood against soft, white and brown rot as well as the relevant types of water uptake and release. Norway spruce was used as reference species in all tests in accordance to the design guideline by Isaksson *et al.* (2014). Verification of the model was done using above ground field test data from three different test sites in Norway. The model was found to be reasonably reliable and it had the advantage of being implemented into the existing engineering design guideline. Figure 9 shows the relationship between the relative resistance dose calculated on the base of the various laboratory and in-ground tests and the mean relative decay rate of above ground specimens determined at the three Norwegian test sites.

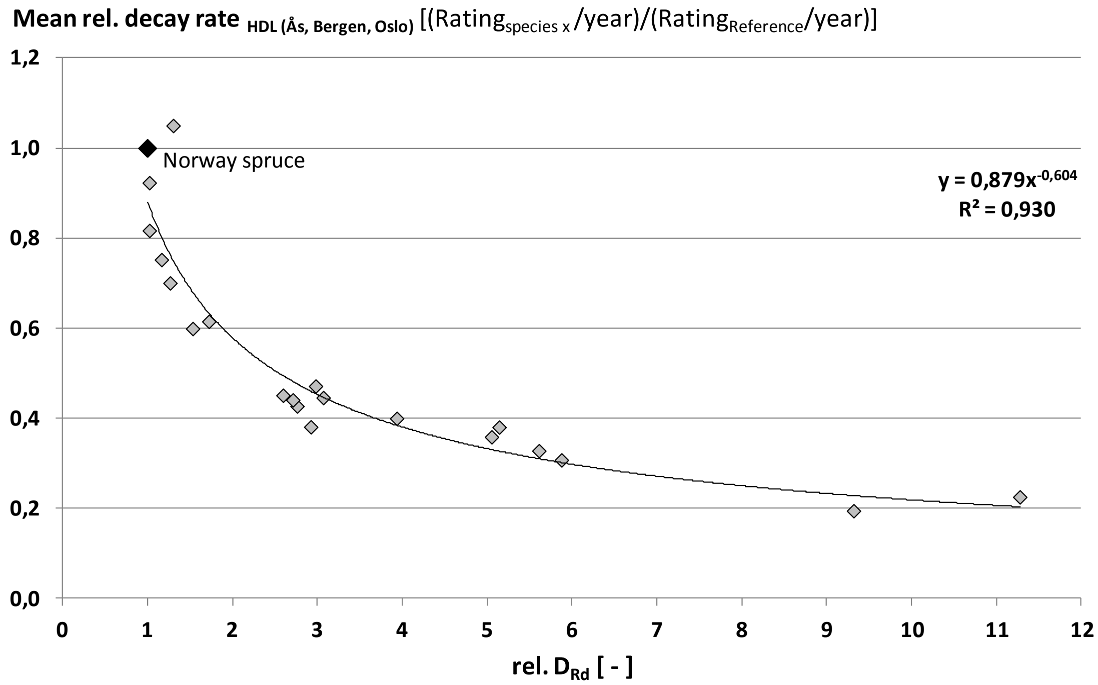

Figure 9. Mean relative decay rate of horizontal double layer specimens averaged for three Norwegian test sites versus relative calculated resistance dose D_{Rd}. Reference species Norway spruce is marked. Wood species with a relative resistance dose (*rel. D_{Rd}*) < 1.0 were excluded (taken from Brischke *et al.* (2015)).

For the first time a model approach based on the combined effect of wetting ability and durability to predict field performance of wood has been applied to long-term field test data and was found to be feasible. Further improvements of the approach can include climatic aspects as well as the effect of crack formation and other ageing agents.

3.6 Potential effects of climate changes on the performance of wood-based products

Climate changes were discussed in many disciplines during recent years. The discussion mainly focused on three aspects: the significance of climate changes, anthropogenic sources for climate changes and finally potential consequences on ecological and economical patterns. In principal each chemical, physical and biological reaction and every other moisture and temperature induced process is potentially affected by climate changes. Hence, global warming and corresponding moistening may also affect the durability of wooden components, since it is directly affected by the material climate.

Therefore, in **publication 6.17** a first attempt was made to quantify the influence of climate changes on wood decay rates for various scenarios. The climate induced dose occurring in horizontal double layers has been estimated on the basis of the decay model described above (Equation 18). Critical doses necessary to reach a mean decay rating 2 (moderate decay) were calculated based on long-term monitoring of Scots pine sapwood and Douglas fir heartwood specimens exposed at the sites Uppsala, Portsmouth, Freiburg, Bordeaux, and Zagreb. In addition to the current climate conditions, the annual dosage and resulting service lives were prognosticated for a homogenous warming by 1, 2, and 3 K. A homogenous warming by only 1 K led to a reduction of the expected service life of between 5 and 18 %. The percentage of the reduction of service life was higher for the more durable Douglas fir. An increase by 3 K corresponded to 20 – 38 % reduction of service life to be expected. While in some regions, e. g. in the Mediterranean countries droughts are forecasted, in other regions warming is expected to come along with increasing rainfalls. At currently rather dry places like Bordeaux a homogenous increase in wood moisture content by 10 %-points would lead to service life reductions of between 57 and 68 %.

In order to get more realistic values it would be necessary to translate the complex prognosticated climatic changes more precisely into daily changes of wood *MC* and temperature. Furthermore, seasonal variations need to be considered. However, even though this study worked with strongly simplified auxiliary conditions, the partly drastic effects of climate change on the durability of wood became evident. The quantity of climate induced changes strongly depends on the geographical position and the present climate.

4 CONCLUSIONS AND OUTLOOK

From the various surveys and experimental studies regarded in this thesis it became obvious that instruments are needed to break up the rigid traditional ways of durability and efficacy testing as manifested in European standards. To pave the way for performance based building and design, durability testing needs to be linked to service life prediction as well as life cycle analysis and life cycle costing. It has been shown that well-functioning performance models, transparent test data, and a universally applicable set of instruments are needed to deliver reliable wood-based components of controlled durability with minimum maintenance needs and life cycle costs. A tool that is considered universal on the one hand, should be specific for certain applications on the other hand.

The model type developed and applied within this thesis describes dose-response relationships, but can also provide resistance dosage when combined with a set of feasible methods to characterise inherent protective properties and the moisture dynamics of wood in a quantitative manner. Respective test protocols have been developed and used to verify the models.

The set of models described in this thesis will be able to predict service lives as absolute numbers in years, and allow discrete quantification of decay influencing factors as relative values. This factorisation approach can further be used for implementation in design guidance as well as for performance prediction. Nevertheless, the models developed on the base of field test results so far turned out to be decay type specific. Therefore, further validation and modification of the models where necessary will be a task for the future.

The system containing different laboratory and field test methods as well as mathematical models to quantify the dose response relationship between climatic parameters and fungal decay was developed and verified for numerous wood species and exposure situations. Therefore, different approaches were followed to achieve i.) precise service life prediction, ii.) quantification of decay influencing factors (factorisation), and iii.) a performance classification system considering material resistance and moisture dynamics of wood-based products.

The upcoming revision of the European standard EN 460 has the potential to generate opportunities for implementing a dosage based design concept addressing both, exposure and resistance of wood based products. Since EN 460 shall serve as interface between the user and the various ‘wood protection standards’, it will be useful to undertake further surveys to identify the needs and demands of different target groups such as the wood-working industry, traders, architects and planners, engineers, local authorities, and finally end-consumers. More information is needed about acceptance and tolerance of performance deficits as well as service life expectations. In this respect, the focus also needs to be on linking performance with the respective consequence of failure, which needs to get harmonised with relevant Eurocodes. Furthermore, from an engineering viewpoint the reliability of single instruments as well as the entire standardisation body needs to be quantified. Still there is an evident need to solve how statistical variations as well as safety margins can be adequately considered for performance based building with timber products. This does also require improving the quality of test data with respect to availability, transparency, and additional information, e. g. with regards to moisture and climate parameters.

Information about regional peculiarities and markets become increasingly important in a globalised world. However, currently it is a task for national authorities to deal with the adaptation of standards in their countries. Setting thresholds and defining safety margins may be operated on national level. Guidance on how to treat climatic differences within and beyond Europe should be provided on a European or even international level. For a better handling of differences in climate induced hazards it will therefore be beneficial to develop more precise and more reliable climate models. Respective work has been initiated and will be linked to performance prediction on macro, meso or even local level.

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6 PEER REVIEW PUBLICATIONS

Own contribution is indicated.

Publication I	Kutnik M, Suttie E, **Brischke C** (2014) *European standards on durability and performance of wood and wood-based products – trends and challenges*. Wood Material Science and Engineering 9: 122-133[1]
Publication II	**Brischke C**, Meyer L, Alfredsen A, Humar M, Francis L, Flæte PO, Larsson-Brelid P (2013) *Natural durability of timber exposed above ground – a survey*. Drvna Industrija 64: 113-129[2]
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Publication VII	**Brischke C**, Meyer-Veltrup L, (2015) *Modelling timber decay caused by brown rot fungi*. Materials and Structures: DOI 10.1617/s11527-015-0719-y.[6]

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[2] Conception, literature research, data analysis, writing and publishable formatting
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[5] Experimental work, participation in conception, data analysis, modeling, literature research, writing and publishable formatting
[6] Conception, literature research, data analysis, writing, and publishable formatting; participation in experimental work and data acquisition

Publication VIII	**Brischke C**, Meyer L, Bornemann T (2013) *The potential of moisture content measurements for testing the durability of timber products.* Wood Science and Technology 47: 869-886[6]
Publication IX	**Brischke C**, Meyer L, Bornemann T, Bilstein M, Lauenstein B, Lück J-M, Wulf C (2013) *Service life of timber structures – prognosis based on 3 years high-frequency monitoring*. European Journal of Wood and Wood Products 71: 79-90[6]
Publication X	Bornemann T, **Brischke C**, Alfredsen G (2014) *Decay of wooden commodities – moisture risk analysis, service life prediction and performance assessments in the field*. Wood Material Science and Engineering 9: 144-155[7]
Publication XI	**Brischke C**, Meyer-Veltrup L (2015) *Moisture content and decay of differently sized wooden components during 5 years of outdoor exposure.* European Journal of Wood and Wood Products 73: 719-728.[6]
Publication XII	**Brischke C,** Welzbacher CR, Rapp AO, Augusta U, Brandt K (2009) *Comparative studies on the in-ground and above-ground durability of European oak heartwood (Quercus petraea Liebl. and Quercus robur L.)*. European Journal of Wood and Wood Products 67: 329-338[8]
Publication XIII	**Brischke C**, Rolf-Kiel H (2010) *Durability of European oak (Quercus spp.) in ground contact – A case study on fence posts in service.* European Journal of Wood and Wood Products 68: 129-137[6]
Publication XIV	**Brischke C**, Behnen CJ, Lenz M-T, Brandt K, Melcher E (2012) *Durability of oak timber bridges – Impact of inherent wood resistance and environmental conditions*. International Biodeterioration and Biodegradation 75: 115-123[6]
Publication XV	**Brischke C**, Olberding S, Meyer L, Bornemann T, Welzbacher CR (2013) *Intrasite variability of fungal decay on wood exposed in ground contact.* International Wood Products Journal 4: 37-44[6]

[7] Participation in conception, experimental work, data analysis, writing and publishable formatting

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Publication XVI **Brischke C**, Meyer L, Olberding S (2014) *Durability of wood exposed in ground – Comparative field trials with different soil substrates.* International Biodeterioration and Biodegradation 86: 108-114[6]

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6.1 Publication I: European standards on durability and performance of wood and wood-based products – trends and challenges.

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ORIGINAL ARTICLE

European standards on durability and performance of wood and wood-based products – Trends and challenges

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Abstract
Standardization work in the field of wood durability and preservation is managed, at the European level, by the technical committee TC 38 'Durability of wood and wood-based products' of the European Committee for Standardization (CEN). Producing sustainable wood-based materials is challenging. A crucial aspect of their provision is reliable standards that take consideration of both the expectations of end-users and the broad set of parameters that may influence the service life of wooden components such as exposure to moisture, climatic variations and design. In order to reach these objectives, most CEN/TC 38 standards are currently being revised based on the recent scientific, technological and legal developments in the field of wood protection. There is an increasing need for performance classification of wood products in construction and to radically consider how wood durability test methods and standards can inform on service life and how they might be translated into a performance classification system. This paper describes the changes during the past 5–10 years in Europe and how the trajectory of standards development is now on a different pathway. Classification and service life demands are described as well as current approaches to consider key issues such as material resistance, moisture risk and adaptation of existing standards.

Keywords: *CEN/TC 38, service life prediction, performance standards, moisture risk, time of wetness, material resistance, use class*

Introduction

Standardization work in the field of wood durability is managed, at the European level, by the European Committee for Standardization technical committee (CEN/TC 38) 'Durability of wood and wood-based products', which is a part of a huge network of interconnected entities including the European Commission, National Standardization bodies, etc. as illustrated in Figure 1. Its goal is the elaboration of standards for wood preservatives and preservative-treated wood, modified wood and untreated wood, developing terminology, analytical methods, biological tests, classifications and specifications in accordance with the market needs and European regulations. CEN/TC 38 is organized in the following eight working groups (WG):

- WG 21: Durability – classification
- WG 22: Performance – assessment and specification
- WG 23: Fungal testing
- WG 24: Insect testing
- WG 25: External factors
- WG 26: Physical/chemical factors
- WG 27: Exposure aspects
- WG 28 Performance classification

So far some 50 standards have been adopted by CEN/TC 38, their objectives including ensuring quality and satisfying consumer expectations, eliminating trade barriers, harmonizing the methods used in the sector of wood protection, thus facilitating the understanding between producers and users, and promoting sustainable development by delivering reliable wood products with an adequate service life.

The European landscape of wood protection has changed considerably during the past two decades. An example is the new wood-based products, whose durability has been enhanced with the help of non-biocidal processes that have entered the wood

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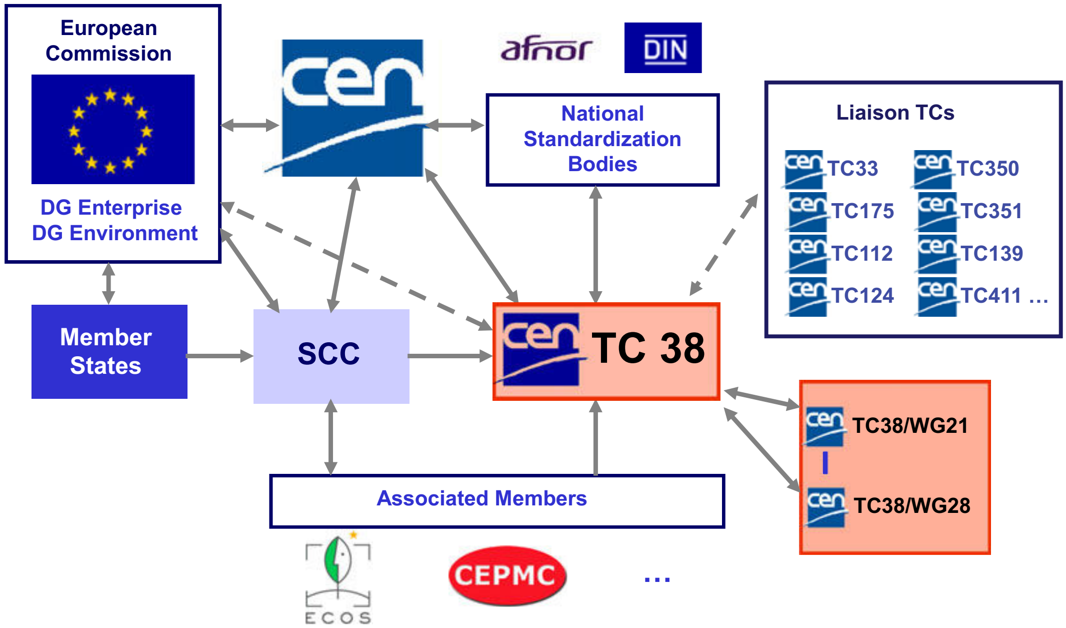

Figure 1. Organizational structure of CEN

construction market (e.g. Hill 2007, Jones 2012, Scheiding and Welzbacher 2012). In addition, national forest sectors have put effort into promoting national resources, with the objective of increasing the use of native untreated wood – often by offsetting low durability through optimized design, adapted to wood products' targeted conditions of use. European regulations also encourage manufacturers to develop products which are more efficient and less harmful for the environment and human health, and whose performance takes into account end-user expectations. These developments have resulted in a gradual shift in the global approach from traditional 'wood preservation' to 'wood protection', which is a more general concept based not only on the inherent characteristics of the material itself but also on its interactions with the environment (design, maintenance, exposure and moisture risk).

New products, processes and construction rules require validation tools to ensure their reliability and future development. In this challenging context, CEN/TC 38 is the main source of methods for assessing the characteristics of new products and as such it plays a key role. Several essential issues crucial for the future improvement of standards are now discussed here.

Compliance with EC regulations

CEN/TC 38 plays an important role in providing manufacturers with adequate qualification methods for their products, thus helping them to meet the requirements of European regulations such as the construction products regulation (CPR, EC 2011) and the biocidal products regulation (BPR, EC 2012), recently adopted by the European Commission (EC) and replacing the corresponding directives (89/106/European Economic Community and 98/8/EC). Both regulations have a major impact on the wood industry, including the field of wood preservation. They compel us to assess the performance of wood-based products and wood preservatives as well as the risk management and resource efficiency in the wood protection sector. Recently, some overlap regarding the specific requirements of the two regulations has been identified. Consequently, it is crucial to ensure efficient communication between CEN/TC 38 and the wood product technical committees (TCs) related to topics which have already been handled by CEN/TC 38.

Dealing with new products

Because of the history of CEN/TC 38, the current standards are meant for the assessment of the efficacy of wood preservatives and the inherent resistance of wood species. No specific standards have been developed yet for assessing the resistance and performance of new wood-based products whose durability has not been enhanced with the help of biocides (such as thermally modified timber, modified wood, glue-laminated wood, wood-based panels, wood polymer composites, wood treated with water-repellents) and the existing standards are typically inadequate for their qualification. Furthermore, the desired as well as expected durability of a certain product may vary significantly between different exposures. This is illustrated in Figure 2 for thermally modified ash, which can suffer from permanent wetting, e.g. when it is exposed in ground contact.

This raises the question of adapting the existing standards and efficacy tests to innovative technologies of wood protection, to make them suitable for all wood products and durability enhancement technologies. For example, resistance against basidiomycetes shall be assessed according to the standard EN 113 (CEN 1996) for preservative-treated wood and the standard CEN/TS 15083-1 (CEN 2005) for untreated solid wood, but no further guidance is given for thermally and chemically modified wood (e.g. CEN 2008, Plaschkies *et al.* 2010, Bollmus 2011, Bollmus *et al.* 2012).

The first step is currently being achieved in the framework of the revision of the European standard EN 350 (CEN 1994a, 1994b) 'Natural durability of solid wood', parts 1 and 2, which is one of the fundamental standards developed by the CEN/TC 38. Agreement has been reached on enlarging the scope of this standard to wood-based materials, which are defined as 'Any processed homogeneous matrix containing and/or made of a defined percentage of wood'. Particular attention should be given to the selection of samples to be used in the assessment of the durability of such products. Especially, the sampling should take into consideration the variability of the material for heterogeneous products.

Selecting reliable references

The origin of test specimens and the number of replicates are of great importance for the validity of the test results. Moreover, to ensure that the tested material is representative of the marketed product, especially in those cases where the material to be tested is modified wood or a processed wood-based product, it may be necessary to include samples collected from more than one production batch and to provide further details concerning the sampling procedure prior to initiating the tests.

Additionally, it is necessary to include reference products or materials in the test protocols in order to validate the results and to allow for their interpretation. Many questions have been raised about what should be considered a 'good' reference. When testing the efficacy of wood preservatives, it is common practice to include products which have previously demonstrated high levels of efficacy as references. However, some of these products, such as CCA (copper chromium arsenic; extensively used as a reference biocidal product, mainly for field tests), are nowadays banned from the European market or not registered in the framework of the BPR. However, the fact is that member states differ in their approach to this controversial matter, some allowing the use of such products, some preventing it and some undecided. Regarding the BPR, it appears that this European regulation does not provide exemptions allowing for the use of prohibited substances for research and/or development

Figure 2. Testing thermally modified ash (*Fraxinus excelsior* L.) in the field under differently severe exposure conditions in Hannover, Germany. Left: severe white rot decay after 2.5 years exposure in ground according to EN 252 (CEN 1989). Right: sandwich specimen after 2.5 years above ground exposure without signs of decay (Photos: L. Meyer & Ch. Brischke)

purposes, which mean that the standards requiring the use of reference products prohibited on the European market shall be consequently modified and propose other reference products.

When enlarging the scope of what admissible products to untreated wood and to non-conventional products such as modified wood, the question of reference products is even more complicated. Does a reference product or material has to be the best possible one for a given application? Should all the laboratories performing durability tests rely on the same references? One option to consider in the future is using different internal references that are, simply, well known and easy to apply products and which exhibit low variability of the results. The aim of reference products and materials is to allow comparison and benchmarking with other products such as wood preservatives or materials such as wood species or engineered wood-based products. Consequently, a reference product could be a wood species treated with an extensively tested biocide or untreated wood of a species whose durability is known to be very constant and ideally independent of the age of the tree or of its geographical origin. For example, Scots pine sapwood and beech, which are the species used at present as references in EN 350-1 (1994a), show variation ranging from 30 to 60 % in their mass loss when exposed to decay fungi, which makes their status as reference species questionable.

Handling data variability and reliability

Paying attention to variability in test methodologies and data analyses is essential, especially for heterogeneous biological materials such as wood (Larsson-Brelid *et al.* 2011, Brischke *et al.* 2013b, De Windt *et al.* 2013). Increasing the number of test specimens usually not only improves the reliability of test results but also increases their cost. Therefore, it is important to optimize the amount of delivered data and to select the most relevant approaches making the characterization of the products possible, without presenting unnecessary cost burdens on those procuring the tests.

The variability which is often observed in the results of durability tests results from the variability of both the operators and the tested material itself. Variability among laboratories and/or technicians performing the same tests is frequently reported (e.g. Peek *et al.* 1999, Acker Van *et al.* 2003, Brischke *et al.* 2013a, Klamer *et al.* 2013). Although the same standards and protocols are used, their levels of complexity and the fact that the assessment criteria are often qualitative, and thus more subjective than quantitative criteria, explain why different results may be obtained. The variability of the tested material can be due to sampling, but also due to its intrinsic characteristics, which are influenced by the origin and the age of the tree and the position the test samples are taken from within the tree. When selecting a set of samples to be as similar as possible, the variability of the test is accounted for, but cannot be fully prevented. On the other hand, a certain number of sources (assortments) should be considered to assure representativeness of the test results.

The classification of the natural durability or biocidal efficacy is generally based on the mean or median values of the recorded data. However, the spread of individual values is sometimes wide, which makes the interpretation of the data complicated. Expressing the results in a way that will provide customers with relevant information regarding the level of natural durability is one major challenge for the future.

Another source of variability is misguided attempts to correlate two evaluation approaches, laboratory tests and field tests, which are totally different and do not involve the same microorganisms (e.g. Brischke *et al.* 2011, Mathieu *et al.* 2013). Laboratory tests usually involve a limited number of strains of white rot and brown rot fungi that are carefully referenced and maintained; in field tests, the fungal species involved in the degradation of wood are almost never identified and, therefore, largely unknown (Figure 3). Consequently, laboratory tests only allow assessment of wood resistance to a well-known set of decay fungi and provide no information on how this wood will perform in the field.

The major risk of underestimating the importance and the impact of high variability, and thus of neglecting implementation of robust statistical approaches, is that manufacturers, users and authorities may be supplied with data whose reliability is doubtful. The statistical approach in CEN/TC 38 standards is being strengthened in order to deliver robust methodologies to the laboratories performing durability tests and, consequently, deliver more reliable wood-based products to the market.

Assessing natural durability and performance

The natural durability of a wood species is defined as its inherent resistance to wood-destroying agents; it can vary widely depending on the age of the tree, its geographical origin, and the growing conditions. The European standards EN 350-1 (CEN 1994a) and EN 350-2 (CEN 1994b) are widely used by the wood industries as the reference document which provides information on the resistance of wood species used mainly in the construction sector against decay fungi, wood-boring beetles and

Figure 3. Examples of rot causing fungi not represented as obligatory test fungus in recent European standards, but frequently found on field test samples and timber structures. Left: white rot by *Hypholoma* sp. on Douglas fir heartwood (*Pseudotsuga menziessii* Franco.) exposed in ground in Hannover, Germany (Photo: L. Meyer). Right top: brown rot by *Serpula himantioides* on buried test stake at Oléron test site, Southern France (Photo: R. Gründlinger). Right centre: brown rot decay by *Leucogyrophana pinastri* on Scots pine heartwood (*Pinus sylvestris* L.) exposed in ground in Hannover, Germany (Photo: L. Meyer). Right bottom: brown rot on above-ground exposed thermally treated beech (*Fagus sylvatica* L.) after eight years exposure caused by *Dacrymyces* sp. (Photo: Ch. Brischke)

termites. The standard also refers to the appropriate standards for testing these properties of wood and interpreting the results. However, the natural durability classes given in EN 350-2 (CEN 1994b) are based mainly on the results of field tests performed in situations of exposure corresponding to the use class 4 (UC4) as defined in EN 335 (CEN 2013) as well as long-term experience and expert advice. Consequently, (1) their relevance compared to current test methods and current timber sources (e.g. plantation grown timber) is uncertain and (2) the durability classification is only relevant for UC4 and is difficult to apply to other situations of outdoor use (UC 3.1 and 3.2) without further testing or expert opinion. After examining the current situation of the wood protection market and the shortcomings of the existing EN 350 standard (CEN 1994a, 1994b), the expert group in charge of its revision decided to introduce some major changes. Inherent resistance of a wood-based product should not be interpreted in terms of use class and should be totally independent of the environment in which the material will be placed. Conversely, its service life, or performance, being obviously environment dependent has to be expressed in terms of duration, not as a relative classification. Based on these considerations, the decision was made to define test methodologies suitable for determining both natural durability against wood-destroying organisms or performance in real-use conditions.

To determine natural durability, a single laboratory test should be used in order to provide a robust, easy and quick methodology that can be applied by all laboratories with a good level of repeatability. To determine performance, a relevant test methodology should be selected based on the intended final end-use of the product (in-ground = use class 4 or above-ground = use class 3.1 or 3.2 conditions). Performance is expected to vary depending on the selected test field and test methodology. The aim is to determine to which extent a wood species can be tested as closely as possible to the real-use conditions of the intended wood product (e.g. cladding, decking, window joinery and fence posts).

Considering the moisture risk as a factor influencing performance

The penetration of water when wood is exposed to humidity and the rate of release when wood is allowed to dry have a significant influence on determining performance and expected service life. Permeability to water is likely to vary between different regions of the stem (e.g. between sapwood and heartwood). Because permeability to water is one of the key factors affecting the performance of a wooden component as it controls the possibility of fungal decay, one may assume that, for an equal level of natural durability to decay fungi, the performance would be better for wood species with lower levels of permeability to water. Consequently, wood species that are less permeable to water are expected to perform better than permeable species in use classes where wood is exposed to intermittent wetting (for instance in UC 3.1 applications such as partially sheltered cladding). Because no harmonized European standards have been developed yet, CEN/TC 38 decided to start work out on a draft document to address this issue. Inter-comparison tests have been initiated in 2013 in the framework of the PerformWOOD research project in order to compare different methods applied both across Europe and at the national level to measure wood's permeability to water. The results of these tests will provide a useful outcome allowing for the development of a new European standard.

Time of wetness is also a key factor for fungal development and should not be neglected, in particular for use classes UC 2, UC 3.1 and UC 3.2 (CEN 2013). Time of wetness is affected by environmental parameters, including design, building physics, exposure and maintenance, which have a remarkable effect on performance and vary greatly across Europe. No internationally agreed methods for assessing these parameters exist (Meyer *et al.* 2013), but various national approaches based on experience take them into account.

Assessing performance

In their present form, CEN/TC 38 standards almost exclusively consider the material and not the final products such as windows or wooden poles. The general approach to performance, which can be defined as the level of ability to withstand deterioration over time, focuses mainly on material resistance (natural or enhanced by preservatives) and not on the primary influence of external factors such as moisture risk, design, exposure and maintenance. Biological durability is the key factor determining the performance of wood in different use classes, but numerous factors contribute to the likelihood of a worst-case scenario occurring in practice, such as exposure, geographical location, moisture risk, maintenance or presence/absence of wood-destroying agents.

The existing standards offer little or no information about the performance of wood-based products in a context of constantly increasing expectations of customers and end-users regarding information about the service life of treated and untreated products or commodities in real-use conditions (indoor, outdoor, above-ground or in-ground contact, etc.). However, since its creation in 2010 the new CEN/TC 38 working group 28 'Performance', the approach to durability and performance classification have been changing. The future of sustainable wood products clearly relies on having a system of standards that can adapt to real-world practice and provide better service life or performance classification information. Moreover, evaluation of the performance of wood and wood-based materials will provide the wood sector with data supporting the seventh essential requirement of the construction products directive (CPD/CPR).

The major difficulty regarding the assessment of performance is that the development of adequate methods requires models capable of predicting performance in a quantitative and probabilistic format. The relation between performance during testing and in service needs to be quantified in statistical terms, and the resulting predictive models need to be calibrated to provide a realistic measure of service life including a defined acceptable risk of non-conformity. A combination of tests which allow estimating the so-called 'moisture risk' (depending on geographical location, climate, exposure and also wood permeability to water which can be measured) and field tests or accelerated semi-field or laboratory tests in which the wood-based material is exposed to both weathering and wood-destroying organisms could be the first step towards predicting how this material will perform in service.

Most of the challenging questions raised above are currently being discussed in the framework of the PerformWOOD project (Figure 4). This project's main objective is to kick-start the development of new standards to enable service life specification of wood and wood-based materials for construction. This is crucial for ensuring future sustainable use of European forests, guaranteeing that customers of wood products get satisfactory and reliable products and providing supplementary evidence for life cycle evaluations of construction products. Simplifying EN standards in order to facilitate their use in practice is also an essential objective to be reached in the future.

The performWOOD approach

Background and motivation

The construction sector is under pressure to improve its cost effectiveness, quality, energy efficiency and environmental performance and to reduce the use of non-renewable resources. A key issue for the competitiveness of wood is the delivery of reliable components of controlled durability with minimum maintenance needs and life-cycle costs. The importance of service-life issues is reflected in the CPD with its six essential requirements, which should be fulfilled by construction products during a 'reasonable service life'.

In parallel, the increasing European softwood resource (which is largely non-durable) needs be utilised sustainably which demands the appropriate use of protection systems to enhance durability. The development of performance standards by CEN for wood preservatives in Europe has largely been driven by the CPD which specifies one durability class into construction, class 1 (very durable). This is ensured by a suite of biological tests in the laboratory and the field (EN 599-1, CEN 2009), which derive pass criteria related to test timber species or control wood preservatives.

Research into the performance of wood and treated wood ranges from early predictive methodology (Purslow 1977), predictive models (Leicester *et al.* 2003), service life prediction research (Tang Engelund *et al.* 2009, Brischke and Rapp 2010, Brischke *et al.* 2010, Suttie and Englund 2010, Van Acker et al. 2010) to current advanced modelling (Bornemann *et al.* 2012) and research (Brischke *et al.* 2011, Thelandersson *et al.* 2011, Wang and Morris 2011, Van Acker *et al.* 2012). There is a considerable wealth of existing research and knowledge. PerformWOOD focuses on the consolidation of the technical background for standardisation to deliver a new standardisation document on the service life performance of wood in construction.

Sustainability for construction products centres on life cycle assessment (LCA) and environmental product declarations in practice, with ranking and comparison in numerous tools and databases. Pivotal to tackling the need to reduce impacts of the construction industry is to reduce the embodied impacts of the materials and processes and ensure that they deliver reliable, meaningful function and service lives.

Existing durability test standards are largely mature and were developed for the assessment of wood preservative technologies and the determination of the natural durability of wood species. Now there are numerous ways of enhancing durability of a wood product such as wood modification, coatings, improved design and use of water repellents. The tests were exacting but collectively used to determine if a treatment was fit for purpose in a specific end use. More recent activity in the PerformWOOD project has concentrated on an accelerated programme of activity to tackle:

- Material resistance and classification, where the ongoing revision of EN 350 (CEN 1994a, 1994b), have enable consideration of including permeability to water moving closer towards material resistance (Brischke *et al.* 2013a, Kutnik 2013).
- Moisture dynamics and time of wetness, where ongoing work seeks to gather considerable new data on moisture regimes in wooden test specimens (Van den Bulcke *et al.* 2011, Bornemann *et al.* 2013, Brischke *et al.* 2013b, Fredriksson *et al.* 2013, Meyer *et al.* 2013).
- Data handling and variability, as different statistical tools are applied to biological test data to begin to understand the best way to present variability and distribution data (De Windt *et al.* 2013, Frühwald Hansson *et al.* 2013, Van den Bulcke *et al.* 2013).
- Modelling and estimation of service life approaches, considering engineering approaches and combinations of key parameters (Hansson *et al.* 2013, Suttie *et al.* 2013, Thelandersson 2013).

The approach for the development of new standards to enable the service life specification of wood and wood-based materials for construction has a logical progression that includes their aggregation of properties and tests (data handling, physical and biological tests and moisture risk), their application (service life expectations) and their standardisation (modification of existing standards and drafting of new standards, especially with regard to the user interface). Figure 5 shows the stages of the project and some of the innovations and collaborations that are occurring or are needed.

Performance classification

Service-life prediction or planning is a process for ensuring that, as far as possible, the service life of a building will equal or exceed its design life, while taking into account (and preferably optimising) its life-cycle costs. For a long time, the international organisations Conseil International du Bâtiment (CIB) (International Council for Research and Innovation in Building and Construction) and RILEM (International Union of Laboratories and Experts in Construction Materials, Systems and Structures) have been leading this development,

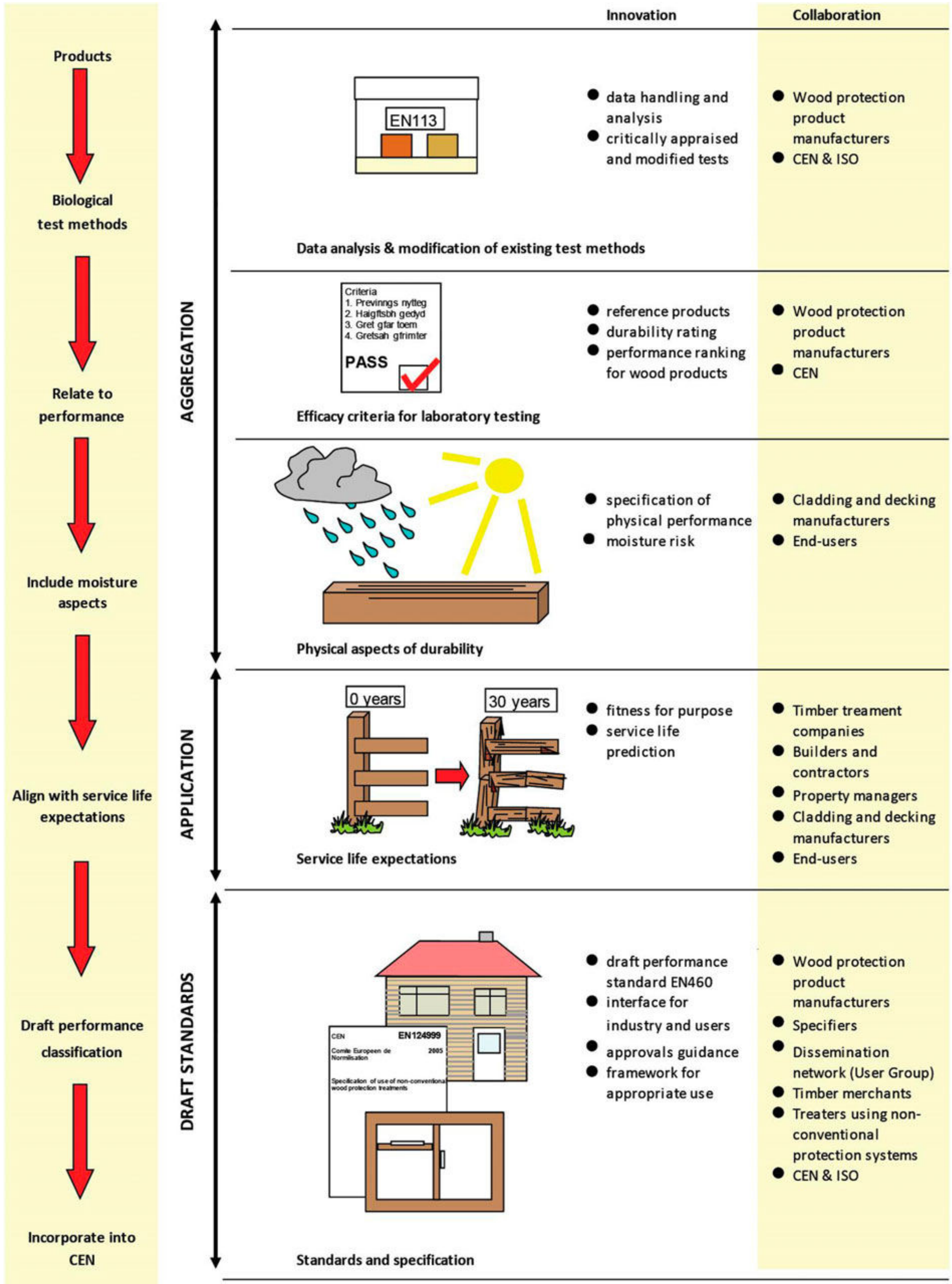

Figure 4. Representation of project PerformWOOD showing the phases of work and the impacts, innovations and collaborations

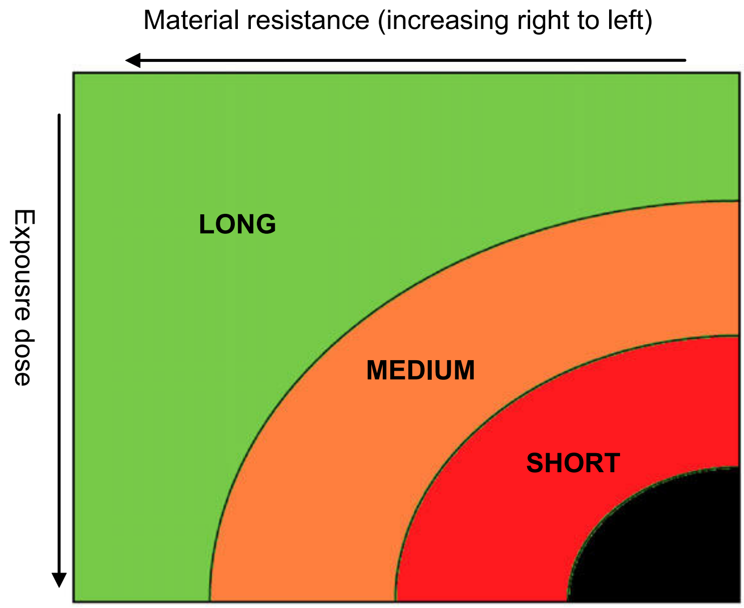

Figure 5. Conceptual chart for determine 'performance classes' for a combination of material and exposure parameters

which has had an impact on standardisation work nationally, regionally and globally through ISO (International Standardization Organisation). Drivers for establishing service-life planning methodology and routines include the need for building owners to be able to forecast and control costs throughout the design life of a building or construction. It also influences the reliability of constructed assets, and hence the health and safety of users.

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 (CEN 2013), assuming a worst-case scenario. Other factors determine the likelihood of the worst-case scenario occurring in practice.

However as noted earlier, the majority of CEN/TC 38 efficacy tests are relevant to preservative-treated wood. The system involves a framework in which specifications for preservation can be made on a country-by-country basis depending on the requirements of any given country, yet using the same set of efficacy tests. This framework for specification is laid down in European standards EN 350-1 (CEN 1994a) and EN 599-1 (CEN 2009). Of these, it is EN 599-1 (CEN 2009) which governs the choice of appropriate test methods depending on the use class in which the treated wood is to be used.

User expectations

It is vital that standards that are easier to use to enable wider appropriate specification of wood products based on performance classification and that we create a meaningful user interface. At present, the multitude of standards is logically navigated by the wood durability expert but not by the architect, designer or manufacturer of products. PerformWOOD and other research activities propose the concept of mapping together the two essential components of performance classification:

- Exposure dose (the climate, the moisture regime around in the wood product, the design of the product) and
- Material resistance (durability class, permeability to water/vapour, the biological agencies that are present)

The outcome of bringing these two parameters together – the performance classification – will likely be expressed as performance class short, medium or long life. The definitions of these are to be decided as different national approaches have been put forward in standards in France (Fascicule de Documentation (FD) P20-651, presented in Kutnik *et al.* 2011), Germany (Deutsches Institut für Normung 68800-1, 2011) and the UK (British Standards 8417, 2011). PerformWOOD is gathering user expectation information on how long architects, engineers, professional bodies and members of the public expect wood products to last. This provides valuable feedback to the development process, keeping in touch with our ambition to create a relevant user interface.

Further, there is a need to consider different use class applications for the products and also the consequences of failure, and thus the confidence intervals for parameters demanded for an application. The consequences of failure of a cladding board are low to medium, water ingress into the building, poor aesthetic and easily replaced. The consequences of failure of a structural beam are very high, building collapse, resulting in death or injury and very difficult to replace.

The user interface

EN 460 (CEN 1994c) is almost 20 years now and simply brings together the concept of hazard class (precursor to use class) alongside durability class to identify if preservative treatment was required in order to deliver a product that was fit for purpose. Our proposition is more sophisticated, and the concept of exposure dose is alongside material resistance. In the future, CEN/TC 38 will likely need a robust process via a technical report or new standards to enable existing test method outcomes to be interpreted into these two key parameters. This will support the user interface standard that is envisaged to comprise of charts. Figure 5 is conceptual in presenting a user friendly ‘tool’ with a continuum of material resistance and exposure dose. The continuum is important in enabling further decision-making by the user should the performance class desired not be met by selections, then the user is encouraged to consider (1) a material of higher material resistance and/or (2) a design that further minimizes moisture risk. It is important that the derivation of the material resistance and exposure dose comes from input parameters that again have a high degree of user sensitivity and use designer and architect familiar terminology concerning its construction, its detailing, its location, its materials, etc. This work is exploratory at the moment and we are receiving feedback to help shape the way forward.

Conclusions

The future sustainable use of the European forest resource lies with enhancing durability with environmentally improved and targeted systems to meet service life expectations. Work is progressing to take the first step towards meaningful performance classification for wood products so end-users can be assured that wood is a reliable and thus low impact material. The outcomes of project PerformWOOD are essential in moving forward to:

- Confirm a material resistance measure
- Confirm a moisture risk measure
- Kick start refinements to TC 38 standards and improve test methods
- Provide a draft standard (EN 460) for consideration of service life

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6.2 Publication II: Natural durability of timber exposed above ground – a survey.

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Natural Durability of Timber Exposed Above Ground – a Survey

Prirodna trajnost drva izloženoga iznad zemlje – pregled istraživanja

Review paper • Pregledni rad
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ABSTRACT • *Besides its inherent resistance against degrading organisms, the durability of timber is influenced by design details and climatic conditions, making it difficult to treat wood durability as an absolute value. Durability classification is, therefore, based on comparing performance indicators between the timber in question and a reference timber. These relative values are grouped and related to durability classes, which can refer to a high range of service-lives. The insufficient comparability of such durability records has turned out to be a key challenge for service-life prediction.*
This paper reviewed literature data, based on service-life measures, not masked by a durability classification. It focused on natural durability of timber tested in the field above-ground. Additionally, results from ongoing above-ground durability studies in Europe and Australia are presented and have been used for further analysis. In total, 163 durability recordings from 31 different test sites worldwide based on ten different test methods have been considered for calculation of resistance factors. The datasets were heterogeneous in quality and quantity; the resulting resistance factors suffered from high variation. In conclusion, an open platform for scientific exchange is needed to increase the amount of available service-life related data.

Keywords: *durability classes, field tests, resistance factor, service life prediction, test methodology, use class 3*

SAŽETAK • *Osim otpornosti drva prema štetnim organizmima, na prirodnu trajnost drva utječe i dizajn detalja na proizvodima od drva te klimatski uvjeti, pa je teško razmatrati svojstvo trajnosti drva kao apsolutnu vrijednost. Stoga je klasifikacija trajnosti drva utemeljena na usporedbi pokazatelja izgleda drva, čija se trajnost određuje prema izgledu referentne drvne građe. Te su relativne vrijednosti grupirane i povezane s klasama trajnosti, što se može odnositi na veliki raspon životnog vijeka drvnih proizvoda. Nedovoljna usporedivost takvih zapisa trajnosti pokazala se kao ključni izazov za predviđanje životnog vijeka drvnih proizvoda.*
U radu se daje pregled literaturnih podataka utemeljenih na životnom vijeku drvnih proizvoda koji nisu maskirani klasifikacijom trajnosti. Naglasak je na prirodnoj trajnosti drva ispitanoj pri izloženosti drva iznad zemlje. Osim toga, prezentirani su rezultati aktualnih istraživanja prirodne trajnosti drva iznad zemlje u Europi i Australiji te su

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iskorišteni za daljnju analizu. U obzir za izračun faktora otpornosti uzeta su ukupno 163 podatka o trajnosti drva dobivena s 31 različitoga ispitnog mjesta u svijetu na temelju deset različitih metoda ispitivanja uzeti . Skupovi podataka su heterogeni s obzirom na kvalitetu i količinu, što je rezultiralo velikom varijacijom čimbenika otpornosti. Zaključno, potrebna je otvorena platforma za znanstvene razmjene kako bi se povećala količina dostupnih podataka o životnom vijeku proizvoda.

Ključne riječi: *klase trajnosti, terenska ispitivanja, faktor otpornosti, predviđanje životnog vijeka, metodologija ispitivanja, uporabna klasa 3*

1 INTRODUCTION
1. UVOD

The natural durability of timber products is influenced by the interaction of wood properties, environmental conditions and structural design. Wood anatomy and the presence of natural protective chemicals (extractives) provide resistance against biodeterioration by microorganisms and insects. Communities of wood-destroying organisms vary between different locations, and their activity is influenced by climatic factors. Fungal decay and termite attack, for example, are generally more severe in warm and humid environs (Scheffer, 1971; Brischke, 2007; MacKenzie *et al.,* 2007; Thelandersson *et al.,* 2011). The extent to which timber components are affected by biodeterioration and weathering is also mediated by the design and maintenance of timber structures; for instance, the position of different structural elements and use of surface coatings alter their rates of wetting and drying, while untreated joinery and cracks in poorly maintained timber coatings may trap water and thus support decay (Norton and Francis, 2008).

Worldwide building codes and standards have traditionally provided natural durability information in a prescriptive context. Timber species are generally categorized into heartwood durability classes and the allowable uses of timbers belonging to those durability classes are prescribed (Stirling, 2009). Criteria for natural durability classification differ between countries and include combinations of field test data, laboratory test data, history of performance and expert experience (CEN, 1994; CEN, 2006; Standards Australia, 2008).

Many different field and laboratory tests are used to measure natural durability. These include standardized and non-standardized methods, among which test environments, configurations and evaluation methods vary widely (Gobakken and Viitanen, 2004; Råberg *et al.;* 2005; Stirling, 2009; Fredriksson, 2010). Tests that present a high biodeterioration hazard often involve soil contact or inoculation with microorganisms or insects. Above ground field tests generally pose a lower biodeterioration hazard, but most test configurations are designed to accelerate decay by various moisture trapping elements. Durability evaluation procedures for field tests commonly involve objective or subjective measures of strength loss, while mass loss is commonly measured for laboratory tests. Traditionally, field test results are reported in a variety of ways, including mean or median measures of specimen service life or arbitrary scores that represent levels of biodeterioration. The performance of test species is commonly compared with the ones of non-durable reference species such as the sapwood of Scots pine (*Pinus sylvestris* L.) or southern yellow pine (*Pinus* spp.) for softwoods and common beech (*Fagus sylvatica* L.) wood for hardwoods. Beyond the relative performance of specimens in the circumstances of each test, however, the practical implications of durability test data are only beginning to be explored. Willeitner and Peek (1997) highlighted that comparing different durability tests is difficult, as in addition to the heterogeneity of test methodology, one may face results that are mostly codified - sometimes in a cryptic way - or even incompletely published.

A major challenge remains to extract information from durability tests to help quantify the key factors that affect natural durability and integrate this information so that it is useful for predicting the service life of timber building products. Modern performance-based construction criteria require building products to be characterized in terms of the reliability that they will perform as expected over time. For timber, the current level of understanding of durability is far less developed than for other properties such as structural and fire safety performance, and continued research is required to develop robust service life models (Foliente, 2000). Reliable service life data are also of crucial importance for Life Cycle Assessment (LCA) studies that are used to compare the environmental impacts of wood competing building materials.

Timber performance models have been developed that incorporate climate, durability classification and design factors (Wang *et al.,* 2008b; Viitanen *et al.,* 2010; Brischke and Frühwald Hansson, 2011; Thelandersson *et al.,* 2011), however more data are sought for calibration and fine tuning. As an alternative to using durability class categories to represent wood properties in design guides (MacKenzie *et al.,* 2007), the use of a resistance index and resistance classes has been proposed (Thelandersson *et al.,* 2011). Incorporation of 'durability factors' into a factor method has also been suggested (Dickinson, 2005; ISO 15 686-1, 2000).

Despite the importance of above ground structures in timber engineering, reports of natural durability studies involving above-ground exposures are relatively rare. Numerous laboratory decay tests have been reported, but their relationship with timber performance in service appears limited (Da Costa, 1979; Van Acker *et al.,* 1999). Publications containing in ground 'graveyard' test data are more readily available, but their usefulness for service life modeling of above ground structures is unclear. The need for above ground durability to support performance modeling was more recently recognized, but due to their long duration, many above ground tests are incomplete and yet to be published. Above ground test results are likely to be most heterogeneous as they take a long time to complete and a wider range of standardized and non standardized methods may be used.

The aims of this review paper were to: (1) survey above-ground natural durability test data from published and ongoing field studies; (2) examine the usefulness of data obtained for service life prediction; and (3) compute resistance factors and consider their implications for understanding the effects of differences between field test sites and methods.

2 MATERIALS AND METHODS
2. MATERIJAL I METODE

2.1 Literature survey on above ground durability test data
2.1. Pregled literature o ispitivanjima trajnosti drva iznad zemlje

Relevant literature was reviewed concerning the natural durability of timber species determined in field tests above ground. Modified and preservative treated timber was not considered as this would be unmanageable, due to increased amount of data and different testing approaches compared to non-treated timbers. Two a priori criteria for articles or data inclusion were set: (1) published in a peer reviewed journal, printed conference proceedings, international standard, project report or PhD thesis; (2) a focus on natural durability, field testing or service life.

The reference lists in the articles found and publication lists from durability researchers worldwide were checked for additional articles. The studies which met the a priori criteria used only four different test methods: the horizontal lap-joint test (CEN, 2003; Palanti *et al.,* 2011); the horizontal double layer test (Augusta, 2007; Brischke *et al.,* 2009); the cross brace test (Eslyn *et al.,* 1985; Highley, 1995); and the accelerated L-joint test (Van Acker and Stevens, 2003). The principal configurations of these methods are illustrated in Figure 1. In most cases, there were minor variations in the basic set up for each test method between different studies, for instance in terms of shading, distance to ground, test rig size and material. Untreated control specimens included in tests of treated timber were included if necessary and appropriate.

2.2 Above ground field tests
2.2. Testovi trajnosti drva iznad zemlje

In addition to published information, data from ongoing tests, which had not been published to date but were accessible to the authors, were included (Tab. 1).

Table 1 Above ground field trials and corresponding literature sources considered for service life related data (Test ID and abbreviations refer to data in Tab. 7 and 8)
Tablica 1. Ispitivanja trajnosti drva iznad zemlje i odgovarajući literaturni izvor za podatke o njegovu životnom vijeku (ID testa i kratice odnose se na podatke u tablicama 7 i 8)

ID	**Test method** *Metoda ispitivanja*	**Abbr.** *Kratica*	**Durability measure** *Mjera trajnosti*	**Reference species** *Referentna vrsta*	**Reference** *Referenca*
1	Lap-joint test	LpJ	SL_{mean}	Scots pine sapwood	Original data
2	Lap-joint test	LpJ	v_{5years}	Scots pine sapwood	Palanti *et al.* 2011
3	L-joint coated	LJc	$v_{21years}$	Radiata pine sapwood	Original data
4	L-joint uncoated	LJu	$v_{21years}$	Radiata pine sapwood	Original data
5	Accelerated L-joint test	ALJ	$v_{ML,\ 4\ years}$	Scots pine sapwood	Van Acker & Stevens 2003
6	Cross brace test	CB	SL_{median}	SYP sapwood[1]	Highley 1995
7	Cross brace test	CB	SL_{median}	SYP sapwood[1]	Highley 1995, Eslyn *et al.* 1985
8	Double layer	DL	v_{6years}	Scots pine sapwood	Original data
9	Double layer	DL	v_{8years}	Scots pine sapwood	Original data
10	Double layer	DL	v_{9years}	Scots pine sapwood	Original data
11	Double layer	DL	v_{7years}	Scots pine sapwood	Brischke *et al.* 2009
12	Double layer	DL	SL_{mean}	Scots pine sapwood	Original data
13	Double layer	DL	SL_{median}	Scots pine sapwood	Original data
14	Double layer	DL	v_{6years}	Scots pine sapwood	Original data
15	Double layer	DL	v_{7years}	Scots pine sapwood	Original data
16	Double layer	DL	v_{8years}	Scots pine sapwood	Original data
17	Double layer	DL	$SL_{5th\ percentile}$	Scots pine sapwood	Rapp *et al.* 2010
18	Double layer	DL	$SL_{25th\ percentile}$	Scots pine sapwood	Rapp *et al.* 2010
19	Double layer	DL	v_{7years}	Scots pine sapwood	Rapp *et al.* 2010
20	Multi layer, bottom	MLb	$v_{10years}$	Scots pine sapwood	Original data
21	Multi layer, upper	MLu	$v_{10years}$	Scots pine sapwood	Original data
22	Bundle test A	BuA	v_{4years}	Scots pine sapwood	Original data
23	Bundle test B	BuB	v_{4years}	Scots pine sapwood	Original data
24	Bundle test C	BuC	v_{4years}	Scots pine sapwood	Original data
25	Bundle test D	BuD	v_{4years}	Scots pine sapwood	Original data

[1]SYP = Southern Yellow Pine

L-joint tests in Australia
Testovi L-spoja u Australiji

Above-ground durability L-joint tests were established in 1987 at different exposure sites in Australia (Francis and Norton 2005, Francis *et al.* 2007, Wang *et al.* 2008a). Eight untreated wood species were exposed at 10 field test sites throughout eastern Australia, while an additional 19 untreated wood species were set out at the Beerburrum test site, 65 km north of Brisbane (Tab. 2 and 3).

L-joint test units were constructed according to Fig. 1d using timber 35 x 35 mm² in cross section. Half of the specimens for each species were painted. Each joint was pulled apart after painting to completely break the paint film along the frame of the joint and therefore create a uniformly high decay hazard by allowing moisture to enter and remain in the joint and under the broken paint. The 35 x 35 mm² faces at the distal ends of the joint components were sealed with bituminous tape.

At each site L-joints were placed on exposure racks that were constructed using CCA treated plywood and durable framing timbers that are resistant to insect attack. Plastic strips and brackets were fixed to the racks to support L-joints and prevent them from coming into direct contact with each other or the plywood. At all locations the racks were faced north, and they were constructed the way that L-joints placed on them were oriented 10° backward from vertical to channel moisture toward the joint.

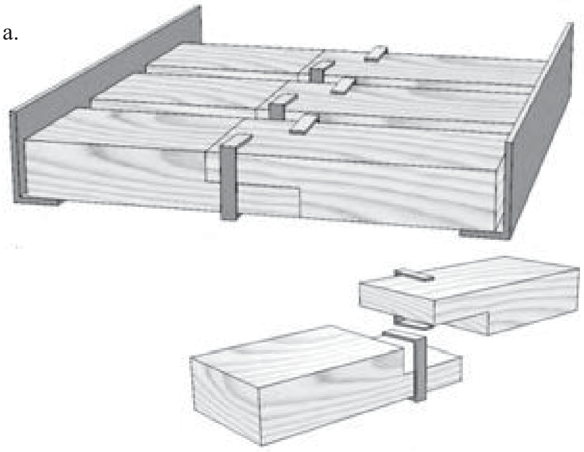
Assessment of the specimens was undertaken after 3, 5, 7, 9, 11, 16, 19 and 21 years of exposure. Only the 35 x 35 x 11 mm³ face of the tenon part of each joint - the component most susceptible to decay - was assessed. The depth and distribution of decay was detected using the pick test, which involves firm probing using a small knife. Decay scores were assigned between 0 (sound, resistant to probing and no apparent loss of structural integrity) and 4 (failure, severe decay through the 11 x 35 mm² tenon part of an L-joint) according to Carey *et al.* (1981).

Table 2 Mean decay rating according to EN 252 (CEN 1989) of specimens exposed in horizontal L-joint tests after 21 years of exposure in Beerburrum, Australia.
Tablica 2. Prosječna ocjena trulosti uzoraka izloženih testu horizontalnog L-spoja prema EN 252 (CEN 1989) nakon 21 godine izlaganja u Beerburrumu, Australija

Wood species *Vrsta drva*	**Botanical name** *Botanički naziv*	**Mean decay rating [0-4]** *Prosječna ocjena trulosti [0-4]*	
		unpainted / *neobojen*	painted / *obojen*
Johnstone River hardwood	*Backhousia bancroftii*	1.2	3.7
Rose alder	*Caldcluvia australiensis*	3.7	4.0
Northern silky oak	*Cardwellia sublimis*	4.0	3.8
Spotted gum	*Corymbia citriodora*[1]	2.5	3.5
Kapur	*Dryobalanops* spp.	1.6	3.1
Kamamere	*Eucalyptus deglupta*	3.3	3.7
Alpine ash	*Eucalyptus delegatensis*	3.8	3.8
Grey ironbark	*Eucalyptus drepanophylla*	0.8	2.9
Rose gum	*Eucalyptus grandis*	2.2	3.0
Messmate	*Eucalyptus obliqua*	3.7	3.6
Black butt	*Eucalyptus pilularis*	2.3	2.9
Mountain ash	*Eucalyptus regnans*	4.0	3.8
Red mahogany	*Eucalyptus resinifera*	1.1	2.7
Sydney blue gum	*Eucalyptus saligna*	2.3	2.8
Forest red gum	*Eucalyptus teretticorni*	1.2	2.6
Queensland maple	*Flindersia brayleyana*	3.7	4.0
Brush box	*Lophostemon confertus*	2.3	3.0
Fishtail silky oak	*Neorites kevedianus*	1.5	3.3
Light red meranti	*Shorea* spp.	3.9	4.0
Red balau	*Shorea* spp.	0.7	2.9
White Eungella satinash	*Syzygium wesas*	1.9	3.1
Hoop pine	*Araucaria cunninghammii*	4.0	3.4
Black cypress	*Callitris endlichrei*	4.0	4.0
White cypress	*Callitris glaucophylla*	1.8	2.2
White cypress sapwood	*Callitris glaucophylla*	4.0	4.0
Carribean pine	*Pinus caribaea*	3.6	3.8
Slash pine	*Pinus elliottii*	3.9	3.9
Radiata pine	*Pinus radiata*	4.0	3.9
Douglas fir	*Pseudotsuga menziesii*	3.9	3.9
Western Red Cedar	*Thuja plicata*	4.0	3.3

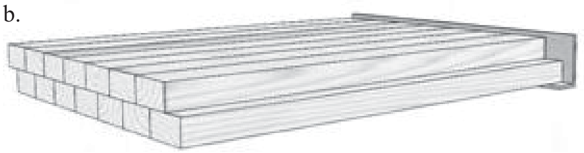
[1] *Corymbia citriodora* subsp. *variegata*

a.



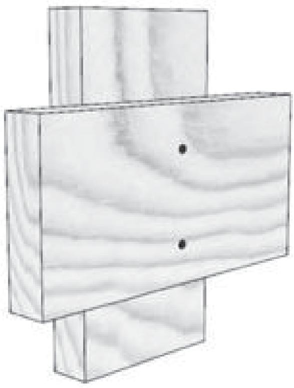
Horizontal lap-joint test
(CEN, 2003)
Horizontalni test lap-spoja
Specimens (38 x 85 x 300 mm³) are exposed horizontally on test rigs with supports 1 m above ground. The two lap-joint segments are fixed through stainless steel clamps or plastic cable strips. The end-grain of each lap-joint is sealed with polyurethane or silicone.

b.



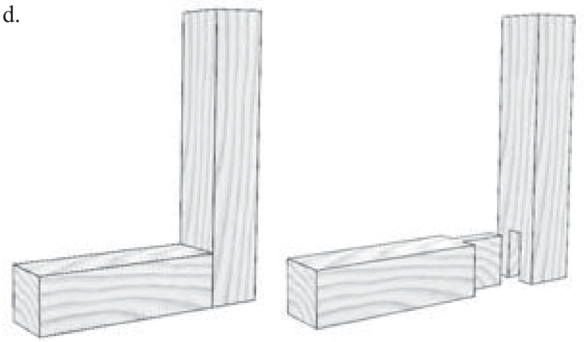
Horizontal double layer test
Horizontalni test dvostrukog sloja
Specimens (500 x 50 x 25 mm³) are exposed horizontally in double layers according to Augusta (2007) with the upper layer displaced laterally by 25 mm to the lower layer. Supports are 25 cm above ground and made from aluminum L-profiles or Norway spruce beams with or without a bituminous foil.

c.



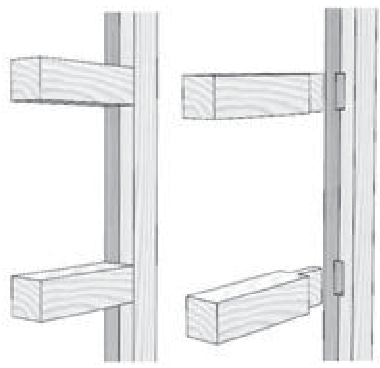
Cross brace test – *Križni test*
Test units are constructed of 19 x 76.2 x 152.4 mm³ boards, that are nailed together at their centers to form a cross (e.g. Highley, 1995) and installed on test fences.

d.



L-joint test (CEN, 1993)
Test L-spoja
Specimens with dimension of 38 x 38 mm² in the cross section with a machined mortise and tenon joint are used. The members measure 203 mm in length. The whole L-joint assembly is either coated and afterwards disassembled or stays uncoated. Different modifications of the standard procedure are also considered.

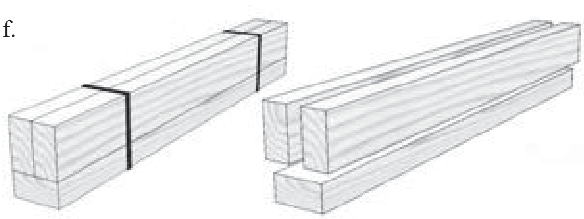
e.



Accelerated L-joint test
Ubrzani test L-spoja
A modified version of the L-joint test (CEN, 1993) is applied, e.g. according to Van Acker and Stevens (2003). L-joint tenon members are made from the test species. In contrast, the mortise member is half made of beech, and half made of Scots pine sapwood acting as feeder specimen.

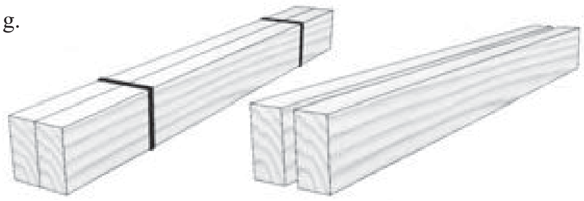
Figure 1 Above ground test set ups considered for durability records
Slika 1. Testovi trajnosti drva iznad zemlje

f.



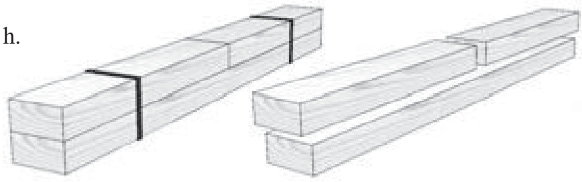
***Bundle test Type* A**
Test svežnja tipa A
Each specimen consists of three segments, which are stakes of 25 x 50 x 500 mm³ and are ex-posed as a bundle.

g.



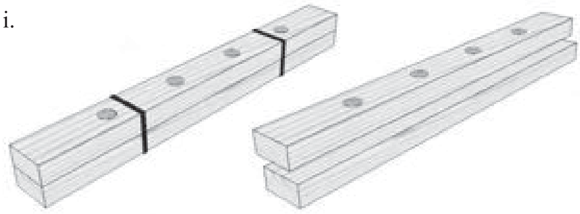
Bundle test Type B
Test svežnja tipa B
Each specimen consists of two segments, which are stakes of 25 x 50 x 500 mm³ and are exposed as a bundle.

h.



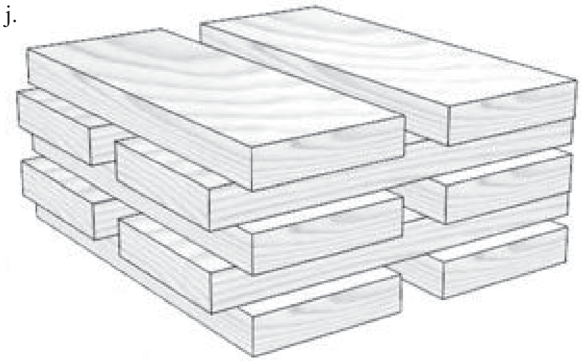
Bundle test Type C
Test svežnja tipa C
Each specimen consists of three segments, one bottom stake of 25 x 50 x 500 mm³ and two top stakes of 25 x 50 x 250 mm³, which are exposed as a bundle.

i.



Bundle test Type D
Test svežnja tipa D
Each specimen consists of two segments, which are stakes of 25 x 50 x 500 mm³ and are exposed as a bundle. The upper specimen has four circular drill holes with a diameter of 20 mm to allow water trapping.

j.



Ground-proximity multiple layer test
Višeslojni test u blizini zemlje
Each test unit consists of ten specimens of 22 x 95 x 250 mm³, stacked two by two in five crossed layers, bottom layer on the ground, e.g. according to Edlund (2004). To avoid weed growth the ground is covered with a geotextile. Either the two upper boards or the two bottom boards are assessed (indicated as 'upper' and 'bottom').

Figure 1. cont'd: Above ground test set ups considered for durability records.
Slika 1. (nastavak). Testovi trajnosti drva iznad zemlje

Horizontal double layer tests in Europe
Horizontalni dvoslojni testovi u Europi

Double layer tests have been performed at 23 different European test sites to establish dose-response functions for above ground wood decay with wood moisture content (MC) and temperature. A detailed description of the study and a corresponding dose-response performance model is given by Brischke and Rapp (2008a, 2008b, 2010).

Specimens made from Scots pine sapwood (*Pinus sylvestris* L.) and Douglas fir heartwood (*Pseudotsuga menziesii* (Mirb.) Franco) were monitored in terms of MC, wood temperature and the progress of fungal decay up to a period of eight years. The specimens (500 x 50 x 25 mm³), according to EN 252 (CEN 1989), were exposed horizontally in double layer test rigs (see Fig. 1b) producing a decay risk corresponding to European Use Class 3 (CEN 2006). The upper layer was displaced laterally by 25 mm with respect to the lower layer. The lower layer consisted of seven pine sapwood specimens and six Douglas fir specimens; the upper layer consisted of six pine sapwood specimens and five Douglas fir specimens. The whole test set-up formed a closed deck (73 x 65 x 21 cm³). The specimens were evaluated yearly through a pick-test using a small knife and rating the extent and distribution of decay according to EN 252 (CEN 1989) as: 0 (sound), 1 (slight attack), 2 (moderate attack), 3 (severe attack) or 4 (failure).

Horizontal double layer tests in Norway
Horizontalni dvoslojni testovi u Norveškoj

Horizontal double layer tests (Fig. 1b) were conducted with 29 different wood species (Tab. 6) as described by Evans *et al.* (2011) and Flæte *et al.* (2008, 2011). Specimens were exposed at three different locations in Norway: Oslo (exposed in 2002), Bergen and

Table 3 Mean decay rating according to EN 252 (CEN 1989) of specimens exposed in horizontal painted and unpainted L-joint tests after 21 years of exposure at ten different test sites in Australia.
Tablica 3. Prosječna ocjena trulosti obojenih i neobojenih uzoraka izloženih testu horizontalnog L-spoja prema EN 252 (CEN 1989) nakon 21 godine izlaganja na deset različitih mjesta u Australiji

	Mean decay rating [0-4] / *Prosječna ocjena trulosti [0-4]*									
	Beer-burrum	Dalby	Frank-ston	Pennant Hills	Rock-hampton	South Johnstone	Toow-oomba	Yarra-lumba	Mount Isa	Towns-ville
Painted / *Obojeno*										
Northern silky oak	3.8	3.7	3.8	3.7	3.7	3.9	3.9	3.6	2.2	3.5
Spotted gum	3.5	3.1	2.9	3.8	3.1	3.4	3.1	3.0	0.1	2.7
Grey ironbark	2.9	3.1	2.6	3.8	2.9	3.5	2.7	2.6	0.6	2.8
Brush box	3.0	3.0	3.2	3.8	3.4	4.0	2.9	3.1	1.6	2.9
White cypress	2.2	3.2	3.4	3.7	3.2	4.0	3.1	3.0	2.0	3.3
White cypress sapwood	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	2.4	4.0
Radiata pine	3.9	4.0	4.0	4.0	4.0	4.0	4.0	3.8	2.9	4.0
Douglas fir	3.9	3.9	4.0	3.9	4.0	4.0	3.9	3.7	2.7	3.9
Western red cedar	3.3	2.7	3.8	3.9	3.6	4.0	2.2	2.4	1.4	2.4
Unpainted / *Neobojeno*										
Northern silky oak	4.0	3.8	3.9	3.8	3.6	4.0	4.0	3.5	2.7	2.1
Spotted gum	2.5	1.5	1.7	2.4	0.8	3.7	0.7	0.3	0.0	0.6
Grey ironbark	0.8	1.5	1.2	2.2	1.0	3.5	0.4	1.0	0.6	1.3
Brush box	2.3	2.0	1.8	2.6	1.7	3.8	1.6	2.0	1.8	2.2
White cypress	1.8	2.9	2.4	3.3	3.6	4.0	3.3	3.0	1.8	3.7
White cypress sapwood	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	2.8	4.0
Radiata pine	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	2.6	3.9
Douglas fir	3.9	3.9	3.9	4.0	3.9	4.0	4.0	3.8	2.9	3.6
Western red cedar	4.0	2.9	3.4	3.8	3.8	4.0	3.9	3.6	1.7	3.4

Ås (exposed in 2004). In Oslo the test site is on the roof of the Norwegian Institute of Wood Technology, an 8 floor building, while the two test sites in Bergen and Ås are on ground level. Test set up and assessment of the specimens were identical with the above described procedure apart from the test rack size, which was larger due to a higher number of tested wood species. Samples were evaluated every year.

Lap-joint and ground-proximity multi layer tests in Sweden
Lap-spoj i prizemni višeslojni testovi u Švedskoj

Horizontal lap-joint tests (Fig. 1a) according to CEN TS 12 037 (CEN 2003) and ground-proximity multi layer tests (Fig. 1j) according to Edlund and Jermer (2007) were conducted in Borås, Sweden. Besides different treated timbers, the following untreated control wood species were tested: European larch (*Larix decidua* Mill.), Siberian larch (*Larix sibirica* Ledeb.), Norway spruce (*Picea abies* (L.) H. Karst.), Scots pine (*Pinus sylvestris* L.), European beech (*Fagus sylvatica* L.), Aspen (*Populus tremula* L.), and English oak (*Quercus robur* L.).

The lap-joint tests were started in 1996 and the specimens were assessed after 5, 8, 10, 12, 13, and 15 years of exposure. The ground-proximity trials were started in 2001 and assessed after 1, 2, 3, 5, and 10 years. Each ground-proximity multi layer test unit consisted of ten specimens, 22 x 95 x 250 mm³, that were stacked two by two in five crossed layers, with the bottom layer on the ground. The assessment of the specimens in the stacks was carried out separately for the bottom and the upper part (Tab. 1) using the pick-test. To avoid weed growth around the stacks, the ground had been covered with a geotextile, permeable for micro-organisms.

Bundle tests in Germany
Testovi svežnja u Njemačkoj

Bundle tests of four different types (A-D) after Brischke *et al.* (2011) were conducted in Northern Germany. The specimens were made from Norway spruce as illustrated in Fig. 1f-i and exposed in 2007. Afterwards they were evaluated annually by using the pick-test and rating the extent and distribution of decay according to EN 252 (CEN 1989).

2.3 Durability measures
2.3. Mjere trajnosti

Numerous evaluation and assessment procedures were analyzed with respect to their significance and informative value for the prediction of service life. The following ranking of preference was applied to the different durability assessment measures:

1. Mean service life of specimens SL_{mean} (1)
2. Median service life of specimens SL_{median} (50^{th} percentile, 2)
3. 25^{th} percentile of service life of specimens $SL_{25th\ percentile}$ (3)
4. Decay rate (after x years) v_{mean} (4)
5. 5^{th} percentile of service life of specimens $SL_{5th\ percentile}$ (5).

$$SL_{mean} = \frac{\sum_{i}^{n} SL_i}{n} \quad (1)$$

$$SL_{\text{median}} \begin{cases} SL_{\frac{n+1}{2}} & \text{; if } n \text{ is uneven} \\ \frac{1}{2}\left(SL_{\frac{n}{2}} + SL_{\frac{n}{2}+1}\right) & \text{; if } n \text{ is even} \end{cases} \quad (2)$$

$$SL_{\text{median}} \begin{cases} SL_{\frac{n+1}{4}} & \text{; if } n \text{ is uneven} \\ \frac{1}{2}\left(SL_{\frac{n}{4}} + SL_{\frac{n}{4}+1}\right) & \text{; if } n \text{ is even} \end{cases} \quad (3)$$

$$v_{\text{mean}} = \frac{\sum_{i}^{n} v_i}{n} = \frac{\sum_{i}^{n} \frac{R}{t}}{n} \quad (4)$$

$$SL_{\text{median}} \begin{cases} SL_{\frac{n+1}{20}} & \text{; if } n \text{ is uneven} \\ \frac{1}{2}\left(SL_{\frac{n}{20}} + SL_{\frac{n}{20}+1}\right) & \text{; if } n \text{ is even} \end{cases} \quad (5)$$

Where SL_i is the service life of a single specimen (the year when a specimen was recorded to have failed) [y], v_i is the decay rate of single specimen [y^{-1}], R is the decay rating (score), t is the exposure time [y], and n is the number of replicate specimens.

Decay rate, as represented by the rate of change in decay rating over time, was considered as less desirable quantity with which to determine resistance factors. Whilst decay does not necessarily proceed at a linear rate, it was necessary to consider it as such for the purposes of this study. Different decay rating schemes had been applied, e.g. the five step scales according to EN 252 (CEN, 1989) and EN 330 (CEN, 1993). Alternatively, the decay rate was expressed as 'mass loss rate v_{ML}', when only mass loss, but not decay ratings were available (e.g. Van Acker and Stevens, 2003).

2.4 Resistance factors
2.4. Čimbenici otpornosti

To make the different durability measures comparable, they were related to the respective reference species and resistance factors f were calculated according to 6 and 7.

$$f_{SL} = \frac{SL_{\text{tested species}}}{SL_{\text{reference species}}} \quad (6)$$

$$f_{v} = \frac{v_{\text{reference species}}}{v_{\text{tested species}}} \quad (7)$$

Where f_{SL} and f_v are resistance factors based on service life and decay rate (after x years), respectively, SL is the service life [y], and v is the decay rate [y^{-1}]. The equation used depended on the durability measure applied for each test: Equation 6 if service life measures were reported or equation 7 if decay ratings were recorded. Resistance factors were calculated for the six species with most available data: spotted gum (*Corymbia* spp.), oak (*Quercus robur/petraea*), Norway spruce (*Picea abies* (L.) H. Karst.), Scots pine (*Pinus sylvestris* L.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), and western red cedar (*Thuja plicata* Donn ex D. Don).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Ongoing durability studies
3.1. Aktualna istraživanja trajnosti

*In total, results from six published and five different ongoing durability studies were considered for this survey. To illustrate the latest state of the ongoing studies, which took place at different locations around the world and made use of seven different tests methods, the mean decay ratings are presented for all timber species tested (Fig. 2 and Tab. 2 to 6).

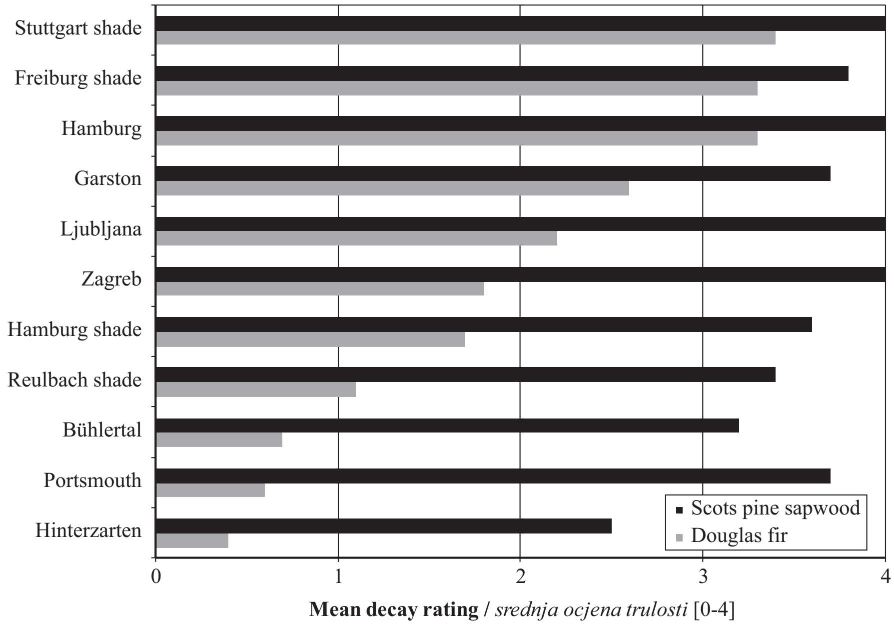


Figure 2 Mean decay rating according to EN 252 (CEN, 1989) of Douglas fir and Scots pine sapwood specimens after 6.5 years exposure in horizontal double layer tests at different locations in Europe.
Slika 2. Prosječna ocjena trulosti uzoraka od bjeljike duglazije i bora izloženih horizontalnome dvoslojnom testu prema EN 252 (CEN 1989) nakon 6,5 godina izlaganja na različitim lokacijama u Europi

Table 4 Mean decay rating according to EN 252 (CEN 1989) of specimens exposed in horizontal lap-joint tests after 12 years of exposure in Borås, Sweden.
Tablica 4. Prosječna ocjena trulosti uzoraka izloženih testu horizontalnog lap-spoja prema EN 252 (CEN 1989) nakon 21 godine izlaganja u Borâsu, Švedska

	Mean decay rating [0-4] / *Prosječna ocjena trulosti [0-4]*			
	Scots pine sapwood *(Pinus sylvestris)*	Scots pine heartwood *(Pinus sylvestris)*	Norway spruce *(Picea abies)*	European larch *(Larix decidua)*
after 5 years	0.4	0.1	0.8	0.3
after 8 years	2.7	0.5	3.4	1.5
after 10 years	3.7	2.1	3.9	2.3
after 12 years	4.0	2.2	4.0	2.5
after 13 years	-	2.6	-	2.8
after 15 years	-	2.9	-	3.0

Table 5 Mean decay rating according to EN 252 (CEN 1989) of specimens exposed in ground-proximity multi layer tests after 10 years of exposure in Borås, Sweden.
Tablica 5. Prosječna ocjena trulosti uzoraka izloženih prizemnom višeslojnom testu prema EN 252 (CEN 1989) nakon deset godina izlaganja u Borâsu, Švedska

Wood species *Vrsta drva*	**Botanical name** *Botanički naziv*	**Mean decay rating [0-4]** / *Prosječna ocjena trulosti [0-4]*	
		Bottom part / *Donji dio*	Upper part / *Gornji dio*
Scots pine sapwood	*Pinus sylvestris*	4.0	4.0
Scots pine heartwood	*Pinus sylvestris*	4.0	1.0
European larch	*Larix decidua*	3.0	0.5
Norway spruce	*Picea abies*	4.0	4.0
Beech	*Fagus sylvatica*	2.8	4.0
English oak	*Quercus robur*	2.5	0.5
Aspen	*Populus tremula*	4.0	3.3

Table 6 Mean decay rating according to EN 252 (CEN 1989) of specimens exposed in horizontal double layer tests after 6 years of exposure at three test locations in Norway.
Tablica 6. Prosječna ocjena trulosti uzoraka izloženih horizontalnome dvoslojnom testu prema EN 252 (CEN 1989) nakon šest godina izlaganja na tri različite lokacije u Norveškoj

Wood species *Vrsta drva*	**Botanical name** *Botanički naziv*	**Mean decay rating [0-4]** / *Prosječna ocjena trulosti [0-4]*		
		Oslo	Ås	Bergen
Norway maple	*Acer platanoides*	-	1.5	3.0
Lime	*Tilia cordata*	-	1.5	3.2
Aspen	*Populus tremula*	2.1	1.1	2.2
Silver birch / Downy birch	*Betula pendula / B. pubescens*	2.1	1.5	2.0
Alder / Grey alder	*Alnus glutinosa*	2.4	1.5	3.5
Rowan	*Sorbus aucuparia*	-	1.2	2.0
Goat willow	*Salix caprea*	-	0.5	2.1
European oak	*Quercus spp.*	0.5	0.5	1.4
Ash	*Fraxinus excelsior*	-	0.9	1.7
Wych elm	*Ulmus glabra*	-	0.5	2.0
Beech	*Fagus sylvatica*	-	2.0	3.1
Cedrela	*Cedrela spp.*	0.0	-	-
Sitka spruce	*Picea sitchensis*	0.4	1.7	3.0
Norway spruce 6 mm rings	*Picea abies*	-	2.4	2.1
Norway spruce 3 mm rings		2.2	2.1	1.9
Norway spruce 1 mm rings		-	0.9	1.9
Norway spruce standing rings		-	1.9	2.4
Silver fir	*Abies alba*	-	2.9	2.9
Scots pine 3 mm rings	*Pinus sylvestris*	0.2	1.2	1.5
Scots pine 1 mm rings		0.0	1.0	1.9
Scots pine sapwood		2.4	1.2	2.3
Scots pine sapwood + heartwood		-	0.6	2.1
Western red cedar (N-America)	*Thuja plicata*	-	0.2	1.2
Western red cedar (Norway)		-	1.3	1.4
Juniper	*Juniperus communis*	-	0.3	0.9
Larch (Russia)	*Larix sibirica*	0.4	0.9	1.4
Larch (Norway)	*Larix decidua*	-	0.3	1.2
Douglas fir (N-America)	*Pseudotsuga menziesii*	-	0.2	1.2

Site characteristics were found to affect the performance of particular wood species differently. The mean decay ratings for Douglas fir heartwood after 6.5 years of exposure in horizontal double layer tests at 11 different locations in Europe is shown in Fig. 2 in order descending severity of decay. The respective 'non-durable' reference Scots pine sapwood did not show the same trend for decay severity amongst the 11 test sites. The differing ratio between mean decay rating for Douglas fir and the reference species was presumably caused by a combination of their respective wood properties and climatic differences between sites. The particular properties of each species, such as moisture permeability and potential for leaching of protective extractives, may cause differences in the effects of climatic conditions, such as rainfall and temperature. Similar observations were made for the horizontal double layer samples exposed at three Norwegian test sites (Tab. 6). For instance, the mean decay ratings of grey alder (*Alnus glutinosa* L.) and Scots pine sapwood were almost the same after 6 years of exposure in Oslo and Ås, whilst the mean decay rating was significantly higher for grey alder in Bergen compared to the Scots pine sapwood reference (Tab. 6). For other species, such as aspen (*P. tremula*), the ratios between tested timber and reference were nearly the same at all three test locations.

In addition to differences in decay progress between species at climatically different locations, the impact of test methods and test design became apparent. As shown in Tab. 5, the ratio of the mean decay ratings for seven wood species differed significantly between the upper and bottom parts of ground-proximity multi layer tests in Borås, Sweden. The higher moisture load and limited potential for re-drying in the bottom parts of the stack diminished the differences between different timbers, which coincides with the reports by Augusta (2007) and Rapp *et al.* (2010), who compared the decay development of different European wood species under different exposure conditions above ground. For instance, the good moisture performance of the heartwood of European larch (*L. decidua*), Douglas fir (*P. menziesii*) or Scots pine (*P. sylvestris*) is abolished when permanent wetting is provoked. For further comparative analyses of the different above ground trials considered for this survey, resistance factors were considered.

3.2 Resistance factors
3.2. Čimbenici otpornosti

The computation of resistance factors allowed the wide range of previous and ongoing tests to be compared, irrespective of test configurations and assessment methods. We found, however, that the number of durability recordings that were freely accessible from publications and relevant for service life prediction was generally sparse. Apart from the fact that above ground durability studies are rare, many of the reported studies contained insufficiently detailed results. The condensed format of presenting test results that is often used for publication inhibited the calculation of resistance factors with sufficiently high statistical reliability. The significance of this problem can be illustrated by considering the Australian L-joint test, which includes 29 different wood species represented by painted and unpainted specimens installed at various locations, and the test has been assessed eight times to date. If the results were reported together, there would be 1808 mean scores alone. It is obviously beyond the scope of one publication to deal with this volume of data, so selected results have been published over time. If only mean scores at a particular time are reported in a single publication, they are not very useful to timber engineers researching service life prediction, as they attempt to find and compile a complete set of data for analysis (Tab. 2 and 3). Furthermore, representative measures of durability may need to be transformed for analysis, for example from ratings (scores) to service life values, so raw data are required. While it is possible to seek data directly from researchers managing durability tests, they may be difficult to find. Individual publications may not reveal the full extent of an entire durability test when only specific elements of data are reported.

Tab. 1 gives an overview of the data regarded for this survey. In total, 163 durability measures from 31 different test sites have been considered for the calculation of resistance factors: 37 for hardwoods and 126 for softwoods. Only three reference species were used to compare the different durability tests: Scots pine sapwood (*P. sylvestris*), Radiata pine sapwood (*Pinus radiata* D.Don) and southern yellow pine sapwood (*Pinus* spp.). The resistance factors for six selected wood species, for which most durability records were found, are presented in Tab. 7 and 8. Several of these timbers are commonly used untreated for above ground structures that are exposed to the weather, including oak (*Quercus* spp.), spotted gum (*Corymbia* spp.) and western red cedar (*T. plicata*).

Most of the durability recordings were based on preliminary test results, and consequently, decay ratings after 4 to 21 years were used for calculating resistance factors. For most species the range of resistance factors was quite high, for example between 0.90 and 4.54 for Douglas fir (*P. menziesii*), and in extreme - between 15.88 and 43.03 - for spotted gum (*Corymbia* spp.). In the case of Douglas fir this can be translated to durability classes (DC, according to EN 350-1, CEN 1994) between DC 5 (non durable) and DC 2 (durable). This variation and how it can be related to at least three, in some cases even to four or five durability classes, is shown for six selected wood species in Fig. 3. The importance of this variation becomes even more obvious when calculating the expected service life: Based on a mean service life of 6.5 years of the Scots pine sapwood reference (Tab. 8), the service life to be expected for Douglas fir ranges from 7.4 to 29.5 years. Even more drastic is the range for spotted gum (*Corymbia* spp.), which is from 18.7 years and 473.3 years. These findings highlight the potential value of service life modeling to greatly increase the accuracy and relevance of information available regarding the expected durability of timber used at different locations.

Table 7 Service life related data from above-ground field tests according to Tab. 1 Hardwoods.
Tablica 7. Podaci o životnom vijeku povezani s testovima izloženosti drva iznad zemlje prema tablici 1. za tvrde vrste drva

Wood species *Vrsta drva*	**Botanical name** *Botanički naziv*	**Site** / *Mjesto*	**Country code** *Kod zemlje*	**Test method** *Metoda*	**Test ID**	**Resistance factor** *Faktor otpora*	$SL_{Reference}$[1]
Spotted gum	*Corymbia citriodora*	Beerburrum	AUS	LJu	4	**12.40**	5.1
					4	**4.62**	8.5
				LJc	3	**7.23**	3.7
					3	**3.68**	5.0
		Dalby	AUS	LJu	4	**9.02**	6.8
				LJc	3	**7.00**	4.1
		Frankston	AUS	LJu	4	**7.39**	7.4
				LJc	3	**4.24**	7.0
		Pennant Hills	AUS	LJu	4	**4.87**	7.9
				LJc	3	**2.56**	7.3
		Rockhampton	AUS	LJu	4	**16.34**	7.7
				LJc	3	**4.98**	5.2
		South Johnstone	AUS	LJu	4	**3.49**	5.7
				LJc	3	**5.23**	5.1
		Toowoomba	AUS	LJu	4	**20.69**	6.8
				LJc	3	**8.51**	3.4
		Yarralumla	AUS	LJu	4	**31.61**	8.7
				LJc	3	**3.48**	7.0
		Mount Isa	AUS	LJu	4	**43.03**	11.0
				LJc	3	**15.88**	11.0
		Townsville	AUS	LJu	4	**6.43**	5.3
				LJc	3	**2.06**	5.0
English oak	*Quercus robur*	Hamburg	D	DL	11	**1.56**	6.5
		Hamburg shade	D	DL	11	**1.35**	6.1
		Reulbach	D	DL	11	**1.83**	n.a.
		Stuttgart	D	DL	11	**1.66**	n.a.
		Freiburg	D	DL	11	**1.52**	n.a.
		4 German sites	D	DL	17	**1.70**	6.6
		Ghent	B	ALJ	5	**5.67**	n.a.
		Borås	S	MLu	21	**4.00**	10.0
				MLb	20	**1.33**	10.0
European oak	*Q. robur/ Q. petraea*	Ås	N	DL	8	**2.50**	n.a.
		Oslo	N	DL	9	**3.00**	*8.0*
		Bergen	N	DL	8	**1.67**	n.a.

[1]mean value or median (in italics) / *srednja vrijednost ili medijan (u kurzivu)*; n.a. = not available / *nije dostupno*

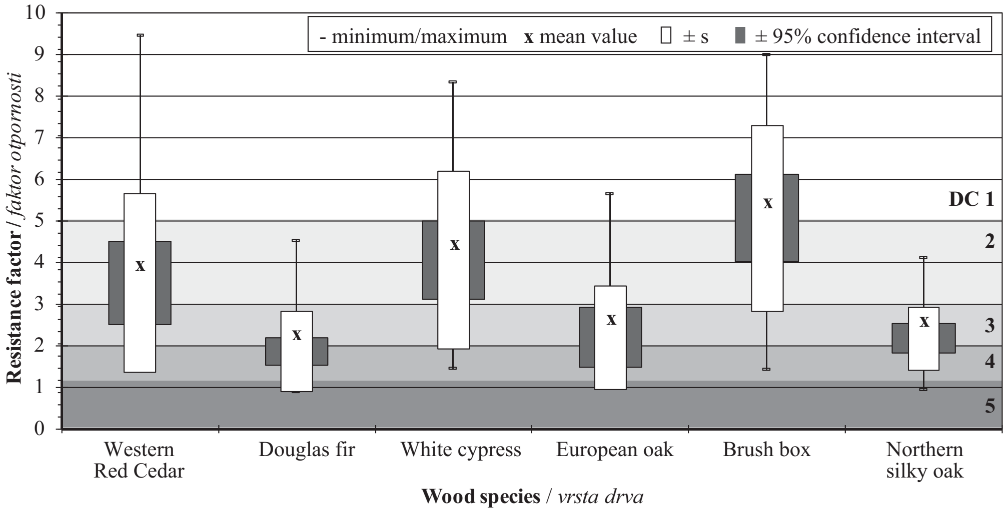


Figure 3 Variation of resistance factors of six selected wood species and corresponding durability classes (DC) according to EN 350-1 (CEN, 1994).
Slika 3. Varijacija čimbenika otpornosti za šest različitih vrsta drva i odgovarajuće klase trajnosti prema EN 350-1 (CEN, 1994).

Table 8 Service life related data from above-ground field tests according to Tab. 1 Softwoods.
Tablica 8. Podaci o životnom vijeku povezani s testovima izloženosti drva iznad zemlje prema tablici 1. za meke vrste drva

Wood species *Vrsta drva*	**Botanical name** *Botanički naziv*	**Site** / *Mjesto*	**Country code** *Kod zemlje*	**Test method** *Metoda*	**Test ID**	**Resistance factor** *Faktor otpora*	$SL_{Reference}$ [1]
Norway spruce heart	*Picea abies*	Hamburg	D	DL	19	**0.96**	6.5
		Hamburg shade	D	DL	19	**0.78**	6.1
		Stuttgart	D	DL	19	**0.89**	n.a.
		Freiburg	D	DL	19	**0.75**	n.a.
Norway spruce	*Picea abies*	Oslo	N	DL	9	**1.19**	*8.0*
		Hannover	D	BuA	22	**0.82**	*4.0*
				BuB	23	**0.92**	n.a
				BuC	24	**0.96**	n.a.
				BuD	25	**1.00**	*4.0*
		Borås	S	LpJ	1	**1.00**	8.0
				MLu	21	**1.00**	10.0
				MLb	20	**1.00**	10.0
		Ghent	B	ALJ	5	**2.16**	n.a.
Norway spruce, 6 mm rings	*Picea abies*	Ås	N	DL	8	**0.48**	n.a.
		Bergen	N	DL	8	**1.11**	n.a.
Norway spruce, 3 mm rings	*Picea abies*	Ås	N	DL	8	**0.56**	n.a.
		Bergen	N	DL	8	**1.20**	n.a.
Norway spruce, 1 mm rings	*Picea abies*	Ås	N	DL	8	**1.36**	n.a.
		Bergen	N	DL	8	**1.25**	n.a.
Norway spruce, standing rings	*Picea abies*	Ås	N	DL	8	**1.00**	n.a.
		Bergen	N	DL	8	**0.94**	n.a.
Norway spruce sap	*Picea abies*	Hamburg	D	DL	19	**0.79**	6.5
		Hamburg shade	D	DL	19	**0.98**	6.1
		Stuttgart	D	DL	19	**0.67**	n.a.
		Freiburg	D	DL	19	**0.45**	n.a.
Scots pine	*Pinus sylvestris*	4 German sites	D	DL	18	**1.34**	6.6
		Ghent	B	ALJ	5	**9.31**	n.a.
		Hamburg	D	DL	10	**1.37**	6.4
		Hamburg shade	D	DL	10	**1.18**	*7.8*
		Borås	S	LpJ	1	**1.25**	8.0
				MLu	21	**4.00**	10.0
				MLb	20	**1.00**	10.0
Scots pine resinous	*Pinus sylvestris*	Borås	S	MLu	21	**4.00**	10.0
				MLb	20	**1.14**	10.0
Scots pine, slow grown	*Pinus sylvestris*	Oslo	N	DL	9	**3.79**	*8.0*
Scots pine, normal	*Pinus sylvestris*	Oslo	N	DL	9	**3.27**	*8.0*
Scots pine, 3 mm rings	*Pinus sylvestris*	Ås	N	DL	8	**1.00**	n.a.
		Bergen	N	DL	8	**1.50**	n.a.
Scots pine, 1 mm rings	*Pinus sylvestris*	Ås	N	DL	8	**1.15**	n.a.
		Bergen	N	DL	8	**1.25**	n.a.
Scots pine heart + sap	*Pinus sylvestris*	Ås	N	DL	8	**1.07**	n.a.
		Bergen	N	DL	8	**1.11**	n.a.
Douglas fir	*Pseudotsuga menziesii*	4 German sites	D	DL	18	**1.45**	6.6
		Hamburg	D	DL	12	**1.25**	6.5
		Hamburg shade	D	DL	16	**2.14**	7.1
		Hamburg	D	DL	10	**4.17**	6.4
		Hamburg shade	D	DL	10	**2.12**	*7.8*
		Stuttgart shade	D	DL	13	**1.22**	6.0
		Freiburg shade	D	DL	13	**1.08**	7.3
		Reulbach shade	D	DL	13	**2.50**	*8.1*
		Hinterzarten	D	DL	16	**3.18**	n.a.

[1]mean value or median (in italics) / *srednja vrijednost ili medijan (u kurzivu)*
[2]based on estimated median service life / *utemeljeno na procjeni medijana životnog vijeka*
n.a. = not available / *nije dostupno*

Table 8 cont'd: Service life related data from above-ground field tests according to Tab. 1 Softwoods.
Tablica 8. (nastavak) Podaci o životnom vijeku povezani s testovima izloženosti drva iznad zemlje prema tablici 1. za meke vrste drva

Wood species *Vrsta drva*	**Botanical name** *Botanički naziv*	**Site** / *Mjesto*	**Country code** *Kod zemlje*	**Test method** *Metoda*	**Test ID**	**Resistance factor** *Faktor otpora*	$SL_{Reference}$[1]
Douglas fir	*Pseudotsuga menziesii*	Bühlertal	D	DL	16	**3.98**	*7.7*
		Garston	GB	DL	14	**1.63**	*6.1*
		Portsmouth	GB	DL	15	**4.54**	6.0
		Ljubljana	SI	DL	16	**3.31**	3.2
		Zagreb	HR	DL	14	**3.38**	4.3
		Madison, WI	USA	CB	6	**> 2.31**[2]	*13.0*
		Starkville, MI	USA	CB	7	**> 2.00**[2]	*10.0*
		Beerburrum	AUS	LJu	4	**1.74**	5.1
				LJc	3	**1.12**	3.7
		Dalby	AUS	LJu	4	**1.29**	6.8
				LJc	3	**1.28**	4.1
		Frankston	AUS	LJu	4	**1.40**	7.4
				LJc	3	**1.39**	7.0
		Pennant Hills	AUS	LJu	4	**1.34**	7.9
				LJc	3	**1.36**	7.3
		Rockhampton	AUS	LJu	4	**1.20**	7.7
				LJc	3	**1.16**	5.2
		South Johnstone	AUS	LJu	4	**0.96**	5.7
				LJc	3	**1.17**	5.1
		Toowoomba	AUS	LJu	4	**1.14**	6.8
				LJc	3	**1.43**	3.4
		Yarralumla	AUS	LJu	4	**1.33**	8.7
				LJc	3	**1.58**	7.0
		Mount Isa	AUS	LJu	4	**0.90**	n.a.
				LJc	3	**1.79**	11.0
		Townsville	AUS	LJu	4	**1.28**	11.0
				LJc	3	**1.95**	5.3
Douglas fir (Norway)	*Pseudotsuga menziesii*	Bergen	N	DL	8	**1.88**	n.a.
Douglas fir (N-America)	*Pseudotsuga menziesii*	Bergen	N	DL	8	**2.31**	n.a.
Western Red Cedar	*Thuja plicata*	Madison, WI	USA	CB	6	**> 2.30**[2]	*13.0*
		Beerburrum	AUS	LJu	4	**3.03**	5.1
				LJc	3	**4.53**	3.7
		Dalby	AUS	LJu	4	**3.54**	6.8
				LJc	3	**7.97**	4.1
		Frankston	AUS	LJu	4	**3.04**	7.4
				LJc	3	**2.22**	7.0
		Pennant Hills	AUS	LJu	4	**1.98**	7.9
				LJc	3	**2.06**	7.3
		Rockhampton	AUS	LJu	4	**2.93**	7.7
				LJc	3	**3.59**	5.2
		South Johnstone	AUS	LJu	4	**2.19**	5.7
				LJc	3	**1.97**	5.1
		Toowoomba	AUS	LJu	4	**2.14**	6.8
				LJc	3	**9.48**	3.4
		Yarralumla	AUS	LJu	4	**2.00**	8.7
				LJc	3	**3.68**	7.0
		Mount Isa	AUS	LJu	4	**1.52**	n.a.
				LJc	3	**3.44**	11.0

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Table 8 cont'd: Service life related data from above-ground field tests according to Tab. 1 Softwoods.
Tablica 8. (nastavak) Podaci o životnom vijeku povezani s testovima izloženosti drva iznad zemlje prema tablici 1. za meke vrste drva

Wood species *Vrsta drva*	**Botanical name** *Botanički naziv*	**Site** / *Mjesto*	**Country code** *Kod zemlje*	**Test method** *Metoda*	**Test ID**	**Resistance factor** *Faktor otpora*	$SL_{Reference}$ [1]
Western Red Cedar	*Thuja plicata*	Townsville	AUS	LJu	4	**2.23**	11.0
				LJc	3	**6.69**	5.3
WRC (Norway)	*Thuja plicata*	Ås	N	DL	8	**0.88**	n.a.
		Bergen	N	DL	8	**1.67**	n.a.
WRC (N-America)	*Thuja plicata*	Bergen	N	DL	8	**2.00**	n.a.

[1]mean value or median (in italics) / *srednja vrijednost ili medijan (u kurzivu)*
[2]based on estimated median service life / *utemeljeno na procjeni medijana životnog vijeka*
n.a. = not available / *nije dostupno*

Although most of the results are still preliminary, they indicate that the resistance factor, and hence the relative durability of different species, is not necessarily the same at climatically different places. This is confirmed by the results for European oak (*Quercus robur* / *Quercus petraea*): While the resistance factors for eight German test sites differed only between 1.35 and 1.83, a variation between 1.67 and 3.00 was found for three Norwegian sites. As there were only a few species for which multiple recordings were available, no clear relationship between the test site and resulting relative durability was discernible. Significantly more durability recordings from different sites are needed. As previously discussed, chemical and anatomical properties of different species may influence the extent to which they are affected by climate variables, and this topic requires further investigation.

Another example is illustrated in Fig. 4, where the resistance factors of eight wood species determined in L-joint tests have been compared between ten test sites in Australia. Many additional wood species were installed at the Beerburrum site, while only nine wood species were installed at all ten sites. It would be ideal if resistance factors for the nine species tested at all sites could be used to gauge the performance of the additional species at Beerburrum, if they were used at the other locations. No simple relationship between relative resistance factors and test location was observed that represented all species. The higher the resistance factor - and thus the expected service life - the higher was the site-specific variation. In extreme, the factors differed between 4 and 32. For those wood species, showing resistance factors below 5, which is equivalent to durability class 2 = 'durable' according to EN 350-1 (CEN, 1994), the variation between most of the sites diminished, while differences between sites for the species with higher resistance factors showed the opposite. The test sites represent a wide range of climatic conditions, and preliminary analysis revealed that there is a strong relationship between climate variables and relative durability of each wood species exposed at different locations (Francis and Norton, 2006). The influence of the

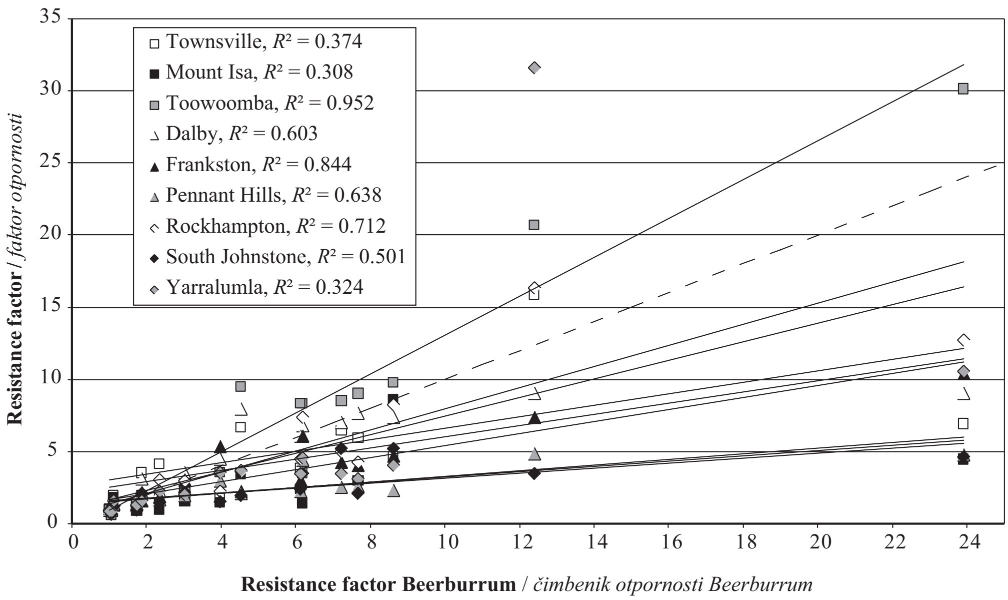

Figure 4 Relationship between resistance factors of eight wood species determined in L-joint trials for ten Australian test sites. Dashed line refers to resistance factors determined for Beerburrum (ideal line).
Slika 4. Odnos između čimbenika otpornosti za osam vrsta drva određenih testom L-spoja za deset lokacija u Australiji. Isprekidana se linija odnosi na čimbenike otpornosti određene za Beerburrum (idealna linija).

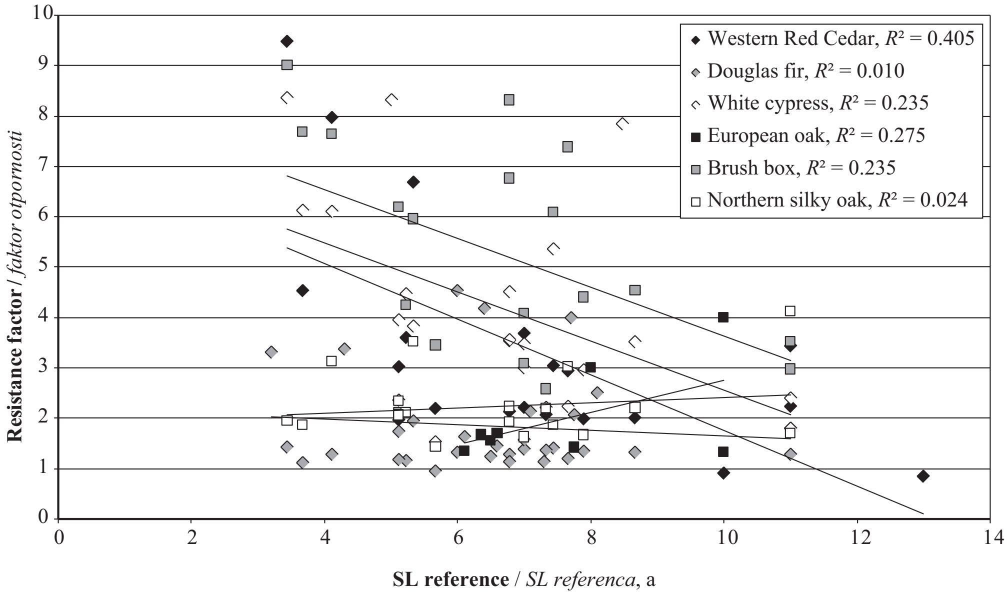

Figure 5 Resistance factors of six selected wood species related to the mean or median service life in years of the reference species
Slika 5. Čimbenici otpornosti za šest vrsta drva u odnosu prema srednjoj vrijednosti ili medijanu životnoga vijeka referentne vrste drva

analyzed climate variables differed amongst the eight species. Further research is required to explore the possibility of using resistance factors to predict durability between different locations based on indicating wood species that are selected to represent groups of wood species with similar properties. For example, the resistance factors for spotted gum may more accurately predict the service life of dense hardwoods that contain extractives that are highly toxic to decay fungi, while resistance factors for brush box may be used to predict the service life of dense hardwoods that contain moderately toxic extractives.

To further examine the potential relationship between the severity of a test site and respective durability of timber species, resistance factors were correlated with the service life (mean or median) of the reference wood species for all sites at which these data were available. As shown exemplarily for three softwoods and three hardwoods in Fig. 5, no clear relationship was obtained. It leads to the conclusion that other factors than the site-specific decay intensity determine the relative resistance, such as climatic peculiarities, different decay types, or detoxifying agents.

In addition to potential site-specific effects, the test method and especially the durability measure seem to influence the resistance factors. While no clear differences between the use of mean or median service lives on the one hand and decay rates after certain exposure times on the other hand were observed, the use of mass loss differences led to significant outliers for English oak (*Quercus robur*), Scots pine and Norway spruce (*Picea abies*) and the relative effects of durability measures, therefore, need to be verified.

The influence of the test methods on the resulting resistance factors of a certain wood species is superposed by the effect of climatic conditions. Basically it is the microclimate within a wood specimen that determines the conditions for fungal growth and decay. Consequently, the combination of mesoclimate (environmental conditions at the test site) and the design of the respective test set up affect the microclimate. This is demonstrated by considering resistance factors calculated for Douglas fir, which varied as follows: in double layer tests between 1.08 and 4.54, in uncoated L-joint tests between 0.90 and 1.74, in coated L-joint tests between 1.12 and 1.95, and in cross brace tests between 2.00 and 2.13 (Tab. 8). Obviously the variation within one test method was higher compared to the variation between the different test methods, which coincides with the findings of De Groot (1992), who exposed Southern yellow pine sapwood in Mississippi, USA, and in a rainforest in Panama using 18 different test designs. While he found a significant impact of the test design in the temperate location, differences diminished in the tropical rainforest. Within this study, test data from different test methods at the same test location were available only for a few wood species, so the potential effect of the test configurations was not quantifiable.

4 CONCLUSIONS
4. ZAKLJUČCI

We do not claim that this literature and data survey on above ground durability tests is complete. This is mainly due to the fact that many studies around the world are known to exist, but respective data are not freely available. The lack of freely available data is strongly indicated through the fact that 80 % of durability records used for this study was unpublished. Furthermore, in many cases information was too condensed and incomplete, which is inescapable for journal articles, but prevented the data transformation necessary to calculate specimen service life measures.

The range of test results observed for each wood species further highlighted that the current timber durability classification systems, which assign a species to a durability class irrespective of site and design, are not precise enough for many scientific and engineering purposes. Data need to meet a number of requirements in terms of specificity, background information and formatting.

We conclude that further research into the relative effects of climate on decay progress amongst different species is required, and future comparative studies should focus not only on differences between test sites, but also on different test configurations at the same location to determine the effects of structural design on timber durability. To facilitate this goal, a suitable platform is needed to increase the quantity and availability of useful data. Service life related durability recordings should be shared amongst the scientific community to allow the exchange and advancement of knowledge in this field. The value of these durability data is expected to rise through collaborative comparative studies and meta analyses.

Similar or even more complex challenges are faced for predicting the service life of modified and preservative treated wooden material because additional information of treatment agents and processes are needed. Wood used outdoors is commonly treated with different wood preserving agents and formulations, and field studies on the durability of preservative treated and modified timber include additional parameters, including preservative type, penetration and retention.

For these reasons, a proposal for a 'Durability Data Base' has been made to the 'International Research Group on Wood Protection, IRG-WP' (Brischke *et al.* 2012). Requirements and feasible formats for durability recordings have been suggested for all types of wood products: naturally durable timber, thermally and chemically modified timber, water repellent and preservative treated timber as well as for composite products. The database shall allow availability of test results from field and laboratory studies dealing with wood-degrading fungi, insects, and marine borers.

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6.3 Publication III: REVIEW ARTICLE: Modelling the outdoor performance of wood products – a review on existing approaches

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Review

Modelling the outdoor performance of wood products – A review on existing approaches

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HIGHLIGHTS

- Approaches to reflect biotic and abiotic agents affecting performance of wood-based building materials have been reviewed.
- Efforts in developing performance models for fungal decay and mould growth have been intensified in recent years.
- A framework is available to link exposure, design and the material-intrinsic ability to take up and release water.
- Methods and models have the potential to get implemented in design guidelines and European and international standards.

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ABSTRACT

Service life planning and performance classification are key issues in the building sector. Well-functioning 'performance models' are absolutely essential to predict the service life and functionality of buildings, building assets, and building products over time. Different types of performance models have been established for various building materials, but cannot necessarily transferred to wood-based materials, primarily due to their organic character. For performance modelling of wood products biological agents need to be considered, such as wood disfiguring and degrading organisms.

Different approaches to adequately reflect the influence of biotic and abiotic factors on the performance of wood have been reviewed and evaluated with respect to their usability in the building trade. We found that efforts in developing performance models for both fungal decay and mould growth have been intensified in recent years. A high heterogeneity among the numerous attempts became visible, different strategies have been followed, and were roughly distinguished according to the respective objectives, governing variables (e.g. mass loss, strength loss, remaining strength, decay ratings, service life, aesthetic appearance, etc.), data sources and the resulting level of accuracy.

A framework of how exposure, dimension, design details, and the material-intrinsic ability to take up and release water can be linked to model the moisture risk in wood products is in principal available. Methods and models have the potential to get implemented not only in design guidelines, but also in European and international standards. In particular, various dosimeter models could serve as reliable tools to quantify the effects of different construction details.

Contents

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1. Background – Modelling the risk for decay

For service life planning and performance classification of buildings, building assets, and building products well-functioning 'performance models' are absolutely essential. The term 'performance model' is ambiguous in a double sense: On the one hand 'performance' needs to be carefully defined, because it can have very different meanings depending on the respective type of material, product, commodity and its application. On the other hand, the general meaning of 'model' is the 'schematic description of a system, theory, or phenomenon that accounts for its known or inferred properties and may be used for further study of its characteristics'. An important issue is to define the governing variables. Building components that are exposed outdoors to the weather are mainly affected by moisture and temperature related effects. In addition moisture and temperature can also play an important role indoors and in the building envelope. In particular for bio-based building materials such as wood, biological agents should be considered in order to predict service lives. In contrast, other degradation processes such as corrosion, erosion, and hydrolysis of wood substance play a minor role.

Wood can be degraded by wood-destroying insects (e.g. beetles and termites), bacteria, fungi, and marine borers. Their occurrence and the risk of infestation respectively depend on the exposure conditions and the geographical position. While for instance the presence of termites in Europe is mainly restricted to the Southern-European countries, and shipworms live only in sea water with certain salinity, wood-destroying fungi are ubiquitous and can occur worldwide. However, there are physiological cardinal points that determine the ability of other organisms to grow and to attack wood. For example, fungi demand wood moisture contents above fibre saturation for transporting their degrading enzymes [1,2]. These deviating living conditions allow a principle differentiation of organism groups referring to the exposure conditions of wooden components. This principle is basically reflected by the use class approach described in EN 335 [3] where six use classes (UC) are defined according to the respective moisture regime and the potential presence of wood-degrading organisms (Table 1).

In particular UC 2, UC 3.1 and UC 3.2 are characterized through the respective moisture conditions, whereby UC 4 ("ground contact") is considered to be permanently wet and therefore equalized with "fresh water contact". Consequently, developing performance models with respect to fungal decay above ground covers a wide range of exposure conditions, wherefore various dosimeter approaches have been applied to address the varying moisture loads impacting on wooden components.

Generally, it becomes evident from the classification scheme of EN 335 [3] that one general model cannot display the whole diversity of exposure conditions; rather a set of models is needed each considering a particular exposure range and group of potentially occurring organisms.

In addition to the so-called 'wood-destroying organisms' which are able to degrade wood substance, and partly also digest and metabolize lignocellulose, 'only' aesthetical damage is caused by 'wood disfiguring fungi' in terms of mould growth and blue stain. Besides the optical impairment moulds have the potential to cause allergic reactions and human health problems. This is an issue especially in indoor environment, where damp water can cause moisture accumulation. Mold and rot fungi are basically different in biology and physiology as well as in their strategy to use wood as a nutrition source. While mould is more or less a surface phenomenon without significant impact on the mechanical properties of wood, rot fungi degrade cell walls in the full volume of a building component. Moisture and temperature minimum thresholds also vary between both groups and require consequently different modelling approaches. A comprehensive review

Table 1
Summary of use classes and their respective harmful organisms of wood and wood products according to EN 335 [3].

Use class	General service conditions[a]	Occurring organisms[b,c]				
		Wood disfiguring fungi	Wood-destroying fungi	Beetles	Termites	Marine organisms
1	Interior, dry	–	–	U	L	–
2	Interior or under roof, not exposed to weather, possibility of condensation	U	U	U	L	–
3	Exterior, without soil contact, exposed to weather If class-divided: 3.1 limited moist conditions 3.2 persistently moist conditions	U	U	U	L	–
4	Exterior, in contact with soil or freshwater	U	U	U	L	–
5	Permanently or regularly immersed in salt water	U[d]	U[d]	U[d]	L[d]	U

U = is spread all over Europe and in the area of the European Union.
L = occurs locally all over Europe and in the area of the European Union.
[a] There are borderline- and extreme cases for the use of wood and wood products. These can cause the result, that a use class will be allocated, which differs from the definition of this standard.
[b] Protection against all listed organisms is not absolutely required because they do not occur under all use conditions and at all geographical locations or they are not economically significant or not able to infest specific wood products due to the specific state of the product.
[c] See Annex C.
[d] The area above water surface of certain wooden components can be susceptible to all stated organisms.

on mould prediction models has been provided by Vereecken and Roels [4]. In the following we will therefore focus on models to describe fungal decay.

2. Model types

The mathematical background for any service life prediction is a performance model. Mathematical models are widely used in natural sciences to handle different variables, such as input variables, state variables, exogenous variables, random variables, and output variables. Depending on the system to be analyzed the type and structure of the most suitable model might significantly differ, and so do the preferences of scientists. For instance engineering models often work with limit states (Limit state design LSD), and therefore the limit state theory is already established in numerous building codes around the world [e.g. 5,6].

However, the limit state concept does often conflict with biological approaches aiming on displaying the full process of degradation till the definite end of service life. Therefore dose–response functions are preferential instruments, because they describe the change in effect on an organism caused by differing levels of exposure (or dosage) to a stressor after a certain exposure time. For service life prediction of timber constructions the biodegradation of wood must be seen as a negative growth process – the (positive) growth and degradation activity of the decay organism causes a reduction of wood substance, with consequences for serviceability as well as safety against failure.

Fig. 1 gives an example of a dose–response function, which serves as performance model for wooden commodities exposed above ground. The dose is expressed as a function of daily wood moisture content and wood temperature, whereby the level of decay was considered as response indicated as decay rating according to EN 252 [7], which is described in detail in Table 2. The experimental set up and the various modelling steps had been described in detail by Brischke and Rapp [8]. The overall result of the numerous field trials, which had been conducted with Scots pine sapwood and Douglas fir heartwood for up to 8 years, is the sigmoid graph shown in Fig. 1. It is representing the full life span of the specimens starting slowly with an initial lag phase before onset of decay (rating 1) and finally ending with an approximation to complete failure (rating 4).

This mathematical model is neither based on linear functions nor does it provide one exclusive limit state, which might apparently conflict with the ideal pre-conditions of an engineering approach. But it is the opposite: Besides the fact that the description of growth processes through logistic functions is definitely the more precise way, the approach even provides to define more

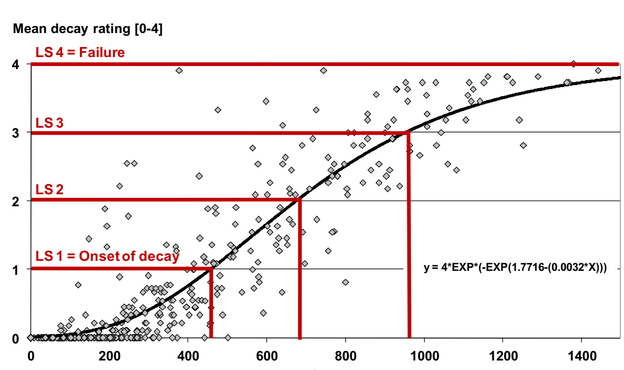

Fig. 1. Dose–response relationship for fungal decay in above-ground exposures, determined on the basis of field trial results performed at 28 test sites in Europe. Dose is expressed as a function of wood moisture content MC and wood temperature and accumulated from daily values over the whole exposure period of 4–8 years. Response is expressed as decay rating to EN 252 [7]. LS = limit states.

than one limit state. Thus, purpose specific limit states can be defined, e.g. the onset of mould or decay to define aesthetic service lives or the failure in ground contact as one might prefer to use for fence and utility posts. To quantify the impact of a certain construction detail on the service life of a whole construction, many engineering tools work with factorization and normalization of the impact variables. Also this aspect does not stand in contrast with the dose–response approach, simply the measure is some kind of special – it is the dimensionless dose as a function of MC and temperature. Using the mean annual dose (=accumulated daily dosages over 1 year of exposure) as an operand allows comparing the protective effectiveness of every conceivable building component and exposure situation [9].

Biological growth processes and degradation processes follow very similar rules. However, depending on the material, the component dimensions, and the type of decay the degradation progress may sometimes deviate from the normal case. For example, preservative treated wood degrades after certain patterns as shown by Larsson-Brelid et al. [10]. While the decay progress of untreated non-durable wood in ground contact is more or less linear from the very beginning, creosote treated wood is known to show a 'break phase' after decay had already started significantly. Again different from this is the decay progress in certain soils of wood treated with some organic copper containing preservatives, which often show a long time lag before onset of decay, but degrade very fast as soon as the lag phase has been overcome.

Similar observations had been reported by Brischke et al. [11] for natural durable timber. As shown in Fig. 2, also English oak exposed above ground revealed 'break phases' after decay had already started. In contrast, the non-durable Scots pine sapwood decayed very steadily. If now different levels of decay (=different limit states) need to be considered for service life prediction, which generally is the case, these irregularities in decay development must not be ignored. Otherwise extrapolation from decay development in the first half life-time may lead to misinterpretation, as demonstrated for oak in Fig. 2, which decayed much slower during the first 4 years of exposure compared to the average decay development.

Depending on how much a priori information is available for a system one can distinguish between black box models and white box models, whereby these terms describe only extremes and usually a mathematic model is somewhere in between. It seems to be trivial that using as much a priori information as possible makes a model more accurate, but anyhow it might be worth to consider black box models as well for certain applications. Nowadays neural networks (NN) and case-based reasoning systems (CBR) are well established methods [12] to handle data related to very complex interrelationships and allow artificial intelligence, e.g. in robotics.

Also for service life prediction issues computer programs would be eligible, into which users enter information and the system utilizes pre-programmed logic to return output to the user. However, the 'black box' portion of such systems contains formulas and calculations that the user does not see and does not need to know to use the system. Especially for biological processes this may cause problems, why "white-box" models usually are preferred if available.

The advantages of using white box models for service life calculations of timber and other wood-based products become obvious, when facing the huge variety of potential data sources, materials, constructions, exposure situations, and biological, physical as well as chemical deteriorating agents coming into consideration. The existing knowledge about many of these decay influencing factors can be utilized efficiently with white box models only as illustrated through the following examples. Various approaches had been undertaken to predict the decay resistance of wood by colour measurements and other spectroscopic methods [e.g. 13,14] and were

Table 2
Rating scale according to EN 252 [7] for assessment of field test specimens.

Rating	Description	Definition
0	Sound	No evidence of decay, discoloration, softening or weakening caused by microorganisms
1	Slight attack	Limited evidence of decay, no significant softening or weakening up to 1 mm depth
2	Moderate attack	Signification evidence of decay, with areas of decay (softened or weakened wood) from 2 to 3 mm depth
3	Severe attack	Strong evidence of decay, extensive softening an weakening, typical fungal decay at large areas from 3 to 5 mm depth or more
4	Failure	Sample breaks after a bending test

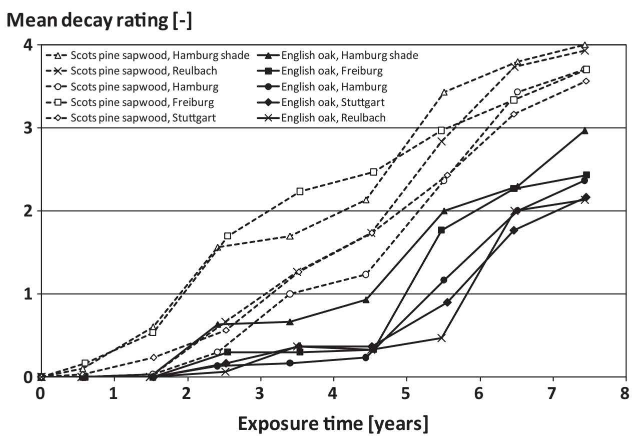

Fig. 2. Mean decay rating after EN 252 [7] of English oak and Scots pine sapwood specimens exposed above ground in horizontal double layers at different test sites; taken from Brischke et al. [11].

partly found to be very promising. However, although good correlations had been observed between, e.g. colour values and resulting durability classes, there is still some variation remaining, which is most likely caused by different moisture dynamics of the various wood assortments, rather than by the content of biocidal extractives itself.

Similar observations have been made for thermally modified timber by Welzbacher et al. [15,16]: While colour values L^*, a^*, and b^* showed striking correlations with the heat treatment intensity for all treatments applied, other wood properties such as dimensional stability and decay resistance did strongly depend on the respective treatment temperature. Consequently, the exclusive use of such indirect measurands means somehow to deal with 'black boxes' as we still not understand the whole mode of action.

An ideal service life prediction tool should therefore be based on a completely transparent performance model (=white box) with traceable functional relationships to allow continual adjustment and considering more and more input data. As manifold data sources need to be tapped, the model approach needs to be 'open' – open for lab and field test data, moisture recordings from in-service components, commodity tests, surveys and questioning results, case studies, expert and non-expert opinion as well as results from complementary studies. Finally as indicated above, the model should also allow defining different limit states and different types of 'target performance' as well as recalibration on the base of short-term, long-term, and real life in situ tests.

3. Modelling approaches

3.1. Climate indices

Pioneer work on service life prediction has been carried out by Theodore Scheffer in the early 1970s. The climate index presented by Scheffer [17] was the first attempt to correlate climatic data with the hazard for decay. The hazard potential of different climates in the USA was estimated by empirically determined decay intensity from field tests at four different sites. Scheffer focussed in this early attempt on the parameters temperature and distribution of rainfall as follows:

$$\text{Climate index} = \frac{\sum_{Jan}^{Dec}[(T-35)(D-3)]}{30} \quad (1)$$

in which T is the mean day temperature of the month (°F), and D is the mean number of days with more than 0.001 inch of rain per month (–).

The hazard for decay of wood increases with the value of the index, which ranges from 0.0 for Yuma, Arizona, to 137.5 for West Palm Beach, Florida, for the continental part of the USA, where three climate zones represent three levels of above ground decay potential (Fig. 3). Later on the Scheffer Index has been used by authors to develop hazard maps for Canada [18] North America [19], China [20] Australia [21], Norway [22], and Europe [23, Fig. 4]. Finally Carll [24] published a revised hazard map for the United States using climate data from 1971 to 2000.

According to Carll [24] the Scheffer Index is a "metric by which relative hazard can be compared between geographic locations, the Scheffer Index is not intended to predict decay propagation rate nor time to failure in specific constructions". This peculiarity is not necessarily a limitation of the approach, but has been controversially discussed in numerous reports [e.g. 24,27–31,32–36]. Nevertheless, without doubt the Scheffer Index is still the most frequently used index of its kind for estimating the relative decay hazard of geographical sites [22,24,37–40].

Further climate indices have been developed and considered for service life prediction [e.g. 35,41–44]. However, one may conclude that many previous attempts to correlate macroclimatic data with decay rates lacked sufficient fit, because more influences on wood decay need consideration such as the microclimate provoked by details in design [29,38,45–47].

Another factor having significant effect on the moisture exposition of buildings and construction details is wind-driven rain (WDR), which has been intensively investigated to develop models and driving rain hazard maps [e.g. 48–51]. Consequently the relationship between the weather parameters rain fall sum, rain fall intensity, wind speed, and wind direction on the one hand and resulting wind-driven rain on the other hand has been described sufficiently and used for WDR maps [48,52]. In contrast, studies on the effect of WDR on moisture content of wooden building components such as claddings are sparse [53] and the effect of WDR on moisture performance of buildings is rather estimated than precisely determined [e.g. 33,45,54], not at least because design details have a predominating effect on the final amount of rain water arriving on vertical building faces. Usually WDR loads are therefore modelled based on local weather conditions, not necessarily measured by use of driving rain gauges.

3.2. TimberLife

Extensive research on modelling fungal decay, termite and marine borer attack has been conducted in Australia [21,55–61] taking different data sources into consideration. Results from large field

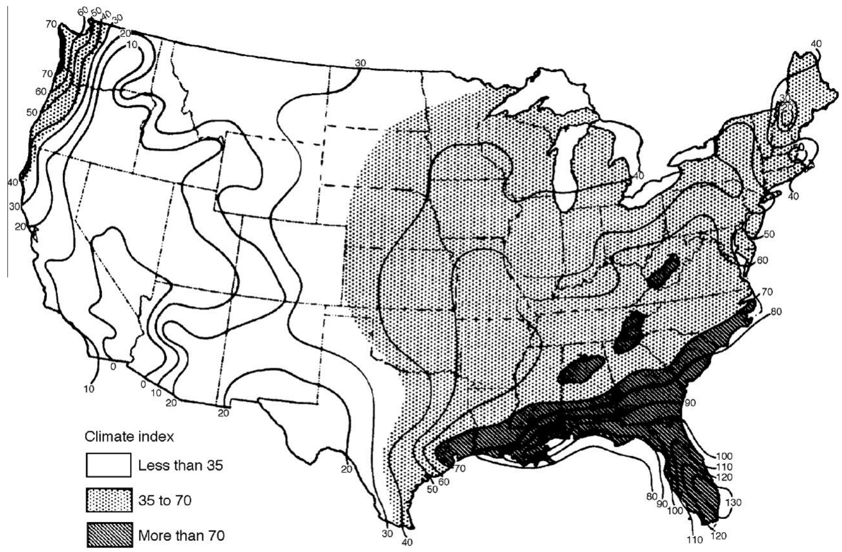

Fig. 3. Climate index map for decay hazard based on Scheffer [17] and reproduced in the Wood Handbook [25].

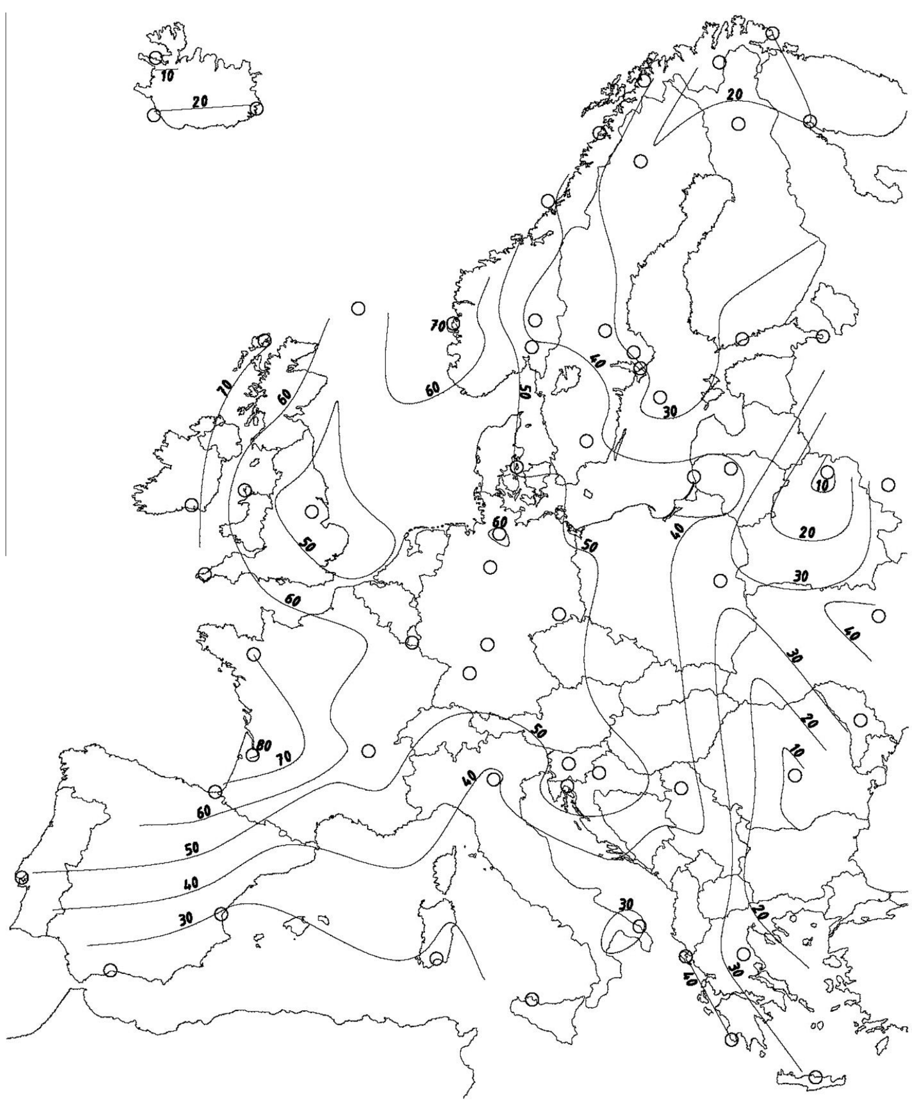

Fig. 4. Relative decay potential for Europe indicated as Scheffer's climate index for 60 European sites (circles) based on data from ECA & D; taken from: Brischke et al. [26].

test studies at different test location as well as country-wide surveys on timber structures were used to establish probabilistic performance models. Models were in first instance developed on the base of field test results, and in a second step calibrated and verified through information from in-service structures and by expert opinion. Besides material related parameters (such as resistance against different degrading organisms) macroclimatic and microclimatic aspects were considered by means of design details.

The results of the 10 years project flew into a series of manuals published by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and numerous scientific publications. Finally a "Timber service life design guide" with corresponding software tool "TimberLife" was released [62]. The TimberLife approach was widespread and the most comprehensive of its kind, not only in Australia.

The basic model for timber decay above ground (Fig. 5) was established on the base of field test results and is expressed as decay depth over time [21]. The rate of decay is hereby considered as the product of different factors according to the following equation:

$$r = k_{wood}k_{climate}k_p k_t k_w k_n k_g \tag{2}$$

in which r is the decay rate, k_{wood} is a wood parameter, $k_{climate}$ is a climate parameter, k_p is a paint parameter, k_t is a thickness parameter, k_w is a width parameter, k_n is a fastener parameter, and k_g is a geometry parameter.

Furthermore a time lag (before onset of decay) was determined according to Eq. (3).

$$time\ lag\ t_{lag} = 8.5r^{-0.85} \tag{3}$$

Algorithms for the different k-factors were provided in CSIRO Manual No. 4 by Wang et al. [21]. The CSIRO models have been later on used by other researchers; they were applied to other regions than Australia and adapted or simplified for various purposes. Freitas et al. [63] used the 'in-ground model' by Leicester et al. [64] to model timber decay in Brazil. Lourenço et al. [65] used an adapted version of the model presented by Leicester [66] for modelling residual cross sections of beams in old buildings in Portugal. Reliability analysis of roof structures and safety analysis of timber structures were performed using modifications of the different CSIRO models [67–70].

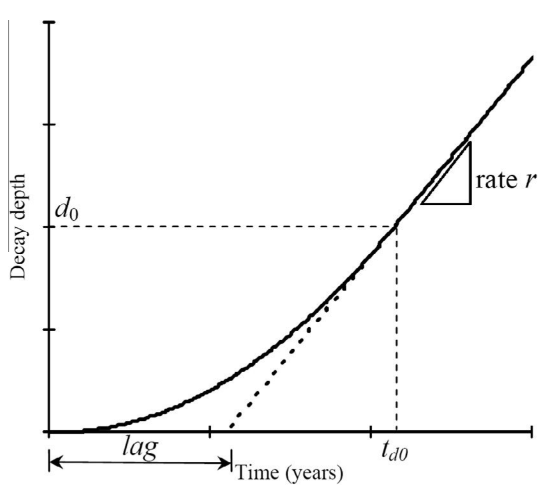

Fig. 5. Idealised progress of decay depth with time used as basic model for timber decay; taken from Wang et al. [21].

3.3. Decay models based on laboratory test results

The physiological cardinal points for brown rot fungi have been systematically studied by Viitanen and Ritschkoff [71] and Viitanen [72,73]. Fig. 6 shows the parameters relative humidity RH and temperature T as a function of time t for start of decay development (mass loss less than 3%) in untreated Scots pine sapwood. According to Viitanen et al. [33] the isopleths shown in Fig. 6 can be used for evaluation of dose–response relation between decay and humidity, temperature and exposure time. For decay development different dose response relations exist. Fig. 7 shows a model for decay development expressed as mass loss of wood in accelerated tests at high humidity and at different temperatures [33]. Based on these earlier findings Viitanen and his co-workers developed an empirical model of decay development, whereby mass loss caused by brown rot fungi is expressed as a function of RH, T, and time t (Eq. (4)).

$$ML(RH, T, t) = -42.9t - 2.3T - 0.035RH + 0.14t \cdot T + 0.024T \cdot RH + 0.45RH \cdot t \tag{4}$$

The model by Toratti et al. [74] and Viitanen et al. [33] was furthermore adapted with respect to variable RH and T conditions as they occur in real life. Therefore it was assumed that decay development can be modelled as two processes: an activation process and a mass loss process. A parameter α was defined as a relative measure of the state of the fungus with respect to its state at the initiation of the mass loss process. It is initially 0 and grows gradually to a limit of 1, at which the mass loss process is initiated. Both processes have been modelled.

The idea of assuming an activation stage in the fungal degradation process coincides with earlier models based on field test data in Australia [e.g. 21]) represented through the lag phase before onset of fungal decay. The general existence of a lag phase – consequently

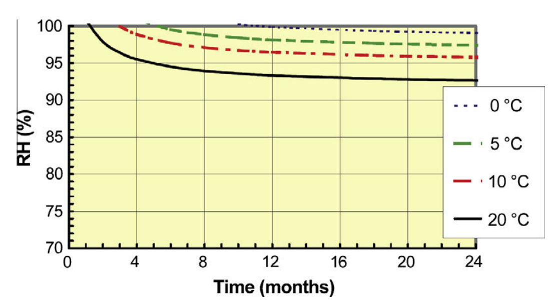

Fig. 6. Relative humidity of the ambient air (RH) and temperature isopleths as a function of time for start of decay development (mass loss less than 3%) in untreated pine sapwood; taken from: Viitanen et al. [33].

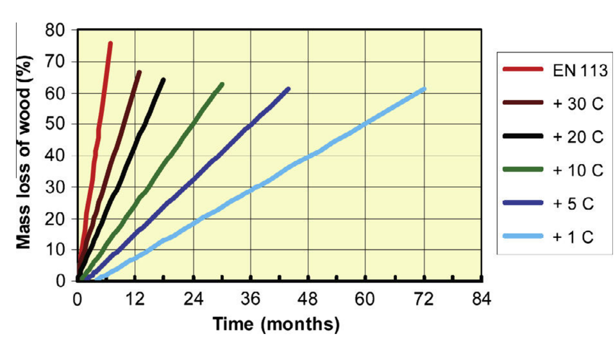

Fig. 7. Development of decay of *Coniophora puteana* on Scots pine sapwood at high humidity (RH 100%) of ambient air at different temperatures. The curves are fits to the mean values of laboratory test data; taken from: Viitanen et al. [33].

indicating that fungal degradation can be described as a two stage process – became evident in further field studies as reported by Francis and Norton [75], Brischke [76], Hansson et al. [77] and Isaksson et al. [78]. From an engineering point of view it is interesting to note that the concept of initiation and progression phases is also used for e.g. reinforcement corrosion.

A different approach of a decay model mainly based on laboratory test data taken from literature was proposed by Nofal and Kumaran [79]. For their 'wood-rotting' model results from experiments by Viitanen [73,80] and Viitanen and Ritschkoff [71] were used. In analogy to Viitanen et al. [33] they were assuming that an initial lag phase (here: initial response time) before onset of decay exists, whereby it shall depend on the respective wood species. For the decay process itself the model considered critical growth conditions as well as survival conditions of wood-rotting fungi [79]. The overall aim of their study was to relate biological damage function models with hygrothermal computer models to allow for use in design and performance assessment of wall components.

Saito et al. [81] presented a model based on own test results with the brown rot fungus *Fomitopsis palustris*. The experimental set up did not allow for moisture uptake from an external source, such as malt agar. Wood samples were stored at certain *RH* and temperature after inoculation with fungal mycelium. Consequently the focus of the model was to describe the moisture availability from the decay process itself, where wood rot fungi degrade cellulose through enzymatic reactions, and produce both, H_2O and CO_2. The decay model was furthermore coupled with hygrothermal simulations.

Laboratory test data have also been the base for damage models and damage accumulation functions presented by Van de Kuilen [82] and Montaruli et al. [83], whereby the effect of fungal decay on mass loss and strength loss was considered. Furthermore, Van de Kuilen and Gard [84] described a damage accumulation model for wooden pilings.

3.4. Decay models based on field test results

A dosimeter approach was proposed by Brischke and Rapp [30] for modelling the service life of wooden specimens exposed above ground. Therefore field test data have been used considering both, dose parameters such as wood moisture content and wood temperature and the response in terms of fungal decay. The model was based on double layer above ground field tests carried out at different sites in Europe (Fig. 8). Starting from literature data on physiological minima, optima, and maxima wood MC and temperature for wood-destroying fungi both parameters were optimized using field test data. The final dose–response model is shown in Fig. 9 (top) as later on described by Isaksson et al. [Eqs. (5) and (6), 78].

The total daily dose D is a function of one component D_u dependent on daily average of moisture content u and one component D_T dependent on daily average temperature T.

$$D = f(D_T(T), D_u(u)) \tag{5}$$

For n days of exposure the total dose is given by

$$D(n) = \sum_1^n D_i = \sum_1^n (f(D_T(T_i), D_u(u_i))) \tag{6}$$

where T_i is the average temperature and u_i is the average moisture content for day i. Decay is initiated when the accumulated dose reaches a critical dose.

The total dose D is then calculated as a function of D_u and D_T according to Eq. (9), where D_T was weighted by a factor a.

$$D_u(u) = \begin{cases} 0 & \text{if } u < 25\% \\ e\cdot u^5 - f\cdot u^4 + g\cdot u^3 - h\cdot u^2 + i\cdot u - j & \text{if } u \geqslant 25\% \end{cases} \tag{7}$$

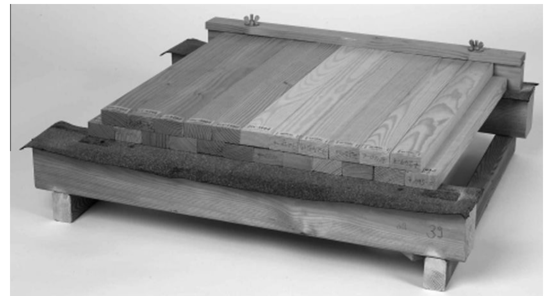

Fig. 8. Photograph showing the double-layer set-up with the upper layer shifted 25 mm horizontally to the lower layer. Specimens are separated with bitumen foil from CCB-impregnated support beams.

$$D_T(T) = \begin{cases} 0 & \text{if } T_{min} < 0\,^\circ\text{C or if } T_{max} > 40\,^\circ\text{C} \\ k\cdot T^4 + l\cdot T^3 - m\cdot T^2 + n\cdot T & \text{if } T_{min} \geqslant 0\,^\circ\text{C or if } T_{max} < 40\,^\circ\text{C} \end{cases} \tag{8}$$

$$D = (a\cdot D_T[T] + D_u[u])\cdot(a+1)^{-1} \quad \text{if } D_u > 0 \text{ and } D_T > 0 \tag{9}$$

where T_{min} is the minimum and T_{max} is the maximum wood temperature for the day considered (°C), a is the temperature weighting factor, and $e, f, g, h, I, j, k, l, m, n$ are variables.

The total dose over a certain time period is given by Eq. (10) and the decay rating is given by the dose–response function:

$$DR(D(n)) = 4\cdot\exp(-\exp(1.7716 - (0.0032\cdot D(n)))) \tag{10}$$

where DR is the mean decay rating according to EN 252 (1990) and $D(n)$ is the total dose for n days of exposure.

A sigmoid curve described the logistic regression function between moisture and temperature induced dose and fungal decay expressed as decay rating according to the European standard EN 252 [7]. Wood degradation is hereby understood as a negative growth process, which is usually described by sigmoid shaped curves [30].

While the logistic model by Brischke and Rapp [30] can be described as a biological approach [23], more engineering based models were developed with the same data set by Isaksson et al. [77]. Therefore a simplified logistic model (Fig. 9 middle, Eqs. (11)–(14)), a set-back dose response model, and finally a two-step dose–response model (Fig. 9 bottom, Eqs. (15)–(18)) were developed.

Simplified logistic model [77]:

$$D = D_u(u)\cdot D_T \tag{11}$$

$$D_u(u) = \begin{cases} (u/30)^2 & \text{if } u \leqslant 30\% \\ 1 & \text{if } u > 30\% \end{cases} \tag{12}$$

$$D_T(T) = \begin{cases} 0 & \text{if } T < 0\,^\circ\text{C} \\ T/30 & \text{if } 0\,^\circ\text{C} \leqslant T \leqslant 30\,^\circ\text{C} \\ 1 & \text{if } T > 30\,^\circ\text{C} \end{cases} \tag{13}$$

$$DR(D(n)) = 4\cdot\exp(-\exp(1.9612 - (0.0037\cdot D(n)))) \tag{14}$$

Two-step dose–response model [77]:

$$D = D_u(u)\cdot D_T(T) \tag{15}$$

$$D_u(u) = \begin{cases} 0 & \text{if } u < a \\ \frac{u-a}{b-a} & \text{if } a \leqslant u \leqslant b \\ 1 & \text{if } u > b \end{cases} \tag{16}$$

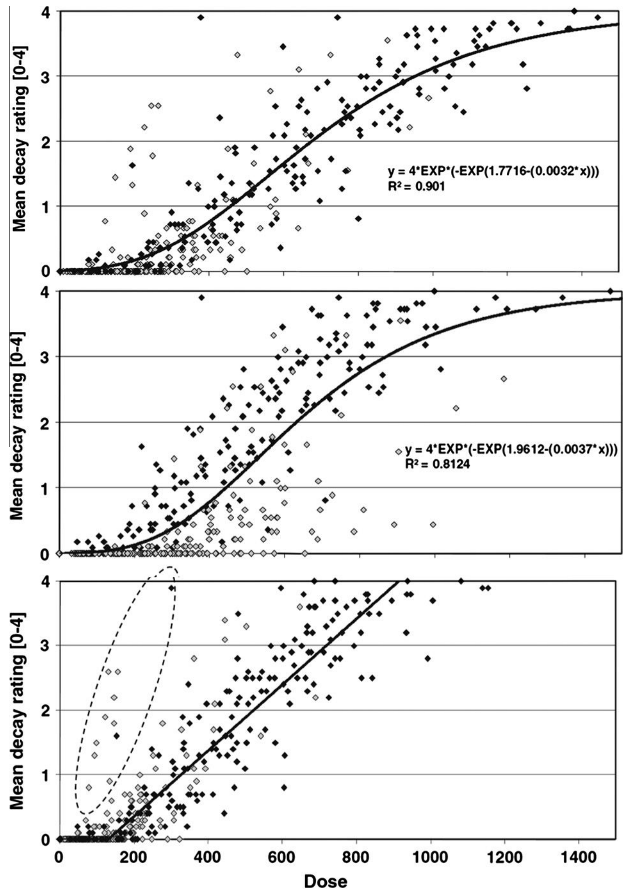

Fig. 9. Relationship between dose and mean decay rating according to EN 252 [7] of Scots pine sapwood (black) and Douglas fir heartwood (grey) exposed at 28 different field test sites using different dose–response models. Top: logistic model, middle: simplified logistic model, bottom: two-step model (each dot represents the mean decay rating at one exposure site at a certain time of exposure; black line Gompertz smoothing function); taken from Isaksson et al. [78].

$$D_T(T) = \begin{cases} 0 & \text{if } T < c \\ \frac{T}{d-c} & \text{if } c \leqslant T \leqslant d \\ 1 & \text{if } T > d \end{cases} \tag{17}$$

where a is the lower moisture content limit (25%), b is the upper moisture content limit (30%), c is the lower wood temperature limit (0 °C), and d is the upper wood temperature limit (30 °C).

$$DR(D(n)) = \begin{cases} 0 & \text{if } D \leqslant 130 \\ 0.0051 \cdot D - 0.66 & \text{if } D > 130 \end{cases} \tag{18}$$

The simplification of the logistic dose–response model led to a decrease in accuracy of the model. Also the implementation of a set-back parameter – which allowed for negative dose values – did not lead to a better fit. The idea of Viitanen et al. [33] to model an activation process was obviously not transferable to the field test data set used by Isaksson et al. [78]. Finally the two-step dose–response engineering model showed sufficiently high accuracy and was believed to be more efficient in building design applications than the logistic model.

For comparative analysis the logistic model [30] has been applied also to plywood that was exposed outdoors and assessed regarding moisture performance and fungal susceptibility by Van den Bulcke et al. [85]. However, it was pointed out that a performance model is not easily transferable to different substrates (or as in this case composites) due to their different moisture performance and susceptibility to potentially different decay types [76,85]. The logistic dose–response model was based mainly on white and soft rot decay, the use of other materials and/or under different exposure conditions may provoke favourable conditions for brown rot decay.

3.5. Time-series analysis

For service life prediction issues it is essential to determine not only the relationship between material climate and responding wood degradation, but also to model the effect of macro- and microclimatic parameters on the material climate [76]. Besides various laboratory studies on the sorption and capillary water uptake behaviour of wood [e.g. 86], only a few studies are available using long-term field test data to establish ‘climate models’ such as the approach of continuous moisture measurements (CMM) at Ghent University in Belgium [85,87–88]. Experimental base for the studies has been a long-term outdoor exposure of mainly plywood samples on load cells. Moisture content was determined in short intervals for several years and correlated with weather parameters which had been measured in parallel. Van den Bulcke et al. [87] applied different methods of correlation analysis ranging from standard correlation analysis to wavelet-based semblance analysis to model the effect of weather parameters and the local climate respectively on the moisture performance of plywood as an example.

Reliable climate models describing the effect of *RH*, air temperature, wind speed and direction and all kinds of precipitation are strongly needed for instance to estimate the climate based hazard of a certain location. However, while a climate based hazard map might inform about the general risk of fungal attack, a more precise evaluation of the respective building component needs to consider microclimatic conditions as well. It should be noted that under natural climate exposure including rain the moisture conditions of wood will vary continuously both in time and space. When linking to performance models with moisture content as governing parameter one must decide more precisely how it shall be defined, because the moisture content usually differs in different positions within a wood component.

4. Application of models

4.1. Hazard mapping

Viitanen et al. [33] developed a decay risk model based on laboratory test data and further utilized it to estimate wood decay at different locations in Europe. Therefore the model was applied to ERA-40 reanalysis data using 6-h weather observations in Europe. Based on the weather parameters *RH*, temperature and precipitation the mass loss of Scots pine sapwood caused by brown rot fungi was modelled for wood exposed to rain (Fig. 10) and for wood protected from rain (Fig. 11). The latter was calculated based on *RH* and temperature data only; in case of rain events the *RH* was set to 100% (at non-freezing temperatures), which means that no capillary uptake of liquid water was allowed by the model.

With respect to the absolute values of estimated mass loss the model appeared to be conservative at least for sheltered wood. As shown in Fig. 11 Scots pine sapwood was expected to show more than 20% mass loss by brown rot after 10 years. When wood is protected from rain – and provided there is no external moisture source – less mass loss shall be expected from a biological viewpoint since the presence of liquid water inside wood is an essential requirement for its degradability by fungi [e.g. 1,21,29].

The performance model developed by Brischke [76] has been utilized for a dosimeter based decay hazard map by Frühwald Hansson et al. [36]. Therefore an additional ‘climate model’ has been developed that described the relationship between the weather parameters *RH*, temperature and precipitation on the one hand and the material climatic parameters wood moisture content and wood temperature on the other hand [46].

For the decay hazard mapping, the decay risk at 206 sites in 38 European countries was calculated and related to the decay risk (annual dose) of Uppsala in Sweden. A decay hazard above 1 means higher decay potential compared to Uppsala, a number below 1 means lower decay potential than in Uppsala. Isopleths of the same decay hazard have been calculated by interpolation using splines as shown in Fig. 12.

4.2. Service life prediction

The majority of research activities on performance modelling was motivated by the need to establish useful tools for service life prediction and planning, which is an essential element of performance based building (PBB) [46,78]. Consequently, the overall objective has often been to develop models enabling service life estimates for buildings or building components, whereby the focus was not always on determining discrete numbers of years, but rather performance indicators or relative measures (related to reference products with a reference service life).

A principal methodology for service life planning is given in the ISO 15686 standard series with the ‘factor method’ as a key element (ISO 15686-1 [91]). The method is named according to the calculation of an estimated service life (ESL) by multiplication of a reference service life (RSL) with different modifying factors, which consider the deviation of influences from reference conditions:

$$\mathrm{ESL} = \mathrm{RSL} \times A \times B \times C \times D \times E \times F \times G \quad (19)$$

in which *A*–*G* are modifying factors for each of the following: *A* is quality of components, *B* is design level, *C* is work execution level, *D* is indoor environment, *E* is outdoor environment, *F* is in-use conditions, and *G* is maintenance level.

The multiplicative character of this approach has been discussed controversially by various authors. In particular the high risk of error propagation has been seen as a drawback [29] and numerous modifications of the factor method have been suggested [e.g. 45–46,90–94]. Nevertheless the idea of considering the full spectrum of potential impact factors is beyond controversy and can be reflected by a more general formulation of the factor method as follows [76]:

$$\mathrm{ESL} = f(\mathrm{RSL}, A, B, C, D, E, F, G) \quad (20)$$

Various performance models have been applied for service life prediction on practical examples and building components. For instance the logistic decay model by Brischke [76] has been used to estimate service lives of wooden claddings with different eaves and compass orientations, fence elements and terrace decking [95–98]. For the majority of examples plausible service lives were obtained and clear differences became obvious between wood species, design details and exposure conditions. In addition Frühwald Hansson et al. [36] showed with the same model differences in expected service life between different locations in Europe.

Further experimental studies with continuous MC recordings on different design and construction details have been conducted by Isaksson and Thelandersson [47]. They estimated the behaviour (in terms of performance) of an arbitrary detail by scaling the behaviour of a reference detail up or down using a constant value. Future submission of their datasets to different performance models is foreseen.

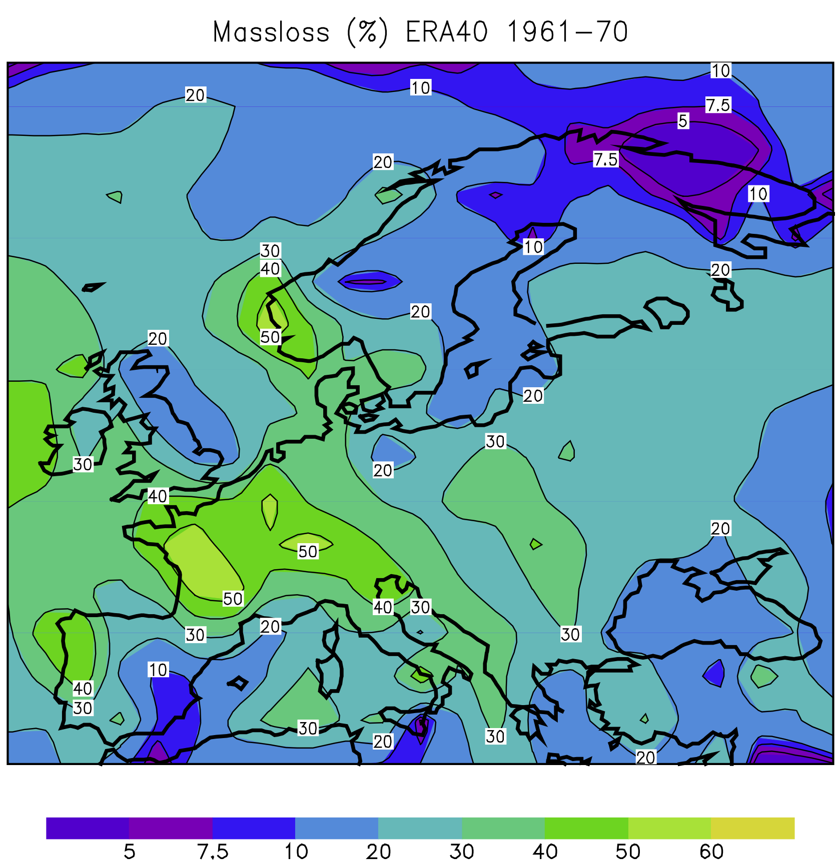

Fig. 10. Modelled mass loss (in %) of small pieces of pine sapwood exposed to rain in 10 years in Europe; from Viitanen et al. [33].

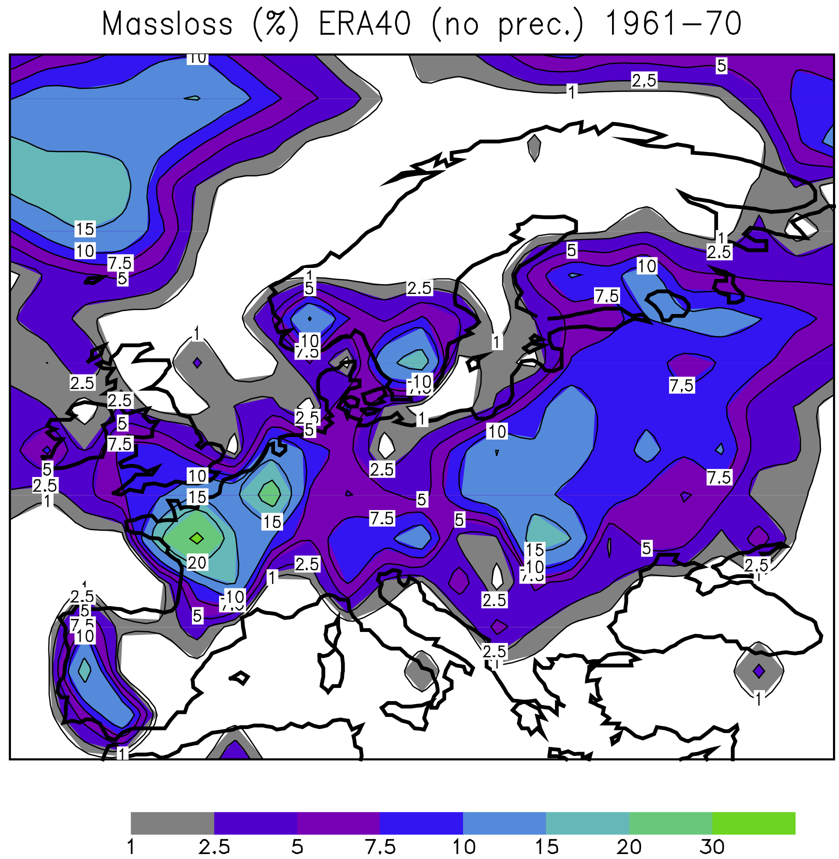

Fig. 11. Modelled mass loss (in %) of small pieces of pine sapwood protected from rain in 10 years in Europe; from Viitanen et al. [33].

The effect of different joints and other design details on the moisture performance of timber elements has been examined by Fredriksson [99]. The results might be seen as a supplement to findings from field studies and can be used to complement performance models.

4.3. Design guidelines

A first technical guideline in Europe for design of wooden constructions with respect to durability and service life has been produced within the European WoodWisdomNet project 'WoodExter' [45,46]. It is based on a limit state described as "onset of decay". On an engineering level the design condition is formulated as follows:

$$I_{Sd} = I_{Sk}\gamma_d \leqslant I_{Rd} \tag{21}$$

in which I_{Sk} is the characteristic exposure index, I_{Rd} is a design resistance index and γ_d depends on a consequence class, which refers to the expected consequences if the limit state is violated. In analogy to the principles of ISO 13823 [100] the design is accepted if the condition in Eq. (7) is fulfilled, otherwise it is not accepted.

According to Thelandersson et al. [45] I_{Sk} intends to describe the severity in terms of combined moisture and temperature conditions favourable for decay fungi.

The exposure index I_{Sk} is determined by

$$I_{Sk} = k_{s1} \cdot k_{s2} \cdot k_{s3} \cdot k_{s4} \cdot I_{S0}c_a \tag{22}$$

in which I_{S0} is the basic exposure index depending on geographical location/global climate, k_{s1} is the factor describing the effect of local climate conditions (meso climate), k_{s2} is the factor describing the effect of sheltering, k_{s3} is the factor describing the effect of distance from ground, k_{s4} is the factor describing the effect of detailed design, and c_a is the calibration factor to be determined by reality checks and expert estimates.

The WoodExter approach is using a reference similar to the factor method [89]. A horizontal Norway spruce sapwood board exposed to rain but without moisture trapping is chosen as reference and $I_{S0} = 1.0$ at the specific site Helsinki, Finland.

For other sites the (relative) basic exposure index varies and was determined with the help of a performance model as described by Isaksson et al. [78] and shown in Fig. 9. According to Thelandersson et al. [46] a dose value was determined for moisture content u and temperature T.

For application of the performance model, wood moisture content was calculated from weather data ["global climate data", 46]. The other modifying factors k_{s1} to k_{s4} were partly defined on the base of results from field studies at Lund University (later on described by Isaksson and Thelandersson [47]), partly on expert judgment. The latter was also the base for defining the design resistance index I_{Rd}. It was defined on the basis of resistance classes (Table 3), which shall be seen as a simplified first step for material resistance classification based on a balanced "expert judgment of moisture dynamics and durability class" [46].

Finally, the calibration factor c_a can be used to adopt the design system. A number of reality checks on facades and decking has been evaluated with respect to their performance [46]. The cases were evaluated with the 'WoodExter' guideline with the calibration factor set as $c_a = 1.0$, see Eq. (8). Though the majority of guideline results agreed with reality, a final calibration of the design rule will need a higher number of reality checks.

Within the Swedish research program 'WoodBuild' further efforts were made to develop performance models (regarding fungal decay as well as mould growth). Starting from the WoodExter approach a new design guideline was developed which shall

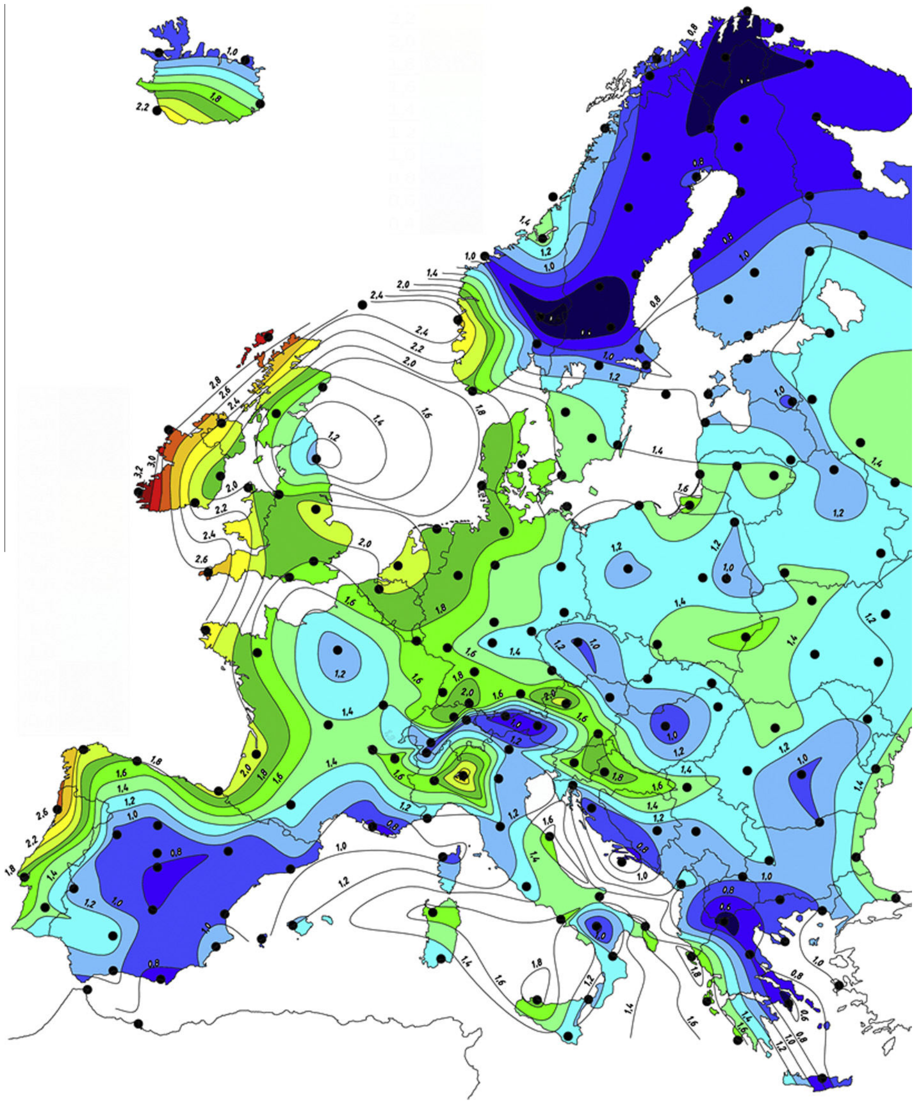

Fig. 12. Relative decay potential for Europe indicated as relative doses for 206 European sites (circles) based on Meteonorm climate data. Relative dose compared to Uppsala, Sweden; modified after Frühwald Hansson et al. [36].

Table 3
Resistance rating of selected wood materials and corresponding design resistance index I_{Rd}, taken from Isaksson and Thelandersson [47].

Material resistance class	Examples of wood materials[a]	I_{Rd}
A	Heartwood of very durable wood species, 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 classes 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

[a] 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 material in that region.

consider results from various field studies and monitoring projects of timber structures in service. Modifying factors describing the effect of different design details are based on long-term measurements and observations on real buildings. Therefore the simplified logistic dose–response model developed by Isaksson et al. [78] will be applied on data sets obtained from studies in Sweden, Denmark, Norway and Germany [47,95].

The first but most likely the most comprehensive attempt to utilize performance models regarding biological degradation of timber structures for design guidance has been developed by Australian researchers [62] and published in the following 12 manuals:

- Manual No. 1: Processed climate data for timber service life prediction modelling [101].
- Manual No. 2: Reliability equations [102].
- Manual No. 3: Decay in ground contact [103].
- Manual No. 4: Decay above ground [21].

- Manual No. 5: Atmospheric corrosion of fasteners in timber structures [104].
- Manual No. 6: Embedded corrosion of fasteners in timber structures [105].
- Manual No. 7: Marine borer attack on timber structures [106].
- Manual No. 8: Termite attack [107].
- Manual No. 9: Service life models for timber structures protected in building envelope [108].
- Manual No. 10: Commentary on a proposed timber service life design code [109].
- Manual No. 11: Equations for use in a service life design guide [110].
- Manual No. 12: Equations for use in TimberLife [111].

5. Conclusions

Efforts in developing performance models for both fungal decay and mould growth have been intensified in recent years. Various approaches have been followed and different models have been proposed to be implemented in design guidelines. However, a high heterogeneity among these attempts became visible and different strategies have been followed. The modelling attempts can be roughly distinguished according to the following criteria:

- *Objectives:* Precise service life estimation (ideally in years) or comparative evaluation (to quantify effects, e.g. of design details; to compare alternatives, e.g. materials or design solutions).
- *Governing variables:* Mass loss, strength loss, remaining strength, decay ratings, decay depth, service life according to different limit states, aesthetic appearance, etc.
- *Data sources:* Laboratory test data, field test data, survey data, expert opinion, reality checks, multi-source approaches, etc.
- *Level of accuracy/reliability:* Use and durability classes, dosimeter approaches, combined approaches.

Furthermore from an engineering point of view decay and biological degradation in general are only part of the overall performance of wooden structures. A comprehensive engineering model can therefore be dominated by the effect of crack formation, ageing, UV degradation, corrosion of fasteners, or building physical phenomena.

It became obvious that a lot of approaches for modelling service lives and performance of wood and wood products are available and many of those have already been implemented into design guidance documents. Furthermore as shown with the TimberLife, WoodExter and WoodBuild concepts open approaches have been used which allow integration of further data sets as well as an improvement of models. Consequently, a framework of how exposure, dimension, design details, and the material-intrinsic ability to take up and release water can be linked to model the moisture risk in wood products is in principal available. Methods and models have the potential to get implemented not only in design guidelines, but also in European and international standards. In particular, the various dosimeter models could serve as reliable tools to quantify the effects of different construction details.

Nevertheless, still there is a need to enhance the available data base to feed the existing models. Models need verification by use of reality checks and under consideration of different materials (e.g. preservative treated wood, modified timber and wood composites) and under different exposure conditions (e.g. under the full range of climatic conditions worldwide).

Finally one might conclude that a set of powerful and easily applicable models is needed rather than one universal model to rule performance issues in a global manner.

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6.4 Publication IV: Resistance based moisture content measurements on native, modified and preservative treated wood

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BRIEF ORIGINALS KURZORIGINALIA

Resistance based moisture content measurements on native, modified and preservative treated wood

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Abstract Resistance characteristics were determined for a total of 27 wood-based materials containing native soft- and hardwoods, differently modified timbers and preservative treated timbers. A functional relation between measured electrical resistance and gravimetrical wood moisture content (MC) was established in a range between 15 and 50 % MC. Most precise MC estimation was found for salt-treated timber (±2.5 %), followed by native timber (±3.5 %) and modified timber (±7 %) in the hygroscopic range. As expected, preciseness decreased above fiber saturation, but was still sufficient for native timber (±8 %) and preservative treated wood (±5 %) at approx. 50 % MC.

Holzfeuchtemessungen nach dem Widerstandsprinzip an unbehandeltem, modifiziertem und mit Schutzmitteln behandeltem Holz

1 Introduction

Wood durability is the consequence of wood extractives having biocidal or inhibiting effects and the moisture performance of wood. Since fungal degradation of wood requires liquid water in the wood to allow transporting fungal enzymes, a risk of decay is given when the wood moisture content (MC) is above fiber saturation. To characterize the moisture performance of wood and to quantify the effect of moisture loads on the resulting durability it is unavoidable to measure wood MC in the field as well as on real structures in service.

Generally, there are different possibilities for measuring and recording wood MC over longer periods of time: Direct measurements can be conducted using load cells (Van den Bulcke et al. 2009), which is a precise method that allows determining the global MC of a wooden specimen, but not the particular MC at a certain position. Furthermore, the method is sensitive to wind loads and the size of test objects is limited. Hygroscopic MC measurements are based on the relationship between relative humidity RH, temperature and equilibrium wood MC. Temperature and humidity in a bore hole allow calculating the corresponding MC of the wood which is in equilibrium with the ambient air (e.g., Evans 2004). However, this method is only applicable for MCs below fiber saturation.

Finally, electrical resistance measurements provide information about wood MC and are frequently used for continuous outdoor measurements and recordings. A system for long-term data logging on timber structures and field trials has been developed by Brischke et al. (2008). A 2 k-epoxy resin was used as isolating glue and as conductive glue when mixed with graphite powder. Partly isolated stainless steel cables acted as both electrode and cable. This system was further tested in combination with mobile mini data loggers. However, since the electrical conductivity depends on wood species and wood temperature, a calibration curve describing the functional relation between electrical resistance and local moisture content is needed for every single material tested (Du 1991). Earlier results showed that measurements with sufficient accuracy were possible in a range between 15 and 50 % wood MC for different native softwoods (Brischke et al. 2008). However, cell wall modification as well as impregnation

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with preservatives, which are commonly applied on wood in outdoor use, is expected to have a significant impact on electrical conductivity of wood, as for instance reported by Smith et al. (2007) and Brischke et al. (2013).

Therefore, this study aimed at the determination of material-specific resistance characteristics of native soft- and hardwoods, thermally and chemically modified timber as well as timber impregnated with different types of wood preservatives.

2 Materials and methods

Resistance characteristics were determined for a wide range of materials, which were studied in terms of durability field tests and moisture monitoring of timber structures. As summarized in Table 1, native soft- and hardwoods, differently modified and preservative treated timbers were included in the tests.

Data loggers (Materialfox, Scanntronik Mugrauer) were used for resistance-based measurements. Their memory capacity comprised up to 16,000 readings. The data loggers were equipped with three ports and the effective range of measurements was between 2×10^4 and 5×10^8 Ω. A sampling interval of 30 s was chosen for the calibration experiments. The measuring principle was based on the discharge-time-measurement method. First a capacitor was charged through a small ohmic resistance and then discharged through the material to be measured. Based on the time needed for discharging, the resistance of the material was calculated.

For determination of resistance characteristics, eight replicate specimens of 50 (ax.) $\times$ 20 $\times$ 30 $\times$ mm^3 were used for each MC/wood species combination. Two holes of 4 mm diameter were drilled into the specimens with a distance between the centers of 30 mm parallel and 6 mm orthogonal to the grain as described in detail by Brischke et al. (2008). To determine the relationship between electrical resistance and wood moisture content (MC) gravimetric and electric MC comparative measurements were carried out at four target MCs (15, 18, 25 and 50 %) and three target temperatures (T = 4, 20, and 36 °C).

To achieve the target MCs, the specimens were stored in well ventilated miniature climate chambers filled with saturated solutions of NaCl (75 % RH; 15 % MC), KCl (85 % RH; 18 % MC), and K_2SO_4 (98 % RH; 25 % MC), respectively. To obtain 50 % MC the following procedure was applied: Water pressure impregnation, storing in polyethylene (PE) bags for 6 days at 4 °C, afterwards drying down to 50 % MC at room temperature, subsequent

Table 1 Materials used for determination of resistance characteristics (durability tests including moisture monitoring were conducted with same materials in the field as described by Meyer et al. 2012)
Tab. 1 Materialien für die Erstellung von Widerstandskennlinien (Dauerhaftigkeit der Materialien wurde in Freilandprüfungen einschließlich langfristigen Feuchte-Monitorings von Meyer et al. (2012) bestimmt)

	Material	Botanical name
Native softwoods	Scots pine heartwood	*Pinus sylvestris* L.
	Scots pine sapwood	*Pinus sylvestris* L.
	Scots pine heartwood, highly resinous	*Pinus sylvestris* L.
	Southern yellow pine sapwood	*Pinus* spp.
	Radiata pine sapwood	*Pinus radiata* D. Don.
	Norway spruce	*Picea abies* Karst.
	European larch heartwood	*Larix decidua* Mill.
	European larch sapwood	*Larix decidua* Mill.
	Douglas fir heartwood	*Pseudotsuga menziesii* Franco
	Douglas fir sapwood	*Pseudotsuga menziesii* Franco
	Western Red Cedar	*Thuja plicata* Donn ex D. Don
Native hardwoods	Beech	*Fagus sylvatica* L.
	English oak heartwood	*Quercus robur* L.
	English oak sapwood	*Quercus robur* L.
	European ash	*Fraxinus excelsior* L.
	Black locust	*Robinia pseudoacacia* L.
Modified timbers	Furfurylated Southern yellow pine	*Pinus* spp.
	Acetylated Southern yellow pine	*Pinus* spp.
	Thermally modified Scots pine	*Pinus sylvestris* L.
	Oil-heat treated Norway spruce	*Picea abies* Karst.
	Oil-heat treated European ash	*Fraxinus excelsior* L.
Preservative treated timbers	Copper chromium arsenic 2 kg/m^3	*Pinus sylvestris* L.
	Copper chromium arsenic 4 kg/m^3	*Pinus sylvestris* L.
	Copper chromium arsenic 9 kg/m^3	*Pinus sylvestris* L.
	Alkaline copper quaternary ACQ	*Pinus sylvestris* L.
	ACQ micronized copper	*Pinus sylvestris* L.
	Metal-free	*Pinus sylvestris* L.

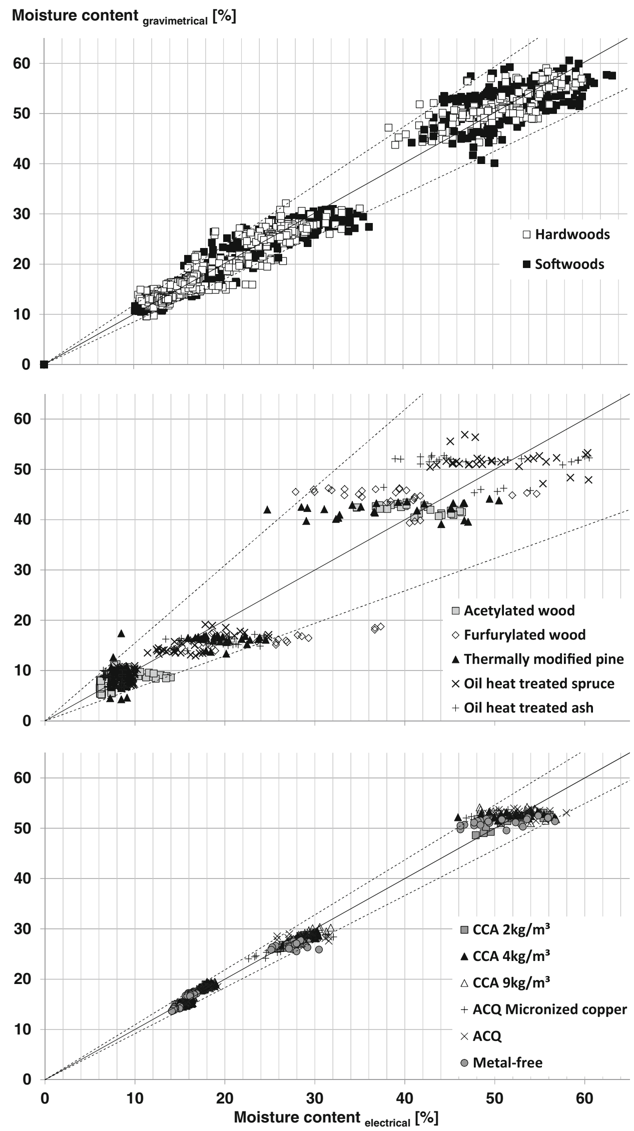

Fig. 1 Calculated MC based on resistance measurements (MC electrical) compared with gravimetrically measured MC. *Top* native hardwoods and softwoods. *Centre* Differently modified timbers. *Bottom* Preservative treated timbers. *Dashed lines* indicate 95 % confidence intervals

Abb. 1 Vergleich von auf Basis der Widerstandsmessungen errechneter Holzfeuchten und gravimetrisch bestimmter Holzfeuchten. Oben: Unbehandelte Nadel- und Laubhölzer. Mitte: Unterschiedlich modifizierte Hölzer. Unten: Schutzmittelbehandelte Hölzer

storage in PE bags for another 6 days at 4 °C. PTFE isolated stainless steel electrodes were driven into the predrilled holes. The MC measurements were conducted successively at the three temperatures with a Materialfox data logger, the mean values of 4–6 recordings were used for plotting the electrical resistance against the gravimetrically measured MC.

3 Results and discussion

Resistance characteristics were determined for each material as a function of electrical resistance R and wood temperature T. Therefore the exponential base function (Eq. 1) below was used for all materials:

$$MC(R;T) = a \cdot T + b \cdot EXP((c \cdot T + d) \cdot R) + (e \cdot T + f) + \left(g \cdot R^2\right) + (h \cdot T) + i \quad (1)$$

where MC is the wood moisture content, R is the electrical resistance in 10 lgΩ, T is the wood temperature in °C, and a, b, c, d, e, f, g, h, and i are material-specific variables.

An approximation was sought for each material based on the triples of electrical resistance R, gravimetrically determined MC, and wood temperature T. Therefore the method of least squares was applied with the help of MS Excel Solver.

By using the specific calibration functions the accuracy of the MC estimation was acceptable for most material below fiber saturation (Fig. 1). In particular the resistance of the preservative treated timbers was surprisingly well correlated with their wood moisture content. Consequently the precision of MC estimation of the measurements was highest for preservative treated wood (±2.5 %) followed by native timbers (±5 %). Only the different modified timbers suffered from higher variation (±10–20 %), but still a moisture content range was indicated to estimate the level of wetness. Apparently conductivity of modified wood varied stronger than that of untreated wood, which might be explained by changes in the nanostructure of the cell walls coming along with changes of accessibility and transportability of ions as well as an increase in ions dissociated from acetic, formic and other acids in thermally modified or acetylated wood. Since the modification intensity can vary between processes, batches or even within one batch, one can expect significant variations in electrical conductivity too. However, generally the electrical conductivity was increased for all modification processes.

In contrary, the preservative treatment led to an increase in accuracy of the measurement system, whereby also here the conductivity was increased compared to native wood. This effect has been shown for some preservatives by Smith et al. (2007) and points to the need to determine not only species-specific, but also treatment and treatment-intensity specific resistance characteristics. The equilibrium MCs were slightly increased (2–3 %-points) due to the impregnation with salts.

As reported earlier by different authors (e.g., Du 1991; Brischke et al. 2008) the measuring accuracy of resistance based MC meters decreased drastically with MCs above fiber saturation, but the MC estimations still allowed fairly precise estimates for most of the native timbers (Fig. 1). Surprisingly, the preservative treated timber showed highest accuracy over the whole calibration range. Even at approximately 50 % MC, the accuracy of the investigated preservative treated timbers was ±5 %. Consequently, an increase in conductivity due to an increase in mobile ions as observed in both groups, the modified and the preservative treated timbers, does not necessarily lead to a reduction in accuracy. In summary, the immanent need for material-specific resistance characteristics to receive highest possible exactness of the measurements became obvious.

4 Conclusion

The results of the study point to the possibilities of applying electric wood MC measurements on different variations of wood durability testing including different types of wood modification and preservative treatments. A strong need to determine material-specific resistance characteristics was highlighted when precise MC estimation is required.

Considering the fact that fungal activity becomes critical at fiber saturation and above, it becomes obvious that for durability testing and monitoring of outdoor structures the relevant MC range starts shortly below fiber saturation point. The obtained characteristics clearly showed that MC measurements are applicable not only in the hygroscopic range, but also for higher MCs. Solely, the application of modified wood led to remarkable problems regarding accuracy, but were dependent on the type of modification. For estimating MC of modified wood the reduced equilibrium MC in the hygroscopic range caused by the reduced sorption of the cell wall needs to be considered.

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6.5 Publication V: Modeling the influence of thermal modification on the electrical conductivity of wood

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Modeling the influence of thermal modification on the electrical conductivity of wood

Abstract: A model has been developed aiming at the description of the effect of thermal modification on the electrical conductivity of wood. The intention was to calculate the moisture content (MC) of thermally modified timber (TMT) through the parameters electrical resistance *R*, wood temperature *T*, and CIE $L^*a^*b^*$ color data, which are known to correlate well with the intensity of a heat treatment. Samples of Norway spruce (*Picea abies* Karst.) and beech (*Fagus sylvatica* L.) samples were thermally modified in laboratory scale at 11 different heat treatment intensities and the resistance characteristics of the samples were determined. Within the hygroscopic range, a linear relationship between the resistance characteristics and the mass loss (ML) through the heat treatment was established. Based on this, a model was developed to calculate MC from *R*, *T*, and ML. To validate this model, color values of 15 different TMTs from industrial production were determined for estimation of their ML and fed into the model. MC of the 15 arbitrarily heat-treated TMTs was calculated with an accuracy of ±3.5% within the hygroscopic range. The material-specific resistance characteristics based on experimental data led to an accuracy of ±2.5%.

Keywords: electrical resistance, moisture content measurement, moisture meter, moisture monitoring of timber structures, resistance characteristics, thermally modified timber (TMT)

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Introduction

In recent years, thermal cell wall modification has become one of the most established wood modification processes in Europe with still increasing market volume (Welzbacher and Scheiding 2011). Initially, thermally modified timber (TMT) has been produced for outdoor application due to its improved dimensional stability and durability against wood-destroying fungi (Tjeerdsma et al. 1998, 2002; Vernois 2001; Welzbacher 2007). More recently, TMT is also considered for indoor use, for instance, as parquet flooring or furniture (Militz 2008; Jones 2012). Higher durability as well as dimensional stability of TMT is closely related to lower water sorption (Tjeerdsma et al. 1998; Welzbacher 2007; Olek et al. 2013; Ringman et al. 2013). In other words, the hygroscopicity of wood is reduced through thermal modification due to changes of chemical composition and structural changes of the cell wall. In particular, the number of reactive hydroxyl groups and thus the number of sites for binding water molecules is decreased (Krackler et al. 2011). The intensity and the type of heat treatment are essential with this regard (Vernois 2001; Hofmann et al. 2008; Welzbacher et al. 2012; Wetzig et al. 2012). In the hygroscopic range, the equilibrium moisture content (EMC) of TMT can be reduced by more than 50% (Schneider 1966, 1971, 1973; Burmester 1970, 1981; Wang and Cooper 2005; Schnabel et al. 2007; Welzbacher 2007; Akyildiz and Ates 2008).

The knowledge of the actual MC of TMT is important in view of its altered moisture uptake behavior (CEN 2007). For example, in parquet or window joinery, the correct EMC needs to be known before installation or assembling to avoid unacceptable dimensional changes in service. For TMT in outdoor applications, the actual MC plays an important role for determining the risk of decay under certain conditions (Meyer et al. 2012). MC measurements based on electrical resistance (*R*) are common (Du 1991; Forsén and Tarvainen 2000), because they are rapid and accurate over a wide measuring range and can be performed automatically by means of data logging devices (Brischke et al. 2008). On the contrary, a lot of parameters have an effect on the electrical conductivity (σ) of wood and need to be considered for MC measurements, such as wood species, origin, anatomical direction, *T*, type and amount of extractives, and the type and position of electrodes (Davidson 1958; Brown et al. 1963; Du 1991; Brischke et al. 2008). Several authors recommended determining wood species-specific resistance characteristics in addition to a temperature compensation of the measurements (Du et al. 1991; Brischke et al. 2008; Meyer et al. 2012). Beyond that, the impregnation of wood with preservatives as well as chemical and thermal modification have the potential to alter σ (Holleboom and Homan 1998; Smith et al. 2007; Meyer et al. 2012). According to Hearle (1953) and Brown et al. (1963), R is affected by (1) the number or concentration of conducting ions (i.e., the number of charge carriers) and (2) the mobility of the existing charges, which means the ease of charges to move in an electric field. Thermal modification is believed to cause changes of the cell wall nanostructure coming along with changes of accessibility and transportability of ions and an increase of ions dissociated from acetic and formic acid formed during heat treatment (Tjeerdsma et al. 1998; Weiland and Guyonnet 2003; Wikberg and Maunu 2004).

Thus, R measurements on TMT are influenced by many parameters among which the treatment intensity is the most relevant. Therefore, this study aimed on developing a model that generally describes the relationship between thermal modification intensity and σ (and R). The expectation is that the model will allow applying resistance-based MC measurements on an arbitrarily treated piece of wood without the need for a material-specific characteristic.

Materials and methods

TMT – laboratory-scale production and conditioning

In total, 155 specimens of 25 (tan.)×25 (rad.)×80 (ax.) mm^3 were prepared from each European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* Karst.). The specimens were oven-dried at 103°C until constant mass ($m_{0,1}$), weighed to the nearest 0.001 g, and submitted to a laboratory thermal modification process according to the parameters shown in Table 1. Before heat treatment, the specimens were wrapped tightly in aluminum foil to minimize oxidation processes. The mass loss (ML) by thermal modification was determined after weighing the specimens again after the treatment ($m_{0,2}$) according to Eq. (1).

$$ML\% = 100\times(m_{0,1} - m_{0,2})/m_{0,2} \quad (1)$$

Two holes of 4 mm diameter and with a depth of 17°mm were drilled into each specimen for installation of measuring electrodes. The distance between both holes was 30 mm, which were shifted by 6 mm from the axial direction to avoid crack formation. Specimens were afterwards oven-dried again and weighed. From a total of 15 replicates per batch (treatment intensity), 3 replicates were dedicated to each moisture conditioning regime. For conditioning, specimens were stored in ventilated miniature climate chambers over saturated salt solutions for up to 10 weeks: NaCl, target relative humidity (RH) 75%; KCl, target RH 85%; and K_2SO_4, target RH 97%.

Table 1 Wood species, treatment parameters, ML, and EMC in different climates of TMT for determination of electrical resistance characteristics produced in laboratory scale (SD in brackets).

Wood species	Batch ID	Treatment		ML (%)	% EMC at 20°C/75% RH	% EMC at 20°C/85% RH	% EMC at 20°C/97% RH
		T (°C)	*t* (h)				
European beech (*F. sylvatica* L.)	B0	–	0.0	0.0 (0.0)	13.2 (0.4)	17.1 (0.3)	29.2 (0.3)
	B1	220	1.0	2.9 (0.9)	8.6 (0.6)	12.7 (1.1)	22.6 (3.0)
	B2	220	2.0	6.5 (1.0)	7.8 (0.3)	10.4 (0.2)	21.4 (0.4)
	B3	220	3.0	10.5 (1.6)	7.2 (0.7)	9.6 (0.4)	16.8 (0.3)
	B4	220	4.0	13.4 (0.9)	6.6 (0.1)	8.7 (0.2)	14.7 (0.1)
	B5	220	6.0	15.7 (1.4)	6.3 (0.2)	8.6 (0.2)	12.7 (0.7)
	B6	180	1.5	1.0 (0.6)	11.5 (0.1)	16.7 (0.2)	26.9 (0.9)
	B7	180	4.0	1.7 (0.6)	10.6 (0.1)	15.0 (0.3)	25.1 (0.7)
	B8	180	8.0	2.5 (0.5)	9.8 (0.1)	13.9 (0.1)	22.5 (0.5)
	B9	180	16.0	3.7 (0.6)	8.5 (0.1)	12.0 (0.2)	20.0 (0.1)
	B10	180	36.0	7.8 (0.8)	7.3 (0.1)	10.1 (0.2)	N.A. (N.A.)
Norway spruce (*P. abies* Karst.)	S0	–	0.0	0.0 (0.0)	12.5 (0.2)	16.4 (0.7)	24.9 (0.9)
	S1	220	1.0	2.9 (0.4)	8.6 (0.4)	12.4 (0.4)	18.9 (1.6)
	S2	220	2.0	4.6 (0.6)	8.2 (0.3)	10.9 (0.6)	16.6 (2.1)
	S3	220	3.0	5.5 (0.6)	7.7 (0.3)	11.2 (0.2)	16.4 (1.0)
	S4	220	4.0	9.4 (0.8)	6.2 (0.2)	9.1 (0.3)	14.7 (0.2)
	S5	220	6.3	10.4 (0.5)	6.3 (0.2)	8.9 (0.2)	13.5 (0.7)
	S6	180	1.5	0.4 (0.1)	10.7 (0.6)	14.9 (0.2)	25.0 (0.6)
	S7	180	4.0	1.1 (0.2)	10.7 (0.2)	14.3 (0.4)	23.9 (0.8)
	S8	180	16.0	2.4 (0.2)	9.8 (0.2)	13.1 (0.4)	22.2 (1.6)
	S9	180	36.0	4.0 (0.4)	9.3 (0.1)	12.1 (0.4)	21.2 (0.9)
	S10	180	72.0	5.5 (0.3)	8.7 (0.1)	11.6 (0.3)	20.6 (1.4)

To establish also MC above fiber saturation (40% and 50%), specimens were vacuum-pressure impregnated with distilled water (4 kPa for 20 min→750 kPa for 30 min), kept submersed for further 24 h, and afterwards dried down to the respective target MC at room temperature (20°C). As soon as the specimens reached their target weight, they were tightly packed into polyethylene bags and stored at 5°C for at least 96 h.

TMT – industrial-scale production and conditioning

To validate the model describing the relationship between MC, *R*, and modification intensity, a second set of specimens was prepared from industrially heat-treated timber. In total, 15 different TMTs of unknown heat treatment intensity were used, 4 Norway spruce (TMT 1-4, treated in nitrogen atmosphere) and 11 European beech (TMT 5-12, treated in nitrogen atmosphere, and TMT 13-15, treated in water vapor). From each TMT, n=30 replicate specimens of 20×30×50 (ax.) mm^3 were prepared (5 per target MC) and provided with two bore holes for installation of electrodes as indicated above. Conditioning of the specimens was done in analogy to the specimens from laboratory production apart from vacuum-pressure impregnation: After 20 min vacuum at 4 kPa, a pressure phase was applied for 15 min at 750 kPa followed by 24 h water submersion. The specimens were dried to the target MC (i.e., 50%).

Electrical resistance measurements at different temperatures

For measuring *R*, pairs of polytetrafluorethene-coated stainless steel electrodes (length, 45 mm) were driven centrally into the bore holes. The mass of the specimens with and without electrodes was determined to the nearest 0.001 g. The specimens were tightly packed into polyethylene bags after connecting the electrodes with data logging devices with the help of crocodile clamps. To obtain different *T* for calibration, the packed specimens were put into precision incubators for conditioning them exactly at 4°C, 20°C, and 36°C. Exposure to a certain *T* did not exceed 2 h, whereby the *T* of a reference specimen was recorded with a data logger (Thermofox; Scanntronik, Zorneding, Germany). *R* was measured by data logging devices type "Materialfox" (Scanntronik). The data loggers were equipped with three ports. The measuring ranged from 2×10^4 to 5×10^8 Ω and a sampling interval of 5 s was chosen. The measuring principle is based on the discharge-time-measurement method. First, a capacitor was charged through a very small ohmic *R* and then discharged through the material to be measured. Based on the time needed for discharging, *R* can be calculated. Directly after measuring *R*, the specimens were weighed again (m_c) to determine gravimetric MC according to Eq. (2).

$$MC\% = 100\times(m_c - m_{0,2})/m_{0,2} \quad (2)$$

Determination of resistance characteristics

Based on the triples – R(10lgΩ), gravimetrically determined MC, and T – an approximation was sought for each material. Therefore, the method of least square was applied with the help of MS Excel Solver. The exponential function shown in Eq. (3) was used as base function to display the whole MC range considered. The material-specific variables *a* to *i* were sought.

$$MC(R;\ T) = (aT+b)\times \mathrm{Exp}((cT+d)R+eT+f)+gR^2+hT+i[\%] \quad (3)$$

In addition, smoothing functions for hygroscopic behavior of wood between 0 and 30% MC were determined based on a linear function according to Skaar (1988) as shown in Eq. (4) using material-specific variables *a* to *c*.

$$MC(R;\ T) = a+bR+cT[\%] \quad (4)$$

CIE *L*a*b** color measurements

Color measurements were conducted on planed surfaces at three points per specimen with a colorimeter (Spectro-Guide Sphere Gloss; BYK-Gardner GmbH, Wiesbaden, Germany). The measurements were taken in CIE *L*a*b** coordinates. A cumulated color value based on the addition of the lightness *L** and the chromatic coordinates of the blue-yellow axis *b** (*L**+*b**) was calculated and correlated with ML, as suggested by Brischke et al. (2007).

Results and discussion

ML and EMC

Expectedly, the ML caused by evaporation of wood substances during the heat treatment increased with increasing treatment times and temperatures in agreement with the literature (Tjeerdsma et al. 2002; Paul 2006; Welzbacher et al. 2007). In total, thermal modification intensity covered a range between 0.0 and 15.7% ML for beech and 0.0 and 10.4% for Norway spruce (Table 1), which is approximately the range pursued in industrial TMT production (Welzbacher 2007). The beech specimens showed higher ML compared with spruce specimens modified with same treatment parameters, which can be explained by the higher content of pentosans of beech (as a hardwood), which are less thermally stable than the hexosans in softwoods (Tjeerdsma et al. 2002; Weiland and Guyonnet 2003).

In analogy to ML, the EMC of the TMT is significantly reduced. This is shown for three different climates in Table 1. The reasons for reduced sorption of TMT is still not fully understood but most likely attributed to a decreased number and accessibility of the hydroxyl groups in the cell wall (Tjeerdsma and Militz 2006; Ringman et al. 2013). Accordingly, the lower EMCs will influence the *R* characteristics of TMT. In extreme, the EMC was reduced by 57% compared with the untreated controls for beech (B5) and by 46% for spruce (S5) as shown in Table 1. However, the target MC above fiber saturation was unaffected.

Resistance characteristics for the whole MC range

For all thermally modified beech and spruce, resistance characteristics were determined according to the function shown in Eq. (3). Exemplarily, such characteristics are presented in Figure 1a/b for untreated beech wood and beech treated at 220°C for 4 h. The relationship between MC, *T*, and *R* was found to be defined based on nine variables *a* to *i*. It became apparent that different treatment intensity levels led to different *R* characteristics. Generally, TMT showed significantly lower *R* compared with untreated wood, which might be due to acetic and formic acid formed during heat treatment (Tjeerdsma et al. 1998; Weiland and Guyonnet 2003; Wikberg and Maunu 2004). In contrast, a decrease in density as well as the cleavage of hemicellulose side chains may have the opposite effect (Stamm 1964; Vermaas 1984; Du 1991), but obviously these parameters do not superpose the effect of dissociated acids serving as charge carriers in wood. Furthermore, *R* decreased with increasing *T* at constant MC, which has been reported earlier by Lin (1967), James (1968), and Du et al. (1991).

The feasibility of this approach has been shown earlier for different native, modified, and preservative-treated timbers (Brischke et al. 2008; Fredriksson 2010; Meyer et al. 2012). The obtained regression suffered from increasing variation with increasing MC. The accuracy of the measurements in the hygroscopic range was found to be sufficient apart from single outliers, whereas the variation increased remarkably above fiber saturation (Figure 2a). This might be explained not only by increasing MC coming along with increasing amount of free water in the cell lumina but also with increasing heterogeneity of moisture distribution in the specimens. On the one hand, capillary water uptake of TMT is considered to be higher compared with untreated wood (Vernois 2001; Metsä-Kortelainen et al. 2006); on the other hand, its sorption is generally decreased; therefore, water transport into and through cell walls hindered or decelerated (Ringman et al. 2013).

Besides increasing error in measurement (Figure 2a), the progression of the regression curves for the different TMTs differed remarkably stronger above fiber saturation as shown for constant *T* at 20°C in Figure 3a/b. In contrary, the relationship between gravimetric MC and logarithmic *R* was almost linear below fiber saturation of wood, which is in line with results from Skaar (1988) and Gellerich et al. (2012). For this reason, in the following, the interdependency between thermal modification intensity, *R*, MC, and *T* will be analyzed for the hygroscopic range exclusively.

Resistance characteristics for the hygroscopic range

R characteristics were determined for the hygroscopic range between 0 and 30% MC based on Eq. (4) according to Skaar (1988). The relationship between *R* and MC is shown in Figure 1a′/b′ with the same examples of

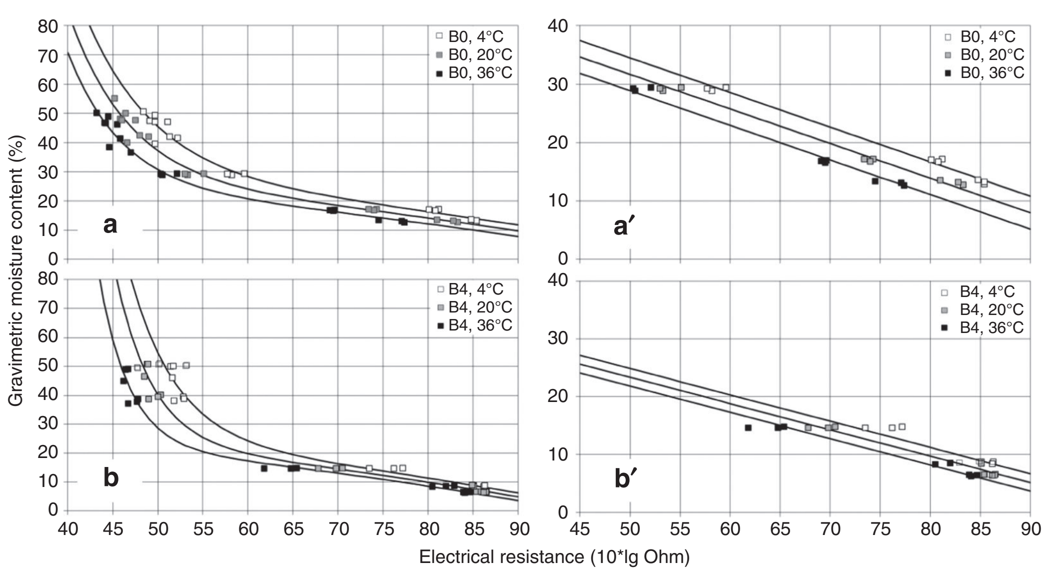

Figure 1 Resistance characteristics for beech at three different temperatures: untreated beech (B0) for the full MC range (a) and in the hygroscopic range (a′) and thermally modified beech (B4) for the full MC range (b) and in the hygroscopic range (b′).

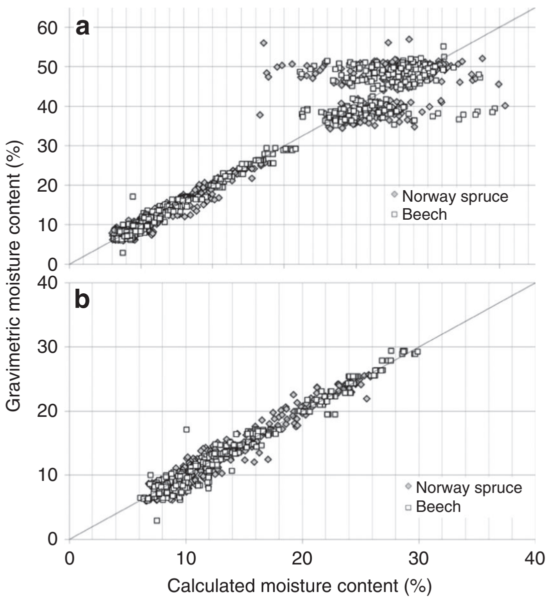

Figure 2 Calculated MC compared with gravimetrically determined MC for all untreated and differently thermally modified samples for the full MC range (a) and the hygroscopic range (b).

untreated beech and beech treated at 220°C for 4 h. Due to a linear correlation, the T parameter shifted the characteristics solely on the ordinate (Figure 1a′/b′). Furthermore, the impact of T on R was significantly reduced compared with the untreated wood, which became apparent through smaller parallel shift of the R characteristics of TMT. The error estimation for both wood species as shown in Figure 2b revealed only marginal variation of ±2.5%, which coincides with most other studies on unmodified timber (Du 1991; Du et al. 1991; Forsén and Tarvainen 2000; Fredriksson 2010).

In analogy to the examples in Figure 1a′/b′, all linear regression curves have similar gradients and they were shifted toward lower MC as a function of increasing treatment intensity (i.e., increasing ML). Consequently, R decreased with increasing treatment intensity at constant T.

To allow for a more precise description of the relationship between heat treatment intensity and R, the original base function [Eq. (4)] was extended aiming at the consideration of ML as a measure of treatment intensity. Because T solely led to a shift of the characteristics on the ordinate axis and a is a material-specific constant, their gradients depend only from the term $b{\cdot}R$. Due to the small variation among gradients of the different R characteristics, the parameter b was assumed to be the average gradient d of all characteristics for each wood species. In the case of temperature being T=0, the function depends only on R and the material-specific constant a [Eq. (5)].

$$MC(R;\,0)=a+dR+c0 \Longleftrightarrow MC(R)=a+dR \tag{5}$$

The ordinate value was thus shifted depending on the respective material-specific constant a and the function MC(R) gave an array of straight lines provided that T=0. The respective ordinate intercepts for the different TMT batches can be seen from the arrays of straight lines

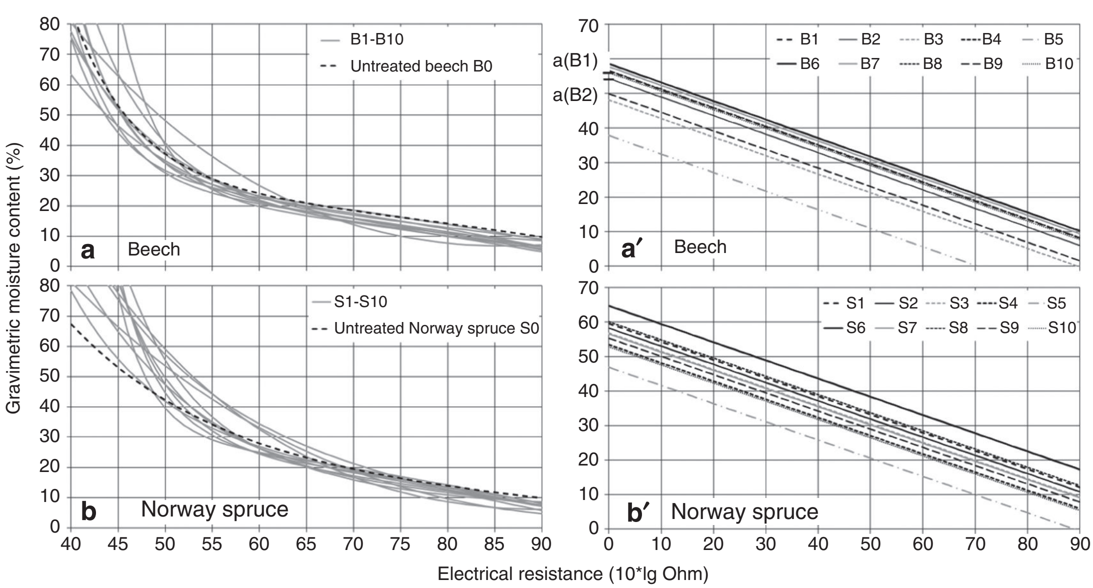

Figure 3 Regression curves (resistance characteristics).
Left: Beech (a) and Norway spruce (b) at constant temperature of 20°C. Right: Array of straight lines according to Eq. (5) provided that T=0 and using the average gradient of all regression lines d. (a′) Thermally modified beech, d=-0.536, ordinate intercept indicated for batches B1(a(B1)) and B2 (a(B2)). (b′) Thermally modified Norway spruce, d=-0.527.

shown in Figure 3a′/b′. To describe the interrelationship between the different *R* characteristics and the ML, a projection rule was sought, which allowed to project, for instance, *a*(B1) on *a*(B2) (Figure 3a′). As the material-specific constant *a* decreased with increasing treatment intensity, a linear relationship was assumed and both parameters were correlated as shown in Figure 4. For both wood species, a satisfying linear correlation was achieved, which can be expressed as follows [Eq. (6)]:

$$a = e \cdot \mathrm{ML} + f \tag{6}$$

where *e* and *f* are material-specific variables.

Consequently, the relationship between MC, *R*, and ML can be described for *T*=0 as follows [Eq. (7)]:

$$\mathrm{MC}(R) = a + dR \leftrightarrow \mathrm{MC}(R;\ \mathrm{ML}) = (e \cdot \mathrm{ML} + f) + dR \tag{7}$$

To allow consideration of *T* as another influence parameter, which can also be described as parallel shift of the *R* characteristics on the ordinate, an additional term was added to Eq. (7). Thus, according to Eq. (8), MC can be described as function of *R*, *T*, and ML.

$$\mathrm{MC}(R;\ T;\ \mathrm{ML}) = dR + e \cdot \mathrm{ML} + f + gT \tag{8}$$

where *d* to *g* are material-specific variables.

Based on the quadruples according to Eq. (8), the following regressions were derived for beech [Eq. (9)] and Norway spruce [Eq. (10)] based on the method of least squares and led to highly sufficient accuracy of the model as shown by respective error estimation in Figure 5.

$$\mathrm{MC}(R;\ T;\ \mathrm{ML}) = -0.49951757R - 0.26144678\mathrm{ML} + 55.3843824 - 0.11374414T \tag{9}$$

$$\mathrm{MC}(R;\ T;\ \mathrm{ML}) = -0.54265832R - 0.37609149\mathrm{ML} + 59.7319416 - 0.11151095T \tag{10}$$

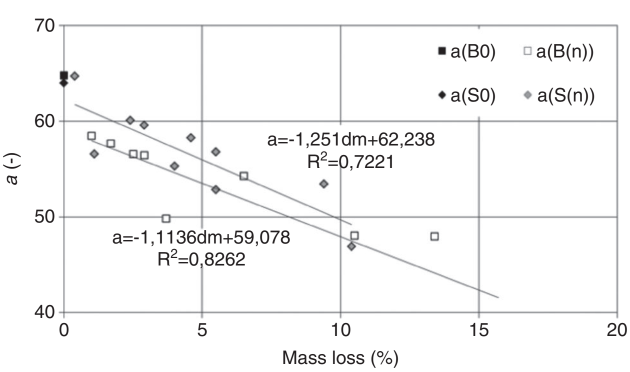

Figure 4 Interrelationship between material-specific constant *a* and ML of thermally modified beech and Norway spruce.

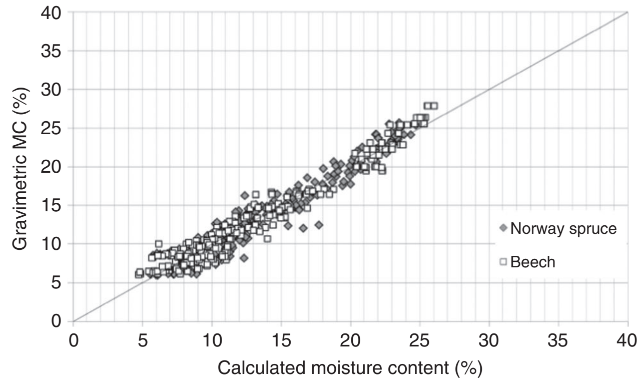

Figure 5 Calculated MC compared with gravimetrically determined MC in the hygroscopic range for all untreated and differently thermally modified samples based on a function MC (*R*, *T*, ML) [Eqs. (9) and (10)].

Correlation between color values and heat treatment intensity

The cumulated color values L^*+b^* correlated well with ML, which can be seen as reliable measure of the heat treatment intensity (Bekhta and Niemz 2003; Brischke et al. 2007; Altgen et al. 2012). The color values decreased with heat treatment intensity; consequently, the wood was darkened as shown for both wood species in Figure 6. Similar correlations were found in former studies with heat-treated Norway spruce, beech, and further 12 wood species (Walter 2010; Welzbacher et al. 2012); thus, the color data seem to be reliable to characterize the thermal modification intensity. Consequently, in the following, the ML of the second set of specimens, which were prepared from industrially heat-treated timber, has been calculated from the regression functions given in Figure 6.

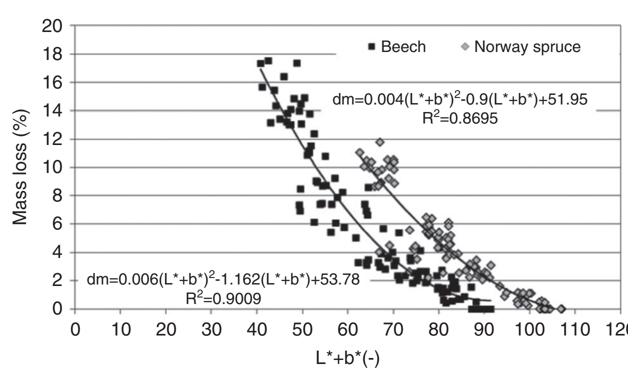

Figure 6 Relationship between cumulated color values L^*+b^* and ML for all differently thermally modified beech and Norway spruce.

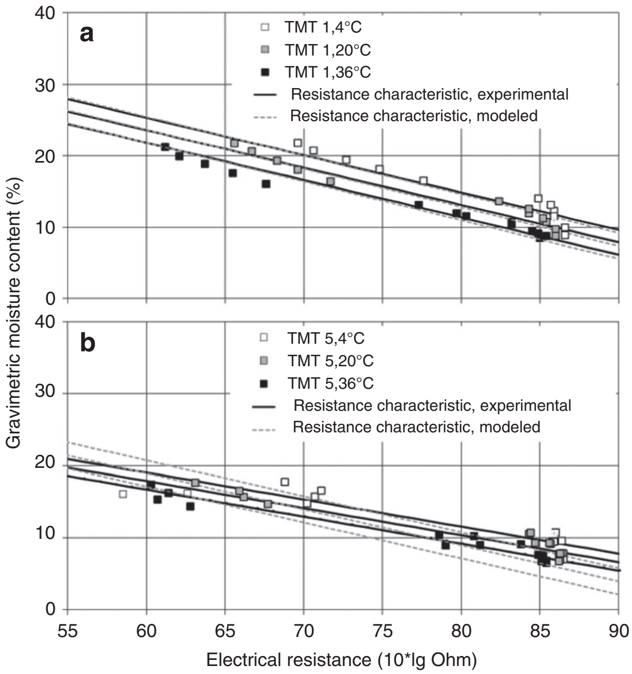

Figure 7 Resistance characteristics based on experimental data according to Skaar (1988) (continuous lines) and based on the developed model (dashed lines) for thermally modified wood in the hygroscopic range at three different temperatures: (a) thermally modified Norway spruce (TMT 1) and (b) thermally modified beech (TMT 5).

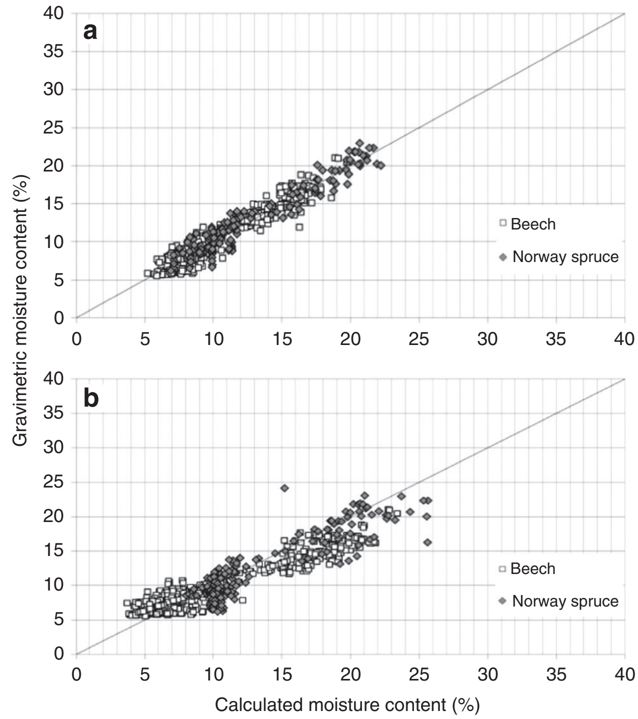

Figure 8 Calculated MC compared with gravimetrically determined MC in the hygroscopic range for all untreated and differently thermally modified samples from industrial production.
(a) Resistance characteristics derived from experimental data according to Eq. (4) after Skaar (1988). (b) Resistance characteristics derived from the model [Eqs. (9) and (10)]; ML based on regression function [Eqs. (11) and (12)].

Validation of the model on industrial TMTs

The model that describes the effect of thermal modification on σ was validated by means of 15 different TMTs from industrial production. For each material, a resistance characteristic was determined for the hygroscopic range based on Eq. (4). For comparison, further characteristics were derived from Eq. (9) for beech (TMT 5-15) and Eq. (10) for Norway spruce (TMT 1-4). Then, MLs were calculated based on color values L^*+b^* according to the regression curves shown in Figure 6 with Eqs. (11) and (12).

$$ML(L^*+b^*)=0.0063(L^*+b^*)^2-1.1619(L^*+b^*)+53.776 \quad (11)$$

$$ML(L^*+b^*)=0.0038(L^*+b^*)^2-0.897(L^*+b^*)+51.949 \quad (12)$$

A comparison of directly determined R characteristics for industrially produced TMT and characteristics based on the model are exemplarily presented in Figure 7. The model shows significantly better fit with the experimental characteristics for TM-Norway spruce compared with TM-beech. For beech, the gradient of the regression lines was, to some extent, steeper, which led to some inaccuracy of the modeled MC. The directly determined characteristics based on experimental data (Figure 8a) led to similar good approximation compared with laboratory-scale TMTs (Figure 5). In contrast, the accuracy was lower if MC was modeled based on color, R, and T data (Figure 8b).

Conclusions

The need to determine material-specific characteristics is well known for high accuracy of MC measurements (Lin 1967; Du et al. 1991; Brischke et al. 2008; Meyer et al. 2012). Various wood-inherent parameters have an influence on σ and may interact, which leads to scattering results. In the case of TMT, further uncertainties accrue, such as heat treatment intensity, and need to be considered, which is not possible through direct measurements. The indirect determination of the modification levels by means of color values is generating another source of error.

The model developed was found to be feasible in particular for the hygroscopic range, which is traditionally considered for R-based MC measurements. In addition, L^*+b^* color values could serve as auxiliary quantity to determine the heat treatment intensity of a wood piece with unknown heat treatment history. Application of sensors for measuring *R*, *T*, and color data within one device would be advantageous for TMT characterization. The accuracy of modeled *R* characteristics based on color data (±3.5%) was less satisfactory compared with direct measurements of experimental data (±2.5%). A comparison of laboratory- and industrial-scale TMTs is difficult as the parameters concerning the heat-up phase, postconditioning, oxygen content in the chamber, initial MC, and heating medium (nitrogen, steam, oil, and wax) may be very different. Most of all, the models must be wood specific, as the effects of wood species are larger than those of the other parameters. Moreover, further studies should also cover a broader range of MC; therefore, resistometers are needed that allow resistance measuring up to 10^9 Ω.

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6.6 Publication VI: Development of decay performance models for outdoor timber structures

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ORIGINAL ARTICLE

Development of decay performance models for outdoor timber structures

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Abstract Performance based building (PBB) and design is closely connected to various needs and requirements: Performance levels need to be defined, test methods for verification of performance need to be developed, and reliable performance data are needed for materials, products, constructions, and different design solutions. In contrast to other building materials, PBB and thus service life prediction of timber and wood-based products requires particular consideration of wood-degrading organisms and their physiological needs. For the most relevant group of wood-destroying organisms, which are the different decay fungi and bacteria, wood moisture content and temperature need to be considered as key factors. This study aimed on the development of performance models on the basis of hard data obtained in field trials performed under most realistic conditions. Dose–response relationships, which can serve as essential parts of a performance based design model, were derived from material climatic data and corresponding decay development in the field. Different dose–response models are proposed and evaluated for predicting onset (and progress) of decay when wood is exposed to a dynamic and arbitrary climate exposure described in terms of time series of coupled temperature and moisture content. A logistic dose–response model was primarily focused on describing the relation between exposure and decay rating for moisture traps with long periods of high moisture contents. A two-step linear engineering model was more focused on predicting the behavior in a wider, more simplified, sense where periods of high moisture content are interrupted by periods of drier and/or colder climate.

Keywords Climate · Design guideline · Exposure · Moisture performance · Wood resistance · Service life prediction

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1 Introduction

Performance based building (PBB) can be described as a building market environment, in which all involved stakeholders address the need to ensure performance-in-use of buildings [1]. It has the potential to promote innovative technologies and building systems, to reduce technical barriers on free trade, and enhance the overall quality of buildings. However, performance based design of buildings is on the other hand closely connected to various needs and requirements: performance levels need to be defined and implemented in codes and standards. Procedures and test methods for verification of performance need to be developed and established. Finally, reliable performance data are needed for materials, products, constructions, and different design solutions [1–6].

PBB and thus service life prediction of wooden components is a task for many different groups: Wood scientists as well as architects, planners, civil engineers, craftsmen, and house builders. At any time during the building process, when decisions about the most suitable solutions have to be taken, the durability and hence the expected service life of a material or a component needs to be considered. The service life of building components and commodities is hereby determined by very different criteria, e.g. color stability of coated or uncoated surfaces, crack performance, occurrence of mould, blue stain, or fungal decay, damage by insects or marine borers, resistance to abrasion and wear. In contrast to other building materials, wood features a susceptibility to colonization and degradation by organisms. For service life prediction of wooden components it is therefore indispensable to consider also biological processes, which can be neglected for metals, minerals, and most other inorganic materials. Thus, it is a huge challenge to take into account the many different factors having a potential impact on the service life of wooden components.

However, efforts in research on service life prediction have been intensified in several countries. A very comprehensive approach was taken by CSIRO and Timber Queensland Ltd., Australia, which resulted in a "Timber service life design guide" [7, 8] and a corresponding software program "TimberLife". The information provided for estimating timber service life in respect of different exposures is based on several models concerning decay in and above ground, and attack by termites and marine borers. In Europe different projects are focusing on service life prediction of timber components as well, but are partly tracking very different experimental approaches and conceptions for modeling [9–16]. Finally, various studies from North America and Asia deal with decay hazard estimations and other service life prediction issues (e.g. [17–23]).

The aim of the present study was the development of performance models on the basis of hard data obtained in field trials performed under most realistic conditions. Dose–response relationships, which can serve as essential parts of a performance based design model, should therefore derive from material climatic data and corresponding decay development in the field. Different possible modeling approaches will be applied for comparison.

2 Experimental background

2.1 Field trials at different sites

Horizontal double layer field trials were conducted with Scots pine sapwood (*Pinus sylvestris* L.) and Douglas fir heartwood (*Pseudotsuga menziesii* Franco), both from one forest stand in Northern Germany, at 24 different European test sites, which were selected to provide a range of climate regimes. The trials ran between 2000 and 2008 with exposure times between 4 and 8 years (Table 1). A detailed description of the trials is given by Brischke and Rapp [18].

Moisture and temperature data are not available from in-ground field tests. Furthermore, the permanent wetting of wood in ground contact prevents re-drying, wherefore modeling of decay in typical above-ground situations would have been inhibited. To avoid direct contact between wood and soil-inhabiting decay organisms within this study the test setup was restricted to severe above-ground exposures only.

All specimens were monitored in terms of wood moisture content, wood temperature, and the progress of fungal decay. Therefore they were assessed yearly by using a pick-test and rating the extent and distribution of decay according to EN 252 [24] as: 0 (sound), 1 (slight attack), 2 (moderate attack), 3 (severe attack), or 4 (failure). Moisture content and temperature data were recorded daily (MC, T_{max} and T_{min}) using miniature data logger (type Materialfox/Thermofox, Scanntronik Mugrauer GmbH) on $n = 3$ replicate samples for each parameter combination (wood species/test site).

Climate data at all sites were available from official weather stations, where measurements of daily precipitation and average daily temperature were recorded. At some sites additional test rigs were

Table 1 Characteristic data of exposure sites for double layer field trials

Test site and exposure	Country code	Height above sea level (m)	Average air temperature (°C)	Sum of precipitation (mm)	Begin of exposure	Last evaluation
Hamburg sun/shade	D	35	10.6[a]	874[a]	07/2000	06/2008
Greenhouse	D	35	21.6[d]	6257[c]	07/2000	06/2008
Greenhouse winter	D	35	18.6[d]	4092[c,d]	07/2000	06/2008
Reulbach sun/shade	D	620	7.5[b]	820[a]	07/2000	09/2008
Stuttgart sun/shade	D	459	9.9[b]	741[a]	07/2000	09/2008
Freiburg sun/shade	D	302	12.1[a]	911[a]	07/2000	09/2008
Oberrottweil	D	221	11.7[a]	731[a]	12/2000	09/2008
Feldberg	D	1496	4.3[d]	1588[d]	12/2000	09/2008
Bühlertal	D	465	9.8[e]	1664[e]	12/2000	09/2008
Hornisgrinde	D	1131	6.0[e]	2030[e]	12/2000	09/2008
Hinterzarten	D	887	7.0[e]	1586[e]	12/2000	09/2008
Schömberg	D	635	8.0[d]	954[a]	12/2000	09/2008
Heilbronn/Heidelberg[j]	D	173/111	11.2/11.7[j]	769/679[j]	12/2000	09/2008
Dobel	D	706	9.0[i]	1473[i]	12/2000	09/2007
St. Märgen	D	908	8.2[a]	1834[a]	12/2000	09/2008
Uppsala	S	7	6.8[e]	579[e]	05/2001	09/2008
Ljubljana	SLO	299	11.3[a]	1330[a]	04/2001	11/2008
Zagreb	HRO	123	10.7[d]	910[d]	08/2002	10/2008
London	GB	62	11.9[h]	649[h]	07/2002	11/2008
Garston	GB	90	10.7[g]	515[g]	07/2002	09/2008
Portsmouth	GB	1	11.6[f]	667[f]	04/2001	09/2008
Ghent	B	9	10.9[a]	758[a]	08/2002	09/2008
Bordeaux	F	4	14.0[e]	798[e]	01/2001	09/2008
Oslo	N	124	7.5[k]	871[k]	08/2004	09/2008

[a] Average of 2000–2005
[b] Average of 2001–2005
[c] Equivalent to a spraying of 120 l per week
[d] Average of 2000–2004
[e] Average of 2000–2006
[f] Average of 2002–2006
[g] Average of Jul 2002–Jun 2006
[h] Average of 2002–2005
[i] Average of 2000–2003
[j] Site was changed in 10/2003 from Heilbronn to Heidelberg, average of 2000–2003, and 2004–2006 respectively
[k] Average of Oct 2004–Sep 2008

exposed in shaded boxes and in a tropical greenhouse to provoke modifications in terms of the microclimate and to promote the conditions for decay. Thus, results from in total 28 different test set ups were considered for the development of performance models.

2.2 Climate-specific development of wood decay

Onset and progress of fungal decay was different between wood species as well as between the different test sites. Decay of Scots pine sapwood (Fig. 1) developed significantly faster compared to Douglas fir

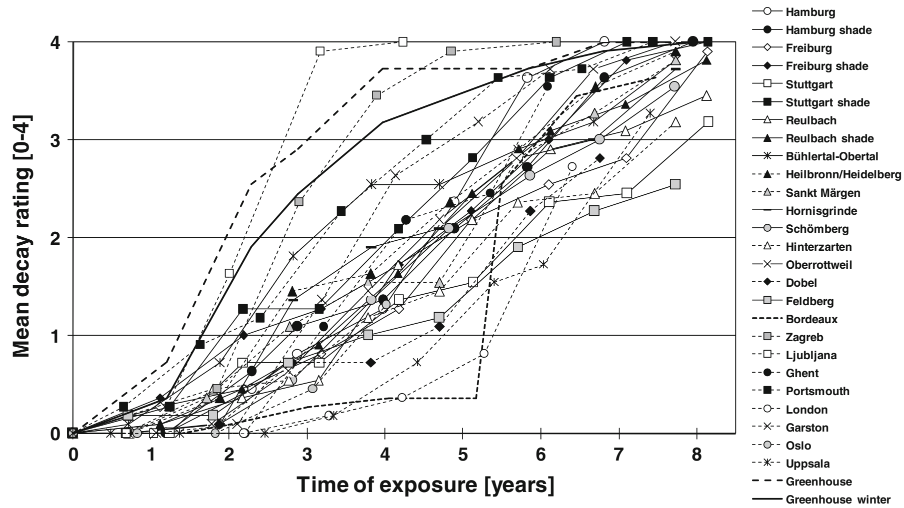


Fig. 1 Relationship between the time of exposure and the mean decay rating according to EN 252 [24] of Scots pine sapwood specimens exposed at 28 different exposure sites

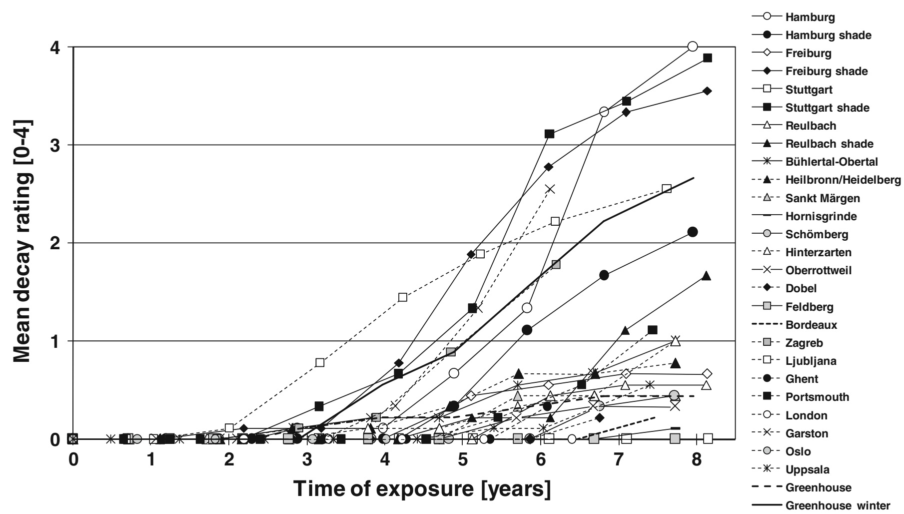


Fig. 2 Relationship between the time of exposure and the mean decay rating according to EN 252 [24] of Douglas fir heartwood specimens exposed at 28 different exposure sites

heartwood (Fig. 2). The high variation of decay development with time is most likely to a large extent caused by the climatic differences between the test sites and exposure conditions.

3 Results and discussion

3.1 Performance model based on dose–response functions

The impact of a general time variation of moisture content u and temperature T on the potential for decay can be described by a so called dose–response relation (e.g. [25]). The advantage of dose–response relationship based models is that they allow for time-series analysis. On the one hand the dose in terms of weather parameters and moisture loads can be directly related to its consequence, i.e. the effect in terms of fungal decay (= response). On the other hand the dose can be related to performance (materials, design detailing, etc.).

The total daily dose D is a function of one component D_u dependent on daily average of moisture content u and one component D_T dependent on daily average temperature T.

$$D = f(D_T(T),\ D_u(u)) \tag{1}$$

For n days of exposure the total dose is given by

$$D(n) = \sum_{1}^{n} D_i = \sum_{1}^{n} (f(D_T(T_i),\ D_u(u_i))) \tag{2}$$

where T_i is the average temperature and u_i is the average moisture content for day i. Decay is initiated when the accumulated dose reaches a critical dose. Different ways of deriving the function of T and u are presented in the following sections.

Performance models of the type investigated here are important as linking elements between exposure and resistance in rational performance based design. The dose–response type of model is an effective tool which can be used to characterize exposure described by arbitrary combined time series of moisture content and temperature. This allows both to estimate service lives (i.e. the expected time to reach a defined level of decay) and evaluate relative performance between different design details, materials, geographic locations and climatic conditions (i.e. the relative dose).

3.2 Logistic dose–response model

The first approach to describe the relationship between the development of fungal decay on wood and corresponding exposure conditions followed strictly the consideration of physiological base parameters of wood decay fungi. Therefore a dose–response model was developed to establish a logistic relationship between wood moisture content and temperature based dose and responding timber decay. The total daily dose, which impacts on the wood, was therefore assumed to be a function of moisture induced component D_u and a temperature induced component D_T. Starting from literature data, the cardinal points of the parameters wood temperature and moisture content for fungal growth and decay activity were sought and used to set up polynomial base functions for both dose components (Eqs. 3, 4). The total dose D is then calculated as a function of D_u and D_T according to Eq. 5, where D_T was weighted by a factor a.

$$D = (a \cdot D_T[T] + D_u[u]) \cdot (a+1)^{-1} \quad \text{if } D_u > 0 \text{ and } D_T > 0 \tag{5}$$

where D is the dose [d], D_T is the temperature induced dose component (−), D_u is the moisture induced dose component (d), u is the moisture content (%), T is the daily average wood temperature (°C), T_{min} is the minimum wood temperature for the day considered (°C), T_{max} is the maximum wood temperature for the day considered (°C), a is the temperature weighting factor, *e, f, g, h, I, j, k, l, m, n* is the variables.

The best fit for this model against the available data was obtained with the following parameters and the final logistic model function according to Eq. 6.

$$\begin{array}{llll} a = & 3.2 & j = & 4.98 \\ e = & 6.75 \cdot 10^{-10} & k = & 1.8 \cdot 10^{-6} \\ f = & 3.50 \cdot 10^{-7} & l = & 9.57 \cdot 10^{-5} \\ g = & 7.18 \cdot 10^{-5} & m = & 1.55 \cdot 10^{-3} \\ h = & 7.22 \cdot 10^{-3} & n = & 4.17 \\ i = & 0.34 & & \end{array}$$

The total dose over a certain time period is given by Eq. 2 and the decay rating is given by the dose–response function:

$$\mathrm{DR}(D(n)) = 4 \cdot \exp(-\exp(1.7716 - (0.0032 \cdot D(n)))) \tag{6}$$

where DR is the decay rating according to EN 252 [24], $D(n)$ is the total dose for n days of exposure.

Figure 3 shows the daily dose D as a function of temperature and moisture content. The effect of temperature is dominating on the total dose. The reason for this is that the empirical data from double layer tests used to fit the model is dominated by observations with continuously high moisture content for pine sapwood. The best fit against these data will therefore primarily reflect the effect of temperature on decay rating.

$$D_u(u) = \begin{cases} 0 & \text{if } u < 25\,\% \\ e \cdot u^5 - f \cdot u^4 + g \cdot u^3 - h \cdot u^2 + i \cdot u - j & \text{if } u \geq 25\,\% \end{cases} \tag{3}$$

$$D_T(T) = \begin{cases} 0 & \text{if } T_{Min} < 0\,^{\circ}\mathrm{C} \text{ or if } T_{Max} > 40\,^{\circ}\mathrm{C} \\ k \cdot T^4 + l \cdot T^3 - m \cdot T^2 + n \cdot T & \text{if } T_{Min} \geq 0\,^{\circ}\mathrm{C} > \text{or if } T_{Max} < 40\,^{\circ}\mathrm{C} \end{cases} \tag{4}$$

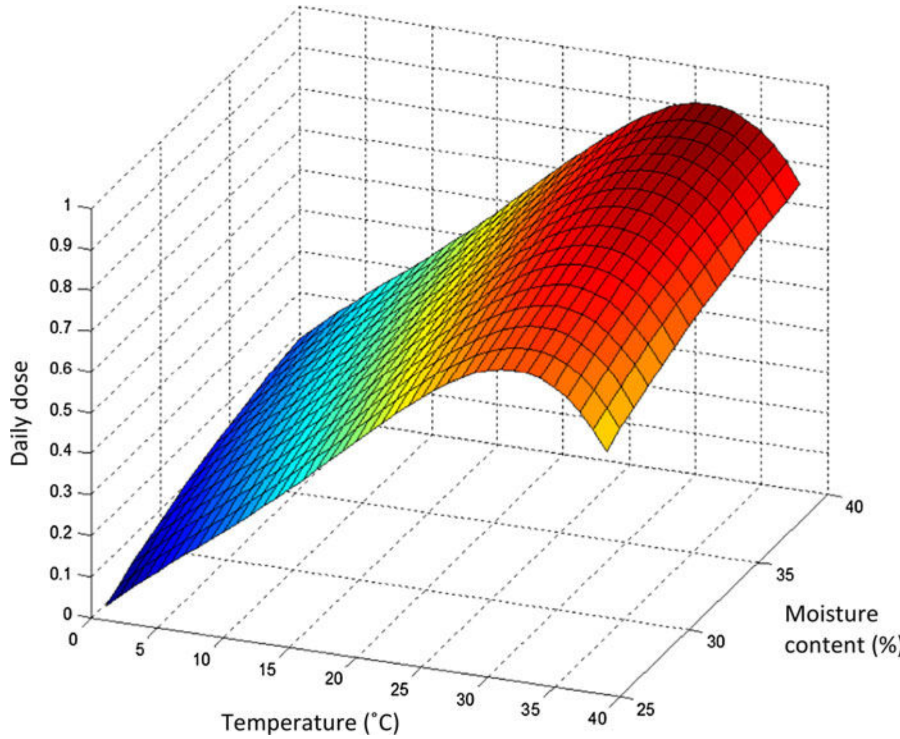


Fig. 3 Relationship between moisture content, temperature and daily dose *D*. The effect of temperature is dominating

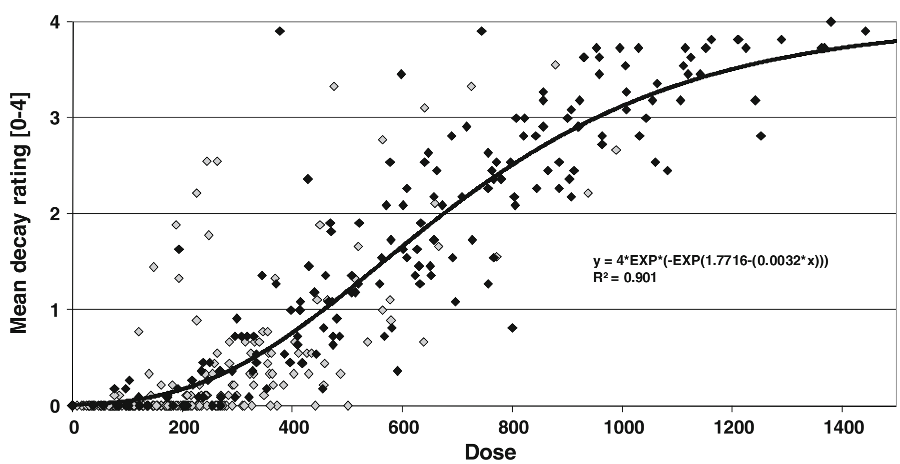


Fig. 4 Relationship between dose and mean decay rating according to EN 252 [24] of Scots pine sapwood (*black*) and Douglas fir heartwood (*grey*) exposed at 28 different field test sites using a logistic dose–response model (each *dot* represents the mean decay rating at one exposure site at a certain time of exposure; *black line* Gompertz smoothing function)

The good fit of the dose response function—as indicated through a degree of determination $R^2 = 0.901$—is illustrated for Scots pine sapwood and Douglas fir heartwood in Fig. 4. However, there were different outliers, where decay developed faster than predicted by the accumulated dose. This happened in particular at the south-eastern sites Ljubljana and Zagreb, where several specimens had been attacked by brown rot, whereas white and soft rot were dominating at most other sites [25].

3.3 Logistic dose–response model: simplified approach

In this case the limit state function is also based on a dose–response model, where the dose is given as a function of wood moisture content and temperature, but here the dose D is assumed to be the product of the two dose components D_u and D_T. The second simplification refers to D_u and D_T, which are expressed as a square function and a linear function respectively [26].

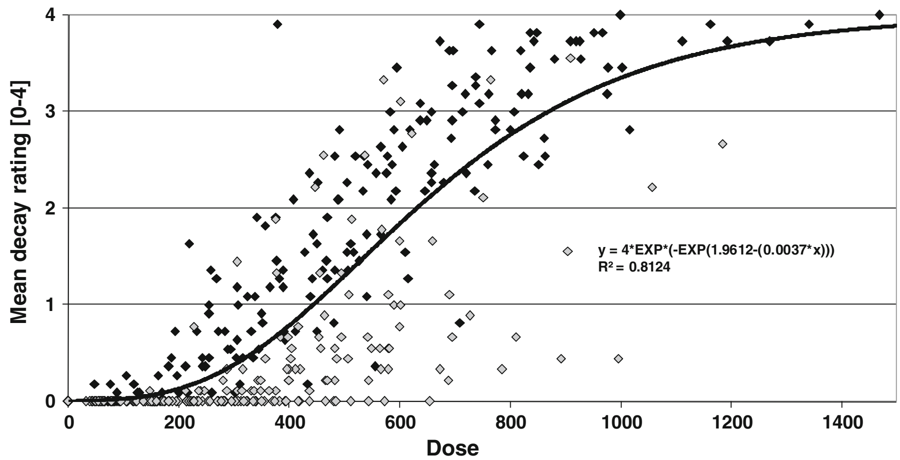


Fig. 5 Relationship between dose and mean decay rating according to EN 252 [24] of Scots pine sapwood (*black*) and Douglas fir heartwood (*grey*) exposed at 28 different field test sites using a simplified logistic dose–response model (each *dot* represents the mean decay rating at one exposure site at a certain time of exposure; *black line* Gompertz smoothing function)

$$D = D_u(u) \cdot D_T(T) \tag{7}$$

$$D_u(u) = \begin{cases} (u/30)^2 & \text{if } u \le 30\,\% \\ 1 & \text{if } u > 30\,\% \end{cases} \tag{8}$$

$$D_T(T) = \begin{cases} 0 & \text{if } T < 0\,^\circ\text{C} \\ T/30 & \text{if } 0\,^\circ\text{C} \le T \le 30\,^\circ\text{C} \\ 1 & \text{if } T > 30\,^\circ\text{C} \end{cases} \tag{9}$$

where D is the dose (d), u is the moisture content (%), T is the wood temperature (°C).

In contrast to the first model, this simplified approach gives non-zero dose values for moisture contents below 25 %. Most research has shown that decay starts at moisture contents above 25 % (e. g. [9, 27]; however, there are some research results that even showed decay at lower moisture contents [28, 29]. The main reasons for choosing the moisture dose to give values also for low moisture contents was the aim to be able to specify the "distance to the risk", but also the uncertainty in moisture content measurements and the potential differences in moisture content within one wooden component.

The total dose over a certain time period is given by Eq. 2 and the decay rating is given by the dose–response function:

$$\mathrm{DR}(D(n)) = 4 \cdot \exp(-\exp(1.9612 - (0.0037 \cdot D(n)))) \tag{10}$$

where DR is the Decay rating according to EN 252 [24], $D(n)$ is the total dose for n days of exposure.

Again, the model itself is based on a logistic Gompertz function, but fitting is not as good as for the first model ($R^2 = 0.81$). As shown in Fig. 5 the model suffers from not exactly matching the decay results of the two wood species. While there is an underestimation of the decay development on Scots pine sapwood, the model seems to be too progressive for Douglas fir heartwood.

3.4 Set-back dose–response model

There is an important difference between the exposure of the double layer test specimens and the exposure, which can be expected from a service life perspective for wooden details exposed to outdoor climate: the moisture content in the majority of the Scots pine sapwood test specimens were more or less continuously above 25 % while wooden details in practice are fluctuating between values below and above 25 %. The best fit for available test data is consequently mostly governed by temperature, see Fig. 3.

The model presented in Sect. 3.2 is optimized for predicting decay under the conditions of moisture contents above 25 %. In this section the attempt is to have a more general engineering approach regarding design of wooden details exposed outdoors, i.e. details with moisture content fluctuating around 25 % with longer periods below 25 %. The Douglas fir heartwood data shows this behavior and is consequently suitable for evaluating the effect of periods with moisture content below 25 %.

As a parallel, when modeling the onset of mould on wood a very clear effect of set-back in the process has been found [30, 31]. This means that the biological process of germination of fungal spores is not only stopped but is also assumed to be "damaged" due to

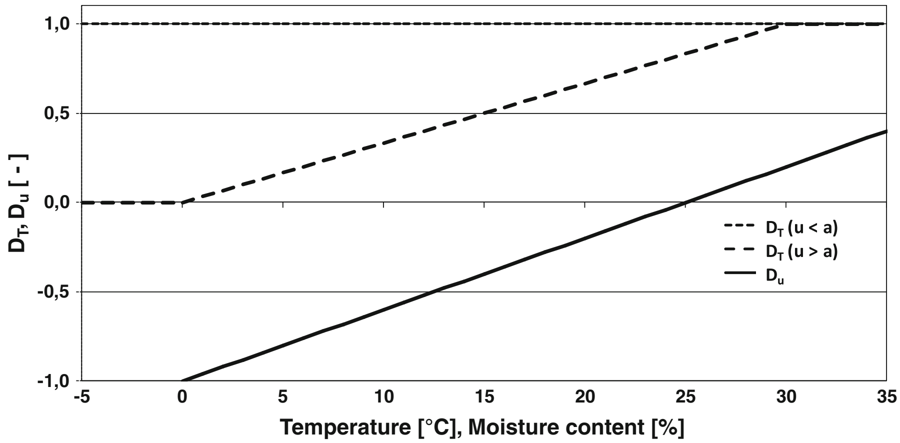


Fig. 6 The temperature (D_T) and moisture induced dose (D_u) and the modeling of set-back for moisture contents below 25 %. The set-back is shown for $e = 0$, i.e. the set-back rate for $u = 0$ is the same as the maximum growth rate

cold and dry conditions (here called set-back), which in a dose–response model can be described through a negative dose. The extent of "damage" to the biological process should be dependent on for example the duration of set-back conditions.

In the present section the daily dose D is again calculated as the product of the two dose components D_u and D_T.

$$D = D_u(u) \cdot D_T(T) \quad (11)$$

However, to enable accounting for a conceivable set-back in the decay process for lower moisture content and/or temperature conditions a set-back parameter s is introduced. The dose related to moisture content (D_u) is given by Eq. 12 where the set-back parameter s is introduced for moisture content levels below a. The effect of temperature is given by Eq. 13, which is the same as Eq. 7 apart from the conditions for $u < a$. D_T and D_u are shown in Fig. 6.

$$D_u(u) = \begin{cases} s & \text{if } u < a \\ \frac{u-a}{b-a} & \text{if } a \le u \le b \\ 1 & \text{if } u > b \end{cases} \quad (12)$$

$$D_T(T) = \begin{cases} 1 & \text{if } u < a \\ 0 & \text{if } T < c \text{ and } u \ge a \\ \frac{T}{d-c} & \text{if } c \le T \le d \text{ and } u \ge a \\ 1 & \text{if } T > d \text{ and } u \ge a \end{cases} \quad (13)$$

where u is the moisture content [%], T is the wood temperature [°C], a is the 25, lower moisture content limit [%], b is the 30, upper moisture content limit [%], c is the 0, lower wood temperature limit [%], d is the 30, upper wood temperature limit [%], s is the set back parameter.

The effect of temperature is modeled as a linear function between 0 and 30 °C. This is in line with what is normally found in studies on the effect of temperature on growth rate of decay fungi (e.g. [32]). The model uses a constant temperature effect above 30 °C while e.g. the results of Boddy [32] show a clear decrease in effect above 30 °C. For practical application ranges of the model, the daily averages of temperature are rarely above 30 °C. For a moisture content below $a = 25$ % the temperature dose equals 1 and for $T < 0$ °C coinciding with $u > 25$ % the temperature dose (and consequently the total dose) equals zero, i.e. for negative temperatures there is no set-back unless the moisture content is below 25 %.

The model uses linear variation in dose with moisture content in the interval 25–30 %, which is what is commonly stated in the literature; see e.g. Griffin and Griffin [33]. It is important to notice that the model is primarily to be used for prediction of the initiation or establishment of decay fungi and not the subsequent growth process.

The accumulation of dose can be done with or without the condition that the dose can never be negative. Allowing for negative dose is a way of having a measure of the behavior of wood in drier conditions. Obviously the dose can never be negative from a biological perspective.

For a specific material there are a critical number of dose-days until decay level 1 is reached (normally around 300–400 days). In this model a parameter D_s is introduced, which allows the set-back to take place as long as the accumulated dose is below D_s. The idea is that set-back is less effective the closer to decay level 1 you get. Decay level 1 implies that decay has started

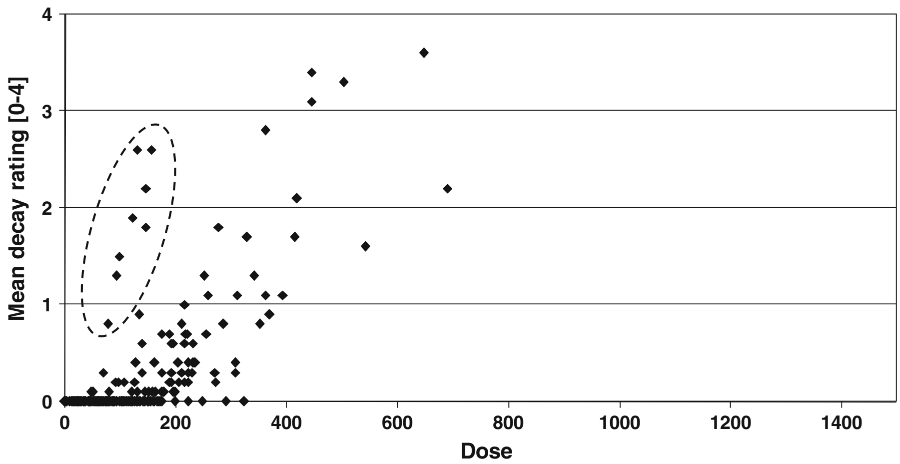


Fig. 7 The relation between dose and mean decay rating according to EN 252 [24] for Douglas fir using no set-back. The condition for accumulated dose is that it should always be above zero. The *dots* shown in the selection represent three specific sites with dominating brown rot

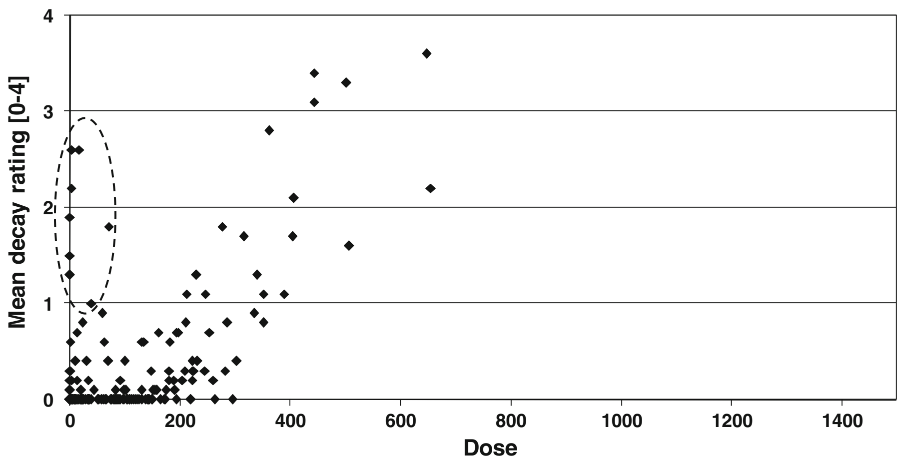


Fig. 8 The relation between dose and mean decay rating according to EN 252 [24] for Douglas fir using set back $D_s = 50$ and $e = 0$, see Eq. 14. The condition for accumulated dose is that it should always be above zero. The *dots* shown in the selection represent three specific sites with dominating brown rot

and above this level, set back is not reasonable. For lower doses ($<D_s$) when decay is in an initiation phase, set-back could be possible. D_s can be given different values to find the best fit against data. The negative set-back parameter s is modeled as linear decreasing with decreasing u according to Eq. 14.

$$s = \frac{u - a}{a - e} \tag{14}$$

s is the set back parameter, u is the moisture content [%], a is the 25, lower moisture content limit [%], e is the parameter to allow for different set back effect.

The parameter e can be varied to evaluate its influence on predicting decay data. Starting with the data from Douglas fir tests, the inclusion of set-back basically shifts the results towards zero dose, but the overall variation is not reduced, see Figs. 7 and 8. The data shown inside the dotted line in the figures represent three sites (Ljubljana, Zagreb and Garston) where several specimens had been attacked by brown rot, whereas white and soft rot were dominating at most other sites, see also Sect. 3.2. Allowing for a negative accumulated dose shifts the results further into negative doses but again the overall variation is not reduced, see Fig. 9.

For Scots pine sapwood data with very few periods with moisture contents below 25 % it is not meaningful to evaluate the set-back model. The response of the model with no set-back included is shown in Fig. 10.

Based on the figures discussed above it can be concluded that set-back cannot be verified and quantified based on the existing data. There could be various reasons for the lack of adequate response to a set-back parameter, e.g. that some important parameters are not measured and accounted for, presence or absence of antagonistic fungi, dirt content, and weathering of specimens.

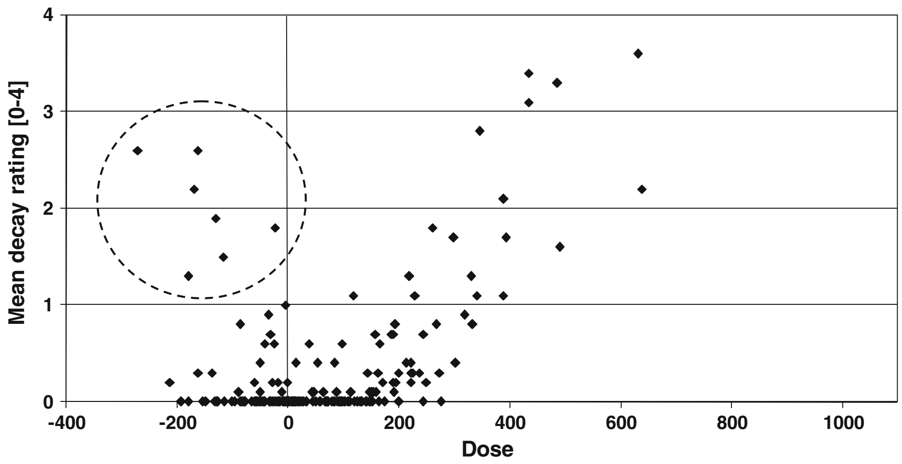


Fig. 9 The relation between dose and mean decay rating according to EN 252 [24] for Douglas fir using set back $D_s = 50$ and $e = 0$, see Eq. 14. The condition for accumulated dose is that it can be negative. The *dots* shown in the selection represent three specific sites with dominating brown rot

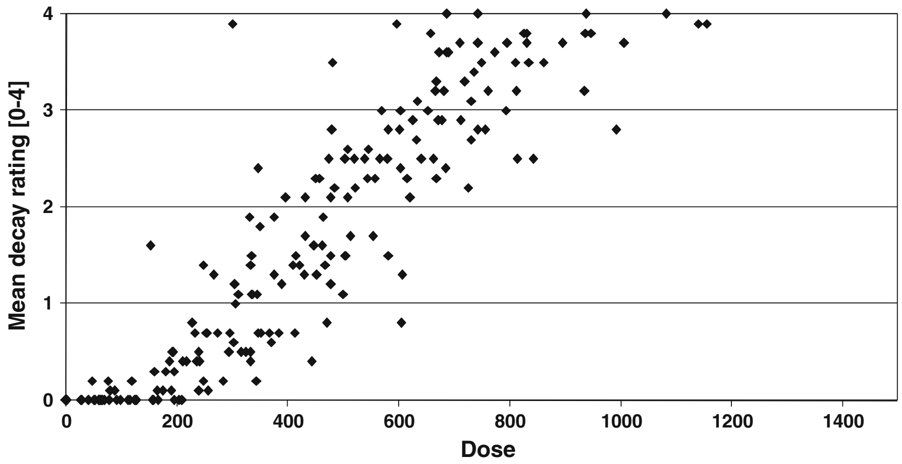


Fig. 10 The relation between dose and mean decay rating according to EN 252 [24] for Scots pine sapwood using no set back

3.5 Two-step dose–response model

Based on the results in the previous section a two-step model without any set-back is proposed.

The total daily dose D is given by

$$D = D_u(u) \cdot D_T(T) \tag{15}$$

The moisture and temperature related doses are assumed as

$$D_u(u) = \begin{cases} 0 & \text{if } u < a \\ \frac{u-a}{b-a} & \text{if } a \leq u \leq b \\ 1 & \text{if } u > b \end{cases} \tag{16}$$

$$D_T(T) = \begin{cases} 0 & \text{if } T < c \\ \frac{T}{d-c} & \text{if } c \leq T \leq d \\ 1 & \text{if } T > d \end{cases} \tag{17}$$

D is the dose (d), u is the moisture content (%), T is the wood temperature (°C), a is the 25, lower moisture content limit (%), b is the 30, upper moisture content limit (%), c is the 0, lower wood temperature limit (%), d is the 30, upper wood temperature limit (%).

Figure 11 shows the dose D as a function of temperature and moisture content. Compared to the model presented in Sect. 3.2 and Fig. 3 the effects of temperature and moisture content are more equally weighted.

Figures 7 and 10 clearly indicate that there is an initiation period, during which no decay will occur. After a critical dose is reached decay is activated. The data set is divided into one subset with zero decay rating values and one group with non-zero decay rating values.

In Fig. 12 the dose developed at the time of the last zero decay rating reading (next decay rating was above zero) is shown for both Scots pine sapwood and Douglas fir. The mean dose for last zero decay ratings

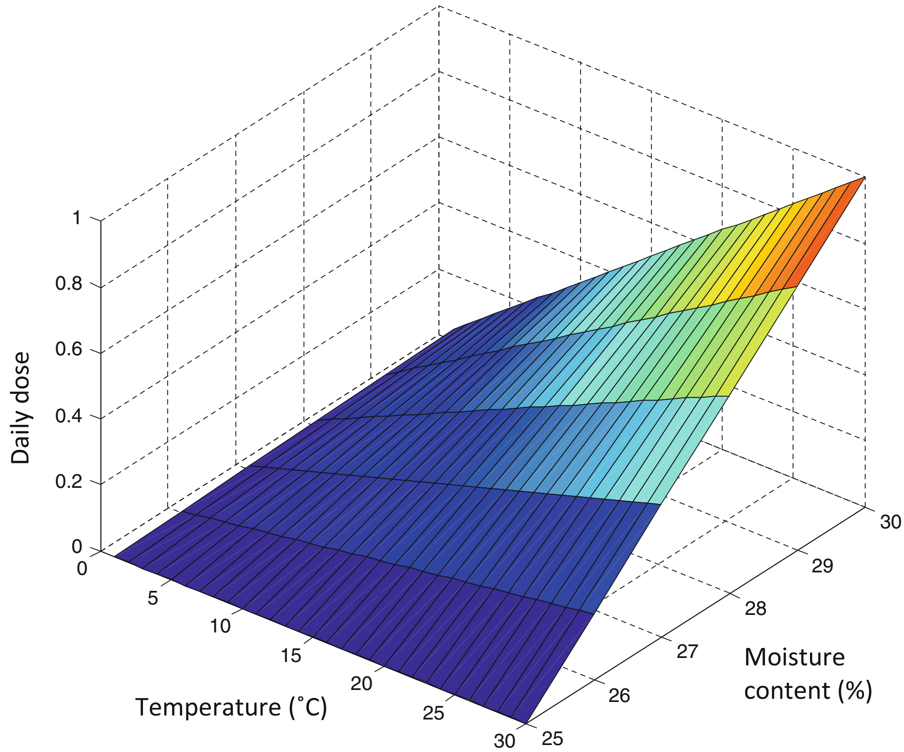


Fig. 11 Relationship between moisture content, temperature and daily dose *D*. Comparisons with Fig. 3 reveals that the effect of temperature and moisture content are more equally weighted

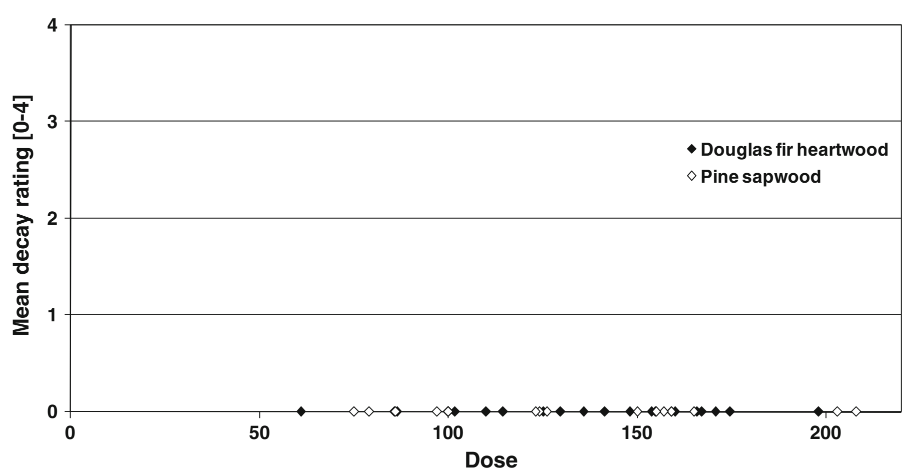


Fig. 12 Dose for data subset with zero decay rating for Douglas fir heartwood and Scots pine sapwood

is 137 and 123 for Douglas fir and Scots pine respectively and the span over which the value varies is also similar. Since decay progresses faster for Scots pine and the interval of decay rating inspection is once a year the estimate of the dose at the last zero decay rating is quite uncertain.

The non-zero decay ratings for Douglas fir and Scots pine respectively as a function of the dose are shown in Figs. 13 and 14. The regression line is forced to cross the horizontal axis at the average dose levels given by Fig. 12.

The difference between the two species regarding critical dose for initiation of decay is small and a single value of 130 is proposed. Using this value and both species in one sample the relation between dose and decay rating is given by Fig. 15.

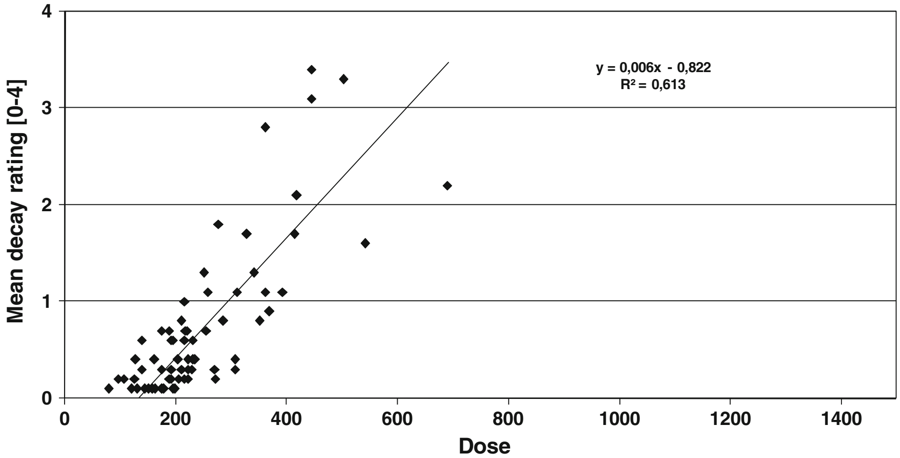


Fig. 13 Dose for data subset with non-zero decay ratings for Douglas fir

Fig. 14 Dose for data subset with non-zero decay ratings for Scots pine sapwood

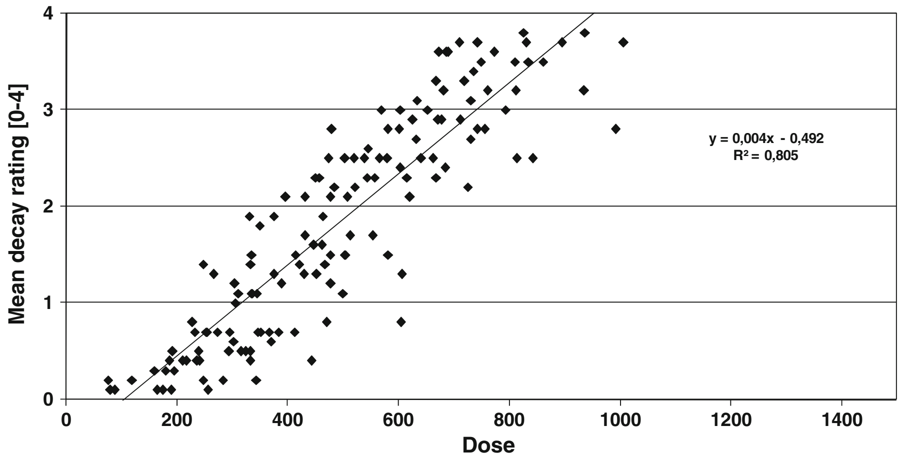
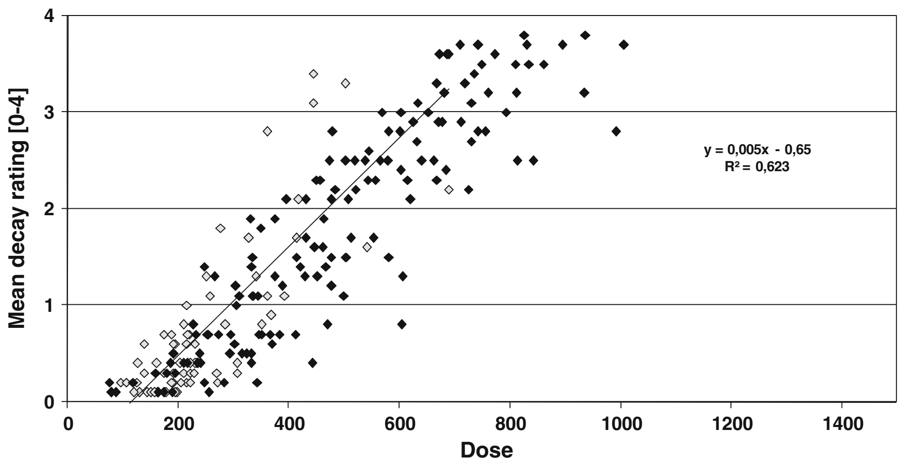


Fig. 15 Dose for non-zero decay rating for Scots pine sapwood (*black*) and Douglas fir heartwood (*grey*)



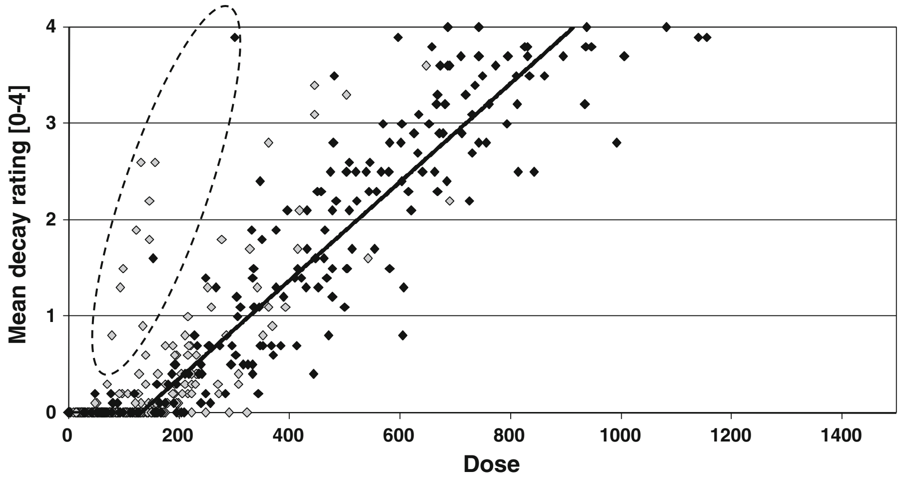


Fig. 16 Relationship between dose and mean decay rating according to EN 252 [24] of Scots pine sapwood (*black*) and Douglas fir heartwood (*grey*) exposed at 28 different field test sites using a two-step dose–response model (each *dot* represents the mean decay rating at one exposure site at a certain time of exposure; *black line* linear two step smoothing function)

The two-step dose-decay rating model can then be written as follows (Eq. 18) and is illustrated for both wood species in Fig. 16. In this figure the values for the two sites with dominating brown rot are included, see also Sect. 3.4.

$$DR(D(n)) = \begin{cases} 0 & if\ D \leq 130 \\ 0.0051 \cdot D - 0.66 & if\ D > 130 \end{cases} \tag{18}$$

where DR is the decay rating according to EN 252 [24], $D(n)$ is the total dose for n days of exposure.

Remarkably, it was possible to calculate a single value (= 130) to describe the critical dose for initiation of decay for both wood species, even more for sapwood and heartwood of the two species. This material-independence of the critical dose might be explained by the negligibly small impact of the biocidal ingredients of Scots pine and Douglas fir, which may also be valid for many other wood species. The moisture performance of the material turned out to be the decisive parameter and thus differences between species become apparent when comparing their dose over time as shown by Brischke and Rapp [25]. A single value of 130 does not mean that decay starts at the same time for the two materials. The moisture characteristics of the materials mean that it will take different lengths of time to reach a dose of 130.

Consequently, a two-step linear model with an initiation period followed by a growth period proved to be good approach for predicting decay rating as a function of a climate related dose. The two-step model is similar to concepts used for other engineering service life applications, i.e. the advantage of recognition.

3.6 Peculiarities of the modeling approach

A pioneer approach to establish a relationship between climate data and the corresponding decay hazard has been carried out by Scheffer [34], who developed a climate index for estimating the potential for decay in wood structures above ground. Originally the index was developed to estimate the decay potential of sites in the continental part of the United States, later on it had also been applied to other parts of the world, e.g. Canada [35], China [22], Japan [36], and Australia [37]. The dose–response performance models in this study should therefore be compared with Scheffer's Climate Index (SCI), which is known to be the most established index of its kind.

$$\mathrm{SCI} = \frac{\sum_{\mathrm{Jan}}^{\mathrm{Dec}} [(T-2)(D-3)]}{16.7} \tag{19}$$

where T is the mean monthly temperature (°C), D is the mean number of days in the month with 0.25 mm or more precipitation.

As reported by Brischke et al. [38] and Frühwald Hansson et al. [39] the Scheffer Climate Index and the dose–response models presented in this study lead to similar estimates of the potential for decay when applied to the European continent with highest decay hazard on the West coast of Norway, Ireland, United Kingdom, and France. However, since the Scheffer Climate Index is based on mesoclimatic data (weather data) only, it can neither be used to characterize microclimatic peculiarities nor material and design aspects.

In contrast, the empirical performance model developed by Viitanen et al. [40] is based on a dose–response approach and considers also climatic parameters.

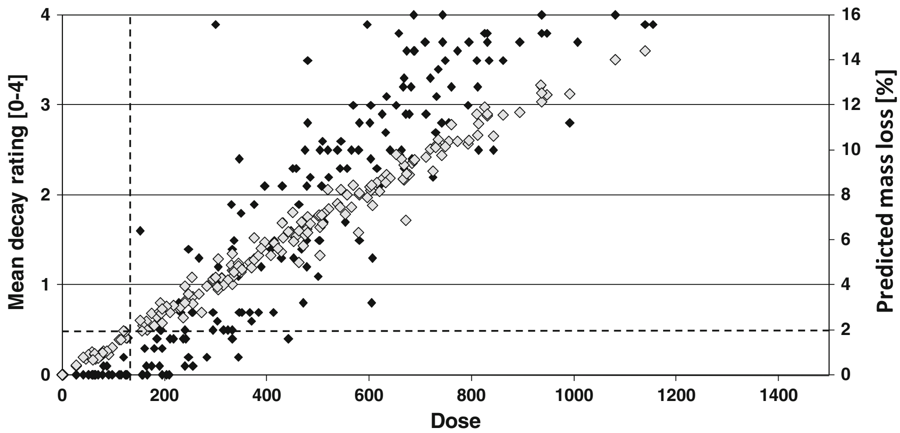


Fig. 17 The relation between dose, mean decay rating according to EN 252 [24] for Scots pine sapwood using no set back (black dots), and predicted mass loss by *Coniophora puteana* (grey dots) according to Viitanen et al. [16]

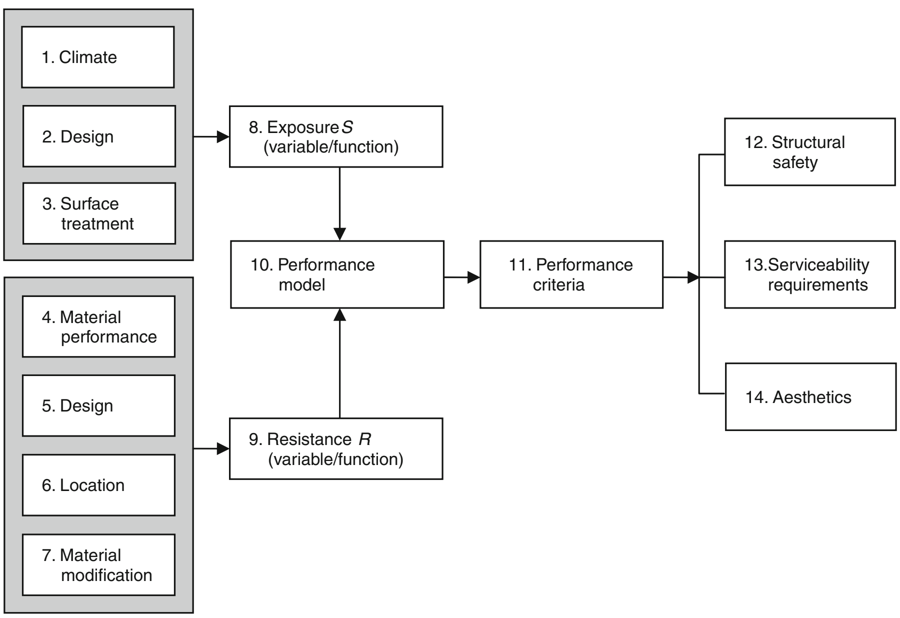


Fig. 18 Principle for performance-based service life design

Major differences to the models presented in this study are:

- The dose is considered to be the combined effect of relative humidity (RH) and air temperature
- The response in terms of decay development is expressed as mass loss of Scots pine sapwood
- Experimental data were taken from laboratory decay tests with Scots pine sapwood and Norway spruce exposed to the brown rot fungus *Coniophora puteana*.
- Activation process and mass loss process are modelled separately (set back allowed)
- Rain events are considered to be equal to days with ≥100 % RH (i.e. moisture contents above fibre saturation are not considered particularly).

A comparison has been made between the dose–response model using no set back (cf. Fig. 10) and the model by Viitanen et al. [40] as shown in Fig. 17. Therefore the mass loss caused by the brown rot fungus *C. puteana* has been predicted for identic time intervals and related to the respective dose. It became evident that the mass loss is linearly correlated with the dose. The initial lag phase before decay starts is not considered, but can easily be determined as shown in Fig. 17. Considering a dose of 130 as starting point of the decay process coincides with 2 % mass loss by *C. puteana*, which is a reasonable threshold value for incipient decay. However, it is obvious that the ideal conditions used for the model by Viitanen et al. [40] do not reflect the various disturbance variables to be considered during field outdoor exposure. Furthermore, in this case a mean decay rating 4 (= failure) is set equal to 16 % mass loss, which might be seen as too pessimistic. If one would consider a higher mass loss as failure the model would be even more conservative. The almost permanent wetting of the specimens is not considered by the model and most likely the reason for underestimating the decay process in Scots pine sapwood double layers. It seems indispensable to allow moisture contents above fibre saturation to adequately consider rain events, water trapping and consequently permanent wetting of wood, as it has obviously the most significant effect on fungal decay.

3.7 Implementation of performance model into engineering guideline

The basic principles of a performance model is to separate the exposure and resistance (Fig. 18). In this paper the focus is on finding a performance model, which connects the exposure and material resistance. The performance criteria is defined by a limit state, in this case representing onset or initiation of decay. This approach has the advantage that the exposure can be expressed as a function of global and local climate, component design and surface treatment in a general way independent of the exposed material [1, 26, 41]. The material resistance is in the same way expressed in terms of response to quantified and standardized conditions independent of the design situation. Based on this model an engineering design guideline can be developed with application on wood in outdoor above ground applications.

4 Conclusions

Different dose–response models are proposed and evaluated for predicting onset (and progress) of decay when wood is exposed to a dynamic and arbitrary climate exposure described in terms of time series of coupled temperature and moisture content. The logistic dose–response model is primarily focused on describing the relation between exposure and decay rating for situations similar to the double-layer test arrangement, i.e. moisture traps with long periods of high moisture contents. The two-step linear engineering model is more focused on predicting the behavior in a wider, more simplified, sense where periods of high moisture content is interrupted by periods of drier and/or colder climate. The model is believed to be more efficient in building design applications. The models are quantified on the basis of comprehensive double-layer test results for Scots pine sapwood and Douglas fir heartwood.

Biologically it seems reasonable that the process of initiation of decay should be affected by dry and cold conditions such that it is not only a matter of having a stop in the initiation of decay process, but also some “damage” to it. The amount of damage is dependent on for example the duration of such conditions. None of the models mentioned above accounts for a conceivable set back in the decay process for lower moisture content and/or temperature conditions. However, several ideas of modeling set-back were evaluated but the models did not improve the accuracy when tested against available field test data. Possibly because there are parameters and properties in the tests that are not documented or monitored. For now, we have to base our models on existing data which means that some properties are accounted for indirectly in the model, i.e. there are elements of “black-box” behavior.

In its present form, the two-step model is less suitable to predict absolute values of decay rating. But, for relative comparisons of different design situations it can be used as a ranking tool. The two-step linear model should be verified by reality checks in order to improve the prediction of decay rating or risk for decay. Also, to make an engineering design tool useful, a model of the exposure side needs to be developed, i.e. the material climate as a function of weather station data.

The following main conclusions can be drawn from the present study:

- The logistic model is the best model for fitting of the behavior of double-layer test and other applications with severe climate exposure.

- The prediction models can in general be quantified on the basis of double-layer tests.

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6.7 Publication VII: Modelling timber decay caused by brown rot fungi

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ORIGINAL ARTICLE

Modelling timber decay caused by brown rot fungi

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Abstract Decay models are key elements for service life prediction and performance classification of wooden products and timber structures. Available models differ in terms of data sources used and prevailing decay types considered. Comparative studies on performance models are therefore rare. In this study we applied data sets from field tests dominated by brown rot decay to a model developed on the basis of white and soft rot decay. Differences in time till colonization, onset of decay and subsequent decay progress between the rot types were found. Brown rot decay turned out to be initiated earlier and proceed faster compared to white and soft rot decay. Microclimate was influenced by shading within this study, whereby the moisture and temperature induced dose was affected as well as the progress of brown rot decay itself. Consequently, for obtaining a more conservative decay model only data sets dominated by brown rot and unaffected by shading were used. The brown model shortened the expected lifetime by 50 % compared to the previous white and soft rot model for a given dosage.

Keywords Above ground exposure · Durability · Service life prediction · Shading · Soft rot · White rot

1 Introduction

Wooden structures exposed to the outdoor environment are subject to a variety of biotic and abiotic agents, which can lead to degradation and deterioration. Mathematical models describing the relationship between different decay influencing factors and the resulting persistence are key elements for service life prediction of timber structures and performance classification of wooden products [8]. Various approaches exist to estimate the expected service life of wooden components or structures under the influence of their environment including the different decay organisms and site-specific climate loads. Besides engineering models and related tools (e.g. [20, 33]), several dosimeter models (e.g. [17, 31, 38]) were found to be applicable for service life planning and could serve as reliable tools to quantify the effect of different construction details [18].

Moisture and temperature are important parameters affecting the physiology of most decay organisms and therefore are important input variables for almost any decay model. Moisture is reflected for modelling either by indirect macroclimatic parameters such as rainfall [32], relative air humidity which is in

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equilibrium with the respective substrate [31, 35–37] or directly as wood moisture content ([2, 17]). Studies comparing different modelling approaches are rare, but the few existing showed that partly immanent differences in predicted service life or at least in the estimated decay risk (hazard) can be obtained for identically designed and located wooden components ([14, 17, 25]). The potential reasons for such differences are manifold. Some consider a defined number of potential impact factors [32, 38], some tend to be more comprehensive (e.g. [18, 21]), some are based on a variety of different data sources (e.g. [20]), some are focusing on field test data [2], and some use solely laboratory test data [38]. However, besides all potential impact factors more or less adequately considered by a model, high uncertainty derives from the fact that it is almost unpredictable, which organism will attack the component in question first and successfully. In particular for wood exposed above ground, a huge variety of potential decay fungi comes into consideration representing three different major decay types, i.e. brown, white and soft rot. In addition, wood-destroying beetles, in many regions also termites can attack the wood. Those various organisms come along with different physiological demands for instance climate related factors such as moisture and temperature. Furthermore, different decay types follow specific patterns with respect to onset and rate of biodegradation. Compared to white and soft rot, brown rot fungi are frequently considered to provoke faster and more severe decay and demand less moisture of the wood substrate to be degraded (e.g. [1]). However, others studies revealed the opposite and found white rot fungi having lower moisture minima for wood degradation compared to brown rot causing basidiomycetes (e.g. [15, 22, 23]). Previously a dosimeter model was developed [6] and found to reflect white and soft rot decay of wood exposed above ground fairly well. However, data sets from brown rot dominated tests turned out to be outliers and were seemingly following deviating growth and degradation patterns. Similarly, differences were found for decay hazard maps based on the white and soft rot model by Brischke and Rapp [6] on the one hand and a brown rot model by Viitanen et al. [38] on the other hand. The latter was derived from laboratory tests with the brown rot fungus *Coniophora puteana* considering different combinations of air temperature and relative humidity.

This study aimed therefore on modelling brown rot decay based on field data from above ground double layer tests performed at different sites in Europe. The above mentioned white and soft rot model by Brischke and Rapp [6] was used, its transferability to brown rot decay was examined and necessary amendments were conducted.

2 Material and methods

2.1 Field test data

Field test specimens cut from Scots pine sapwood (*Pinus sylvestris* L.), Douglas fir sap and heartwood (*Pseudotsuga menziesii* Franco), European larch sap and heartwood (*Larix decidua* Mill.), and Norway spruce (*Picea abies* Karst.) were monitored in terms of moisture content, wood temperature, and the progress of fungal decay up to a period of eight years. The specimens ($500 \times 50 \times 25$ mm^3), according to EN 252 [11], were exposed horizontally in double layer test rigs [30]. The upper layer was displaced laterally by 25 mm with respect to the lower layer. The specimens were supported at the cut ends by aluminum L-profiles or beams of CCB-impregnated pine sapwood, separated with bitumen foil from the preservative-treated supports. The whole test set-up formed a closed deck. To avoid the growth of grass it was placed on paved ground, horticultural foil, or open meshed ground.

The test rigs were exposed at different locations in Europe as shown in Table 1. At some sites the test rigs were artificially shaded. “Shade sets” were put in plywood boxes ($30 \times 90 \times 90$ cm^3) covered with fully water-permeable textile sheets, which were transmitting only 10 % of the incident sunlight.

2.2 Decay assessment

The specimens were evaluated annually by rating the extent and distribution of decay according to EN 252 [11] as: 0 (sound), 1 (slight attack), 2 (moderate attack), 3 (severe attack), or 4 (failure). Therefore a pick test was performed where a pointed knife is pricked into the specimen and backed out again. The fracture characteristics of the splinters were assessed visually to identify the different decay types. The prevailing type of decay was furthermore identified

Table 1 Data sets from field durability tests used for modeling brown rot decay development

Wood species	Test method	Test site	Start	End
Scots pine sapwood	Double layer, shaded	Freiburg (DE)	07/2000	08/2007
	Double layer	Ljubljana (SI)	04/2001	06/2004
	Double layer	Bordeaux (FR)	07/2002	09/2007
	Double layer	Zagreb (HR)	08/2002	06/2007
	Double layer	Hannover (DE)	11/2009	08/2014
Douglas fir sapwood	Double layer	Hannover (DE)	08/2010	08/2014
Douglas fir heartwood	Double layer, shaded	Freiburg (DE)	07/2000	09/2007
	Double layer, shaded	Hamburg (DE)	07/2000	04/2007
	Double layer	Hamburg (DE)	07/2000	06/2008
	Double layer, shaded	Stuttgart (DE)	07/2000	08/2006
	Double layer	Ljubljana (SI)	04/2001	11/2008
	Double layer	Garston (UK)	07/2002	09/2008
Larch sapwood	Double layer	Hannover (DE)	11/2009	08/2014
Larch heartwood	Double layer	Hannover (DE)	11/2009	08/2014
Norway spruce	Double layer	Hannover (DE)	11/2009	08/2014

according to CEN/TS 15083-2 [13] and only specimen sets dominated by brown rot decay were considered for further modelling in this study.

2.3 Moisture and temperature recording

The moisture content of three replicate samples in the bottom layer of each test set was recorded once a day. The measurement system applied in this study was previously described by Brischke et al. [7] and can be summarized in brief as follows: electrodes of polyamide coated stainless steel cables were conductively glued in the specimens. The electrodes were connected to a small data logger (Materialfox Mini, Scanntronik Mugrauer GmbH, Zorneding, Germany), that recorded the electrical resistance of the wood. The data loggers were calibrated in a range between 12 and 50 % moisture content [4, 7]. Measurements above fiber saturation were increasingly inaccurate, but still indicated a tendency within the calibration range. Minimum and maximum temperature below the bottom layer of each test set or in a bore hole inside the wood specimens were recorded daily using Thermofox Mini data logger (Scanntronik Mugrauer GmbH, Zorneding, Germany) and used to calculate the average daily temperature.

2.4 Logistic dose–response performance model (LDR)

The data sets obtained were applied to a performance model describing the relationship between the material climate in terms of wood moisture content and temperature and the corresponding fungal decay. The experimental base for the model have been field results from double layer above ground tests performed with Scots pine sapwood and Douglas fir heartwood at 28 different sites in Europe as described by Brischke [2]. At the majority of test sites wood decay was dominated by soft and white rot.

The impact of a general time variation of moisture content u and temperature T on the potential for decay can be described by a dose–response function (e.g. [6]). The total daily dose D is a function of one component D_u dependent on daily average of moisture content u and one component D_T dependent on daily average temperature T (Eq. 1).

$$D = f(D_T(T), D_u(u)). \tag{1}$$

For n days of exposure the total dose is given by Eq. 2.

$$D(n) = \sum_{1}^{n} D_i = \sum_{1}^{n} (f(D_T(T_i), D_u(u_i))), \tag{2}$$

where T_i is the average temperature and u_i is the average moisture content for day i. Decay is initiated when the accumulated dose reaches a critical dose.

As described in detail by Brischke [2] the cardinal points of the parameters wood temperature and moisture content for fungal growth and decay activity were sought and used to set up polynomial base functions for both dose components (Eqs. 3 and 4). The total dose D is then calculated as a function of D_u and D_T according to Eq. 5, where D_T was weighted by a factor a.

function given by Eq. 6 as previously proposed by Isaksson et al. [17].

$$\mathrm{DR}(D(n)) = 4 \cdot \exp(-\exp(1.7716 - (0.0032 \cdot D(n)))), \quad (6)$$

where DR is the decay rating according to EN 252 [11], $D(n)$ is the total dose for n days of exposure.

The good fit of the dose response function—as indicated through a degree of determination $R^2 = 0.901$—is illustrated for Scots pine sapwood

$$D_u(u) = \begin{cases} 0 & \text{if} \quad u < 25\,\% \\ e \cdot u^5 - f \cdot u^4 + g \cdot u^3 - h \cdot u^2 + i \cdot u - j & \text{if} \quad u \geq 25\,\% \end{cases} \quad (3)$$

$$D_T(T) = \begin{cases} 0 & \text{if} \quad T_{\min} < 0\,^\circ\mathrm{C} \quad \text{or} \quad \text{if}\ T_{\max} > 40\,^\circ\mathrm{C} \\ k \cdot T^4 + l \cdot T^3 - m \cdot T^2 + q \cdot T & \text{if} \quad T_{\min} < 0\,^\circ\mathrm{C} \quad \text{or} \quad \text{if}\ T_{\max} < 40\,^\circ\mathrm{C} \end{cases} \quad (4)$$

$$D = (a \cdot D_T[T] + D_u[u]) \cdot (a+1)^{-1} \quad \text{if} \quad D_u > 0 \quad \text{and} \quad D_T > 0, \quad (5)$$

where D is the dose (d), D_T is the temperature induced dose component (−), D_u is the moisture induced dose component (d), u is the daily average moisture content (%), T daily average wood temperature (°C), $T_{\min}$ is the minimum wood temperature for the day considered (°C), $T_{\max}$ is the maximum wood temperature for the day considered (°C), a is the temperature weighting factor, $e, f, g, h, i, j, k, l, m, q$ is the variables.

The best fit for this model against the available data [6] was obtained with the following parameters and the final logistic model function according to Eq. 6.

$a = 3.2$	$j = 4.96$
$e = 6.75 \times 10^{-10}$	$k = 1.8 \times 10^{-6}$
$f = 3.50 \times 10^{-7}$	$l = 9.57 \times 10^{-5}$
$g = 7.18 \times 10^{-7}$	$m = 1.55 \times 10^{-3}$
$h = 7.22 \times 10^{-3}$	$q = 4.17$
$i = 0.34$	

The total dose over a certain time period is given by Eq. 2 and the decay rating is given by a dose–response

and Douglas fir heartwood in Fig. 1. However, there were different outliers, where decay developed faster than predicted by the accumulated dose. This happened in particular at the South-Eastern sites Ljubljana and Zagreb, where several specimens had been attacked by brown rot, whereas white and soft rot were dominating at most other sites [6].

3 Results and discussion

3.1 Decay progress

Time till onset of decay as well as subsequent progress of wood degradation was different between wood species and the climatically different test sites (Table 2). This is not surprising due to the differences in durability between the various sapwoods (durability class DC 5, EN 350 [12]) and Norway spruce (DC 4) on the one hand and European larch and Douglas fir heartwood (both DC 3–4) on the other hand. Secondly, the test sites considered within this study varied in terms of humidity and temperature as previously

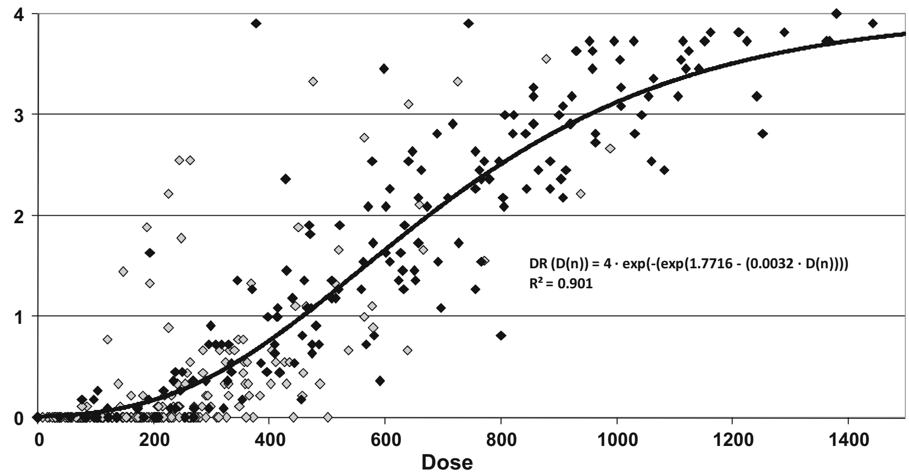

Fig. 1 Relationship between dose and mean decay rating according to EN 252 [11] of Scots pine sapwood (*black*) and Douglas fir heartwood (*grey*) exposed at 28 different field test sites using a logistic dose–response model (*each dot* represents the mean decay rating at one exposure site at a certain time of exposure)

reported by Brischke and Rapp [6]. Therefore the conditions for fungal growth and degradation tend to be more favorable at warm and humid sites such as Ljubljana compared to more moderate climates in Hannover or Hamburg. However, again this relationship was dependent on the wood species and became more prominent for Scots pine sapwood compared to Douglas fir heartwood. Moreover, European larch sapwood decayed extremely fast (median service life of 3.0 years) in Hannover, one of the driest test locations. In summary, no clear relationship between the climate parameters considered and the resulting brown rot decay became apparent.

A comparison of the decay progress of brown rot dominated specimen sets with white and soft rot dominated sets reported previously by Brischke and Rapp [6] showed that brown rot decay proceeded generally faster compared to white and soft rot dominated decay (Fig. 2). This became apparent for both, softwood species with colored heartwood (i.e. European larch and Douglas fir) and sapwood as well as non-colored heartwood of larch, Douglas fir, Scots pine, and Norway spruce respectively. The comparatively faster decay progress of brown rot coincides with previous findings by Edlund [10] and Augusta [1]. However, the effect of site-specific climate variations led to clear overlapping between the two groups of decay types (see Fig. 2).

Independent from the wood species the data sets containing daily wood moisture content and temperature as well as the corresponding annual decay ratings were submitted to the logistic dose–response model described in Sect. 2.4.

3.2 Modelling brown rot decay

The daily dose was accumulated and correlated with the corresponding decay ratings for the different exposure intervals and test sites. The sigmoid course of the dose–response relationship was fitted with a Gompertz-function (Fig. 3). The moisture content and temperature induced dose was clearly correlated with fungal decay as response ($R^2 = 0.8070$), but the model still suffered from scattering. In particular, the Norway spruce specimens exposed in Hannover (black circles in Fig. 3) showed surprisingly high decay ratings, but only little dosage. Apart from that, as expected, no clear wood species-specific deviations became apparent, which supports the assumption of Isaksson et al. [17] that a moisture and temperature induced dose can be calculated independent from the wood substrate, since the moisture dynamics of the latter are considered through the model itself. Wood containing biocidal or inhibiting ingredients, such as those found in more durable hardwoods or preservative treated wood, might be considered separately, for instance by applying a ‘resistance factor’ to the model [3, 18]. However, for the data sets applied to the model no clear effect of the wood species was found, wherefore potential effects of the different test set ups were analysed next.

The major difference in the test set up was the application of shading boxes, which led to an omission of extreme conditions, such as very low or very high temperatures, dampened amplitude of wood temperature and eventually promoted fungal decay activity [5]. Therefore in Fig. 4 both exposures, with and

Table 2 Mean time lag before onset of decay, mean decay rate, and median service life of the different materials, as well as climate parameters of the different exposure sites

Wood species	Test site	Mean time till onset of decay (a)	Mean decay rate (rating/a)	Median service life (a)	Average air temperature (°C)	Sum of precipitation (mm)
Scots pine sapwood	Freiburg shade (DE)	1.9	0.55	7.1	12.1[a]	911[a]
	Ljubljana (SI)	2.3	0.94	3.2	11.3[a]	1330[a]
	Bordeaux (FR)	4.6	0.52	6.7	14.0[c]	798[c]
	Zagreb (HR)	2.6	0.97	3.9	10.7[d]	910[d]
	Hannover (DE)	2.5	0.82	4.1	10.6[f]	643[f]
Douglas fir sapwood	Hannover (DE)	>4.3	0.21	>4.8	10.6[f]	643[f]
Douglas fir heartwood	Freiburg shade (DE)	4.8	0.49	8.1	12.1[a]	911[a]
	Hamburg (DE)	5.2	0.53	8.0	10.6[a]	874[a]
	Hamburg shade (DE)	5.7	0.27	> 8.0	10.6[a]	874[a]
	Stuttgart shade (DE)	5.2	0.56	6.1	9.9[b]	741[b]
	Ljubljana (SI)	>4.4	0.39	> 6.4	11.3[a]	1330[a]
	Garston (UK)	>5.2	0.42	>6.1	10.7[e]	515[e]
Larch sapwood	Hannover (DE)	2.0	1.39	3.0	10.6[f]	643[f]
Larch heartwood	Hannover (DE)	4.3	0.10	>4.8	10.6[f]	643[f]
Norway spruce	Hannover (DE)	>3.6	0.42	>4.8	10.6[f]	643[f]

[a] Average of 2000–2005

[b] Average of 2001–2005

[c] Average of 2000–2006

[d] Average of 2000–2004

[e] Average of July 2002–June 2006

[f] Average of 2010–2014

without shading, are displayed separately. Evidently, the majority of data from shaded test sets was below, and from non-shaded sets was above the common fitting curve. Consequently, with the same accumulated moisture and temperature induced dose the same material suffered from less severe decay when it was exposed to shade. This finding stands to some extent in contrast to earlier findings from Brischke and Rapp [5], who found accelerated decay of Scots pine sapwood in shaded double layer set ups, but agrees with findings from Clausen and Lindner [9], who found decreased decay progress in shaded lap-joints but lower moisture contents compared with unshaded ones. Similarly, Ibach et al. [16] found higher decay progress in terms of mass loss of wood polymer composites samples exposed to sun compared to those exposed to shade, which were affected by brown rot and showed superficial growth of algae. Meyer et al. [24] also used a water permeable textile for shade boxes, but found reduced moisture content in shaded sandwich tests with 30 days above $u = 25$ % compared with 39 days in unshaded sandwich tests for a period of 8 weeks.

Besides the fact that the textile or tarp used to generate artificial shading may influence the effect of wetting and re-drying itself, the results obtained in this study suggest a strong effect of the rot type that has established in the respective set up. Brischke and Rapp [5] reported on accelerated decay under shade conditions, whereby the effect became almost exclusively visible for those specimen sets that were predominantly attacked by soft and white rot fungi. In contrast, the data presented in Fig. 4 are exclusively from specimen sets decayed by brown rot fungi. Obviously, exposure to shade led to both, a dose lag between exposure and initiation of decay and a slower progress of the brown rot degradation itself. However, in terms of time there was no lag phase observable for both shaded and non-shaded specimens as shown in

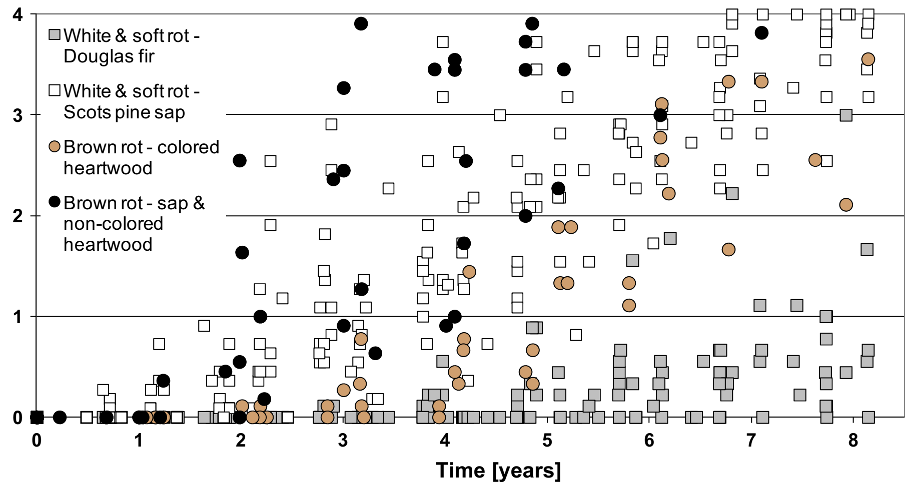

Fig. 2 Relationship between exposure time and mean decay rating according to EN 252 [11] of different softwood species dominated either by *brown rot* or *combined white* and *soft rot* decay exposed at different field test sites (*each dot* represents the mean decay rating of all exposed test specimens at one exposure site at a certain time of exposure). Data for white and soft rot dominated sites taken from Brischke and Rapp [6]. (Color figure online)

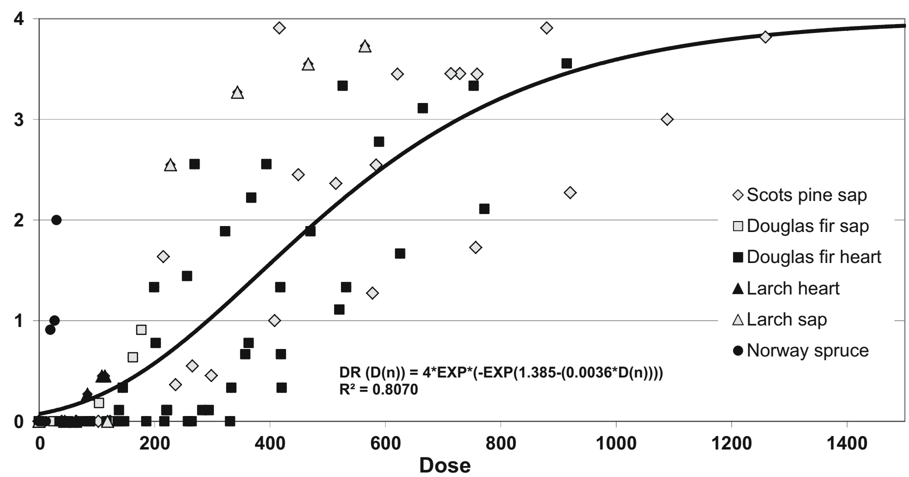

Fig. 3 Relationship between dose and mean decay rating according to EN 252 [11] of different softwood species dominated by *brown rot* decay exposed at different field test sites using a logistic dose–response model (*each dot* represents the mean decay rating at one exposure site at a certain time of exposure)

Fig. 5. Potential reasons for this delay might be the superficial growth of algae and other non-decaying organisms on the specimens as shown in Fig. 6. As already pointed out by Brischke and Rapp [5] a variety of effects come into consideration for the inhibition of fungal growth, e.g. competition and antagonism of fungi, inhibitory extractives, adverse moisture conditions, or UV light. As shown by Råberg et al. [28] a wide range of ascomycete and basidiomycete fungi can be found on Scots pine sapwood exposed in double layer set ups, whereby different types of succession do occur. However, the factors triggering the colonization and establishment of particular fungal species are still far from being fully understood, even though research on this topic was recently intensified (e.g. [19, 26, 27, 29, 34]).

Consequently, the most decisive process for service life prediction of wooden structures is the establishment of fungi representing a certain decay type. This may happen from very incipient stages of decay or in the frame of a succession, but remains an almost unpredictable mechanism. Hence, from an engineering view point the worst

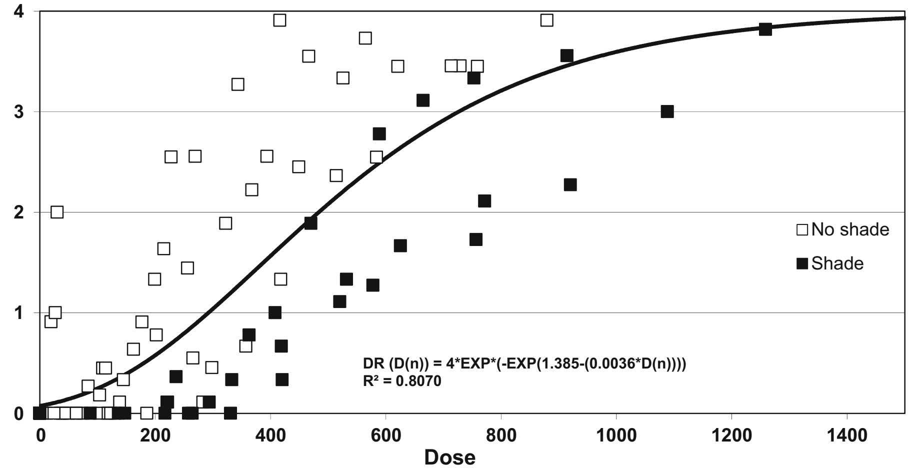

Fig. 4 Relationship between dose and mean decay rating according to EN 252 [11] of different softwood species dominated by *brown rot* decay exposed shaded or non-shaded at different field test sites using a logistic dose–response model (*each dot* represents the mean decay rating at one exposure site at a certain time of exposure)

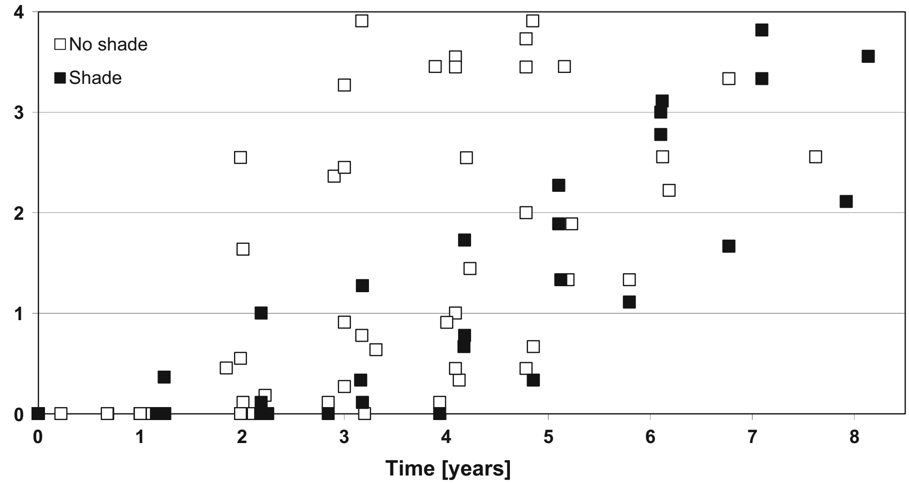

Fig. 5 Relationship between exposure time and mean decay rating according to EN 252 [11] of different softwood species dominated by *brown rot* decay exposed shaded or non-shaded at different field test sites (*each dot* represents the mean decay rating at one exposure site at a certain time of exposure)

Fig. 6 Double layer test set ups after 6 years exposure in Hamburg, Germany, in artificial shade (*left*) and exposed to the sun (*right*). Algae are growing on the upper surface of the shaded Douglas fir heartwood and Scots pine sapwood specimens

case scenario needs to be regarded, which turned out to be the occurrence of brown rot decay under open field conditions in this study.

Therefore, in the preferred model the total dose over a certain time period is given by Eq. 2 and the decay rating of brown rot dominated specimens is

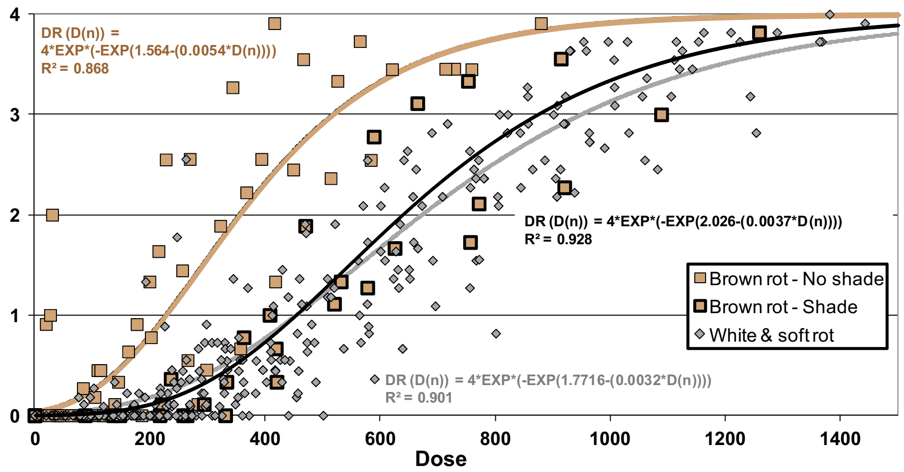

Fig. 7 Relationship between dose and mean decay rating according to EN 252 [11] of different softwood species dominated either by *brown rot* decay and exposed *shaded* or *non-shaded* or dominated by *white* and *soft rot* decay at different field test sites using a logistic dose–response model (*each dot* represents the mean decay rating at one exposure site at a certain time of exposure). (Color figure online)

given by a logistic dose–response function through Eq. 7.

$$\mathrm{DR}(D(n)) = 4 \cdot \exp(-\exp(1.564 - (0.0054 \cdot D(n)))), \quad (7)$$

where DR is the decay rating according to EN 252 [11], $D(n)$ is the total dose for n days of exposure

The logistic brown rot model obtained is clearly more conservative compared to the white and soft rot model presented by Brischke and Rapp [6]. It shows a similarly good fit of the dose response function - as indicated through a degree of determination $R^2 = 0.8681$. Data sets obtained from shaded set ups were intentionally excluded; they are more or less reflected by the model describing white and soft rot as illustrated in Fig. 7. At this stage it was possible to model both decay types using the same dose base functions described through Eqs. 3, 4, and 5 as well as the variables a and e - q.

4 Conclusions

From an engineering viewpoint the most critical hazard needs to be considered for design and service life planning of timber structures. Hence, differences in time till colonization, onset of decay and subsequent decay progress between various fungi or corresponding rot types need to be analyzed separately. Brown rot decay turned out to be initiated earlier and proceeded faster compared to white and soft rot decay at a given dose, even though they do not necessarily demand less moisture and temperature.

The microclimate was influenced by shading within this study, whereby the moisture and temperature induced dose was affected as well as the progress of brown rot decay itself, e.g. through biofilms on the specimen surfaces. Consequently, for obtaining a more conservative decay model only data sets dominated by brown rot and unaffected by shading were used. The brown model shortened the expected lifetime by 50 % compared to the previous white and soft rot model for a given dosage. Accordingly, establishment of a certain decay type on a wooden component can influence its service life by up to factor 2.

Future modeling needs to consider the effect of both, material inherent resistance of wood due to toxic or inhibiting ingredients as well as the wood species specific moisture dynamics. Therefore further studies are in progress that will consider all three decay types occurring on field test specimens made from different groups of wood based materials, untreated less and more durable hardwoods and softwoods, modified as well as preservative treated wood.

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The potential of moisture content measurements for testing the durability of timber products

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Abstract Traditionally, the durability of timber is determined in laboratory decay tests or ground contact field tests. Since it is commonly accepted that results from those tests are not directly transferable to less severe above-ground exposures, this study aimed at assessing alternative durability measures related to the moisture performance of wood. Results from above-ground tests including continuous wood moisture monitoring were analyzed. Decay ratings determined in double-layer field tests were compared with time of wetness, and temperature- and moisture-induced dose according to a dose–response model for above-ground decay. Significant differences between European wood species were found in façade, decking, sandwich, lap-joint, and double-layer tests with respect to their moisture performance. It is concluded that for many wood-based products intended for above-ground use, a combination of short-term laboratory decay tests and mid-term moisture performance field tests may serve as time-saving alternative to long-term decay tests in the field.

Introduction

The group of wood degrading organisms comprises termites, wood-boring beetles, marine borers, and various wood-destroying fungi and bacteria, which all need to be considered for defining the natural durability of timber. In principal, this natural durability can be determined either in field or in laboratory decay tests according to different standardized and non-standardized methods (Råberg et al. 2005; Viitanen and Gobakken 2005; Hertel 2006; Brischke et al. 2011). While laboratory tests allow clearly defined conditions and a high level of reproducibility, it is usually

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impossible to fully mimic real-life conditions. On the one hand, there is a risk of creating too severe test scenarios in terms of moisture and temperature, which are ideal for the degrading organism, and has been criticized as “torture testing” (e.g., Brischke et al. 2011). On the other hand, some parameters having an important impact on the degradation of timber cannot be considered adequately, for instance, the detoxification through so-called “non-target organisms” or the limited number of test organisms considered in European test standards, which are not necessarily responsible for decay under real-life situations.

In contrast, it is generally accepted that field tests provide more realistic test conditions, but often suffer from unacceptably long test durations. While in-ground tests with buried stakes need at least 5 years to give an indication of the effectiveness of wood preservatives (EN 252 1989; Larsson-Brelid et al. 2011), the onset of decay in above-ground trials will take place significantly later, and service lives cannot be calculated before decades have passed (Wang et al. 2008; Brischke et al. 2012). For these reasons, results from laboratory decay tests as well as field test data from in-ground graveyard tests can be found quite frequently, but natural durability studies with respect to above-ground exposures are rare, although they play a more important role in timber engineering.

Apart from in-ground exposures, where adverse moisture conditions can be assumed to exist at any time, a further distinction of fungal hazard is made regarding the respective moisture conditions and corresponding potential decay organisms. This has been done for defining use classes (EN 335 2006) as well as for the differentiation of climate-induced decay hazards (e.g., Scheffer 1971; Wang et al. 2008; Carll 2009). The variety of existing above-ground test methods—representing very different moisture regimes—is also linked to limited comparability of the obtained results. Moisture content measurements could therefore serve as cross-linking element between test methods, test sites, and other boundary conditions for comparative studies. However, they are still sparsely used, and especially for real assemblies and commodities (e.g., Kilpelainen et al. 2000; Fredriksson 2010), moisture data are rare.

A second aspect of wood moisture content and its dynamics is its contribution to wood resistance. Besides biocidal or inhibiting ingredients of wood, hydrophobic substances and anatomic peculiarities have a significant impact on the moisture dynamics of timber and thus on its durability (Hedley et al. 2004; Stirling and Morris 2006). Furthermore, impregnating timber with water repellants as well as modifying the wood cell walls aims on reduced water uptakes. The capability of a wooden material to take up moisture must consequently be seen as the second component of wood resistance (maybe the more important one). At least for the less severe use classes UC 2 and UC 3.1 (EN 335 2006), moisture load tests in the field might be seen as appropriate and time-saving alternative to long-term decay tests.

Therefore, this study aimed at examining the potential of moisture content measurements for testing the durability of timber and timber products. Data from long-term recording of field trials using different test methods, different test sites, and different wood species will be analyzed. Their potential to indicate natural durability of timber will be evaluated as an alternative to traditional decay assessments.

Materials and methods

Field trials

Double-layer tests at different sites

Double-layer tests have been performed at 23 different European test sites to establish dose–response functions for above-ground wood decay with wood moisture content (MC) and temperature. A detailed description of the study and a corresponding dose–response performance model is given by Brischke and Rapp (2008a, b, 2010).

Specimens made from Scots pine sapwood (*Pinus sylvestris* L.) and Douglas fir heartwood (*Pseudotsuga menziesii* Franco) were monitored in terms of MC, wood temperature, and the progress of fungal decay up to a period of 8 years. The specimens (500 × 50 × 25 mm^3), according to EN 252 (1989), were exposed horizontally in double-layer test rigs producing a decay risk corresponding to European Use Class 3 (EN 335-1 2006). The upper layer was displaced laterally by 25 mm with respect to the lower layer. The lower layer consisted of seven pine sapwood specimens and six Douglas fir specimens; the upper layer consisted of six pine sapwood specimens and five Douglas fir specimens. The whole test setup formed a closed deck (73 × 65 × 21 cm^3). The specimens were evaluated yearly by using a pick test and rating the extent and distribution of decay according to EN 252 (1989) as: 0 (sound), 1 (slight attack), 2 (moderate attack), 3 (severe attack), or 4 (failure).

The test rigs were exposed at 23 sites in Europe, which were selected to provide a range of climate regimes (one test rig at each site/for each exposure). Climate data at all sites were available from official weather stations. The characteristic data for those test sites, which have been selected for this study because the mean decay rating of the Douglas fir heartwood was 1 (slight attack) or higher, are listed in Table 1.

Moisture monitoring trials with different wood species

Specimens made from twelve different wood species (Table 2) were submitted to the following six exposure variations:

- South oriented, vertical cladding
  Boards (25 × 100 × 500 mm^3) were mounted horizontally on a combined façade-decking element (Fig. 1a, b) and carried out as board-on-board cladding.
- North oriented, vertical cladding
  Boards (25 × 100 × 500 mm^3) were mounted horizontally on a combined façade-decking element (Fig. 1a, b) and carried out as board-on-board cladding.
- Horizontal single layer (decking)
  Boards (25 × 100 × 500 mm^3) were exposed vertically on two bearings of a combined façade-decking element (Fig. 1a, b).

Table 1 Characteristic data of selected exposure sites

Test site and exposure	Country code	Height above sea level (m)	Average air temperature (°C)	Sum of precipitation (mm)	Begin of exposure	Last evaluation
Hamburg shade	D	35	10.6 [a]	874 [a]	07/2000	06/2008
Reulbach shade	D	620	7.5 [b]	820 [a]	07/2000	09/2008
Stuttgart shade	D	459	9.9 [b]	741 [a]	07/2000	09/2008
Freiburg shade	D	302	12.1 [a]	911 [a]	07/2000	09/2008
Bühlertal	D	465	9.8 [d]	1664 [d]	12/2000	09/2008
Hinterzarten	D	887	7.0 [d]	1586 [d]	12/2000	09/2008
Ljubljana	SLO	299	11.3 [a]	1330 [a]	04/2001	11/2008
Zagreb	HRO	123	10.7 [c]	910 [c]	08/2002	10/2008
Garston	GB	90	10.7 [f]	515 [f]	07/2002	09/2008
Portsmouth	GB	1	11.6 [e]	667 [e]	04/2001	09/2008

[a] Average of 2000–2005

[b] Average of 2001–2005

[c] Average of 2000–2004

[d] Average of 2000–2006

[e] Average of 2002–2006

[f] Average of July 2002–June 2006

Table 2 Wood species used for MC monitoring field trials and corresponding moisture uptake tests

Wood species	Botanical name
Black locust	*Robinia psudoacacia* L.
English oak	*Quercus robur* L.
Beech	*Fagus sylvatica* L.
European ash	*Fraxinus excelsior* L.
Norway spruce	*Picea abies* Karst.
Douglas fir heartwood	*P. menziesii* Franco
Douglas fir sapwood	*P. menziesii* Franco
Larch heartwood	*Larix decidua* L.
Larch sapwood	*Larix decidua* L.
Scots pine heartwood	*P. sylvestris* L.
Scots pine sapwood	*P. sylvestris* L.
Western red cedar	*Thuja plicata* L.

- Horizontal double layer
  Specimens (500 × 50 × 25 mm^3, see section "Double-layer tests at different sites") were exposed horizontally in double layers with the upper layer displaced laterally by 25 mm with respect to the lower layer (Fig. 1g). Supports were 25 cm above ground and made from aluminum L-profiles.

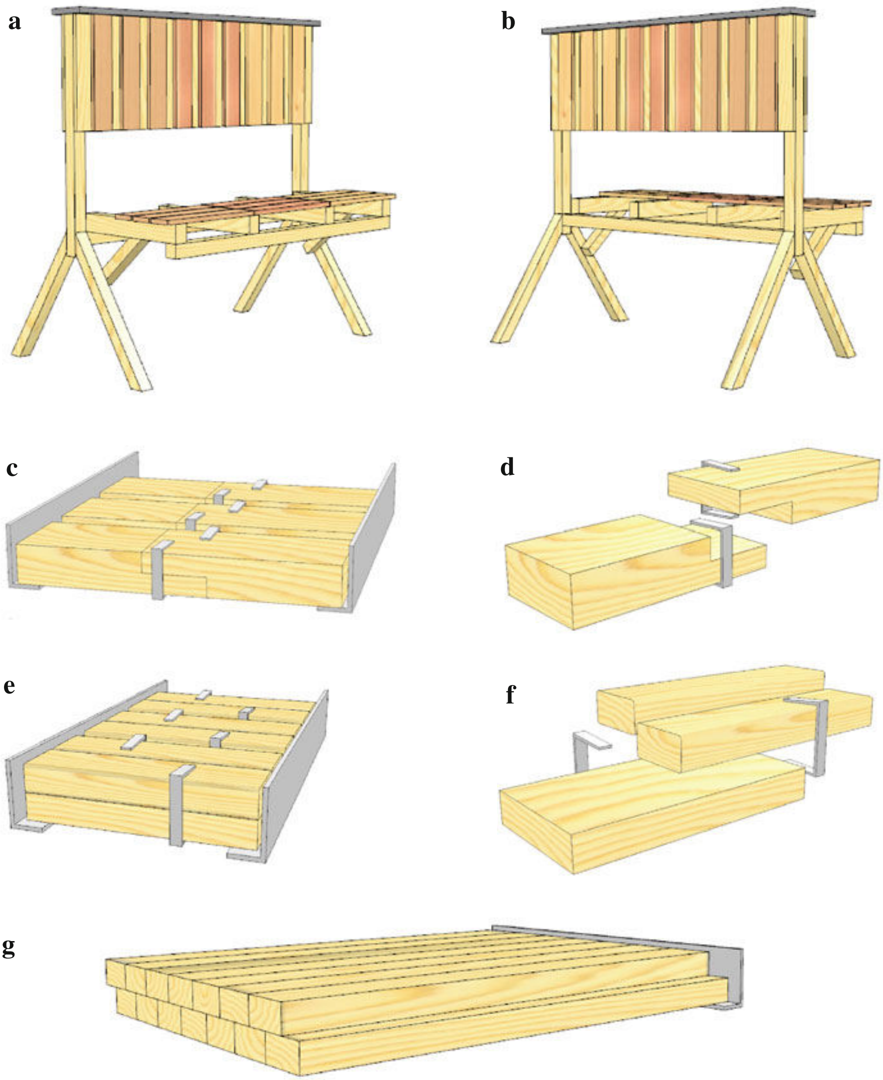

Fig. 1 Test setup for moisture monitoring. **a** Front side of façade-decking element, south oriented, **b** back side of façade-decking element, north oriented, **c**, **d** lap-joint specimens, **e**, **f** sandwich specimens, **g** double-layer specimens

- Lap-joint
  Specimens ($38 \times 85 \times 300$ mm^3) were prepared according to CEN/TS 12037 (2003) and exposed horizontally on test rigs with aluminum L-profile supports 1 m above ground (Fig. 1c, d). The two lap-joint segments were fixed through stainless steel clamps. Before exposure, a polyurethane sealant was applied on the end grain of each specimen member.

- Sandwich
  Segmented specimens consisting of a base member (25 × 100 × 200 mm^3) and two top members (25 × 50 × 200 mm^3) with rounded longitudinal edges ($r = 5$ mm) were exposed horizontally on test rigs with aluminum L-profile supports 1 m above ground (Fig. 1e, f). The three members were fixed through stainless steel clamps.

For each exposure type, three replicate specimens were provided with electrodes for daily MC and temperature recordings. Façade board specimens of European larch sapwood and Douglas fir sapwood contained heartwood portions, which were not considered for the measurements. The façade-decking elements and the double-layer trials started in November 2009, the lap-joint and sandwich trials in April 2011. All test rigs were exposed in Hannover-Herrenhausen, Germany.

Automated moisture and temperature recordings

The measurement system applied in this study was described in an earlier publication (Brischke et al. 2008) and can be summarized in brief as follows: electrodes of polyamide-coated stainless steel cables were conductively glued in the specimens. The electrodes were connected to a small data logger (Materialfox Mini, Scanntronik Mugrauer GmbH, Zorneding, Germany) that recorded the electrical resistance of the wood. The data loggers were calibrated in a range between 12 and 50 % MC and species-specific resistance characteristics were developed (Brischke et al. 2008; Lampen 2010). Measurements above fiber saturation were increasingly inaccurate, but still indicated a tendency within the calibration range. Minimum and maximum temperatures were recorded daily using Thermofox Mini data logger (Scanntronik Mugrauer GmbH, Zorneding, Germany) and used to calculate the average daily temperature. Unless otherwise indicated, the measurement points were placed in the center of the specimens. Measurements close to contact faces, e.g., supporting beams, were avoided.

Durability measures

The durability of Douglas fir heartwood, which had been exposed in double-layer field trials at different sites for a period of up to 8 years, has been determined in different ways. In comparison with the reference species Scots pine sapwood, the following decay and moisture performance-based measures were applied:

The 25th percentile of the service life of specimens SL_{25perc} and the mean decay rate v_{mean} were determined on the basis of decay ratings according to EN 252 (1989) as follows:

$$SL_{25perc}\begin{cases} SL_{\frac{n+1}{4}};\ \text{if } n \text{ is even} \\ \frac{1}{2}\left(SL_{\frac{n}{4}} + SL_{\frac{n}{4}+1}\right);\ \text{if } n \text{ is uneven} \end{cases}$$

SL_{25perc} 25th percentile of service life of specimens [a]; n number of replicate specimens

$$v_{mean} = \frac{\sum_i^n v_i}{n} = \frac{\sum_t^n \frac{R}{t}}{n}$$

v_{mean} mean decay rate of specimens [a^{-1}]; v_i decay rate of single specimen [a^{-1}]; R rating, e.g., according to EN 252 (CEN 1989); t exposure time [a]; n number of replicate specimens.

In addition to the decay-based durability measures, the number of wet days has been considered to estimate the durability of Douglas fir in terms of its moisture performance. Therefore, the number of days with MCs above 25 % and above 5 °C wood temperature, which were considered as lower temperature threshold for fungal activity, was determined.

Furthermore, a dose–response performance model for above-ground decay as described by Brischke and Rapp (2010) and shown in Fig. 2 was applied to the recorded MC and temperature data from the selected test sites. For comparative analysis, the total daily dose D (=cumulated daily dose over time) was determined. Therefore, the moisture-induced dose component d_{MC} and the temperature-induced dose component d_T were calculated according to the following equations:

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

$$d_T = 1.8 \times 10^{-6}\,T^4 + 9.57 \times 10^{-5}\,T^3 - 1.55 \times 10^{-3}\,T^2 + 4.17 \times 10^{-2}\,T; \quad \text{if} \quad T_{min} > -1\,°C \text{ and } T_{max} < 40°$$

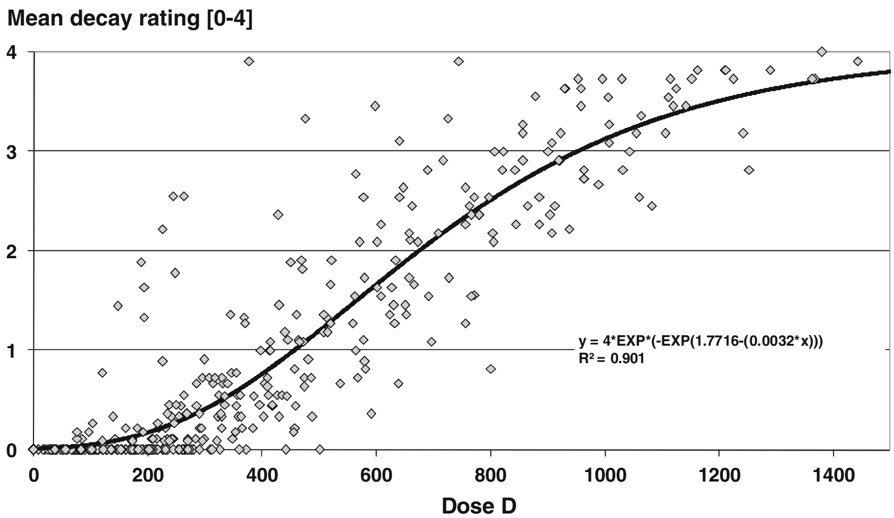

Fig. 2 Relationship between the dose D and the mean decay rating according to EN 252 (1989) of Scots pine sapwood and Douglas fir heartwood specimens exposed at 23 different field test sites (each dot represents the mean decay rating for one wood species at one exposure site at a certain time of exposure; *black line* Gompertz smoothing function), from: Brischke and Rapp (2010)

d_{MC} MC-induced daily dose; d_T temperature-induced daily dose; MC daily moisture content; T daily average wood temperature; T_{min} daily minimum temperature; T_{max} daily maximum temperature

To consider the differently severe impact of MC and temperature on decay the weighting factor a was added to calculate the daily dose as follows:

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

d daily dose; $a = 3.2$ weighting factor of temperature-induced daily dose component d_T

The different durability measures were used to determine durability classes according to EN 350-1 (1994). Therefore, the different durability measures were related to Scots pine sapwood and a durability factor f was calculated and applied to an adapted durability classification scheme (Table 3).

Moisture uptake measurements

Moisture uptake measurements were conducted on small clear specimens of $5 \times 10 \times 100$ mm^3 and $4 \times 20 \times 100$ mm^3 made from the same material used for the MC monitoring field trials (Table 2). The ratios between specimen surface and specimen volume were identical with the double-layer specimen and the façade and decking boards, respectively, but the dimensions were scaled down to one-fifth.

The specimens were oven dried at 103 ± 2 °C till constant mass and weighed to the nearest 0.001 g. For liquid water uptake, one set of specimens was submerged in deionized water for 24 h. The second set was exposed to 20 °C/100 % RH for 24 h to determine the moisture uptake in water saturated atmosphere. Therefore, the specimens were placed in a closed but ventilated small-scale climate chamber over deionized water. After weighing the moist specimens again, the moisture uptake was determined as follows:

$$\text{Moisture uptake} = \frac{(m_w - m_0)}{m_0} \times 100\ [\%]$$

m_w mass after water uptake [g]; m_0 oven-dry mass [g]

Table 3 Classes of natural durability (DC) based on calculated x-values according to EN 350-1 (1994), using results from laboratory tests, and adapted classification according to EN 350-1 (1994) using the durability factor f from field tests instead of the calculated x-values

DC	Definition	Classification based on EN 350-1 (1994)	Classification adapted to EN 350-1 (1994)
1	Very durable	$x \leq 0.15$	$f > 5$
2	Durable	$0.15 < x \leq 0.30$	$3 < f \leq 5$
3	Moderately durable	$0.30 < x \leq 0.60$	$2 < f \leq 3$
4	Slightly durable	$0.60 < x \leq 0.90$	$1.2 < f \leq 2$
5	Not durable	$x \leq 0.90$	$f \leq 1.2$

After initial moisture uptake tests, the specimens were exposed outdoors above ground on test rigs of 1 m height. After 6 months of exposure, the moisture uptake tests were repeated as described above.

Results and discussion

Comparison of durability assessments for Douglas fir heartwood

The different durability measures are summarized for Douglas fir heartwood at the ten different test sites in Table 4. As expected, the measures varied between the sites due to climatic differences. For instance, the mean decay rate was more than four times higher in Stuttgart shade and Freiburg shade compared to Bühlertal and Hinterzarten, although all four sites are located in the southwest of Germany. To determine the durability of Douglas fir and to get independent from the site-specific environmental conditions, all durability measures were related to the reference species Scots pine sapwood. The resulting durability factors and corresponding durability classes according to EN 350-1 (1994) are summarized in Table 5.

Although the results should be considered as preliminary, there is a strong indication of varying durability (classes) depending on the respective exposure, which coincides with findings of Augusta (2007) and Rapp et al. (2010). Based on the mean decay rate v_{mean} Douglas fir reached DC 3–5 for the four shade exposures, but mainly DC 2 for the other open exposures. The 25th percentile of the service life was still not reached for most of the sites after 7–8 years; wherefore, no DCs were determined based on this measure. Secondly, the different material climatic measures were used to calculate durability. The number of wet days also led to generally lower durability for the shaded sites (DC 4) compared to the others (DC 2–4), the temperature-induced dose d_T was not significantly different between both

Table 4 Different durability measures determined for Douglas fir heartwood at different test sites (Material climate-related measures are based on the period 2003–2005 corresponding to a total of 1,095 days)

Test site and exposure	v_{mean} (a^{-1})	$SL_{25perc.}$ (a)	Number of wet days (*d*)	d_T (−)	d_{MC} (−)	*D* (−)
Hamburg shade	0.27	>8.0	382	289	388	219
Reulbach shade	0.21	>8.1	456	383	318	213
Stuttgart shade	0.57	6.1	528	346	419	267
Freiburg shade	0.51	7.1	497	408	363	244
Bühlertal	0.13	>7.7	258	401	211	118
Hinterzarten	0.13	>7.7	405	287	355	172
Ljubljana	0.39	7.6	243	425	207	102
Zagreb	0.29	>6.2	160	439	120	89
Garston	0.42	6.1	249	456	133	107
Portsmouth	0.15	>7.4	494	453	216	187

Table 5 Durability factors based on the different durability measures determined for Douglas fir heartwood at different test sites in relation to Scots pine sapwood (Material climate-related measures are based on the period 2003–2005 corresponding to a total of 1,095 days)

Test site and exposure	v_{mean}	$SL_{25perc.}$	Number of wet days	d_T	d_{MC}	D
Hamburg shade	2.12 (3)	>1.17	1.59 (4)	1.20 (5)	2.60 (3)	2.31 (3)
Reulbach shade	2.50 (3)	>1.15	1.44 (4)	0.83 (5)	3.20 (2)	2.08 (3)
Stuttgart shade	1.22 (4)	1.19	1.27 (4)	1.00 (5)	2.37 (3)	1.72 (4)
Freiburg shade	1.08 (5)	1.00	1.48 (4)	1.00 (5)	2.75 (3)	2.07 (3)
Bühlertal	3.98 (2)	>1.16	2.71 (3)	1.00 (5)	4.71 (2)	4.14 (2)
Hinterzarten	3.18 (2)	>1.00	1.60 (4)	1.00 (5)	2.78 (3)	2.35 (3)
Ljubljana[a]	3.31 (2)	2.40	2.75 (3)	1.05 (5)	4.22 (2)	4.27 (2)
Zagreb	3.38 (2)	>1.59	3.79 (2)	1.00 (5)	7.81 (1)	5.20 (1)
Garston	1.63 (4)	1.18	2.94 (3)	1.00 (5)	6.53 (1)	4.56 (2)
Portsmouth	4.54 (2)	>1.36	1.84 (4)	1.00 (5)	4.20 (2)	2.82 (3)

Durability classes (DC) according to EN 350-1 (1994) in brackets

[a] Material climate data for Ljubljana have been interpolated from the year 2003 for a 3-year period because all specimens failed before end of 2004

species, which led to DC 5 in any case and was therefore inapplicable. In contrast, the moisture-induced dose d_{MC} led to durability between DC 1 and DC 3, which seemed to be optimistic, and finally, the total dose D led to a durability classification, which reflected the decay rate-based classification to a large extent. Thus, the combined consideration of moisture and temperature appeared to be an appropriate measure for durability estimates and was therefore applied to further wood species and exposure variations.

Moisture performance of natural durable timber

Cladding and decking exposures

The durability classification based on the number of wet days (above 25 % MC, Table 6) and the total dose D (Table 7) turned out to be useful indicators for the moisture performance of most wood species tested under different exposure conditions. Generally, best performance showed black locust, Scots pine heartwood and Western red cedar (DC 1 based on total dose D). However, considering the number of wet days, Scots pine heartwood and Western red cedar reached only DC 2 and 3, respectively. This can be explained by a significant number of wet days occurring during the winter half year when temperatures were not favorable for fungal growth. In contrast, moisture content of black locust never exceeded the critical threshold of 25 %.

Furthermore, it became obvious that the moisture performance of timber strongly depends on the exposure situation. With increasing severity of exposure, durability decreased for most of the species. Worst-case situation considered in this study was the double layer with high potential of water trapping between the shifted layers, where only Scots pine heartwood and black locust showed higher durability than DC 3. Surprisingly, beech performed well on both façades and the decking (DC 1); poorer performance was observed for the double layer only (DC 3–4), which might be explained by its high permeability leading to easy water uptake but also allowing fast re-drying.

In contrast, English oak performed unexpectedly poor in each exposure situation, which coincides with results, e.g., by Brischke et al. (2009). While European oak is classified as a "durable" timber species (DC 2, according to EN 350-2 1994), results from different field studies indicated a lower durability (Smith and Orsler 1994; Militz et al. 1996; Lindegaard and Morsing 2003; Evans et al. 2008). Furthermore, laboratory results indicate an intra-specific variability of European oak durability with remarkable percentages of moderately durable, less durable, and not durable timber (Aloui et al. 2004; Ayadi et al. 2001; Guilley et al. 2004; Humar et al. 2008). To assure the reliability of the test results of this study, the electrical resistance measurements have been cross-checked on the field test assemblies. No particular formation of cracks or other defects was found on the oak specimens.

In summary, most wood species revealed high durability (DC 1, apart from English oak) in decking and cladding applications when the total dose D was used to calculate durability factors. For some species, such as black locust, beech, larch, and Scots pine, the dose was zero or negligibly small, so that f was above 100 or even ∞. However, the more severe conditions in the double layer led to a clear distinction in durability between wood species.

Segmented specimens

Compared to sheltered façades and ventilated decking, more severe moisture conditions can be expected from segmented specimens, which are designed to provoke water trapping. Consequently, the number of wet days and the related moisture-induced total dose were generally higher in lap-joint, double-layer, and sandwich tests during the first year of exposure in Hannover (Tables 8, 9). Wood

Table 6 Number of wet days # (d), corresponding durability factor f (related to Scots pine sapwood) and resulting durability classes DC (Material climate-related measures are based on the year 2010 corresponding to a total of 365 days)

Wood species	South oriented façade			North oriented façade			Decking			Double layer		
	# (d)	f (−)	DC (−)	# (d)	f (−)	DC (−)	# (d)	f (−)	DC (−)	# (d)	f (−)	DC (−)
Black locust	0	∞	1	0	∞	1	0	∞	1	0	∞	1
English oak	78	1.28	4	41	1.07	5	164	1.43	4	290	1.11	5
Beech	0	∞	1	0	∞	1	7	33.57	1	205	1.58	4
Norway spruce	14	7.14	1	14	3.14	2	27	8.70	1	167	1.93	4
Larch heartwood	12	8.33	1	49	0.90	5	81	2.90	3	249	1.30	4
Larch sapwood	49	2.04	3	73	0.60	5	85	2.77	3	320	1.01	5
Scots pine heartwood	0	∞	1	0	∞	1	0	∞	1	87	3.71	2
Scots pine sapwood	100	1.00	5	44	1.00	5	235	1.00	5	323	1.00	5
Western red cedar	0	∞	1	0	∞	1	21	11.19	1	133	2.42	3

Table 7 Total dose *D*, corresponding durability factor *f* (related to Scots pine sapwood) and resulting durability classes DC (Material climate-related measures are based on the year 2010 corresponding to a total of 365 days)

Wood species	South oriented façade			North oriented façade			Decking			Double layer		
	D (−)	*f* (−)	DC (−)	*D* (−)	*f* (−)	DC (−)	*D* (−)	*f* (−)	DC (−)	*D* (−)	*f* (−)	DC (−)
Black locust	0.0	∞	1	0.0	∞	1	0.0	∞	1	0.0	∞	1
English oak	4.3	2.61	3	1.7	1.17	5	18.5	3.38	2	83.0	1.48	2
Beech	0.0	∞	1	0.0	∞	1	0.6	>100	1	43.1	2.86	3
Norway spruce	1.1	10.18	1	0.9	2.22	3	3.3	18.94	1	33.2	3.71	2
Larch heartwood	0.1	>100	1	0.3	6.67	1	1.8	34.72	1	55.3	2.23	3
Larch sapwood	0.1	>100	1	0.3	6.67	1	1.2	52.08	1	117.7	1.05	5
Scots pine heartwood	0.0	∞	1	0.0	∞	1	0.0	∞	1	17.2	7.16	1
Scots pine sapwood	11.2	1.00	5	2.0	1.00	5	62.5	1.00	5	123.2	1.00	5
Western red cedar	0.0	∞	1	0.0	∞	1	6.5	9.62	1	19.6	6.29	1

species-specific differences in moisture performance became visible, although the results still need to be considered as preliminary. The performance of oak was likewise poor compared to the façade and decking trials referring to DC 4–5. Similar was the performance of beech and pine sapwood, both suffering from a high number of wet days. Contrarily, black locust performed very well in all tests showing no wet days over the whole exposure period.

Differences between the three test methods became also apparent, whereby the lap-joint test turned out to provoke the highest moisture load. In particular, Douglas fir heartwood had a high number of wet days: 2/3 of the exposure time in lap-joints, and 1/3 in sandwich tests. The number of wet days in double-layer tests was surprisingly little, which might be explained by its exposure on a roof 16 m above ground level with high potential for re-drying.

After 1 year of exposure, the obtained results on moisture performance shall be considered as preliminary only. However, already after this short exposure period, one can expect a useful indication about the material performance. Secondly, the comparative studies provide information about the severity of a test method and will allow estimating the respective comparableness with real-life situations of details in wooden constructions. The decay assessments to be expected during the following years will be used to verify or falsify the predicted durability of the different timber species as well as the severity of the test methods.

Moisture performance indicators

Moisture uptake tests have been performed to get an early indication of the moisture performance that can be expected from the different materials when they are

Table 8 Number of wet days # (*d*), corresponding durability factor *f* (related to Scots pine sapwood) and resulting durability classes DC (Material climate-related measures are based on the period 16.04.2011–15.04.2012 corresponding to a total of 365 days)

Wood species	Double-layer test			Lap-joint test			Sandwich test		
	# (*d*)	*f* (–)	DC (–)	# (*d*)	*f* (–)	DC (–)	# (*d*)	*f* (–)	DC (–)
Black locust	0	∞	1	0	∞	1	0	∞	1
English oak	125	1.08	5	311	0.92	5	230	0.94	5
Beech	228	0.59	5	276	1.04	5	193	1.12	5
European ash	67	2.02	3	87	3.30	2	11	19.64	1
Norway spruce	51	2.65	3	245	1.17	5	11	19.64	1
Douglas fir heartwood	–	–	–	243	1.18	5	119	1.82	4
Douglas fir sapwood	–	–	–	229	1.25	4	110	1.96	4
Scots pine heartwood	33	4.10	2	17	16.88	1	96	2.25	3
Scots pine sapwood	135	1.00	5	287	1.00	5	216	1.00	5

Table 9 Total dose *D*, corresponding durability factor *f* (related to Scots pine sapwood) and resulting durability classes DC (Material climate-related measures are based on the period 16.04.2011–15.04.2012 corresponding to a total of 365 days)

Wood species	Double-layer test			Lap-joint test			Sandwich test		
	D (–)	*f* (–)	DC (–)	*D* (–)	*f* (–)	DC (–)	*D* (–)	*f* (–)	DC (–)
Black locust	0.0	∞	1	0.0	∞	1	0.0	∞	1
English oak	33.1	1.33	4	129.3	0.99	5	71.5	1.28	4
Beech	91.9	0.48	5	110.0	1.17	5	72.4	1.27	4
European ash	12.4	3.54	2	18.6	6.90	1	2.9	31.59	1
Norway spruce	6.3	6.97	1	99.4	1.29	4	1.0	91.60	1
Douglas fir heartwood	–	–	–	77.0	1.67	4	26.9	3.41	2
Douglas fir sapwood	–	–	–	65.0	1.97	4	21.2	4.32	2
Scots pine heartwood	7.0	6.27	1	2.1	61.10	1	21.7	4.22	2
Scots pine sapwood	43.9	1.00	5	128.3	1.00	5	91.6	1.00	5

exposed outdoors. Significant differences were found between wood species for both, uptake of liquid water and in water saturated atmosphere (Tables 10, 11). In general, species with poor moisture performance in the field suffered from high moisture uptakes (e.g., Scots pine sapwood and beech). However, others such as Western red cedar showed extremely high liquid water uptake, which became not apparent when exposed outdoors as decking. The other way round, the poor performance of English oak in different exposure situations could not have been expected from its moisture uptake, which was in the same range of Douglas fir and larch heartwood. The relationship by trend between the water uptake behavior of the different wood species and the total dose, which occurred during 1 year of exposure,

Table 10 Moisture uptakes of oven-dried specimens after 24 h submersion in deionized water and exposure to 20 °C/100 % RH

Wood species	Moisture uptake (%)			
	Board specimens ($4 \times 20 \times 100$ mm^3)		Stake specimens ($5 \times 10 \times 100$ mm^3)	
	24 h 100 % RH	24 h water	24 h 100 % RH	24 h water
Black locust	9.9	26.6	10.3	22.6
English oak	14.1	40.5	18.2	40.6
Beech	17.6	55.7	18.0	55.2
European ash	19.0	67.8	19.7	55.7
Norway spruce	24.0	60.6	21.6	52.6
Douglas fir heartwood	18.0	36.8	18.6	34.8
Douglas fir sapwood	18.8	47.9	20.9	45.2
European larch heartwood	16.0	42.9	15.8	37.0
European larch sapwood	n.a.	n.a.	22.1	61.4
Scots pine heartwood	16.7	41.6	17.9	50.8
Scots pine sapwood	21.0	60.7	21.4	60.8
Western red cedar	14.9	77.3	15.0	69.3

Table 11 Moisture uptakes of oven-dried specimens after 24 h submersion in deionized water and exposure to 20 °C/100 % RH related to the oven-dry volume of the specimens

Wood species	Moisture uptake (g/cm^3)			
	Board specimens ($4 \times 20 \times 100$ mm^3)		Stake specimens ($5 \times 10 \times 100$ mm^3)	
	24 h 100 % RH	24 h water	24 h 100 % RH	24 h water
Black locust	0.07	0.19	0.08	0.16
English oak	0.10	0.28	0.10	0.22
Beech	0.12	0.36	0.12	0.36
European ash	0.11	0.40	0.12	0.34
Norway spruce	0.10	0.26	0.10	0.25
Douglas fir heartwood	0.10	0.20	0.09	0.17
Douglas fir sapwood	0.11	0.27	0.11	0.25
European larch heartwood	0.09	0.23	0.09	0.20
European larch sapwood	n.a.	n.a.	0.10	0.30
Scots pine heartwood	0.09	0.23	0.09	0.25
Scots pine sapwood	0.12	0.35	0.11	0.31
Western red cedar	0.05	0.23	0.05	0.20

is exemplarily illustrated in Fig. 3 for the double-layer tests. Although there is a clear tendency that the total dose is rising with increasing moisture uptake, a number of outliers adulterate the overall result.

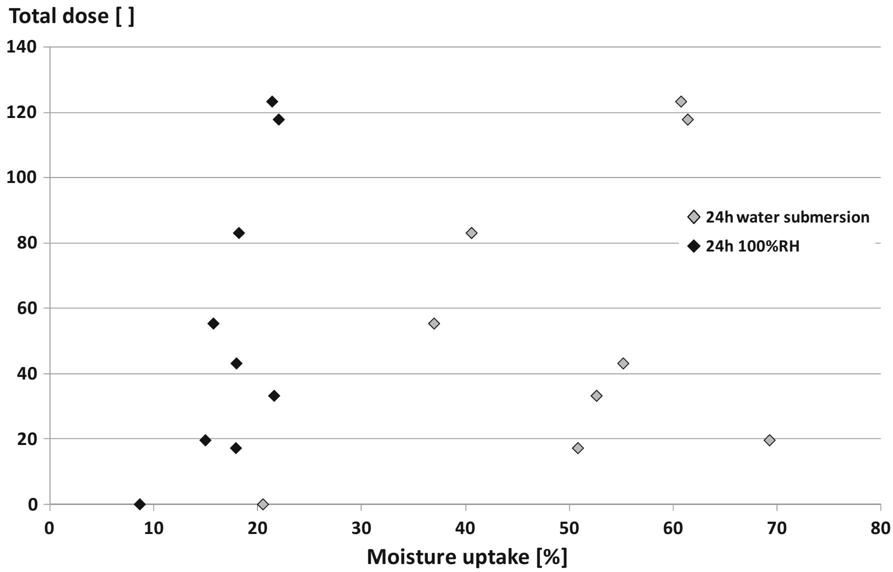

Fig. 3 Relationship between moisture uptake during water submersion or exposure in 100 % RH at 20 °C and the total dose *D* obtained in double-layer tests during the year 2010 (each dot representing one wood species)

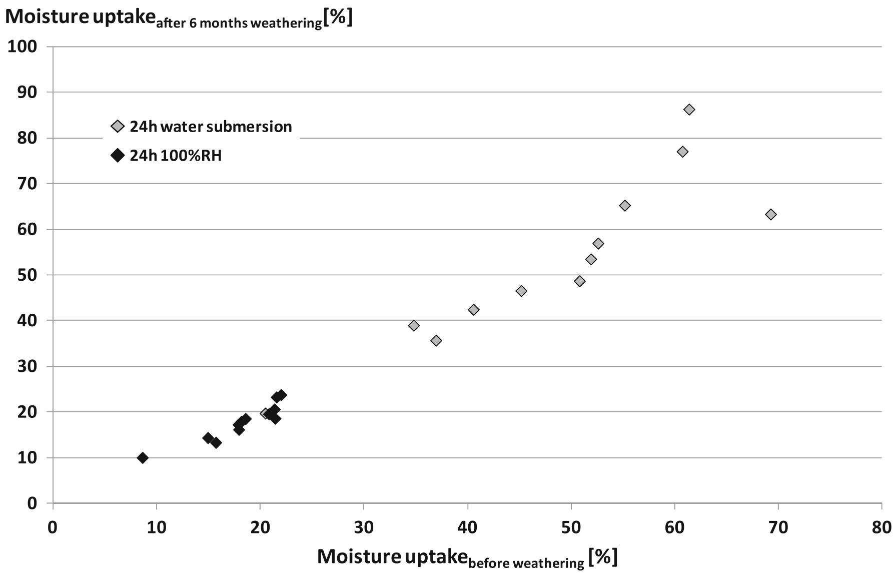

Fig. 4 Relationship between moisture uptake during water submersion or exposure in 100 % RH at 20 °C before and after natural weathering of small-scale specimens (5 × 10 × 100 mm^3) for 6 months (each dot representing one wood species)

The results also showed that one needs to distinguish between liquid and adsorptive water uptake. For instance, Western red cedar showed by far the highest liquid water uptake (Table 10) but a comparatively little uptake after 24 h in water saturated atmosphere, which points on its outstanding performance when used as cladding. On the other hand, Western red cedar is also effectually used for shingles, which are directly exposed to rain (Smith and Swann 1976; Stirling and Morris 2006). Therefore, the percentage moisture uptake shall be related to the oven-dry volume of the specimens (see Table 11). The ratio between specimen surface and volume has already been considered through usage of specimens scaled down to one-fifth of the original.

Furthermore, one should expect that moisture performance in terms of adsorption as well as desorption properties may change over time. In particular, the formation of cracks is assumed to increase the liquid water uptake (e.g., Sandberg and Söderström 2006). However, no significant effect was observed on small-scale specimens, which had been exposed for 6 months outdoors (Fig. 4), because their volume was obviously too small to get affected by cracking.

Conclusion

The comparison of durability assessments for Douglas fir heartwood clearly showed that there exist alternative measures for durability assessments apart from rating the extent of decay. In particular, for less severe exposure situations, moisture performance-based measures have the potential to serve as reliable indicators for timber durability. For screening purposes, even laboratory moisture uptake tests, which are easy to perform and time-saving, can give an indication of the real outdoor performance.

On the other hand, the 1-year results from field studies with façade-decking elements and segmented specimens showed that one needs to consider more than a single year of exposure for both, service life estimates and durability classification. Tests should run for at least 3 years to avoid ignoring the effect of weathering on moisture performance, e.g., through leaching of extractives and cracking of timber, as well as differences in climate between years.

While it is common practice to determine wood MC in laboratory decay tests, it is neither in field trials nor even in studies on whole commodities, constructions, or buildings. In contrast, there are many studies known on moisture dynamics and resulting moisture load of the respective building materials in the field of building physics, e.g., in situ measurements on wall mounting, construction, or rain screen wall assemblies. The wood durability sector on the other hand needs to catch up and should take more advantage of the additional information provided by MC measurements.

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6.9 Publication IX: Service life of timber structures – prognosis based on 3 years high-frequency monitoring

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Eur. J. Wood Prod.
DOI 10.1007/s00107-012-0640-9

ORIGINALS ORIGINALARBEITEN

Service life of timber components: prognosis based on 3 years high-frequency monitoring

Christian Brischke · Linda Meyer · Thomas Bornemann · Maik Bilstein · Boris Lauenstein · Janna-Marcia Lück · Christian Wulf

Received: 16 April 2012

Abstract Within this study various timber components were monitored highly frequently in terms of wood moisture content and wood temperature over a period of 3 years. The data sets were applied to a logistic dose–response performance model which is based on dose functions considering wood moisture content and temperature as key factors for fungal decay. The response in terms of certain decay levels was used to characterize different limit states and thus the expected service life. Service lives were prognosticated for wooden fence posts, lattices, terrace decking, and façades with different orientations, heights above ground and roof overhangs. Significant differences were found between the various commodities and the three investigated wood species which were Norway spruce (*Picea abies* Karst.), Scots pine sapwood (*Pinus sylvestris* L.) and Douglas fir heartwood (*Pseudotsuga menziesii* Franco).

Gebrauchsdauer von Holzbauteilen: Vorhersagen auf Basis eines dreijährigen Monitorings

Zusammenfassung Im Rahmen dieser Studie wurden Holzbauteile hinsichtlich Holzfeuchte und Holztemperatur während drei Jahren überwacht. Ein logistisches Performance-Modell wurde auf die gewonnenen Datensätze angewendet und auf Basis von Dosis-Wirkungsfunktionen wurde die zu erwartende Gebrauchsdauer von Holzpfählen, Zaunlatten, Terrassendecks und Fassaden mit unterschiedlichen Ausrichtungen, Abständen zum Boden und Dachüberständen prognostiziert. Signifikante Unterschiede ergaben sich zwischen den unterschiedlichen Bauteilen und den drei untersuchten Holzarten Fichte (*Picea abies* Karst.), Kiefernsplint (*Pinus sylvestris* L.) und Douglasie (*Pseudotsuga menziesii* Franco).

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1 Introduction

The functional service life of timber structures is predominantly affected by the interdependency of wood resistance on the one hand and climatic loads on the other hand. Biological degradation in terms of fungal decay is the most common reason for structural failures. Therefore consolidated knowledge of the interrelationship between the intensity of fungal degradation over time and the numerous decay-influencing factors is needed to estimate the service life to be expected for wooden components in outdoor applications. In principal, there are three different sources providing information about decay processes. 1. Laboratory experiments, 2. field trials, and 3. surveys on structures in service (in-service performance). Laboratory tests allow setting up exactly defined conditions, e. g., in terms of moisture, temperature, and organisms involved. On the other hand it is difficult to mimic real life conditions in the laboratory, because many factors occurring in the field are not reproducible or are even unknown. Field tests are more time-consuming compared to laboratory tests, but closer to reality (Hedley 1993; Nilsson and Edlund 1995; Augusta 2007). While the test setup may be identical, the local climate conditions vary from one trial to the other in dependence of time and site. As a matter of course most realistic conditions appear on real buildings and building

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components. Surveys on such structures in service are therefore a very important data source (Gobakken et al. 2008; Brischke and Rolf-Kiel 2010). However, in most cases they suffer from long exposure times until decay occurs or lacking information about their history (initial protection measures, environmental conditions during exposure, and maintenance intervals).

The establishment of dose–response functions as described for instance by Brischke and Rapp (2010) and Isaksson et al. (2012) allows overcoming the drawback of long exposure times needed for field trials. Once the interrelationship between the most important decay influencing factors wood moisture content and wood temperature (dose) and fungal decay (response) is determined in long-term field experiments (dose–response functions), the impact of further decay factors may be quantified in terms of dose-time functions. To determine dose-time functions high-frequent medium-term recordings ($\sim$3 years) of moisture content and temperature will be sufficient, because it is no longer necessary to await the onset of decay.

This study aims at quantifying the impact of material, exposure, and design detailing on the expected service life of wooden components. Therefore various timber structures and commodities were monitored highly frequently in terms of wood moisture content and wood temperature over a period of 3 years. The data sets will be applied to a logistic dose–response performance model, which is based on dose functions considering wood moisture content and temperature as key factors for fungal decay. The response in terms of certain decay levels will be used to characterize different limit states and thus the estimated service lives (ESL).

2 Materials and methods

2.1 Moisture and temperature recording

Wood moisture content and wood temperature were measured continuously and recorded daily on a variety of different timber structures and commodities. Therefore, conductively glued stainless steel electrodes were used for electrical resistance measurements. The measurement system using mini data loggers (Type Materialfox mini, Scanntronik GmbH) has been described in detail by Brischke et al. (2008a). Wood temperature measurements and recordings were made in parallel using mini data logger (Type Thermofox mini, Scanntronik GmbH). Temperature data obtained were used to characterize the climatic load and for temperature compensation of the electrical resistance measurements. Wood species-specific resistance characteristics were used for calculating the wood moisture content after Brischke et al. (2008a).

2.2 Test objects

2.2.1 Object 1: cladding in Tåstrup, Denmark

The objective of this study was to examine the influence of a roof overhang on the moisture conditions within a cladding (Brischke et al. 2008b). Therefore, moisture measurements were conducted on a cladding (15 m long, 2.5 m high) with three different roof overhangs (12, 62, 112 cm) on the test site of the Danish Technological Institute (DTI) in Tåstrup, Denmark (Fig. 1). The data loggers were

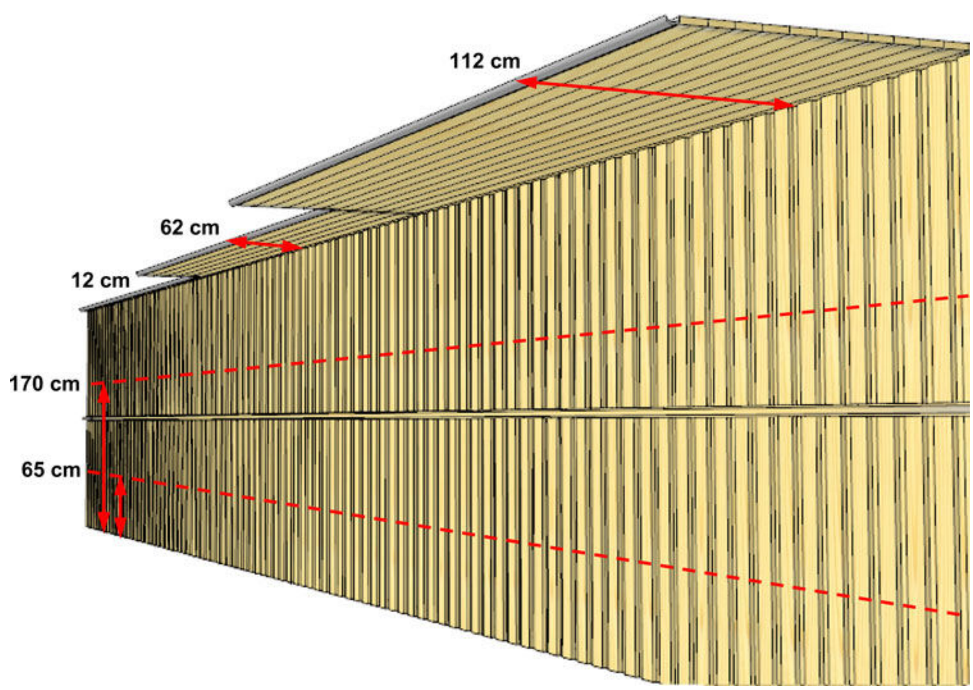
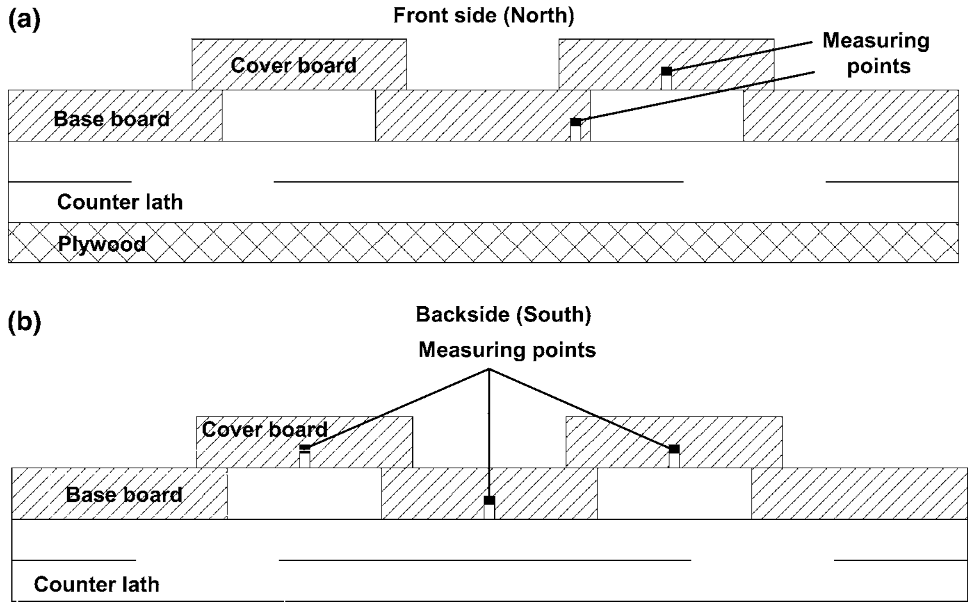


Fig. 1 Board-on-board cladding with different roof overhangs in Tåstrup, Denmark. *Dashed lines* mark the heights of measurement points on the upper and bottom parts of the façade

Abb. 1 Boden-Deckel-Schalung an einer Fassade mit unterschiedlich großen Dachüberständen in Tåstrup, Dänemark. Gestrichelte Linien: Höhe der Messpunkte an der oberen und unteren Fassade

Fig. 2 Cross cut through examined cladding and schematic arrangement of the measurement points. **a** Test assembly in Tåstrup; **b** Test house in Hannover
Abb. 2 Querschnitt durch Boden-Deckel-Schalung an den untersuchten Fassaden. **a** Versuchswand in Tåstrup, **b** Versuchshaus in Hannover



installed in December 2001 and measurements conducted for a period of 3 years between 2002 and 2004. The cladding was made from fine sawn Norway spruce (*Picea abies* Karst.) boards of 1170 × 105 × 25 mm^3, faced to the North, and carried out as a vertical, rear ventilated board-on-board cladding (Fig. 2a). The cladding was split into an upper and a bottom part, each with a height of 117 cm, separated from each other by a horizontal board, acting as a small roof overhang of 4.5 cm width. The distance between the boards of the bottom cladding and the ground was 15 cm. Electrodes for moisture content measurements were glued in from the back of the cladding at two different heights, 65 cm and 170 cm from the ground. In total 18 pairs of electrodes were installed, three for each roof overhang/height combination (Fig. 2a).

2.2.2 *Object 2: test house in Hannover, Germany*

The impact of wall orientation and the distance to the ground on the moisture induced decay risk was studied on the claddings of a test house, which was built in Hannover–Herrenhausen in December 2008. Moisture content and temperature measurements were conducted for a period of 3 years between 2008 and 2011. The house had a quadratic floor plan of 3 × 3 m^2 and a total height of 3.18 m. The four façades were exactly aligned to the cardinal points of the compass. The stud frame, which was made from Norway spruce, carried a board-on board cladding and a pyramidal broach roof. The roof overhang was minimized to a width of 7.5 cm including the gutter. Five planed test boards of Norway spruce, Scots pine sapwood (*Pinus sylvestris* L.) and Douglas fir (*Pseudotsuga menziesii* Franco) were mounted on each side of the building. The spaces in between were filled with so-called blind boards made from Norway spruce. Since the distance between concrete ground and end-grain of the cladding boards was 5 cm, the whole façade was fully rear ventilated.

For measuring the wood MC electrodes were installed at seven different heights: 5, 10, 20, 40, 80, 160, and 240 cm from the bottom end of the boards. Three measurement points per wood species, height and wall orientation were set, which means in total 252 pairs of electrodes. The electrodes were glued in from the back side of the cladding, two pairs in the central cover boards, and one pair in the central base board (Fig. 2b). In addition 84 temperature sensors were installed, one for each parameter combination. Temperature and wood moisture content were recorded every 2 h during the first year and henceforward once a day.

2.2.3 *Object 3: fence and terrace decking elements in Hannover, Germany*

Continuous moisture and temperature recordings were furthermore carried out on fence posts, pickets and terrace decking between August 2008 and August 2011. Three replicate assemblies were made from planed Scots pine sapwood, Norway spruce, and Douglas fir, afterwards instrumented and exposed on the IBW test site in Hannover–Herrenhausen (Figs. 3, 4). The fence posts were buried directly in the ground; the decking elements were placed on pavers. The whole test field was covered with a water-permeable horticultural foil to protect the test devices from growth of grass and other plants.

Measurement points were set at a depth of 15 mm on differently severe exposed positions on the assemblies: On the fence posts close to the ground, close to the picket, and above the picket; on the pickets close to the post and centrally between two posts; on the decking boards close to

Fig. 3 Decking element; measuring points are marked with *dots*
Abb. 3 Terrassendeck-Element; Messpunkte mit Punkten markiert

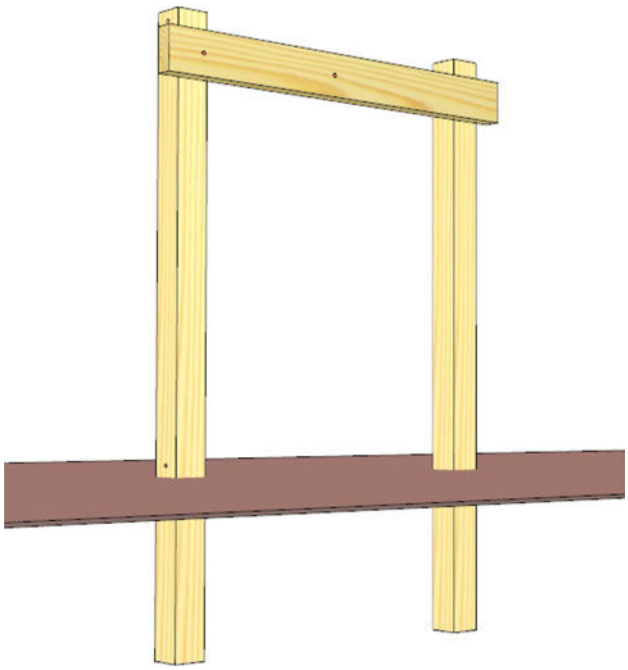


Fig. 4 Fence element; measuring points are marked with *dots* (a fifth non-visible measuring point is located in the post behind the picket)
Abb. 4 Zaun-Element; Messpunkte mit Punkten markiert (ein fünfter nicht sichtbarer Messpunkt befindet sich im Pfahl hinter der Zaunlatte)

the support and centred between two supports; and on the decking supports. For each parameter combination n = 3 moisture electrode pairs and an additional temperature sensor were installed.

2.3 Logistic dose–response performance model (LDR)

Three-year data sets were applied to a performance model describing the relationship between the material climate in terms of wood moisture content and temperature and the corresponding fungal decay. The experimental base for the model have been field test results from double layer above ground trials performed at 28 different test sites in Europe as described by Brischke (2007).

The impact of a general time variation of moisture content u and temperature T on the potential for decay can be described by a dose–response function (e.g. Brischke and Rapp 2010). The total daily dose D is a function of one component D_u dependent on daily average of moisture content u and one component D_T dependent on daily average temperature T.

$$D = f(D_T(T), D_u(u)) \tag{1}$$

For n days of exposure the total dose is given by

$$D(n) = \sum_1^n D_i = \sum_1^n (f(D_T(T_i), D_u(u_i))) \tag{2}$$

where T_i is the average temperature and u_i is the average moisture content for day i. Decay is initiated when the accumulated dose reaches a critical dose.

As described in detail by Brischke (2007) the cardinal points of the parameters wood temperature and moisture content for fungal growth and decay activity were sought and used to set up polynomial base functions for both dose components (Eqs. 3, 4). The total dose D is then calculated as a function of D_u and D_T according to Eq. (5), where D_T was weighted by a factor a.

$$D_u(u) = \begin{cases} 0 & \text{if} \quad u < 25\,\% \\ e \cdot u^5 - f \cdot u^4 + g \cdot u^3 - h \cdot u^2 + i \cdot u - j & \text{if} \quad u \geq 25\,\% \end{cases} \tag{3}$$

$$D_T(T) = \begin{cases} 0 & \text{if } T_{min} < 0\,^\circ\text{C or if } T_{max} > 40\,^\circ\text{C} \\ k \cdot T^4 + l \cdot T^3 - m \cdot T^2 + n \cdot T & \text{if } T_{min} \geq 0\,^\circ\text{C or if } T_{max} < 40\,^\circ\text{C} \end{cases} \tag{4}$$

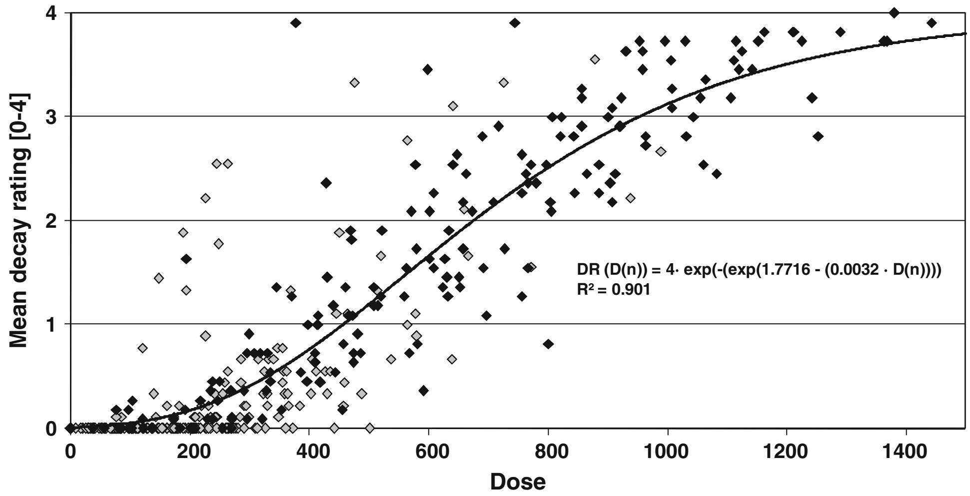


Fig. 5 Relationship between dose and mean decay rating according to EN 252 (1990) of Scots pine sapwood (*black*) and Douglas fir heartwood (*grey*) exposed at 28 different field test sites using a logistic dose–response model (each *dot* represents the mean decay rating at one exposure site at a certain time of exposure; *black line* Gompertz smoothing function) (modified after Brischke and Rapp 2010)

Abb. 5 Zusammenhang zwischen Dosis und mittlerer Abbaubewertung nach EN 252 (1990) von Kiefernsplint (schwarze Punkte) und Douglasienkernholz (graue Punkte) exponiert an 28 Standorten basierend auf einem logistischen Dosis-Wirkungs-Modell (jeder Punkt repräsentiert die mittlere Abbaubewertung an einem Standort zu einem Bewertungszeitpunkt; schwarze Linie: Gompertz-Ausgleichsfunktion (modifiziert nach Brischke und Rapp 2010)

$$D = (a \cdot D_T[T] + D_u[u]) \cdot (a+1)^{-1} \quad \text{if } D_u > 0 \text{ and } D_T > 0 \tag{5}$$

where D = dose [d], D_T = temperature induced dose component [−], D_u = moisture induced dose component [d], u = daily average moisture content [%], T = daily average wood temperature [°C], T_{min} = minimum wood temperature for the day considered [°C], T_{max} = maximum wood temperature for the day considered [°C], a = temperature weighting factor, $e, f, g, h, i, j, k, l, m, n$ = variables.

The best fit for this model against the available data (Brischke and Rapp 2010) was obtained with the following parameters and the final logistic model function according to Eq. (6).

$a = 3.2$
$j = 4.98$
$e = 6.75 \times 10^{-10}$
$k = 1.8 \times 10^{-6}$
$f = 3.50 \times 10^{-7}$
$l = 9.57 \times 10^{-5}$
$g = 7.18 \times 10^{-5}$
$m = 1.55 \times 10^{-3}$
$h = 7.22 \times 10^{-3}$
$n = 4.17$
$i = 0.34$

The total dose over a certain time period is given by Eq. (2) and the decay rating is given by the dose–response function:

$$DR(D(n)) = 4 \cdot \exp(-\exp(1.7716 - (0.0032 \cdot D(n)))) \tag{6}$$

where DR = Decay rating according to EN 252 (1990), $D(n)$=total dose for n days of exposure.

The effect of temperature is dominating on the total dose. The reason for this is that the empirical data from double layer tests used to fit the model is dominated by observations with continuously high moisture content for pine sapwood. The best fit against these data will therefore primarily reflect the effect of temperature on decay rating.

The good fit of the dose response function—as indicated through a degree of determination $R^2 = 0.901$—is illustrated for Scots pine sapwood and Douglas fir heartwood in Fig. 5. However, there were different outliers, where decay developed faster than predicted by the accumulated dose. This happened in particular at the South-Eastern sites Ljubljana and Zagreb, where several specimens had been attacked by brown rot, whereas white and soft rot were dominating at most other sites (Brischke and Rapp 2010).

To prognosticate the service lives of the various timber components examined within this study using Eq. (6), the critical dose D_{crit} was considered according to Fig. 5. The following limit states were defined:

- Mean decay rating 1 ('slight attack') acc. to EN 252 (1990)$-D_{crit} = 455$
- Mean decay rating 2 ('moderate attack') acc. to EN 252 (1990)$-D_{crit} = 670$
- Mean decay rating 3 ('severe attack') acc. to EN 252 (1990)$-D_{crit} = 955$

3 Results and discussion

3.1 Service life prognosis

3.1.1 Roof overhangs

Differently wide roof overhangs influenced the moisture load of the board-on-board cladding of the façade in Tåstrup, Denmark, significantly. Table 1 shows the estimated service life of the cladding for three different limit states referring to decay rating 1 (slight decay), 2 (moderate decay), and 3 (severe decay). The service life to be expected was significantly prolonged through the increasing roof overhang. As expected the biggest differences were observed for the upper part of the façade, where the roof overhang was most effective. The estimated service

Table 1 Mean annual dose according to the LDR model and estimated service lives (SL) for a Norway spruce cladding with different roof overhangs and heights above ground

Tab. 1 Mittlere Jahresdosis basierend auf dem logistischen Dosis-Wirkungs-Modell und vorhergesagte Gebrauchsdauern für eine Fichtenfassade mit unterschiedlich großen Dachüberständen und Abständen zum Boden

				Estimated SL [a]		
Roof overhang	Façade	Board type	Mean decay rating acc. to EN 252 (1990) D_{crit} acc. to Fig. 5 Mean annual dose 2002–2004	3 955	2 670	1 455
112 cm	Upper	Cover	1.09	880	569	386
		Base	1.35	708	497	337
	Bottom	Cover	6.78	141	99	67
		Base	6.46	148	104	70
62 cm	Upper	Cover	5.04	189	133	90
		Base	4.54	210	148	100
	Bottom	Cover	7.86	122	85	58
		Base	6.69	143	100	68
12 cm	Upper	Cover	8.44	113	79	54
		Base	7.51	127	89	61
	Bottom	Cover	8.88	107	75	51
		Base	6.54	146	102	70

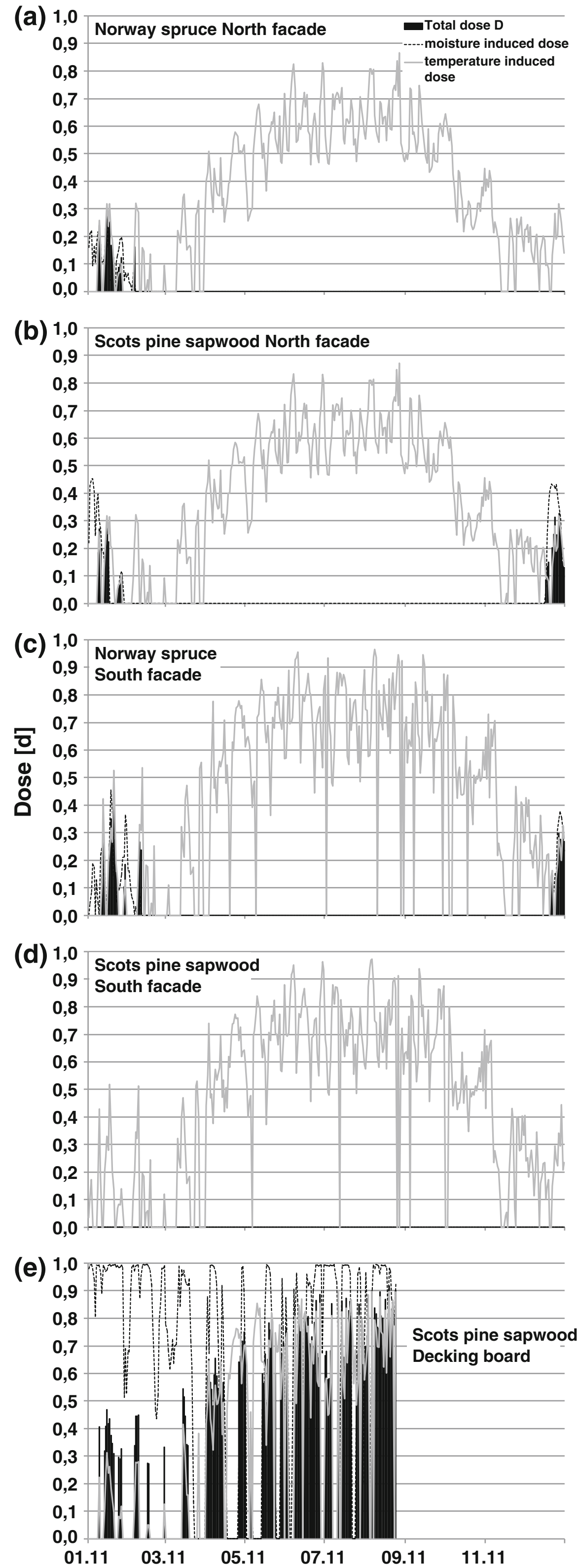
Table 2 Mean annual dose according to the LDR model and estimated service lives (SL) of board-on-board cladding at a height of 10 cm above ground for different compass directions and wood species

Tab. 2 Mittlere Jahresdosis basierend auf dem logistischen Dosis-Wirkungs-Modell und vorhergesagte Gebrauchsdauern für Boden-Deckel-Schalungen in einer Höhe von 10 cm zum Boden, unterschiedliche Ausrichtungen und Holzarten

			Estimated SL [a]		
Wood species	Orientation	Mean decay rating acc. to EN 252 (1990) D_{crit} acc. to Fig. 5 Mean annual dose 08/08–08/11	3 955	2 670	1 455
Douglas fir	East	0.00	∞	∞	∞
	South	2.43	393	276	187
	West	3.48	274	193	131
	North	0.00	∞	∞	∞
Scots pine sap	East	0.31	3,081	2,161	1,468
	South	0.00	∞	∞	∞
	West	6.95	137	96	66
	North	1.50	637	447	303
Norway spruce	East	1.86	513	360	245
	South	1.51	633	444	301
	West	5.09	188	132	89
	North	0.96	995	698	474

Fig. 6 Development of total dose D and dose moisture and temperature induced dose components D_u and D_T over time during 2011. **a** Norway spruce façade north oriented (5 cm). **b** Scots pine sapwood north oriented (5 cm). **c** Norway spruce south oriented (5 cm). **d** Scots pine sapwood south oriented (5 cm). **e** Scots pine sapwood decking board (measurements of decking boards ended in August 2011)

Abb. 6 Zeitliche Entwicklung der Gesamtdosis und der Feuchte- und Temperatur-induzierten Dosiskomponenten D_u and D_T während des Jahres 2011. **a** Fichtenfassade nach Norden ausgerichtet (5 cm). **b** Kiefernsplintfassade nach Norden ausgerichtet (5 cm). **c** Fichtenfassade nach Süden ausgerichtet (5 cm). **d** Kiefernsplintfassade nach Süden ausgerichtet (5 cm). **e** Kiefernsplint-Terrassendeck (Messung endete hier im August 2011)



lives were up to 8 times higher on the façade with 112 cm overhang compared to that with 12 cm. The maximum estimated service life was 880 years (limit state: rating 3) for the cover boards at the upper façade with 112 cm roof overhang and should be seen as an indication of a non-existing risk of decay rather than a serious estimate. However, the estimates for the bottom part of the façades were more realistic. Considering the onset of decay (limit state: rating 1) the estimates were between 51 and 70 years for the bottom façade and no significant impact of the roof overhang was observed. Only for the upper façade the estimated service life increased with larger overhangs up to 386 years, whereby the sheltering effect of the roof became visible. The moisture loads were furthermore lower for the base compared to the cover boards of the cladding, although the electrodes in the base boards were installed, where they were overlapped by the cover boards and hindered drying could be expected (see measuring points in Fig. 2a).

3.1.2 Wall orientation

In addition to the impact of roof overhang and distance to ground, a third influence factor needs to be considered for service life estimations of wooden façades, which is the orientation of the wall. While in Tåstrup the complete test assembly was faced to the North, the test house in Hannover–Herrenhausen contained of four identically constructed façades exactly oriented to the major compass directions. In Table 2 the estimated service lives are summarized for the four façades at 10 cm above ground, which in general showed the highest moisture induced dose and was therefore the most critical part of the respective cladding.

Compared to the Tåstrup cladding the ESL of the North façade in Hannover were much higher. This is due to several reasons, e.g. different test locations, different test periods, and finally different micro climatic conditions. In contrast to the Danish test site, the Hannover site is protected from wind and thus wind-driven rain from the North through a building and some trees. Such topographical differences can have a significant effect on driving wind loads (Ge and Krpan 2009). In general the wind loads are remarkably lower in Hannover.

However, significant differences between the four different orientations became visible. The highest moisture loads for Norway spruce and Douglas fir occurred on the West façade followed by the South wall leading to minimum ESL of 89 years for spruce (Table 2). Since Southwest is the weather side in Central Europe, the results point to the impact of wind-driven rain and the corresponding moisture loads, which coincides also with findings from Nore et al. (2007), who performed MC measurements on a test house in Trondheim, Norway. In contrast, the Scots pine sapwood also showed highest moisture loads on the West side, but followed by the North façade, which might be explained by hindered re-drying of the very permeable sapwood due to less solar irradiation on the North. The East oriented façade was generally unproblematic, because it is the lee side in Central Europe.

The dose development is illustrated in Fig. 6a–d exemplarily for Norway spruce and Scots pine sapwood on the South and North façade at a height of 5 cm during the year 2011. While the dose of Norway spruce was higher on the South façade (6.49 compared to 2.66 on the North wall in 2011), Scots pine sapwood experienced no moisture induced dose on the South, but a dose of 4.59 on the North wall in the same year. Since the temperature induced dose component D_T was nearly equal for both wood species, but generally higher on the South façade, the decisive influence was the moisture content, which decided between 'dose' and 'no dose'.

Secondly, it became evident that for this particular exposure of a cladding the total dose appears exclusively during the winter. In combination with corresponding low temperatures the total dose is relatively little. For comparison, the total dose D and both dose components D_u and D_T of a Scots pine sapwood decking board are illustrated in Fig. 6e. Here the highest dose values occurred during the summer period with sufficiently high wood moisture content and higher temperatures.

3.1.3 *Distance to ground*

The second impact factor examined at the test house in Hannover was the distance to ground and thus the influence of splash water on the one hand and differences in re-drying potential due to varying wind speed at different heights on the other hand. In extreme, closeness to ground had an accelerating effect in terms of increasing the moisture loads at the façade.

However, it became not apparent to which extent the higher moisture loads were caused by splash water or by slower re-drying, respectively. Common practice in building guidelines is to avoid timber products up to a height of 30–50 cm above ground, where one should expect significantly higher moisture ingress through splash water (Heikkilä 2005; Gabriel 2009). A general pattern of increased moisture was not detectable for all wood species and wall orientations. However, it became obvious that splash water needs to be considered on walls with high driving rain loads.

In general it became apparent that the exposure conditions of a well-ventilated wooden cladding are comparatively low in terms of moisture, and the resulting estimated service lives are acceptably long in any case, although the studied façades suffered from poor design. These findings coincide with the wide spread use of untreated timber for façades. Even less durable wood species such as Norway spruce are traditionally used for claddings without any preservative treatment in many countries (Davies et al. 2002, 2004; Sellars and Hale 2004). In contrast, higher

Table 3 Mean annual dose according to the LDR model and estimated service lives (SL) for wooden decking made from different wood species
Tab. 3 Mittlere Jahresdosis basierend auf dem logistischen Dosis-Wirkungs-Modell und vorhergesagte Gebrauchsdauern für Terrassendecks aus unterschiedlichen Holzarten

			Estimated SL [a]		
		Mean decay rating acc. to EN 252 (1990)	3	2	1
		D_{crit} acc. to Fig. 5	955	670	455
Wood species	Commodity	Mean annual dose 08/08–08/11			
Douglas fir	Terrace board centre	14.60	65	46	31
	Terrace board at contact face	22.27	43	30	20
	Bearing	32.27	30	21	14
Scots pine sap	Terrace board centre	102.37	9	7	5
	Terrace board at contact face	96.57	10	7	5
	Bearing	66.10	15	10	7
Norway spruce	Terrace board centre	58.93	16	11	8
	Terrace board at contact face	50.83	19	13	9
	Bearing	36.13	26	19	13

Table 4 Mean annual dose according to the LDR model and estimated service lives (SL) for wooden fence elements made from different wood species

Tab. 4 Mittlere Jahresdosis basierend auf dem logistischen Dosis-Wirkungs-Modell und vorhergesagte Gebrauchsdauern für Zaunelemente aus unterschiedlichen Holzarten

Wood species	Commodity	Mean decay rating acc. to EN 252 (1990) D_{crit} acc. to Fig. 5 Mean annual dose 08/08–08/11	Estimated SL [a] 3 955	 2 670	 1 455
Douglas fir	Picket close to post	1.46	654	459	312
	Picket centred	0.23	4,152	2,913	1,978
	Post above picket	24.41	39	28	19
	Post close to picket	2.60	367	258	175
	Post close to ground	13.16	73	51	35
Scots pine sap	Picket close to post	48.66	20	14	9
	Picket centred	15.75	61	43	29
	Post above picket	46.94	20	14	10
	Post close to picket	20.72	46	32	22
	Post close to ground	76.71	13	9	6
Norway spruce	Picket close to post	13.71	70	49	33
	Picket centred	2.27	421	295	200
	Post above picket	41.28	23	16	11
	Post close to picket	10.48	91	64	43
	Post close to ground	41.06	23	16	11

moisture loads can be expected when wooden components are exposed horizontally and assemblies tend to water trapping.

3.1.4 Terrace and fence

Differently severe exposed details were investigated at typical wooden components. Table 3 shows the ESL for terrace decking made from different wood species, which were between 5 and 31 years to reach limit state 'rating 1' (onset of decay). As expected the shortest ESL was obtained for the Scots pine sapwood followed by Norway spruce and Douglas fir. A clear differentiation between the three examined components became not apparent. The bearing revealed the longest ESL for Scots pine sapwood and Norway spruce, but the shortest for Douglas fir. Negative effects of contact faces were not observed, which might be explained by the generally high moisture loads and not very distinct formation of water traps. In contrast, the differences in ESL between fence pickets with and without contact to the fence post were significant for all three wood species (Table 4).

As expected the highest moisture load occurred in the posts close to ground referring to ESLs between 6 years for Scots pine sapwood and 35 years for Douglas fir heartwood. Second severe was the position close to the upper end grain (post above picket) followed by the picket close to the post due to the contact face where drying was hindered. In contrast, the free ventilated picket centre suffered from low moisture loads. In summary, the estimated service lives were found to be plausible, but need to be checked, wherefore decay assessments in all trials will continue.

3.2 Influencing parameters

3.2.1 Impact of test period on service life estimations

One of the major benefits of implementing moisture content measurements into service life prediction models is to save time. To await the onset or progress of decay up to a certain level of wood degradation would require years or even decades, if wood is exposed above ground (Brischke et al. 2012). Continuous wood moisture content and temperature measurements allow estimating the expected service life of timber structures in considerably shorter time, for instance a couple of years. Nevertheless, the annual output of the performance model depends significantly on the climatic conditions of the respective year. As shown in Tables 5 and 6, the ESL of wooden commodities can vary drastically between years; in extreme up to factor 2.6 for cladding with widest roof overhang between 2002 and 2003. The need for extending the measuring periods to a minimum of 3 years to allow the use of an arithmetic mean

Table 5 Estimated service lives ESL (limit state: Rating 2) for a terrace decking made from different wood species, calculated on the base of different years (08/2008–08/2011) according to the LDR model

Tab. 5 Vorhergesagte Gebrauchsdauern (Grenzwert: Abbaubewertung 2) eines Terrassendecks aus unterschiedlichen Holzarten, berechnet auf Basis unterschiedlicher Jahre (08/2008 bis 08/2011) anhand des logistischen Dosis-Wirkungs-Modells

Wood species	Commodity	Year 1 ESL	Factor		Year 2 ESL	Factor		Year 3 ESL	Factor	
Douglas fir	Terrace board centre	51			80			30		
			1.76			**1.82**			**1.25**	
	Terrace board at contact face	29		**1.76**	44		**1.54**	24		**2.73**
			1.00			**0.85**			**2.18**	
	Bearing	29			52			11		
Scots pine sap	Terrace board centre	8			7			5		
			1.1			**0.88**			**0.83**	
	Terrace board at contact face	7		**0.90**	8		**0.58**	6		**0.50**
			0.8			**0.67**			**0.60**	
	Bearing	9			12			10		
Norway spruce	Terrace board centre	16			12			9		
			0.76			**0.92**			**0.90**	
	Terrace board at contact face	21		**1.00**	13		**0.55**	10		**0.47**
			1.31			**0.59**			**0.53**	
	Bearing	16			22			19		

Table 6 Estimated service lives ESL (limit state: Rating 2) for a Norway spruce cladding with different roof overhangs (bottom boards of upper façade), calculated on the base of different years (2002–2004) according to the LDR model

Tab. 6 Vorhergesagte Gebrauchsdauern (Grenzwert: Abbaubewertung 2) einer Fichtenfassade mit unterschiedlichen Dachüberständen (Bodenbretter der oberen Fassade), berechnet auf Basis unterschiedlicher Jahre (2002–2004) anhand des logistischen Dosis-Wirkungs-Modells

Roof overhang (cm)	Year 2002 ESL	Factor		Year 2003 ESL	Factor		Year 2004 ESL	Factor	
112	361			937			453		
		2.84			**6.21**			**2.65**	
62	127		**5.16**	151		**9.37**	171		**4.19**
		1.81			**1.51**			**1.58**	
12	70			100			108		

became obvious. Furthermore, the factors between two different design details or wood species vary from year to year, wherefore also the relative service lives (related to another wooden component) need to be used with care. In principal, the use of a reference component, for instance a horizontal Norway spruce board as suggested by Thelandersson et al. (2011), is a feasible way to become independent from climatic variations between test sites and test years. However, also this relative estimate should be based on a period of at least 3 years to increase reliability. Another option to consider the climatic conditions of the respective test period adequately is to work with reference years (e.g., ISO 15686-1 2011). Therefore a reference year with well defined 'standard' conditions is characterized and the test period in question needs to be related to the reference year. This procedure requires however detailed knowledge of the interrelationship between macroclimate, microclimate and the resulting climatic conditions within the material (material climate). First approaches to establish such climate models have been published in recent years (Viitanen et al. 2010, 2011; Brischke et al. 2011; Frühwald Hansson et al. 2012).

3.2.2 *Moisture measurements and alternative indicators*

The data loggers used in this study were calibrated in a range between 15 and 50 % wood MC and between 4 and 36 °C. Since the electrical resistance of wood depends on numerous factors, e.g., wood species-specific anatomy and chemistry, resistance characteristics were determined for all three wood species examined (Brischke et al. 2008a). With increasing wood moisture content the accuracy of the measurement system decreased but was still indicating a tendency even above fiber saturation. Moisture content below the lower limit of 15 % occurs occasionally on wooden facades and other commodities, but will not be adequately considered by the measurement system applied. However, the relevant moisture range with the fiber saturation point as the lower limit was satisfactorily considered.

Brischke et al. (2012) and Bornemann et al. (2012) reported on different moisture related measures, which may serve as alternative measures of wood durability. Significant differences were found in moisture development over time, time of wetness, and moisture and temperature induced dosage for a variety of native timbers exposed to different above-ground situations. Nevertheless, a universal ‘measure’ to compare materials, but also allow for a numeric service life prediction needs to be based on a dose–response performance model (Isaksson et al. 2012). Future studies will also consider the effect of ageing on (a) the electrical conductivity of the material, and (b) the water uptake behavior, which both have most likely a significant effect on service life prognoses (Meyer 2012).

4 Conclusion

Service lives were prognosticated for wooden fence posts, lattices, terrace decking, and façades with different orientation, heights above ground and roof overhangs. Significant differences were found between the various design details and the three investigated wood species. The high frequency monitoring of wood moisture content and temperature turned out to be an efficient and helpful tool. The procedure applied has the potential to save time when testing timber and timber product exposed outdoors—particularly under less severe conditions—because there is no need to await the onset of decay. However, the prediction accuracy strongly depends on the reliability of the performance model in the background. Secondly it became apparent that also for moisture performance based estimates the time, during which the dose is determined needs to be a span of several years to assure adequate consideration of climatic variations between years.

In summary, the use of dose–response performance models can provide service life data to be used for performance based design on the one hand, and opens new alternatives for durability testing of timber and timber products on the other hand. However, for most wood-based materials and potential design solutions moisture performance data are still lacking, wherefore more enhanced studies are needed including the development of reliable models describing the relationship between weather parameters and the material climate.

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6.10 Publication X: Decay of wooden commodities – moisture risk analysis, service life prediction and performance assessments in the field

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ORIGINAL ARTICLE

Decay of wooden commodities – Moisture risk analysis, service life prediction and performance assessment in the field

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Abstract
One key issue in wood construction is durability. Constant wetting and suitable temperatures for fungal growth promote the risk of decay and thus a decrease in structural stability and performance. Hence, performance-based prediction models seem to be reasonable to predict the in-service performance of wooden structures in different outdoor exposure situations. Within this study continuous wood moisture content (MC) and temperature measurements were conducted on five different test objects. Four test set-ups were installed at a test site in Hannover, Germany. A fifth set-up was exposed in Ås, Norway. Data-sets were applied to a dose–response performance model considering wood MC and temperature as key factors for fungal decay. The expected service life (SL) was calculated for different materials and constructions. In addition, the depth and distribution of decay was assessed using a pick test and compared with the calculated SL. Differences regarding the risk of fungal decay for various construction details, exposures and materials were quantified. A wide range of SL estimates was estimated and significant differences were found between the various components, design details and wood species. Furthermore, results from the decay assessments were used to verify the performance model. Recommendations for improvements were provided.

Keywords: *Decay assessment, dose–response performance model, fence post, moisture monitoring, service life prediction, terrace decking*

Introduction

Wood shows numerous advantages compared to other building materials like environmental friendliness, aesthetics and its high strength and low weight (Rüther 2005). As a matter of fact wood is increasingly used in outdoor applications. Well-known examples are wooden claddings, terrace decking as well as wooden fence constructions which are traditionally used in many parts of the world. On the downside, the functional service life (SL) of timber structures is predominantly affected by the interdependency of wood resistance on the one hand and climatic loads on the other hand (Brischke *et al.* 2013). Outdoors, wood is exposed to a variety of influences, which reduce its durability against wood degrading organisms (Erler 2002). Wood is biodegradable, primarily by fungal action; under some use conditions, it may decay and weaken or discolour, requiring replacement. Other biological agents also attack wood (Zabel and Morell 1992). Termites are a serious threat to untreated wood in many tropical locations as well as in Southern Europe. Nonetheless, long-term increased moisture content (MC) in combination with temperatures favourable for decay fungi increases the risk of infection and colonisation and can decrease the structural performance, in terms of stability, security and mechanical strength of wood (Rüther 2005, Brischke 2007). Therefore, consolidated knowledge of the interrelationship between the intensity of fungal degradation over time and the numerous decay-influencing factors is needed to estimate the SL to be expected for wooden components in outdoor applications.

In principal, the natural durability can be determined either in the field or in laboratory decay tests

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(Brischke *et al.* 2012b). While laboratory tests allow clearly defined conditions and a high level of reproducibility, it is usually impossible to fully imitate real-life conditions (Brischke *et al.* 2011). Further, parameters having an important impact on the degradation of timber cannot be considered adequately, for instance the detoxification through so-called "non-target-organisms" or the limited number of available test organisms, which are not necessarily responsible for decay under real-life situations (Brischke *et al.* 2012b). In contrast, it is generally accepted that field tests are closer to reality but often suffer from unacceptably long test durations (Hedley 1993, Nilsson and Edlund 1995, Augusta 2007). The onset of decay in above ground trials will often take place significantly later than 5 years, and service lives cannot be calculated before decades have passed (Wang *et al.* 2008, Brischke *et al.* 2012a). For these reasons results from laboratory decay tests as well as field test data from in-ground graveyard tests have been published quite frequently, but natural durability studies with respect to above ground exposures are rare, although they play the more important role in timber engineering.

The understanding of the importance of SL prediction of wooden components increases for the private house owners, within the professional marked and among decision-makers. For the design process, calculation and realisation of construction projects a precise knowledge of the expected SL is essential (Gobakken *et al.* 2008). Norris (2001) stated that the knowledge about the economic SL of building materials, which he defined as "Life Cycle Cost", results in the ability to take both economic and environmental performance – and their trade-off relationships – into account in product/process design decision-making.

The establishment of dose–response functions as described for instance by Brischke and Rapp (2010) and Isaksson *et al.* (2013) allows overcoming the drawback of long exposure times needed for field trials. Once the interrelationship between the most important decay influencing factors wood MC and wood temperature (dose) and fungal decay (response) is determined in long-term field experiments (dose–response functions), the impact of further decay factors may be quantified in terms of dose-time functions. To determine dose-time functions high-frequent medium-term recordings (~3 years) of MC and temperature will be sufficient, because it is no longer necessary to await the onset of decay (Brischke *et al.* 2013). However, besides wood MC and wood temperature there are a lot of other factors influencing the SL of wood used outdoors. Brischke (2007) distinguished between direct and indirect factors whereby the direct factors were divided into exogenous (ambient conditions) and endogenous (material-inherent resistance). Besides toxic or inhibiting ingredients of wood, wood MC and wood temperature were identified to be most important for predicting the SL of wooden structures (Brischke 2007, Brischke and Rapp 2010). Since none of the European-grown wood species is rich of toxic extractives the applied model is found to be applicable for this study.

This study focuses on quantifying the impact of material, exposure and design detailing on the expected SL of wooden components. Therefore, various timber structures and commodities were monitored more frequently in terms of wood MC and wood temperature over a period of three years. The data-sets will be applied to a dose–response performance model, which is based on dose functions considering wood MC and temperature as key factors for fungal decay. The response in terms of certain decay levels will be used to estimate service lives (ESL).

Material and methods

Moisture and temperature recording

The measurement system applied in this study was described in an earlier publication (Brischke *et al.* 2008) and can be summarised in brief as follows: electrodes of polyamide coated stainless steel cables were conductively glued in the specimens. The electrodes were connected to small data loggers (Materialfox Mini, Scanntronik Mugrauer GmbH, Zorneding, Germany) that recorded the electrical resistance of the wood. The data loggers were calibrated in a range between 15% and 50% MC and wood species-specific resistance characteristics were developed (Brischke *et al.* 2008, Lampen 2010). The resistance characteristics were determined for each material as a function of electrical resistance (R) and wood temperature (T). Measurements above fibre saturation were increasingly inaccurate but still indicating a tendency within the calibration range.

Minimum and maximum temperatures were recorded daily using Thermofox Mini data logger (Scanntronik Mugrauer GmbH, Zorneding, Germany) and used to calculate the average daily temperature. The measurement points were placed in the centre of the specimens.

Combined facade-decking elements in Hannover, Germany

Combined facade-decking elements, which had been designed as a reference object for use class (UC) 3.1,

Table I. Wood species used for MC monitoring field trials.

Wood species	Botanical name
Black locust	*Robinia pseudoacacia* L.
English oak	*Quercus robur* L.
Beech	*Fagus sylvatica* L.
European ash	*Fraxinus excelsior* L.
European ash OHT	*Fraxinus excelsior* L.
Norway spruce	*Picea abies* Karst.
Norway spruce OHT	*Picea abies* Karst.
Douglas fir HD	*Pseudotsuga menziesii* Franco.
Douglas fir LD	*Pseudotsuga menziesii* Franco.
Douglas fir sapwood	*Pseudotsuga menziesii* Franco.
Larch heartwood	*Larix decidua* L.
Larch sapwood	*Larix decidua* L.
Scots pine heartwood	*Pinus sylvestris* L.
Scots pine sapwood	*Pinus sylvestris* L.
Western red cedar	*Thuja plicata* L.

Note: OHT, oil heat treated; HD, high density; LD, low density.

exposed outside, above ground (EN 335 2013), had been equipped with samples made from a total of 15 different wood species (Table I). According to Figure 1, board-like specimens were submitted to the following three exposure situations:

(1) South-oriented, vertical cladding: boards (25 × 100 × 500 mm^3) were mounted vertically on a combined facade-decking element and carried out as board-on-board cladding.
(2) North-oriented, vertical cladding: boards (25 × 100 × 500 mm^3) were mounted vertically on a combined facade-decking element and carried out as board-on-board cladding.
(3) Horizontal single layer (decking): boards (25 × 100 × 500 mm^3) were exposed horizontally on two bearings of a combined facade-decking element.

For each exposure type three replicate specimens were provided with electrodes for daily MC and temperature recordings. The MC was measured 10 mm under the surface. Specimens of European larch sapwood (*Larix decidua* L.) and Douglas fir sapwood (*Pseudotsuga menziesii* Franco) contained heartwood portions, which were not considered for the measurements. The facade-decking elements were exposed in November 2009 in Hannover-Herrenhausen, Germany.

Fence and terrace decking elements in Hannover, Germany

As described by Brischke *et al.* (2013), continuous moisture and temperature recordings were furthermore carried out on fence posts (1400 × 75 × 75 mm^3), pickets (900 × 40 × 100 mm^3) (Figure 2) and terrace decking consisting of two bearings (760 × 50 × 80 mm^3) and six boards (1000 × 120 × 25 mm^3) (Figure 3) between August 2008 and August 2011. Three replicate assemblies were made from planed Scots pine sapwood, Norway spruce and Douglas fir; afterwards instrumented and exposed on the test site of the Institute of Vocational Sciences in the Building Trade (IBW) in Hannover-Herrenhausen. The fence posts were buried directly in the ground; the decking elements were placed on pavers. The whole test field

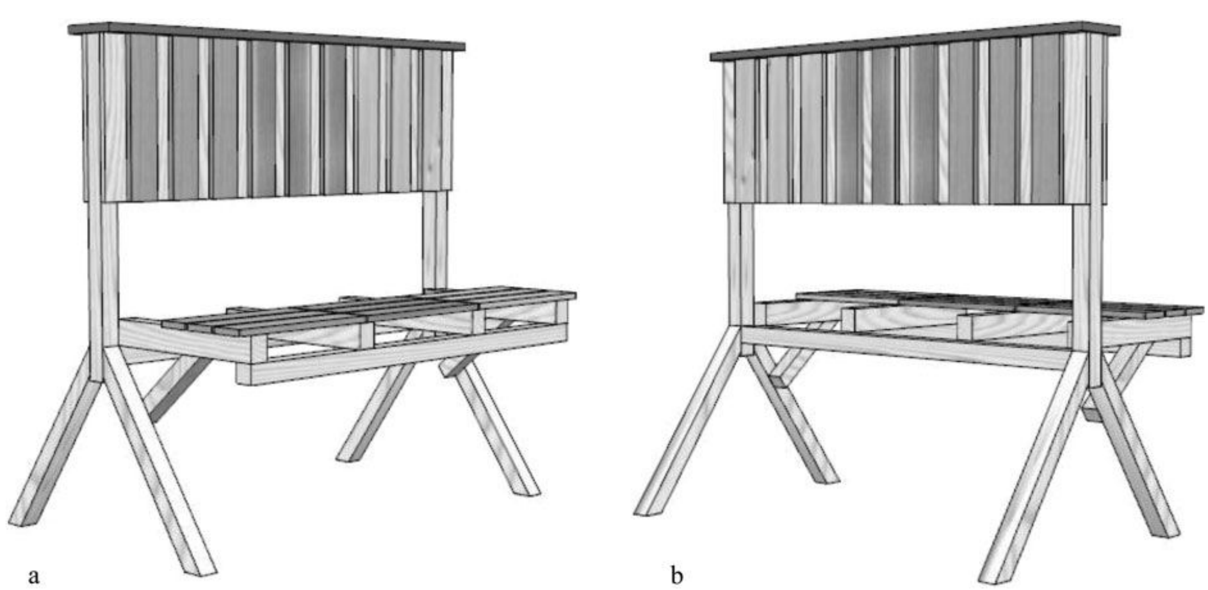

Figure 1. Test set-up for moisture monitoring. (a) Front side of facade-decking element, South oriented. (b) Back side of facade-decking element, North oriented.

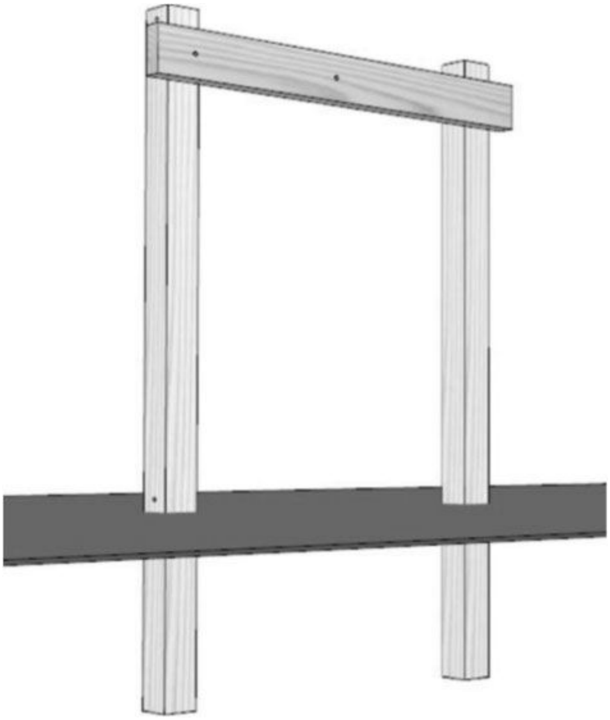

Figure 2. Fence element; measuring points are marked with dots (a fifth non-visible measuring point is located in the post behind the picket).

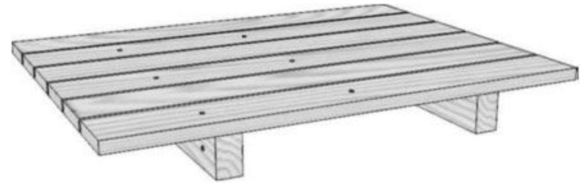

Figure 3. Decking element; measuring points are marked with dots.

was covered with a water-permeable horticultural foil to protect the test devices from growth of grass and other plants. Measurement points were set at a depth of 15 mm on differently severe exposed positions on the assemblies: On the fence posts close to the ground, close to the picket and above the picket; on the pickets close to the post and centrally between two posts; on the decking boards close to the support and centred between two supports; and on the decking supports. For each parameter combination n = 3 moisture electrode pairs and an additional temperature sensor was installed.

Posts with different construction details in Hannover, Germany

The MC and wood temperature were also monitored for posts made from Norway spruce (*Picea abies* Karst.) with a cross section of 9 × 9 cm^2 and a length of 83 cm. Figure 4 shows the different design details used which are described in detail by Wulf

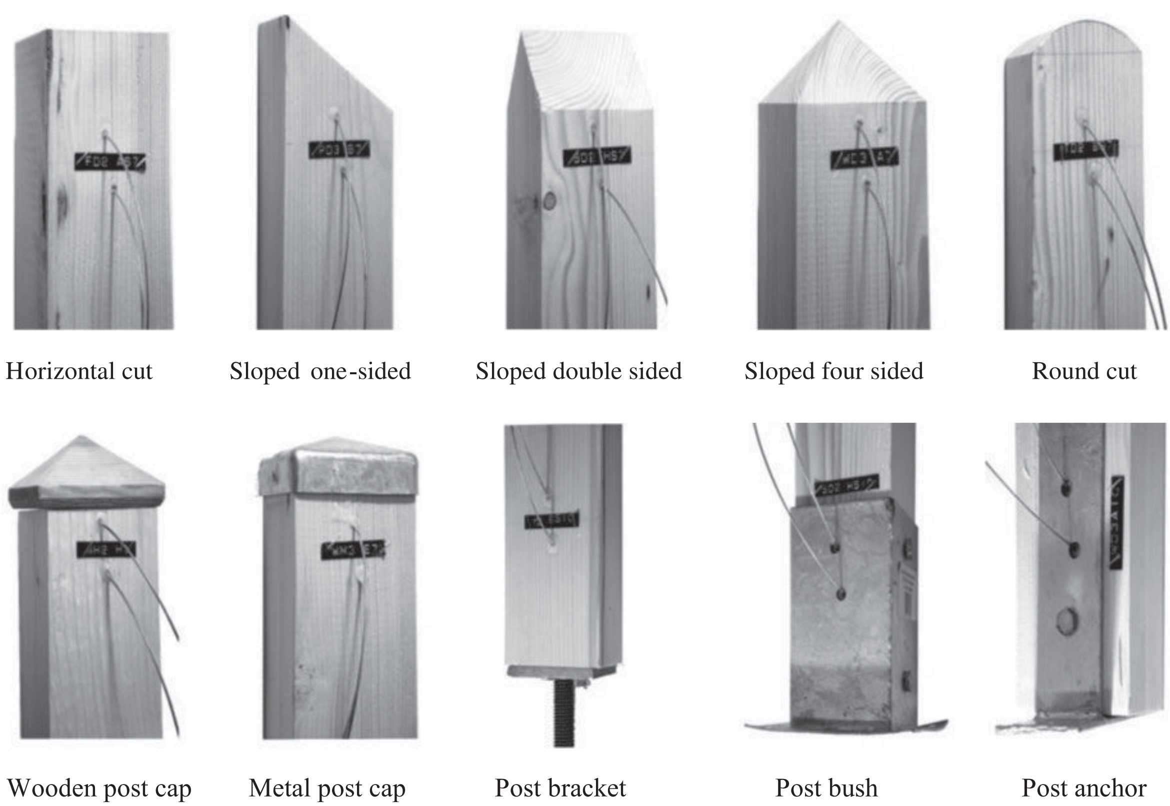

Figure 4. Construction details of post caps and post bearing with glued electrodes.

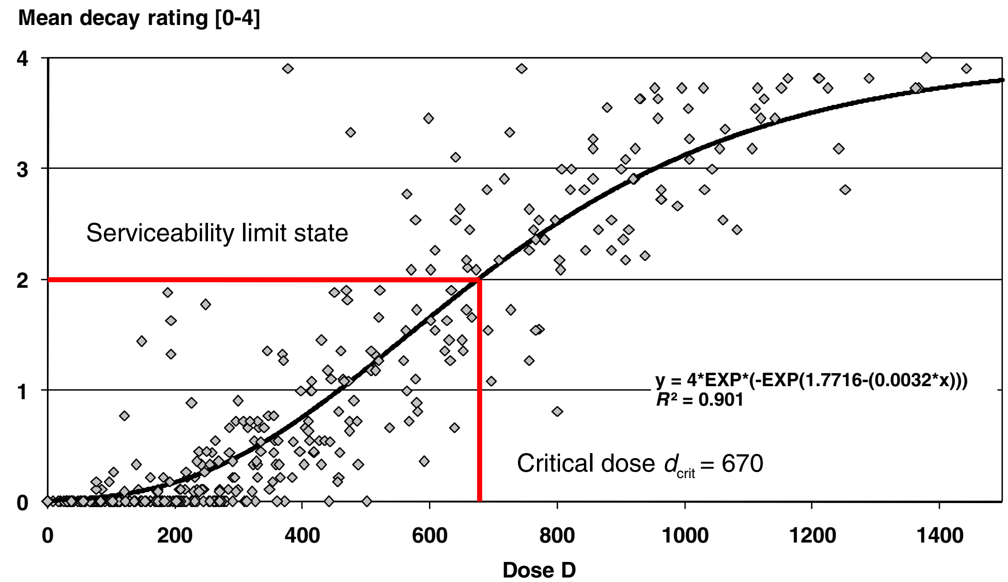

Figure 5. Relationship between the dose D and the mean decay rating according to EN 252 (2012) of Scots pine sapwood and Douglas fir heartwood specimens exposed at 23 different field test sites (each dot represents the mean decay rating for one wood species at one exposure site at a certain time of exposure; black line: Gompertz smoothing function), adapted from Brischke and Rapp (2010).

(2011). For each detail $n = 3$ replicates were produced. The post bearings were exposed within and outside the splash water zone (50 cm above ground). Additionally, three posts with metal bearing were buried in ground. Measurement points were set at a depth of 15 mm on different heights: 10, 25 and 77 cm. For the posts buried in the ground an additional measuring point was installed at the ground area. Wood temperature was measured for all specimens on a height of 25 cm.

Terrace decks in Ås, Norway

To compare the influence of climate at different test sites on the moisture performance, additional wood MC data were recorded on terrace decks, made from Scots pine sapwood and Scots pine heartwood, within the Norwegian research project "Climate Life", exposed at the test site in Ås, Norway.

The boards (25 × 100 × 500 mm^3) were mounted on support beams from the same material and the whole element was exposed horizontally on concrete supports 10 cm above ground. MC was measured in the centre of each specimen. Wood temperature was not recorded. The air temperature, which was recorded at a weather station of the Norwegian University of Life Sciences nearby the test site, was used to calculate the respective wood MC.

Moisture performance indicators

The number of wet days has been considered to estimate the durability of the wood species in terms of their moisture performance. Therefore, the number of days with MCs above 25%, which were considered as lower threshold for fungal activity (Schmidt 2006, Brischke 2007), was determined.

Furthermore, a dose–response performance model for above ground decay as described by Brischke and Rapp (2010) and shown in Figure 5 was applied to the recorded MC and temperature data from the selected test sites. For comparative analysis the total daily dose D (= cumulated daily dose over time) was determined. Therefore, the moisture induced dose component d_u (Equation 1) and the temperature induced dose component d_T (Equation 2) were calculated according to the following equations:

$$d_u = 6.75 \bullet 10^{-10}\, u^5 - 3.50 \bullet 10^{-7}\, u^4 + 7.18 \bullet 10^{-5} u^3 - 7.22 \bullet 10^{-3}\, u^2 + 0.34\, u - 4.98; \text{if } u \geq 25\% \quad (1)$$

$$d_T = 1.8 \bullet 10^{-6}\, T^4 + 9.57 \bullet 10^{-5}\, T^3 - 1.55 \bullet 10^{-3}\, T^2 + 4.17 \bullet 10^{-2}\, T; \quad \text{if } T_{\min} > -1°\text{C and } T_{\max} < 40°\text{C} \quad (2)$$

d_u MC induced daily dose
d_T temperature induced daily dose
u daily MC recorded at 0:00 h
T daily average wood temperature
T_{min} daily minimum temperature
T_{max} daily maximum temperature

To consider the differently severe impact of u and temperature on decay the weighting factor a was added (Brischke 2007) to calculate the daily dose as follows (Equation 3):

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

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

Thereby the dose is defined as material–climate index. The response is considered to be the mean decay rating according to EN 252 (2012).

Service lives were estimated according to Equation (4) and Figure 5 using a mean decay rating of 2 (=moderate decay) as limit state. Any decay rating above this limit state means that the serviceability is no longer given. A critical dose d_{crit} = 670 is needed to be summed up to reach the limit state. In the following the expected SL was considered to be the quotient of the critical dose d_{crit} and the mean annual dose d_a.

Service lives were estimated using a mean decay rating 2 (=moderate decay) as limit state corresponding to a critical dose d_{crit} = 670.

$$\text{ESL} = \frac{d_{crit}}{d_a}\,[\text{yr}] \quad (4)$$

Decay assessment

The distribution and maximum degradation depths of fungal decay were assessed for fence post every year using a pick test. Here a pointed knife is pricked into the specimens and backed out again. The fracture characteristics of the splinters as well as depth and appearance was assessed visually, referred to the different decay types and evaluated.

Results and discussion

Impact of wood species

The number of critical days differed significantly for the combined facade-decking element between the various wood species and their orientation. Furthermore, the dose values differed in dependence of wood species and orientation and consequently also varying SL was estimated (Table II).

A clear relationship between moisture load and orientation of the facade elements could not be verified. It was expected that all wood species at the south-oriented facade received higher moisture loads due to higher driving rain. This was also described by Lauenstein (2010) and Nore *et al.* (2007) who reported that test elements oriented to the south showed higher MCs in terms of high wind-driven rain loads because southwest is the weather side in central Europe and high relative humidity close to the surface due to evaporation of surface water in times of re-drying. Also Auld *et al.* (2007) supported these results by describing wind-driven rain as the moisture source that can impact the most on the performance of a building envelope. On the

Table II. Number of days with a wood MC $u \geq 25\%$ # [*d*], mean annual dose d_a [−] and ESL [yr] for the different wood species at the north- and south-oriented facade and the horizontal decking of the combined facade-decking element in Hannover, Germany (material climatic-related measures are based on the years 2009–2012 corresponding to a total of 34 months).

	North-oriented facade			South-oriented facade			Decking		
	#	d_a	ESL	#	d_a	ESL	#	d_a	ESL
Wood species	[*d*]	[−]	[yr]	[*d*]	[−]	[yr]	[*d*]	[−]	[yr]
Scots pine sapwood	37	0.79	846	209	13.45	50	633	82.37	8
Scots pine heartwood	0	0.00	∞	0	0.00	∞	0	0.00	∞
Larch sapwood	0	0.00	∞	0	0.00	∞	558	3.61	185
Larch heartwood	0	0.00	∞	0	0.00	∞	16	0.64	1041
Norway spruce	0	0.00	∞	0	0.00	∞	54	2.40	273
Norway spruce OHT	0	0.00	∞	0	0.00	∞	0	11.62	58
Douglas fir sapwood	143	13.46	50	156	6.36	105	297	23.91	25
Douglas fir HD	175	9.26	72	134	5.58	120	301	22.50	30
Douglas fir LD	210	6.04	111	248	10.80	62	463	38.85	17
Western Red Cedar	0	0.00	∞	0	0.00	∞	70	8.07	83
Beech	0	0.00	∞	0	0.00	∞	47	1.87	359
English oak	149	5.18	123	206	7.12	94	423	22.99	23
Black locust	0	0.00	∞	0	0.00	∞	0	0.00	∞
European Ash	0	0.00	∞	0	0.00	∞	11	1.05	64
European Ash OHT	15	0.00	∞	0	0.00	∞	0	0.00	∞

Note: Measures for European Ash, European Ash OHT and Norway spruce OHT are based on the years 2011–2012 corresponding to a total of 365 days.

other hand, solar irradiation and higher wind loads on the south-oriented facade fostered re-drying. Therefore, high permeable wood species like Scots pine sapwood (Willeitner and Schwab 1981) received most likely higher dose values on the south-oriented facade whereby more refractory wood species, like larch, experienced higher dose levels at the north orientation where re-drying was inhibited by less wind loads on the leeward and less solar irradiation. Another cause for the lack of correlation between the orientation and the MC can be seen in the measuring depth of 10 mm under the surface. Wood MC close to the surface is expected to follow much faster the changing micro- and mesoclimatic conditions compared to the MC in deeper areas but the decay was to be expected in these deeper areas where moisture/wetting can be established.

For the horizontal decking Scots pine sapwood (633 days), Douglas fir LD (463 days), Douglas fir HD (301 days) and Douglas fir sapwood (297 days) showed the highest count of critical days and thus received highest dose values (Table II). Consequently shortest service lives were determined for Scots pine sapwood (8 years) and for Douglas fir LD (17 years). Also for Douglas fir sapwood (25 years) a relatively short SL was predicted.

The dose values and service lives for the horizontal exposition (decking) differed significantly to the values of the vertical exposition (facades). Standing water on horizontal surfaces due to precipitation consequently led to higher moisture loads. To draw the conclusion that higher moisture loads were leading to shorter SL estimates is also supported by Auld *et al.* (2007) who stated that the deterioration rate of materials increases with increased time of wetness. However, a relatively poor moisture performance in horizontal exposition can not necessarily be transferred to the performance on a vertical cladding. For example, larch sapwood performed relatively poor in the horizontal decking with a count of 558 days with $u > 25\%$ but for none of the vertical expositions a dose was induced. In retrospect the ESL for most of the wood species in the vertical exposition was endless. Since a dose value of 0 leads to a SL of ∞, which appears to be "unrealistic" but still indicates a negligibly small risk of fungal degradation. Furthermore, after 3 years of exposure the results need to be seen as preliminary for the vertical exposition because of lower moisture loads compared to the horizontal exposition. Also the probability of getting one severe year during the measuring period was quite small.

Table III. Mean annual dose d_a [–] and ESL [yr] for decking made from different wood species in Hannover, Germany.

Wood species	Commodity	d_a [–]	ESL [yr]
Douglas fir	Terrace board centre	14.60	46
	Terrace board at contact face	22.27	30
	Bearing	32.27	21
Scots pine sapwood	Terrace board centre	102.37	7
	Terrace board at contact face	96.57	7
	Bearing	66.10	10
Norway spruce	Terrace board centre	58.93	11
	Terrace board at contact face	50.83	13
	Bearing	36.13	19

Table IV. Mean annual dose d_a [–] and ESL [yr] for fence elements made from different wood species in Hannover, Germany.

Wood species	Commodity	d_a [–]	ESL [yr]
Douglas fir	Picket close to post	1.46	459
	Picket centered	0.23	2913
	Post above picket	24.41	28
	Post close to picket	2.60	258
	Post close to ground	13.16	51
Scots pine sapwood	Picket close to post	48.66	14
	Picket centered	15.57	43
	Post above picket	46.94	14
	Post close to picket	20.72	32
	Post close to ground	76.71	9
Norway spruce	Picket close to post	13.71	49
	Picket centered	2.27	295
	Post above picket	41.28	16
	Post close to picket	10.48	64
	Post close to ground	41.06	16

Impact of detailing

Decking and fence elements. The ESL of the decking varied between 7 years for Scots pine sapwood terrace boards and 46 years for Douglas fir boards (Table III). For the fence elements Scots pine sapwood showed with 9 years at the post close to the ground the shortest ESL, whereas Douglas fir performed best at the picket centre with 2913 years (Table IV). Not surprising the shortest SL was predicted for Scots pine sapwood followed by Norway spruce and Douglas fir. A clear

Figure 6. Failure of a fence post made from Douglas fir after only three years of exposure at the test site of the IBW in Hannover, Germany.

differentiation between the two examined components became not apparent. The contact faces at the decking had no negative effects in terms of a higher fungal degradation which might be explained by generally high moisture loads and not very distinct formation of water traps. Douglas fir revealed the longest ESL for the bearing whereby it was shortest for Scots pine sapwood and Norway spruce.

In contrast, the differences in ESL were significant for all three wood species between the fence pickets with and without contact to the fence post (Table IV). As expected the highest moisture load occurred in the post close to the ground. Here SLs between 6 years for Scots pine sapwood and 35 years for Douglas fir heartwood were estimated. The post above picket (close to the upper end grain) was found to be the second severe position followed by the picket close to the post. This was due to the contact face where drying was hindered due to the formation of a water trap. Also Gaby and Duff (1978) as well as Hjort (1997) reported that decay in wooden structures often starts in joints where water gets trapped especially after rain episodes. In contrast, the free ventilated picket centre suffered from low moisture loads. Remarkably was the early failure of a fence post made from Douglas fir after only 3 years although a SL of 51 years was predicted. Figure 6 shows the failure of the post in the ground. These findings were indicating that the prediction model used for the estimation of the expected SL is only suitable for exposures above ground.

Posts with different construction details. The influence of detailing on the moisture performance was investigated for typical post head types. Table V shows the count of "critical days" with u > 25% and the annual dose for each variation, which both differed significantly between the various post head types.

Table V. Count of critical days with a MC above 25% # [d] and annual dose d_a [–] for typical post head details in Hannover, Germany.

Post head	# [d]	d_a [–]
Horizontal cut	23	4
Sloped one-sided	18	3
Sloped double sided	22	3
Sloped four sided	0	0
Round cut	40	8
Wooden post cap	104	22
Metal post cap	38	8

Figure 7. Cracking on a wooden post cap exposed on the weathering station of the IBW in Hannover, Germany.

In the group of post heads without a cap the post with the round cut experienced the highest dose whereby the four sided sloped post head experienced no dose at all. Surprisingly, the horizontal cut was only the second severe design detail. Colling (2000) stated that radiused and angled edges supported the run off of water and can therefore be seen as a less severe construction. The wooden post cap showed the highest dose value of all post heads whereby the metal post cap experienced the same as the round cut post head. Figure 7 displays the explanation for these findings. Large cracking of the wooden bearing, due to high changes in MC which led to high tensions in the cap, led to high moisture ingress in the cross section. In addition, the cap hindered

Table VI. Count of critical days with a MC above 25% # [*d*] and annual dose d_a [−] for different post bearings outside and inside the splash water zone and buried in ground in Hannover, Germany.

	#	d_a
	[*d*]	[−]
Post bearing outside the splash water zone		
Post bracket	25	4.4
Post bush	289	94.3
Post anchor	121	25.9
Post bearing inside the splash water zone		
Post bracket	13	2.7
Post bush	295	103.3
Post anchor	97	23.1
Post buried in ground (MC 10 cm above ground)	48	9.2
Post buried in ground (ground surface section)	294	92.0

Table VII. Mean annual dose d_a [−] and ESL [yr] for Scots pine sapwood and Scots pine heartwood on a horizontal decking exposed in Ås, Norway

	Decking	
	d_a	ESL
Wood species	[−]	[yr]
Scots pine sapwood	67.6	10
Scots pine heartwood	29.5	23

re-drying of the cross section because it protected the cross section from wind loads.

Significant differences regarding "critical days" as well as the induced dose became obvious for different post bearings (Table VI).

The highest count of "critical days" was determined for the post bush (289 days) followed by the post anchor (121 days) which were exposed outside the splash water zone. Consequently highest dose values were induced for both post bearings. The design of the post anchor and post bush formed a water trap and hindered re-drying. This led to a higher moisture stress of the post which is also supported by Colling (2000) who stated that these two post bearings were seen as critical tie point supporting standing water on the construction. In contrast, the internal support bearing of the post bracket formed no water trap and allowed re-drying of the post.

The impact of splash water on the MC is shown in Table VI. Highest dose values were induced for the post bush with 103.3 and in the ground surface section for the post buried directly in the ground (92.0). In the first instance this was due to the formation of a water trap by the post bush and secondly to direct ground contact which led to constant moisture ingress through the soil which accumulated moisture over longer periods. For the measuring point 10 cm above ground the dose for the post buried in the ground was 10 times less than directly in the ground area.

Compared to the dose values for the post bearings outside the splash water zone no significant differences became apparent for the different design details. It became obvious that the design of the bearing is the more dominant factor compared to occurring moisture stress due to splash water. Therefore, it can be stated that the post bracket represented the best design version for a post bearing within this study.

Impact of different climate conditions

Table VII shows the mean annual dose and the ESL for the two horizontal deckings exposed in Ås, Norway. Plausible service lives were estimated for Scots pine sapwood with 10 years and Scots pine heartwood with 23 years. Also here differences in moisture performance of sapwood and heartwood were found. The ESL for Scots pine sapwood was similar to that in Hannover (8 years; Table II). Scots pine heartwood performed differently. With 23 years a significantly shorter SL was estimated for the decking in Ås compared to Hannover (∞).

Different climatic loads (driving rain, precipitation, relative humidity) which led to different moisture loads were observed between Ås and Hannover. Additionally, the potential for re-drying in Hannover was higher due to a higher distance to ground, longer periods with higher temperatures and the exposition of the combined facade-decking element on the roof of a building where higher wind loads fostered re-drying. The impact of climatic loads on the moisture performance of wooden claddings was also described by Engelund *et al.* (2009). They reported that the annual variation of weekly averages of the MC of coated wooden claddings appeared to follow the variation of temperature and relative humidity (Engelund *et al.* 2009). No evidence of a significant effect of precipitation on the weekly average MC of coated claddings was found (Engelund 2007) but for the untreated reference racks the precipitation attributed significantly to the average weekly MC.

Predicted SL and outdoor performance

To investigate if the SL estimates could be verified by the outdoor performance of the different test set-ups, the onset and severity of fungal decay were

Figure 8. Severe decay caused by brown rot on the contact area of the picket and the post of a fence element made from Norway spruce after 4 years exposed at the test field of the IBW in Hannover, Germany.

Figure 9. Failure of a fence post on the ground area made from Norway spruce after 4 years exposed at the test field of the IBW in Hannover, Germany.

assessed every year for the wooden fence elements made from different wood species.

The longest SL estimates were calculated for the centre of the picket of fence elements. For pickets a SL estimates of 259 years for Norway spruce and 43 years for Scots pine sapwood were calculated (Table IV). The pickets made from Scots pine sapwood, which were exposed for 3 years outdoors, showed no signs of attack by wood destroying fungi.

The post above the picket showed first large cracking on the cross section which consequently fostered high moisture ingress. Therefore, only a short SL with 16 years was estimated for the post head made from Norway spruce (Table IV).

The post above the picket (close to the upper end grain) was found to be the second severe position followed by the picket close to the post. Here relatively short service lives were estimated with 14 years for Scots pine sapwood and 28 years for Douglas fir heartwood. Figure 8 shows a severe attack by decay fungi with a maximal degradation depth of 5 mm caused by brown rot at the contact area between the picket and the post made from Norway spruce after 4 years of outdoor exposure. This was contrary to the SL estimate of 64 years. As can be seen in Figure 8, the distribution of the decay was in the contact face of the post and the picket whereas the wood MC was measured in the middle of the picket. As a consequence the high MC at the contact face was not recorded which, as a result, led to a different ESL. Also the occurrence of brown rot which usually leads to fast decay rates reasoned the found differences.

As expected highest moisture loads occurred at the ground area of the posts. Here SLs between 6 years for Scots pine sapwood and 51 years for Douglas fir

Figure 10. Decay on a fence post on the ground surface area made from Douglas fir after 3 years exposed at the test field of the IBW in Hannover, Germany.

heartwood were estimated. The differences between the wood species were also verified by the findings of the decay assessment. Figure 9 shows the failure of a fence post made from Norway spruce after 4 years of exposure in the ground. In contrast, Figure 10 shows a fence post made from Douglas fir heartwood which, in contrast to Figure 9, showed only slight attack after 3 years exposure in the ground.

In retrospect no significant correlation between the SL estimations and the decay performance of the tested wood species and construction details could be established. Reasons can be seen in the underlying calculation model which is based on results of double layer test set-ups representing UC 3.2 (EN 335 2013) and which are not easily transferable to UC 4. Furthermore, there are a lot more organisms involved in the degradation process in ground compared to above ground expositions. The decay activity in a field is influenced by different factors like substrate quality, occurrence of different microbes and climatic conditions (Meyer *et al.* 2013). Fungal attack is also fostered by nutrients in the ground and mycelia of the fungi which allowed better access to the wooden structure whereby the degradation process can start immediately. Additionally, the moisture distribution within the double layer (horizontal, standing water) differs significantly to the moisture distribution on the fence posts (vertical run-off water).

Conclusions

The present study showed that in principal plausible SL can be estimated for different materials, design details and exposures. Nevertheless, it can be stated that occurring uncertainties were due to factors influencing the real-life performance of wood used outdoors which are not yet included in the underlying calculation model. In first instance this can be explained by the ESL model which is based on results of white rot and soft rot attack and therefore cannot reflect fast degradation processes of brown rot attack. Second, the model is not adequate for wooden components in ground exposure because it is based on results for UC 3.2 (EN 335 2013) which are not transferable to UC 4. However, long-term wood MC and wood temperature measurements were found to be applicable for all tested wood materials. Dose values as well as SL estimates differed in dependence of wood species and design detailing. Detailing had a significant impact on the outdoor performance and expected SL. The induced dose and ESL for the horizontal exposition differed significantly to the values of the vertical exposition. A relationship between moisture loads and orientation of the vertical cladding could not be verified, but climatic loads differed for different test sites. No relationship between SL estimates and the real-life decay performance of the tested commodities could be established.

Nevertheless, moisture monitoring allowed for both, characterisation of material quality in terms of moisture performance, and secondly for quantification of various factors having an influence on SL of wooden constructions. In terms of testing outdoor performance of wood in less severe conditions (UC 3.1, UC 3.2, EN 335 2013), the results showed that moisture performance-based durability testing can provide additional information about the respective material itself as well as about its performance in different exposure situations. The results of the study recommend taking more advantage of the additional information provided by continuous MC measurements, in particular with respect for SL prediction issues.

The prediction model has the potential to save time when testing timber and timber products exposed outdoors because there is no need to await the onset of decay. On the other hand, it became apparent that the accuracy strongly depends on factors impacting on the commodities and the exposure situation. Also for ground exposure as well as fast degradation processes caused by brown rot fungi the prediction model is still too vague. Therefore, additional research is currently running to include brown rot in the underlying calculation model as well as other factors like the material-inherent resistance of different wood species. However, for most wood-based materials and potential design solutions moisture performance data are still lacking, wherefore more enhanced studies are needed including the development of reliable models including more factors having a direct and indirect impact on the moisture performance of wooden commodities. Nevertheless, more intense research on this topic is needed and already initiated.

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6.11 Publication XI: Moisture content and decay of differently sized wooden components during 5 years of outdoor exposure

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ORIGINAL

Moisture content and decay of differently sized wooden components during 5 years of outdoor exposure

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Abstract Within this study, the effect of different cross section dimensions on wood moisture content (*MC*), time of wetness (*ToW*), and fungal decay development of Norway spruce (*Picea abies* Karst.) and Scots pine sapwood (*Pinus sylvestris* L.) was examined. Specimens with ten different quadratic and rectangular cross sections were exposed horizontally in Hannover, Germany, and monitored for a period of 5 years. *MC* and temperature were recorded daily and data sets were submitted to a dose–response model based on material climatic data for evaluating the respective decay risk of the different specimen types. After 5 years of outdoor exposure timber dimension was found to be correlated neither with wood *MC* nor with decay development. However, time of wetness and decay were more severe in pine sapwood compared to spruce. Regarding onset and further development of decay, cracks as well as contact faces turned out to be weak points, but interior rot was observed as well. Brown rot, which occurred predominantly in the specimens, was partly difficult or even impossible to detect from the outside, but caused severe degradation also in small-dimensioned samples.

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1 Introduction

The resistance of timber products to wood-destroying organisms is the result of its inherent durability, its ability to take up and release moisture, and the respective exposure conditions. Wood exposed outdoors tends to change its dimensions due to swelling and shrinking with varying moisture. The susceptibility of a wooden component to the formation of cracks is caused by tensions occurring on its surface and its interior parts (e.g. Sandberg 1999). Due to the anisotropy of wood sorption, capillary water uptake and in particular swelling and shrinking are affected by the orientation of the annual rings and have a decisive influence on cracking of wood exposed outdoors (Sandberg 1999, 2005; Müller 2000; Sandberg and Söderström 2006).

The formation of cracks is more pronounced on tangential than on radial surfaces, where latewood and earlywood are alternating and thus shrinkage movements and resulting stresses are buffered (Sandberg 1999; Sandberg et al. 2013). Furthermore, sapwood is usually more susceptible to crack formation than heartwood, because it absorbs more water and therefore undergoes stronger moisture-related movements in wood (Sandberg 2008). In addition to the formation of macroscopically visible cracks, which increase the uptake of liquid and vaporous water (Rapp and Peek 1999; Brischke and Melcher 2015), the wettability of wood increases with proceeding exposure time (Kalnins and Feist 1993) due to micro-cracks and chemical alterations of components on the wood surface. As shown for instance by Müller (2000) the formation of cracks is also influenced by the size of the wooden component and its surface–volume ratio respectively. The risk of crack formation is following the width of a wooden component. Therefore wooden members with small cross section generally show less cracks than bigger sized ones, which is most likely attributed to the occurring shrinkage stresses. It is still controversially discussed to what extent higher wood moisture content (*MC*) in larger dimensioned components is the result of their lower surface-volume ratio and thus lower re-drying potential (e.g. Meierhofer and Sell 1979; Sell 1980; Müller 2000; Augusta 2007; Meyer et al. 2014). Cracks are potential entry ports for moisture (Adachi et al. 2004), but also for spores of wood-destroying fungi. Cracks have the potential to initiate high MC and consequently increase the risk of decay (Austigard et al. 2014). However, formation of cracks does not necessarily lead to fungal infestation, and interior rot can occur as well as rot starting from less durable sapwood portions as shown for split oak fence posts by Brischke and Rolf-Kiel (2010).

Without controversy the dimension of wooden components is affecting the formation of cracks and these are impacting on its moisture performance when exposed to the weather. However, quantitative information to what extent both factors, crack formation and potentially increased *MC*, are affecting the overall durability of wooden components is still lacking, but essential for service life prediction of timber structures and for durability testing under field conditions. As demonstrated by Meyer et al. (2013, 2014) a wide range of methods for durability field testing of wood exists around the globe, but test results suffer from limited comparability. Beside divergent exposure conditions, the methods vary in terms of specimen size, shape and constitution. While for instance Lap-joint specimens CEN/TS 12037 (CEN 2004) approximately reflect the size of real building components in wooden post construction (Zahora et al. 2013), miniaturized specimen types such as pegs (Cookson et al. 2014) or mini-stakes (Meyer et al. 2013) were designed to accelerate tests, but will not experience moisture-induced stresses as real-size components would do. For interpretation of field test results it is consequently of immanent importance to consider the effect of size and shape and to allow utilizing test data for performance and service life prediction.

This study aimed therefore at examining the effect of different cross section dimensions on the moisture content, time of wetness, crack formation and fungal decay development of wooden specimens made from Norway spruce (*Picea abies* Karst.) and Scots pine sapwood (*Pinus sylvestris* L.) exposed horizontally in Hannover, Germany, and monitored for a period of 5 years.

2 Materials and methods

2.1 Specimens and outdoor exposure

Specimens with a length of 500 mm and ten different cross sections were prepared from Scots pine sapwood and Norway spruce, both from central Sweden. Half of the cross sections were quadratic, half were rectangular (Table 1), whereby, apart from the biggest cross sections, specimens were axially matched if possible. For the biggest dimension (100 × 100 mm^2) the sapwood portion of the Scots pine specimens was less than one-third of the cross section. For all wood species and cross sections n = 5 replicates were exposed outdoors on test rigs with 1 m height (Fig. 1) on the roof of a faculty building at Leibniz University in Hannover, Germany.

To reduce the effect of contact with bearings on the decay development, the specimens were exposed on rhombic supports made of Norway spruce. The specimens were exposed with their tangential surfaces upwards. The distance between specimens on the rigs was approximately 10 mm and the margin specimens were sheltered by extra boards to assure homogenous exposure conditions for all test specimens. The initial *MC* of the specimens was between 10 and 15 %.

2.2 Moisture and temperature recording

Wood *MC* and temperature were measured daily on n = 3 replicate specimens of each group for a period of 2 years between 12.09.2010 and 12.09.2012. Therefore conductively glued stainless steel electrodes were used for electrical resistance measurements. The measurement system using mini data loggers (Type Materialfox mini, Scanntronik GmbH) has been described in detail by Brischke et al. (2008). Wood temperature measurements and recordings were made in parallel using mini data logger (Type Thermofox mini, Scanntronik GmbH). Temperature data obtained were used to characterize the climatic load and for temperature compensation of the electrical resistance measurements. Wood species-specific resistance characteristics were used for calculating the wood moisture content according to Brischke et al. (2008).

The electrodes were positioned centrally in all directions, i.e. in depth, width, and length, in all specimen groups. Only the groups Q1 and Q2 were equipped with a second pair of electrodes which was glued in approximately 20 mm beneath the upper surface.

2.3 Decay assessment

Fungal decay was assessed annually and rated according to EN 252 (CEN 2015) as described in Table 2. Therefore a pick-test was performed using a knife to determine depth and distribution of decay in terms of softening of the wood substance.

Since the EN 252 rating scheme has been developed for specimens with a cross section of 25 × 50 mm^2 only, it was necessary to modify the scheme for the other specimen groups.

Table 1 Dimension, cross section and coverage areas, and cross section area—coverage ratios of the different specimen groups

	Width (mm)	Height (mm)	Cross section area A (mm^2)	Coverage area C (mm^2)	C/A ratio (–)
Quadratic					
Q1	100.0	100.0	10,000	200,000	20
Q2	70.7	70.7	4999	141,400	28
Q3	50.0	50.0	2500	100,000	40
Q4	35.3	35.3	1246	70,600	57
Q5	25.0	25.0	625	50,000	80
Rectangular					
R1	100.0	50.0	5000	150,000	30
R2	70.7	35.3	2496	106,000	43
R3	50.0	25.0	1250	75,000	60
R4	35.3	17.6	621	52,900	85
R5	25.0	12.5	313	37,500	120

Fig. 1 Outdoor exposure of specimens. **a** Minimized contact area between specimen and bearing through rhombic supports. **b** Samples mounted with screws and washers. **c** Side shelter boards. **d** Set-up overview (Photo: Mehlich 2009)

Table 2 Rating scheme for fungal decay according to EN 252 (CEN 2015)

Rating	Description	Definition
0	Sound	No change perceptible by the means at the disposal of the inspector in the field. If only a change of color is observed, It shall be rated 0
1	Slight attack	Perceptible changes, but very limited in their intensity and their position or distribution: changes which only reveal themselves externally by superficial degradation, softening of the wood being the most common symptom
2	Moderate attack	Clear changes: softening of the wood to a depth of at least 2 mm over a wide surface (covering at least 10 cm^2) or by softening to a depth of at least 5 mm over a limited surface area (covering less than 1 cm^2)
3	Severe attack	Severe changes: marked decay in the wood to a depth of at least 3 mm over a wider surface (covering at least 25 cm^2) or by softening to a depth of at least 10 mm over a more limited surface area
4	Failure	Impact failure of the stake in the field

Table 3 Modified decay assessment scheme based on minimum remaining cross section and maximum depth of decay according to EN 252 (CEN 2015)

	Rating 0	Rating 1	Rating 2	Rating 3	Rating 4
Minimum remaining cross section (%)	100	88	67	48	0
	Maximum depth of decay [mm]				
Quadratic					
Q1	0	3.0	9.0	15.0	100.0
Q2	0	2.0	6.0	10.5	70.7
Q3	0	1.5	4.5	7.5	50.0
Q4	0	1.0	3.0	5.5	35.3
Q5	0	0.5	2.0	4.0	25.0
Rectangular					
R1	0	2.0	6.0	10.0	100.0
R2	0	1.5	4.0	8.0	70.7
R3	0	1.0	3.0	5.0	50.0
R4	0	0.5	2.0	3.5	35.3
R5	0	0.5	1.5	2.5	25.0

Since the maximum depth of decay is determining the minimum remaining cross section at the different rating steps, the latter was used to adopt the rating for the specimens with non-standard cross section. For each specimen group the maximum decay depth was adopted to obtain the same percentage minimum remaining cross section as illustrated in Table 3.

After 5 years of exposure all samples were removed from the test rig and cut perpendicular to the grain 30 and 170 mm from both end-grains as well as in the center of the specimen for inspection. Interior rot—invisible from the outside—was also considered for determining the minimum remaining cross section of the specimens.

2.4 Logistic dose–response performance model (LDR)

The two year data sets were applied to a performance model describing the relationship between the material climate in terms of *MC* and wood temperature and the corresponding fungal decay. The experimental base for the model was field test results from double layer above ground trials performed at 28 different test sites in Europe as described by Brischke and Rapp (2010).

The impact of a general time variation of moisture content *MC* and temperature *T* on the potential for decay can be described by a dose–response function. The total daily dose *D* is a function of one component D_{MC} dependent on daily average of moisture content *MC* and one component D_T dependent on daily average temperature *T*.

$$D = f(D_T(T), D_{MC}(MC)) \tag{1}$$

For *n* days of exposure the total dose is given by

$$D(n) = \sum_1^n D_i = \sum_1^n (f(D_T(T_i), D_{MC}(MC_i))) \tag{2}$$

where T_i is the average temperature and MC_i is the average moisture content for day *i*. Decay is initiated when the accumulated dose reaches a critical dose.

As described in detail by Brischke and Rapp (2010), the cardinal points of the parameters wood temperature and *MC* for fungal growth and decay activity were sought and used to set up polynomial base functions for both dose components (Eqs. 3 and 4). The total dose *D* is then calculated as a function of D_{MC} and D_T according to Eq. 5, where D_T was weighted by a factor a.

$$D_{MC}(MC) = \begin{cases} 0 & \text{if } MC < 25\,\% \\ e \cdot MC^5 - f \cdot MC^4 + g \cdot MC^3 - h \cdot MC^2 + i \cdot MC - j & \text{if } MC \geq 25\,\% \end{cases} \quad (3)$$

$$D_T(T) = \begin{cases} 0 & \text{if } T_{min} < 0^\circ C \text{ or if } T_{max} > 40^\circ C \\ k \cdot T^4 + l \cdot T^3 - m \cdot T^2 + n \cdot T & \text{if } T_{min} \geq 0^\circ C \text{ or if } T_{max} < 40^\circ C \end{cases} \quad (4)$$

$$D = (a \cdot D_T[T] + D_{MC}[MC]) \cdot (a+1)^{-1} \quad \text{if } D_{MC} > 0 \text{ and } D_T > 0 \quad (5)$$

where D = dose [d], D_T = temperature induced dose component [−], D_{MC} = moisture induced dose component [d], MC = daily average moisture content [%], T = daily average wood temperature [°C], T_{min} = minimum wood temperature for the day considered [°C], T_{max} = maximum wood temperature for the day considered [°C], a = temperature weighting factor, e, f, g, h, i, j, k, l, m, n = variables.

The best fit for this model against the available data (Brischke and Rapp 2010) was obtained with the following parameters and the final logistic model function according to Eq. 6. $a = 3.2$, $e = 6.75.10^{-10}$, $f = 3.50.10^{-7}$, $g = 7.18.10^{-5}$, $h = 7.22.10^{-3}$, $i = 0.34$, $j = 4.98$, $k = 1.8.10^{-6}$, $l = 9.57.10^{-5}$, $m = 1.55.10^{-3}$, $n = 4.17$.

The total dose over a certain time period is given by Eq. 2 and the decay rating is given by the dose–response function:

$$DR(D(n)) = 4 \cdot \exp(-\exp(1.7716 - (0.0032 \cdot D(n)))) \quad (6)$$

where DR = decay rating according to EN 252 (CEN 1990), $D(n)$ = total dose for n days of exposure. The effect of temperature is dominating on the total dose. The reason for this is that the empirical data from double layer tests used to fit the model is dominated by observations with continuously high moisture content for pine sapwood. The best fit against these data will therefore primarily reflect the effect of temperature on the decay rating.

The good fit of the dose response function—as indicated through a degree of determination $R^2 = 0.901$—is illustrated for Scots pine sapwood and Douglas fir heartwood in

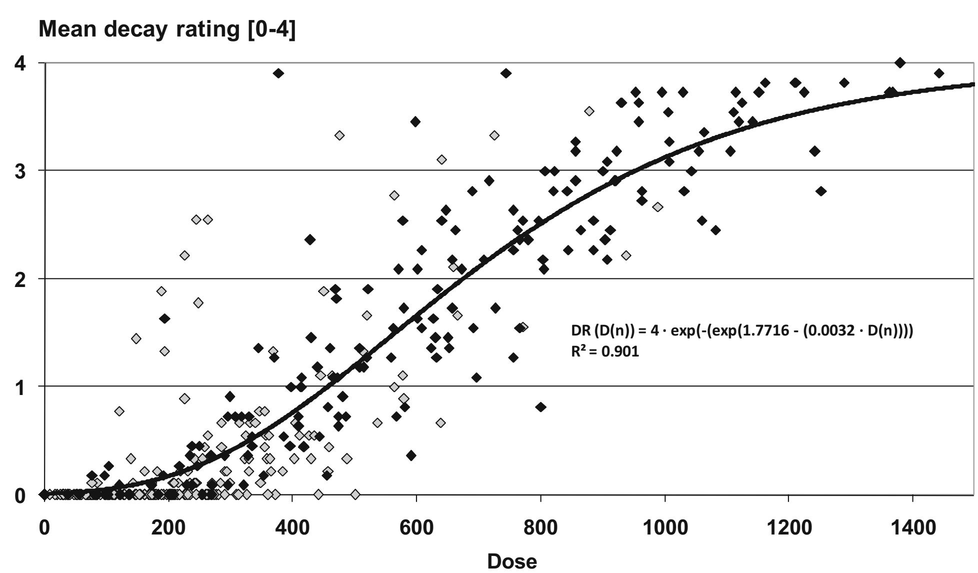


Fig. 2 Relationship between dose and mean decay rating according to EN 252 (CEN 1990) of Scots pine sapwood (*black*) and Douglas fir heartwood (*grey*) exposed at 28 different field test sites using a logistic dose–response model (each *dot* represents the mean decay rating at one exposure site at a certain time of exposure; *black line* Gompertz smoothing function) (figure modified after Brischke and Rapp 2010)

Table 4 Moisture and temperature related characteristics for specimens with different dimensions during 24 months of outdoor exposure

	Scots pine sapwood					Norway spruce				
	Mean MC (%)	ToW (d)*	MC dose D_u (d)	T dose D_T (d)	Total dose D (d)	Mean MC (%)	ToW (d)*	MC dose D_u (d)	T dose D_T (d)	Total dose D (d)
Quadratic										
Q1-center	24.8	297	57	272	105	21.7	114	28	283	25
Q1-20 mm	42.1	630	524	284	272	21.7	144	35	279	29
Q2-center	31.7	592	339	278	243	19.8	65	25	291	18
Q2-20 mm	41.5	669	550	291	301	22.3	197	72	279	47
Q3	34.5	583	411	279	240	19.4	49	14	291	11
Q4	24.5	272	142	284	68	19.9	71	20	285	16
Q5	35.1	462	367	273	180	19.6	71	28	298	21
Rectangular										
R1	32.4	577	348	284	238	19.5	66	17	290	13
R2	31.4	559	332	287	228	20.0	68	19	287	16
R3	36.3	532	394	291	218	19.5	60	25	294	17
R4	28.3	410	275	288	164	19.0	54	16	292	11
R5	29.6	390	293	294	151	20.0	115	46	294	30

* ToW Time of wetness, expressed as number of days with MC $\geq$ 25 %; total exposure time 730 days

Fig. 2. However, there were different outliers, where decay developed faster than predicted by the accumulated dose. This happened in particular at the South-East European sites Ljubljana and Zagreb, where several specimens had been attacked by brown rot, whereas white and soft rot were dominating at most other sites (Brischke and Rapp 2010).

3 Results and discussion

3.1 Wood moisture content and temperature

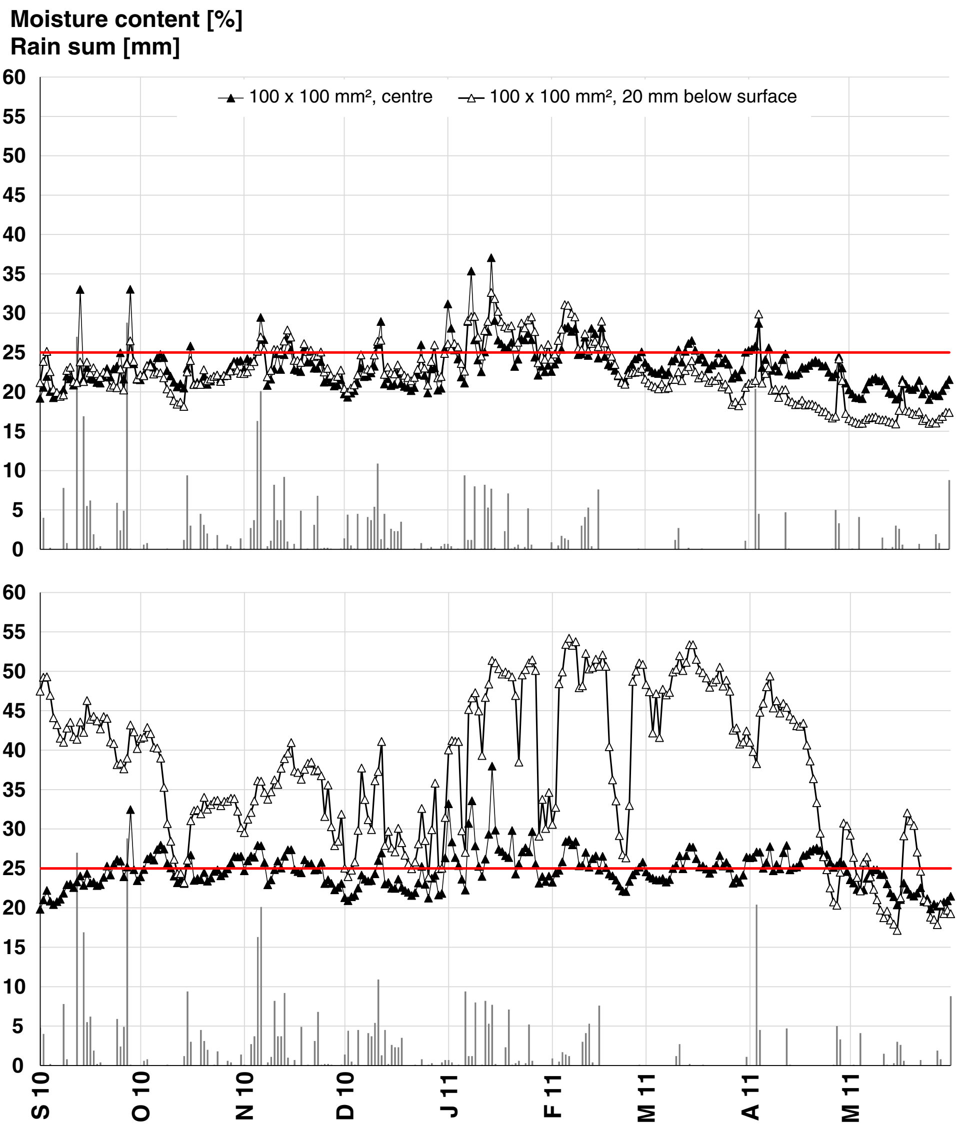
The wood *MC* differed significantly between specimen groups with different dimensions as well as between both wood species. For comparison the average *MC* and *ToW* were calculated over the whole measuring period of two years. A summary is given in Table 4.

In general, the average *MC* was higher in the pine specimens (24.5–36.3 %) than in the spruce specimens (19.0–22.3 %). For a first estimate of the respective moisture induced risk of decay in the different specimen groups the *ToW* was calculated in terms of the number of days with *MC* $\geq$ 25 %, which can be considered as threshold for fungal decay (Schmidt 2006; Brischke and Rapp 2010). As expected, pine sapwood showed higher *ToW* than spruce. However, no clear tendency was observed between the specimen dimensions and their moisture loads. In contrast, the biggest (Q1) and the smallest (R5) spruce specimens showed almost the same number of wet days (114 days and 115 days). Nevertheless, for both wood species remarkable differences in *ToW* were observed which ranged between 54 days (R4) and 115 days (R5) for spruce and between 272 days (Q4) and 592 days (Q2) for pine sapwood. To some extent the effect of specimen dimension on *MC* might be superposed by the fact that *MC* was measured in the centre of the specimens. Variations in *MC* were higher in smaller cross sections and the *MC* amplitude was extenuated with increasing distance between measuring points (in the specimen centre) and specimen surface. This effect became evident when the two measuring points on specimens of group Q1 were compared over time (Fig. 3).

The drastic effects between the measuring points observed for Scots pine are most likely due to heartwood portions in the centre of the specimens, whereas the upper measuring point was located in pure sapwood with higher permeability (Rydell et al. 2005; Metsä-Kortelainen et al. 2006). However, dampening effects on *MC* also became visible for spruce specimens, where sapwood and heartwood were not distinguishable.

Furthermore, *MC* and temperature data were submitted to the logistic dose–response performance model (LDR). As shown in Table 4 the temperature induced dose component D_T was nearly indifferent between the specimen groups. In contrast, the *MC* induced dose D_{MC} varied significantly. Consequently, also the total dose *D* which is a function of both components differed between specimens with different cross sections, i.e. by up to factor 4.4 for pine

Fig. 3 Moisture content of specimens (group Q1, 100 × 100 mm^2) during 2 years of outdoor exposure. Measurements were taken in the specimen center and 20 mm below the surface. *Horizontal line indicates* the MC threshold (25 %) for fungal decay. *Top* Norway spruce. *Bottom* Scots pine



and factor 4.3 for spruce between specimens with the lowest and those with the highest dose. The respective service life of the various components is therefore expected to vary to the same extent (Brischke et al. 2013, see Eq. 6). In particular with respect to the largest dimension considered (Q1 and Q2) clearly different service lives can be expected depending on the measuring position considered, i.e. service lives are shorter up to a factor of 2.6 when the outer specimen part is regarded.

Further aspects which might influence the moisture performance and thus decay susceptibility of the different specimen groups are the formation of cracks (Rapp and Peek 1999; Brischke and Melcher 2015); staining fungi, which can alter the permeability of wood (Saling 1930; Fojutowski 2005), as well as the onset of decay itself. Therefore, decay development was studied on the different specimen groups over time.

3.2 Decay development

Norway spruce specimens generally decayed slower than Scots pine sapwood specimens (Fig. 4) which corresponds to the generally higher *MC* in the pine specimens. After 5 years of exposure all pine specimens of the groups Q1-5 and R3-4 had failed due to decay. In contrast, the mean decay rating of most Norway spruce groups was less than 2 (moderate decay) after the same exposure time. Furthermore, the time lag between exposure and onset of decay was approximately one year longer for the Norway spruce samples.

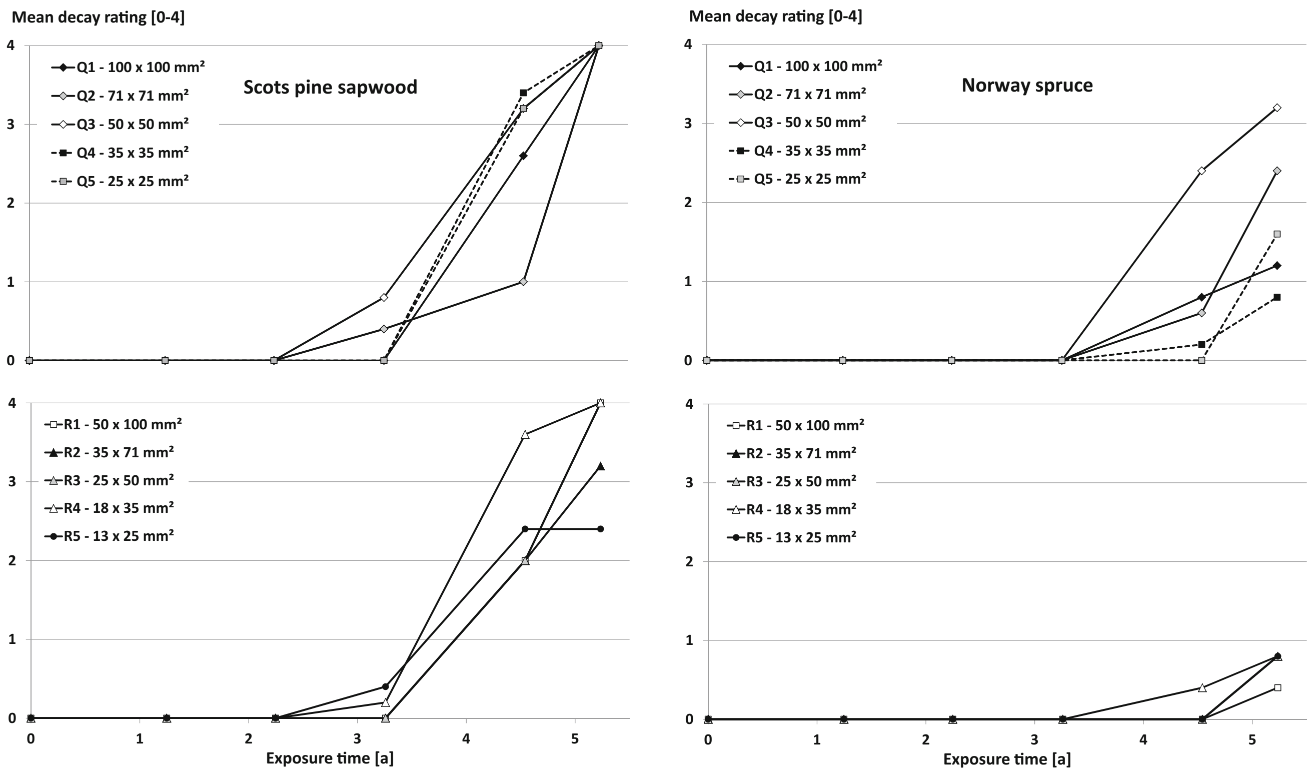


Fig. 4 Mean decay ratings according to EN 252 (CEN 2015) and adopted to various cross sections over exposure time of 5 years for Scots pine sapwood (*left*) and Norway spruce specimens (*right*)

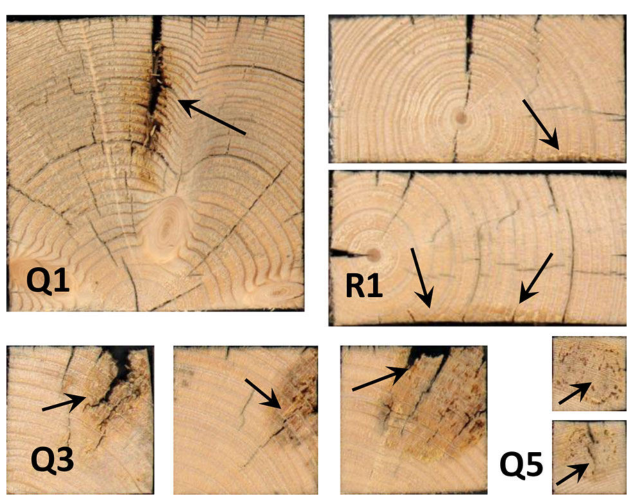


Fig. 5 Cross section scans of Norway spruce specimens after 5 years of exposure. Brown rot decay started from cracks in Q1 (100 × 100 mm^2) and Q3 (50 × 50 mm^2), from the bearing contact face in R1 (50 × 100 mm^2), and from the interior of the specimens in Q5 (25× 25 mm^2)

However, again there was no relationship recognisable between specimen dimension and decay development, neither for pine sapwood nor for Norway spruce. Decay in pine sapwood proceeded very fast in all specimens, so that no significant difference in decay rate became evident. Similarly, the decay rate of the Norway spruce specimen groups with smallest and largest quadratic cross sections was nearly the same. However, distinct differences were found between the specimens groups with respect to the location where they were infested and how decay spread from there. This is exemplarily shown in Fig. 5 for selected Noway spruce specimens that were cut after 5 years of exposure. While deep surface cracks (up to one half of the specimen thickness) served as starting points for decay in Q1 and Q3 specimens, first signs of decay were found in R1 at the contact face between bearing and specimen. Remarkably, all Norway spruce specimens in group R1 showed deep surface cracks, but none of these cracks was infested. So cracks had the potential to initiate high *MC* and consequently decay (Austigard et al. 2014), but they do not necessarily do, e.g. due to the fact the period of high *MC* (*ToW*) is not long enough. How and to what extent water enters into a crack or delamination depends on material, surface treatment, position and size of the crack or delamination (Sandberg 2013). Similar observations were made by Brischke and Rolf-Kiel (2010) on double-split fence posts made from English oak, which had been in ground contact for several decades. Frequently, deep cracks were identified as initiation point of white rot decay, but interior rot was also found. In this study, interior brown rot was found in particular on small cross section specimens, such as within group Q5 (Fig. 5). In these samples only thin and small cracks were observed and no decay was visible from the outside even though more than 80 % of the cross section was severely decayed. A layer of sound wood enclosed the decayed wood portions like a shell. The specimens might have been affected from the end-grain as also suggested for glulam beams by Austigard et al. (2014).

All decayed specimens showed brown rot, only in a few cases pine sapwood samples were also associated with soft rot, but still dominated by brown rot. In other above ground durability studies both wood species, Norway spruce and Scots pine sapwood, frequently showed soft and white rot decay too (Augusta 2007; Welzbacher and Rapp 2007, Brischke and Rapp 2010; Alfredsen et al. 2014), wherefore the above described performance model was also primarily based on the latter rot types. Since the basic requirements for growth and decay of white and brown rot fungi are similar as shown by Huckfeldt and Schmidt 2006; Stienen et al. (2014); Meyer and Brischke (2015), the model might fit for the results obtained. However, to some extent the prominent role of brown rot can explain that the moisture and temperature induced dosage determined in this study does not fully reflect the high decay activity. Furthermore, the moisture load in a single layer set up exposed to strong winds provided high re-drying potential of the specimens. Nevertheless, and to some extent unexpected, even the specimens with the smallest dimension showed severe decay in short time.

These findings stand in contrast to field test results from Sell (1980) which showed a higher decay risk for components with larger dimensions. According to Sell, the low thermal and moisture conductivity of wood leads to high moisture variation close to the surface—as also confirmed within this study. Furthermore, deformation of small-dimensioned specimens and formation of cracks in large-dimensioned components result from hindered swelling and shrinking. Such observations were neither confirmed by Augusta (2007) nor by the results obtained in this study.

4 Conclusion

From the results obtained during 5 years of outdoor exposure no clear effect of the size of the cross section became evident. The specimen dimension was neither correlated with wood *MC* nor with the decay development. *ToW* and decay were more severe in pine compared to spruce. Regarding onset and further development of decay cracks as well as contact faces turned out to be weak points, but interior rot was observed as well. Brown rot, which occurred predominantly in the specimens, was partly difficult or even impossible to detect from outside. Likely due to deviating ways of infection brown rot fungi were able to cause severe degradation also in small-dimensioned samples.

With respect to durability field test methodology one might recommend to use specimens with dimensions close to those used for real-life structures even though this cannot be concluded from *MC* and decay data within this study, but will mimic crack formation as close as possible. To quantify the effect of component dimension on service life further research is needed, whereby the overruling effect of contact faces and further water traps need to be considered carefully.

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6.12 Publication XII: Comparative studies on the in-ground and above-ground durability of European oak heartwood (*Quercus petraea* Liebl. and *Quercus robur* L.)

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ORIGINALS · ORIGINALARBEITEN

Comparative studies on the in-ground and above-ground durability of European oak heartwood (*Quercus petraea* Liebl. and *Quercus robur* L.)

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Abstract The durability of European oak (*Quercus petraea* Liebl. and *Quercus robur* L.) is controversially discussed since a long time. While it is classified as a "durable" timber species (durability class 2, according to EN 350-2), results from different studies indicated a lower durability. Therefore comparative studies with sessile oak and English oak were carried out including laboratory resistance tests against different basidiomycetes, soil box tests against soft rot and other soil-inhabiting micro-organisms, as well as in-ground and above-ground field trials at different test sites. Both oak species were rated "non-durable" (durability class 5, DC 5) in soil box tests and in-ground field trials and "slightly durable" (DC 4) in above-ground field trials. Solely results from laboratory tests with pure basidiomycete cultures led to partly better estimates ("very durable" to "moderately durable" DC 1-3), but did not represent the organisms responsible for decay in the field. For oak, EN 350-2 reflects only laboratory results but not the performance of the material in real field situations.

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Zusammenfassung Die Dauerhaftigkeit von Eichenholz (*Quercus petraea* Liebl. und *Quercus robur* L.) wird seit Langem kontrovers diskutiert. Während es nach der europäischen Norm EN 350-2 als „dauerhaft“ (Dauerhaftigkeitsklasse 2) eingestuft wird, lassen Ergebnisse aus verschiedenen Untersuchungen eine geringere Dauerhaftigkeit vermuten. Aus diesem Grund wurden vergleichende Studien zur Dauerhaftigkeit von Stieleichen- und Traubeneichenholz durchgeführt. Hierzu gehörten Abbauversuche im Labor mit verschiedenen Basidiomyceten, Labor-Erdeingrabeversuche zur Ermittlung der Resistenz gegenüber Moderfäule und anderen bodenbewohnenden Mikroorganismen, sowie Freilandversuche mit und ohne Erdkontakt an verschiedenen Standorten. Beide Eichen-Arten wurden als „nicht dauerhaft“ (Dauerhaftigkeitsklasse 5, DHK 5) in Labor- und Freiland-Erdeingrabeversuchen und „wenig dauerhaft“ (DHK 4) im Freiland außerhalb der Erde eingestuft. Einzig die Ergebnisse aus den Laborversuchen mit Basidiomyceten-Reinkulturen führten teilweise zu einer besseren Einschätzung („sehr dauerhaft“ bis „mäßig dauerhaft“ DHK 1–3), wobei aber die im Freiland dominant aufgetretenen Organismen und Fäuletypen nur bedingt vertreten waren. Die Klassifizierung nach EN 350-2 spiegelt somit lediglich die Laborergebnisse wider, nicht aber das Verhalten des Materials in realen Freilandsituationen.

1 Introduction

For millennia, oaks (*Quercus* spp.) are playing an important role in many parts of Europe. While oak trees were basic elements of European mythology (Chadwick 1900), their wood was and still is a preferential building material, not at least due to its proverbial durability (Kollert 1991). Archaeological oak findings from Roman times can still be made (Haneca et al. 2005) as well as numerous half-timbered oak houses have remained since the Middle ages and point to an extraordinarily durable timber species. On the other hand, little is reported on the quantity of oak timber structures showing long service lives nor on the number of prematurely failing structures (e.g. Schulz 1976). As long as an oak structure stays under conditions adverse for wood-destroying organisms, e.g. submerged foundation piles (Klaassen 2008) or cross-ties protected by large roof overhangs, its longevity is assured. However, sound standing data on the performance of unprotected oak timber in-service are rare.

According to EN 350 (CEN 1994b) the wood of European oak, namely English oak (*Q. robur* L.) and sessile oak (*Q. petraea* Liebl.) is classified as "durable" (durability class 2, DC 2). Hence European oak is one of the most durable domestic wood species in Europe besides black locust (*Robinia pseudoacacia* L., DC 1–2) and sweet chestnut (*Castanea sativa* Mill., DC 2). Results from laboratory tests against different wood-destroying basidiomycetes confirmed or even exceeded this durability classification: English oak was classified as "durable" or "very durable" against the brown rot fungi *Coniophora puteana*, *Gloeophyllum trabeum*, *Daedalus quercina*, and *Serpula lacrymans* and the white rot fungus *Coriolus versicolor* (Van Acker et al. 1999, 2003, Bellmann 1988, Guilley et al. 2004, Wälchli 1973, 1976). However, further laboratory results indicate an inter-specific variability of European oak durability with remarkable percentages of moderately durable, poorly durable and not durable timber (Aloui et al. 2004, Ayadi et al. 2001, Guilley et al. 2004, Humar et al. 2008). Results from soil bed tests against soft rotting and other soil-inhabiting micro-organisms also led to lower durability classes, e.g. DC 3–4 as reported by van Acker et al. (2003).

It is commonly agreed that laboratory results cannot directly be transferred to real life situations, wherefore field studies under different exposure situations may give a more realistic view on the durability of European oak timber. Only few results from in-ground as well as above-ground field studies are available (e.g. Smith and Orsler 1994, Militz et al. 1996, Lindegaard and Morsing 2003, Evans et al. 2008). Although most of these results are preliminary, it is indicated that European oak should be classified worse than "durable" (DC2). Thus, as there still seems to exist a lack in knowledge on the performance and durability of European oak under outdoor exposure, the authors considered English oak and sessile oak in three different comparative studies including laboratory resistance tests against white and brown rot causing basidiomycetes, soil box tests against soft rot and other soil-inhabiting micro-organisms, in-ground field tests with different soil substrates and at different test sites, and above-ground field trials at different test sites.

2 Materials and methods

2.1 Wood material

For the different decay tests clear specimens were prepared from the following wood species: English oak heartwood (*Quercus robur* L.) and sessile oak heartwood (*Quercus petraea* Liebl.) of different origins, and as references Scots pine sapwood (*Pinus sylvestris* L.) and European beech (*Fagus sylvatica* L.). The specimens were free of knots, cracks, decay and other obvious defects.

2.2 Resistance tests against basidiomycetes

The resistance to basidiomycetes was tested according to EN 113 (CEN 1996) using Petri dishes with a diameter of 120 mm and mini-block specimens of $40 \times 10 \times 10\,\text{mm}^3$ for sessile oak, and Kolle flasks and specimens of $15 \times 25 \times 50\,\text{mm}^3$ for English oak, respectively. A detailed description of the specimens and the number of replicates used is given in Table 1. The incubation period was 12 weeks for the mini-blocks and 16 weeks for the standard specimens. The following strains were used for the study: *Coniophora puteana* = (Schum.:Fr.) P. Karsten Ebw. 15; BAM 1/1995, *Oligoporus placenta* var. Monticula = (Fr.) Gilbertson et Ryv. FPRL 280 BAM, 8/1997 and *Coriolus versicolor* = (L.:Fr.) Pilat CTB 863A; 1969.

2.3 Resistance tests in terrestrial microcosms

The resistance to soft rotting micro-fungi and other soil inhabiting micro-organisms was determined in a soil box test (terrestrial microcosm, TMC) according to ENV 807 (CEN 2001). A detailed description of the specimens and the number of replicates used for the different soil substrates is given in Table 1.

Natural top soil substrate from the in-ground test fields in Hamburg, Freiburg, Stuttgart and Reulbach (see also Sect. 2.5) as well as compost soil made from horticultural waste (leaf litter, grass, cut softwoods and hardwoods, sand) was used for the study.

2.4 In-ground durability tests with different soil substrates

Mini-stake specimens of $200 \times 20 \times 8\,\text{mm}^3$ with growth rings at $90 \pm 15°$ to the broad faces from clear sessile oak heartwood and Scots pine sapwood were exposed to different types of soil at the field test site of the Johann Heinrich von Thünen-Institute (vTI) in Hamburg-Lohbrügge, Germany, in June 2003. For preparation of the exposure to different substrates the top layer of the vTI test field was removed up to 25 cm in depth and the different soil substrates were filled into excavations of $25 \times 20 \times 300\,\text{cm}^3$ (depth ×

Table 1 Number of replicates used for the different wood species, test fungi in basidiomycete tests, soil substrates used in decay tests with terrestrial microcosms and mini-stake tests, and test sites for in-ground and above ground durability tests
Tabelle 1 Anzahl der Parallelen für verschiedene Holzarten, Prüfpilze in den Basidiomyceten-Tests, Bodensubstrate in den Abbauversuchen mit terrestrischen Mikrokosmen und Mini-Stake-Tests und Standorte der Dauerhaftigkeitsuntersuchungen mit und ohne Erdkontakt

Test	Test fungus/Test soil	Sessile oak	English oak	Beech	Scots pine sapwood
Basidiomycete test according to EN 113 (CEN 1996)	*Coniophora puteana*	12[a]	45[b]	–	12[a], 45[b]
	Oligoporus placenta	12[a]	45[b]	–	12[a], 45[b]
	Coriolus versicolor	12[a]	45[b]	12[a], 45[b]	12[a], 45[b]
Terrestrial microcosm	Hamburg soil	20[c]	30[d]	–	20[c], 30[d]
	Hamburg shade soil	–	30[d]	–	30[d]
	Freiburg soil	–	30[d]	–	30[d]
	Stuttgart soil	–	30[d]	–	30[d]
	Reulbach soil	–	30[d]	–	30[d]
	Compost soil	20[c]	–	–	20[c]
Mini-stake test	Field soil	10	–	–	10
	Sand	10	–	–	10
	Field soil + sand	10	–	–	10
	Gravel	10	–	–	10
	Compost	10	–	–	10
	Field soil + fertilizer	10	–	–	10
	Concrete	10	–	–	10
EN 252 (CEN 1989)	Hamburg soil	20	30	–	20[e], 30[f]
	Hamburg shade soil	–	30	–	30[f]
	Freiburg soil	–	30	–	30[f]
	Stuttgart soil	–	30	–	30[f]
	Reulbach soil	–	30	–	30[f]
Double layer test	Hamburg	20	30	–	20[e], 30[f]
	Hamburg shade	–	30	–	30[f]
	Freiburg	–	30	–	30[f]
	Stuttgart	–	30	–	30[f]
	Reulbach	–	30	–	30[f]

[a] specimen size: $10 \times 10 \times$ mm^3 (mini block), incubation period: 12 weeks
[b] specimen size: $15 \times 25 \times$ mm^3, incubation period: 16 weeks
[c] specimen size: $5 \times 10 \times$ mm^3, incubation period: 32 weeks
[d] specimen size: $5 \times 10 \times$ mm^3, incubation period: 37 weeks
[e] used as reference to and exposed contemporaneously with sessile oak
[f] used as reference to and exposed contemporaneously with English oak

width × length), which were separated by each other and the subjacent ground by a horticultural water-permeable foil. The specimens were put by 2/3 of their length into the soil. The distance between the specimens was 10 cm. The following soil substrates were used:

- Field soil (natural top soil from the vTI test site)
- Sand (silica sand: grain size: approx. 0.5–3.0 mm)
- Field soil + sand (mix ratio 50 : 50)
- Compost (compost soil made at vTI from horticultural waste, see also Sect. 2.3)
- Gravel (grain size: approx. 15–40 mm)
- Field soil + fertilizer (80 g/m^2 a; ingredients: 7% nitrogen, 4% phosphorus pentoxide, 9% potassium oxide, 2% magnesium oxide, 7.8% sulphur, 0.018% zinc)
- Concrete (specimens concreted with Portland cement in blocks of 14.0 cm height and 6.5 cm diameter by 2/3 of their length).

2.5 In-ground durability tests at different test sites

Specimens of $500 \times 50 \times 25$ mm^3 were used for in-ground field trials according to EN 252 (CEN 1989) at the following test sites: Hamburg (vTI test site), Hamburg shade (vTI test site shaded by deciduous trees), Freiburg (test site at the Forest Research Institute Baden-Wuerttemberg, FVA), Stuttgart (test site at the Research and Materials Institute for Civil Engineering, Otto Graf-Institute (FMPA), and Reulbach (test site at Menz-Holz). The specimens were planted in the fields with a distance of 30 cm to each other. Details about the number of replicates used are given in Table 1.

2.6 Above-ground durability tests at different test sites

Specimens ($500 \times 50 \times 25$ mm^3) were exposed in double layer test rigs (Rapp and Augusta 2004). The test rigs consisted of specimens placed horizontally in two layers and exposed above ground producing a decay risk corresponding to European Use Class 3 (EN 335-1, CEN 2006). For sessile oak (and corresponding Scots pine sapwood references) small rigs consisting of 23 specimens in total were used and exposed in Hamburg. English oak (and corresponding Scots pine sapwood references) was tested in larger test rigs containing specimens of different wood species with more than 300 specimens in total. The rigs were exposed at different tests sites in analogy to the in-ground trials. Details can be seen from Table 1.

2.7 Decay rating and durability classification

To assess the grade of durability in the laboratory tests, the relative durability was calculated as the quotient of mass loss of the oak heartwood and Scots pine sapwood references (x-value, EN 350-1 (CEN 1994a), Table 2).

All field test specimens were evaluated with respect to decay annually according to the rating scheme of EN 252 (CEN 1989), i.e. "0 = no attack", "1 = slight attack", "2 = moderate attack", "3 = severe attack", and "4 = failure". In

Table 2 Classes of natural durability (DC) based on calculated x-values according to EN 350 – 1 (CEN 1994a), using results from laboratory tests (mini block tests, EN 113-tests and soil-box tests), and by adapting the classification according to EN 350-1 (CEN 1994a) using the durability factor f from field tests instead of the calculated x-values

Tabelle 2 Klassen der natürlichen Dauerhaftigkeit (DC) basierend auf errechneten x-Werten nach EN 350-1 (CEN 1994a) unter Verwendung von Ergebnissen der Laborversuche (Mini-Block-Tests, EN113-Versuche und Eingrabeversuche) und adaptiert nach EN 350-1 (1994a) in Freilandversuchen unter Verwendung von Dauerhaftigkeitsfaktoren f anstelle von x-Werten

DC	Definition	Classification based on EN 350-1 (CEN 1994a)	Classification adapted to EN 350-1 (CEN 1994a)
1	Very durable	$x \leq 0.15$	$f > 5$
2	Durable	$0.15 < x \leq 0.30$	$3 < f \leq 5$
3	Moderately durable	$0.30 < x \leq 0.60$	$2 < f \leq 3$
4	Slightly durable	$0.60 < x \leq 0.90$	$1.2 < f \leq 2$
5	Not durable	$x \leq 0.90$	$f \leq 1.2$

Table 3 Percentage mass loss obtained in laboratory decay tests with pure cultures of basidiomycetes and in terrestrial microcosms with different soil substrates and durability classes according to EN 350-1 (CEN 1994a) calculated on the basis of x-values

Tabelle 3 Prozentuale Masseverluste aus Laboruntersuchungen mit reinen Basidiomycetenkulturen und in terrestrischen Mikrokosmen mit verschiedenen Bodensubstraten sowie anhand von x-Werten berechnete Dauerhaftigkeitsklassen nach EN 350-1 (CEN 1994a)

Wood species	Test method	Test fungus/Test soil	Mass loss [%]	x-value [–]	Durability class
Sessile oak	Mini block test	*Coniophora puteana*	3.9	0.06	1
		Oligoporus placenta	0.8	0.03	1
		Coriolus versicolor	14.3	0.43	3
	Terrestrial microcosm	Hamburg soil	39.2	1.68	5
		Compost soil	38.7	1.09	5
Scots pine sapwood	Mini block test	*Coniophora puteana*	60.3	1.00	5
		Oligoporus placenta	26.2	1.00	5
		Coriolus versicolor	35.7	1.00	5
	Terrestrial microcosm	Hamburg soil	23.4	1.00	5
		Compost soil	35.6	1.00	5
Beech	Mini block test	*Coriolus versicolor*	33.0	1.00	5
English oak	EN 113 test	*Coniophora puteana*	2.7	0.05	1
		Coriolus versicolor	2.5	0.10	1
	Terrestrial microcosm	Hamburg soil	20.4	0.76	4
		Hamburg shade soil	14.9	1.18	5
		Freiburg soil	14.4	1.30	5
		Stuttgart soil	22.3	2.52	5
		Reulbach soil	13.6	0.42	5
Scots pine sapwood	EN 113 test	*Coniophora puteana*	54.8	1.00	5
	Terrestrial microcosm	Hamburg soil	27.0	1.00	5
		Hamburg shade soil	12.6	1.00	5
		Freiburg soil	11.1	1.00	5
		Stuttgart soil	8.9	1.00	5
		Reulbach soil	32.1	1.00	5
Beech	EN 113 test	*Coriolus versicolor*	24.5	1.00	5

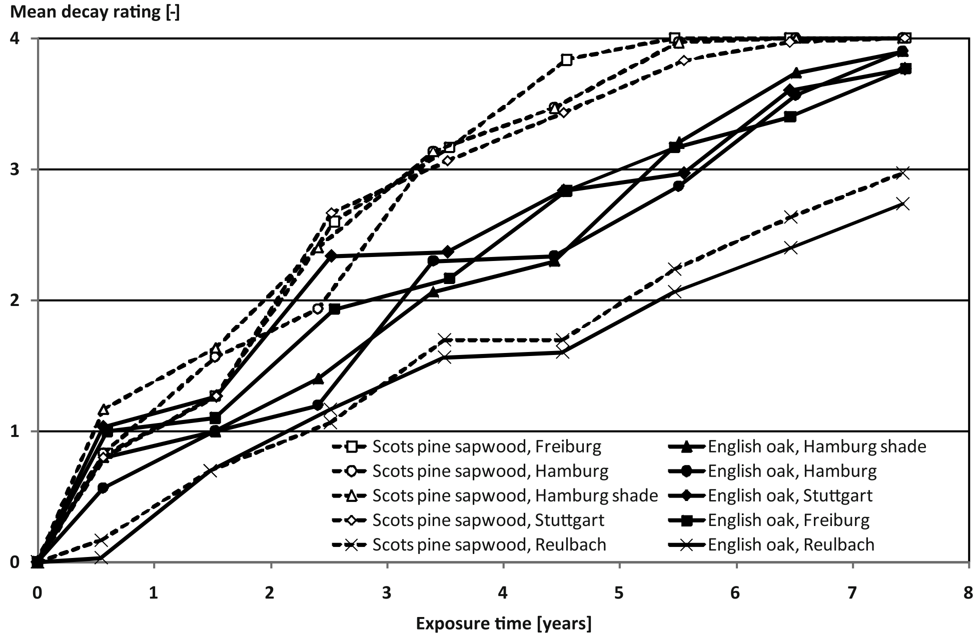

Fig. 1 Mean decay rating according to EN 252 (CEN 1989) of English oak and Scots pine sapwood specimens exposed in ground at different test sites
Abb. 1 Mittlere Abbaubewertung nach EN 252 (CEN 1989) von Stieleichen- und Kiefernsplint-Prüfkörpern nach Exposition im Erdkontakt an verschiedenen Standorten

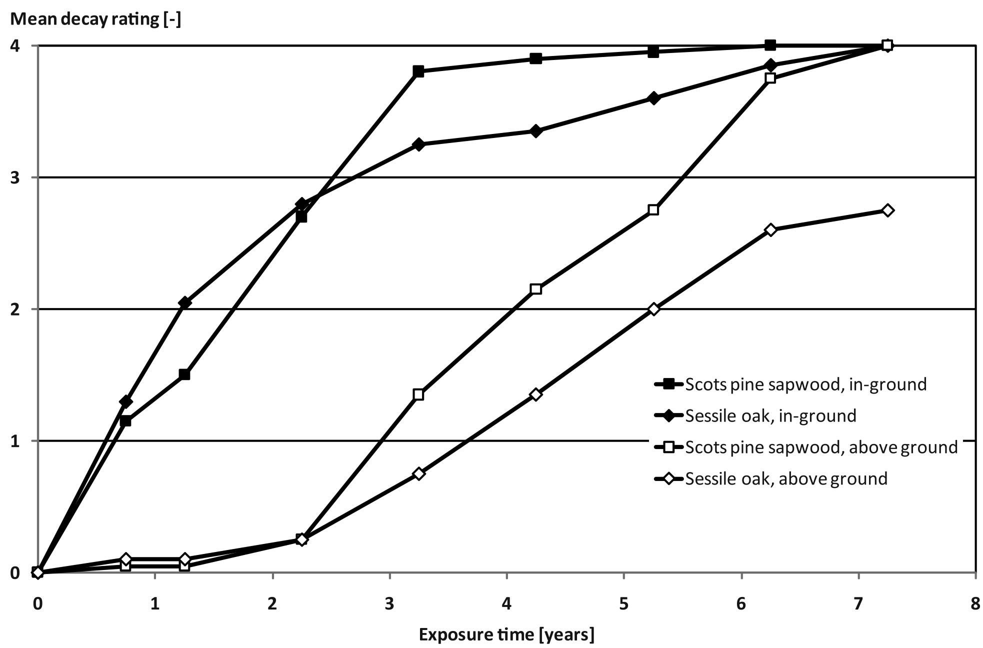

Fig. 2 Mean decay rating according to EN 252 (CEN 1989) of sessile oak and Scots pine sapwood specimens exposed in ground and above ground in horizontal double layer tests in Hamburg
Abb. 2 Mittlere Abbaubewertung nach EN 252 (CEN 1989) von Traubeneichen- und Kiefernsplint-Prüfkörpern nach Exposition im Erdkontakt und in horizontalen Doppellagen-Tests in Hamburg

addition, the specimens were visually inspected regarding the presence of brown rot, white rot, or soft rot.

The results of the decay ratings were used to determine the durability of the tested material, which is defined as a relative value between the wood tested and a control (Scots pine sapwood in this study). According to EN 350-1 (CEN 1994a) x-values are used to calculate the durability.

$$\text{durability } x\text{-value} = \frac{\text{mean lifetime}_{\text{tested specimens}}}{\text{mean lifetime}_{\text{reference}}}$$

The mean lifetime was not yet obtained for all tested materials, wherefore the durability was calculated as the quotient of the decay rate of the controls and the decay rate of the material tested (durability factor f, Table 2) where necessary.

$$\text{decay rate} = \frac{\text{mean decay rating}}{\text{time of exposure}}$$

$$\text{durability factor } f = \frac{\text{decay rate}_{\text{control}}}{\text{decay rate}_{\text{tested specimens}}}$$

For this determination based on the durability factor f the classification of the durability based on x-values according to EN 350-1 (CEN 1994a) was used.

3 Results and discussion

3.1 Resistance against basidiomycetes

The brown rot fungi *Coniophora puteana* and *Oligoporus placenta* caused mass losses less than 4% on sessile oak, which leads to DC 1 for both fungi (Table 3). Significantly higher mass loss was caused by the white rot fungus *Coriolus versicolor* (14.3%) which corresponds with DC 3. In contrast, the EN 113 test with English oak revealed no significant difference between *C. puteana* (2.7%) and *C. versicolor* (2.5%), both leading to DC 1. These results coincide with findings of van Acker et al. (1999, 2003) and Guilley et al. (2004), who determined DC 1 in basidiomycete tests for English oak and sessile oak, respectively.

3.2 Resistance in terrestrial microcosms

Both oak species were significantly stronger decayed in the soil box test compared to the resistance tests with pure

Table 4 Decay rates, corresponding durability factors f, mean life times, corresponding x-values, and durability classes according to EN 350-1 (CEN 1994a) for the different field tests in and above ground

Tabelle 4 Abbauraten, zugehörige Dauerhaftigkeitsfaktoren f, mittlere Standzeiten, zugehörige x-Werte und Dauerhaftigkeitsklassen nach EN 350-1 (CEN 1994a) für die verschiedenen Freilanduntersuchungen mit und ohne Erdkontakt

Wood species	Exposure	Test method	Soil substrate/ Test site	Decay rate [years^{-1}]	Durability factor f [–]	Mean life [years]	x-value [–]	Durability class
Sessile oak	In-ground	Mini stake test	Field soil	0.80	1.00	4.5	0.98	5
			Sand	0.80	1.00	5.0	1.04	5
			Field soil + sand	0.80	1.00	4.7	1.02	5
			Gravel	0.80	1.00	4.6	0.98	5
			Compost	0.80	1.00	4.0	1.00	5
			Field soil + fertilizer	1.00	0.80	3.3	0.79	5
			Concrete	0.80	1.00	4.5	0.94	5
		EN 252 (CEN 1989)	Hamburg	0.55	1.16	3.9	1.20	5
	Above ground	Double layer	Hamburg	0.37	1.45	n.a.	n.a.	4
Scots pine sapwood	In-ground	Mini stake test	Field soil	0.80	1.00	4.6	1.00	5
			Sand	0.80	1.00	4.8	1.00	5
			Field soil + sand	0.80	1.00	4.6	1.00	5
			Gravel	0.80	1.00	4.7	1.00	5
			Compost	0.80	1.00	4.0	1.00	5
			Field soil + fertilizer	0.80	1.00	4.2	1.00	5
			Concrete	0.80	1.00	4.8	1.00	5
		EN 252 (CEN 1989)	Hamburg	0.64	1.00	3.3	1.00	5
	Above ground	Double layer	Hamburg	0.53	1.00	6.5	1.00	5
English oak	In-ground	EN 252 (CEN 1989)	Hamburg	0.52	1.17	n.a.	n.a.	5
			Hamburg shade	0.52	1.17	n.a.	n.a.	5
			Freiburg	0.50	1.45	n.a.	n.a.	4
			Stuttgart	0.51	1.06	n.a.	n.a.	5
			Reulbach	0.37	1.09	n.a.	n.a.	5
	Above ground	Double layer	Hamburg	0.32	1.56	n.a.	n.a.	4
			Hamburg shade	0.40	1.35	n.a.	n.a.	4
			Freiburg	0.33	1.52	n.a.	n.a.	4
			Stuttgart	0.29	1.65	n.a.	n.a.	4
			Reulbach	0.29	1.84	n.a.	n.a.	4
Scots pine sapwood	In-ground	EN 252 (CEN 1989)	Hamburg	0.61	1.00	4.6	1.00	5
			Hamburg shade	0.61	1.00	4.3	1.00	5
			Freiburg	0.73	1.00	4.2	1.00	5
			Stuttgart	0.54	1.00	n.a.	n.a.	5
			Reulbach	0.40	1.00	n.a.	n.a.	5
	Above ground	Double layer	Hamburg	0.50	1.00	n.a.	n.a.	5
			Hamburg shade	0.54	1.00	6.1	1.00	5
			Freiburg	0.50	1.00	n.a.	n.a.	5
			Stuttgart	0.48	1.00	n.a.	n.a.	5
			Reulbach	0.53	1.00	n.a.	n.a.	5

n.a. = not available

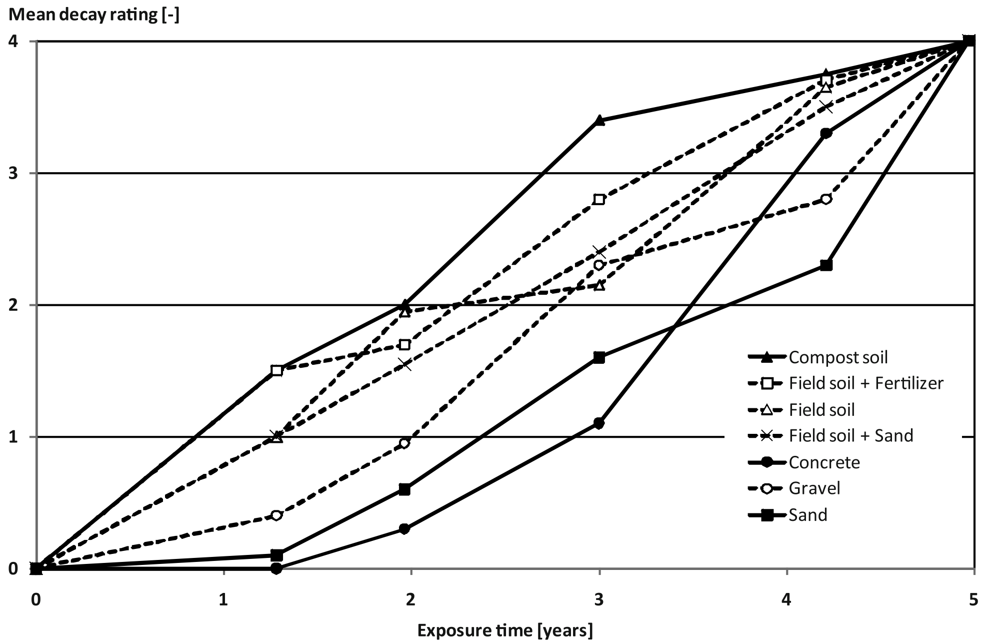

Fig. 3 Mean decay rating according to EN 252 (CEN 1989) of Scots pine sapwood mini stake specimens exposed in different soil substrates
Abb. 3 Mittlere Abbaubewertung nach EN 252 (CEN 1989) von Kiefernsplint-Prüfkörpern nach Exposition in verschiedenen Bodensubstraten

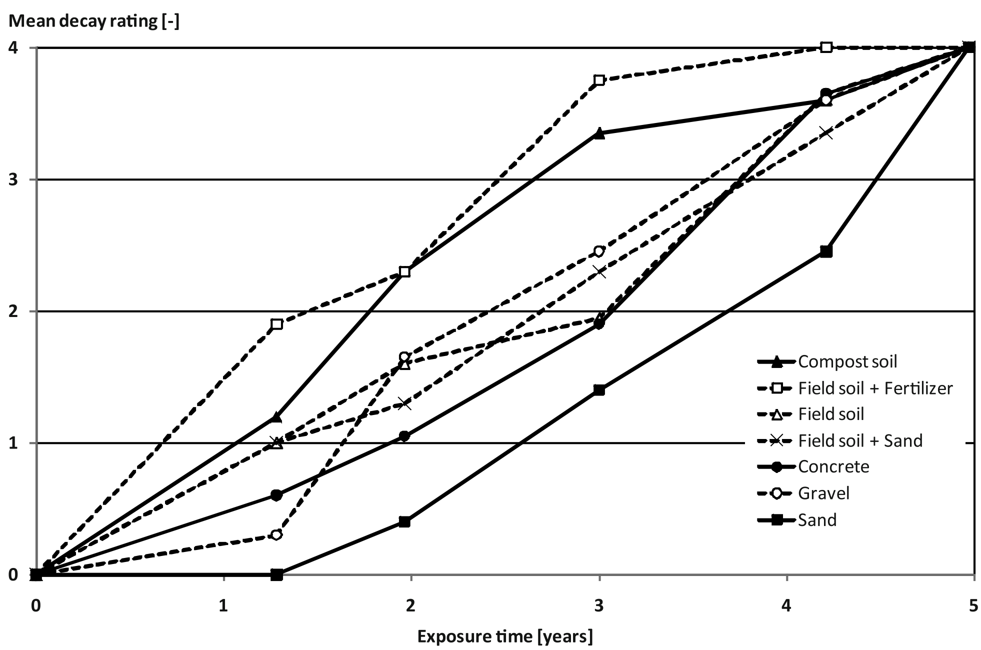

Fig. 4 Mean decay rating according to EN 252 (CEN 1989) of sessile oak mini stake specimens exposed in different soil substrates
Abb. 4 Mittlere Abbaubewertung nach EN 252 (CEN 1989) von Traubeneichen-Prüfkörpern nach Exposition in verschiedenen Bodensubstraten

cultures of basidiomycetes (Table 3). English oak showed mass losses in a range between 14 and 22% in the five different test soils which corresponds to DC 4 for the Hamburg soil and DC 5 for the other soils. Sessile oak was also classed as "non durable" (DC 5) in both soils, but showed significantly higher mass loss (approx. 39%) compared to English oak. Similar differences in oak durability between basidiomycete and soil box tests were reported by Sierra-Alvarez et al. (1998) and Van Acker et al. (1999), who determined for English oak in soil DC 4 and DC 3, respectively.

3.3 Durability in in-ground exposures

The progress of decay over time in soil tests according to EN 252 (CEN 1989) is illustrated in Figs. 1 and 2 for sessile oak and English oak. The mean decay rating of the English oak samples was between 3.8 and 3.9 after 7.5 years of exposure at four different sites; only in Reulbach decay preceded slower, resulting in a mean decay rating of 2.7, which may be explained by the very humid soil conditions at this test site (Augusta 2007). In comparison with the pine sapwood controls, English oak was classified as "slightly durable"

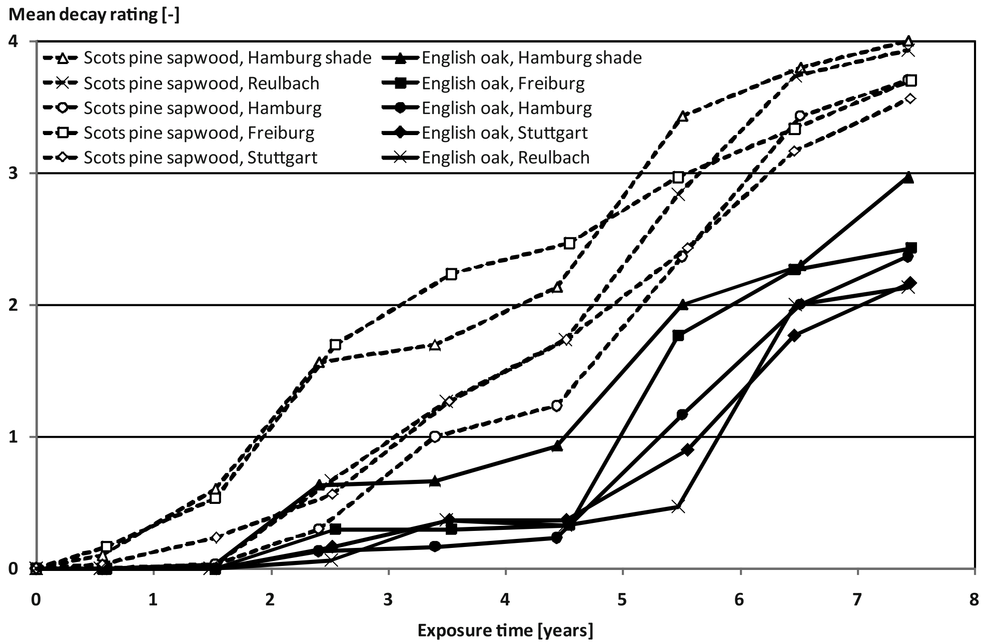

Fig. 5 Mean decay rating after EN 252 (CEN 1989) of English oak and Scots pine sapwood specimens exposed above ground in horizontal double layers at different test sites
Abb. 5 Mittlere Abbaubewertung nach EN 252 (CEN 1989) von Stieleichen- und Kiefernsplint-Prüfkörpern nach Exposition in horizontalen Doppellagen-Tests an verschiedenen Standorten

in Freiburg and as "non-durable" for the other tests sites (Table 4). Even higher decay rates were obtained for sessile oak, which revealed a mean life of 3.9 years in Hamburg and was therefore also classified as "non-durable".

The mini-stake in-ground tests with different soil substrates led to shorter mean lives for sessile oak and pine sapwood compared to the EN 252-tests, after 5 years exposure all oak and pine specimens had failed (Figs. 3 and 4). Pooling all substrates the mean life of sessile oak was 4.4 years, and 4.5 years for pine sapwood. Remarkable differences in decay progress were found between the different soil substrates, in fact similar for both wood species. In compost soil and field soil with fertilizer decay preceded the fastest. The lowest decay progress was observed in pure sand and in concrete. The high decay activity of compost soils is supported by Mieß (1997) and Edlund (1998). Fertilization may increase decay activity in ground contact, because some nutrients, especially nitrogen, are limiting factors for decay fungi owing to their restricted availability in wood (Rayner and Boddy 1988, Schmidt 2006).

However, the initially retarded decay progress in sand and concrete did not lead to significantly higher mean lives, and thus DC 5 was obtained for sessile oak in all substrates (Table 4). It may be assumed that the small dimensions of the mini-stakes were responsible for diminishment of the differences between the soils and that full-sized stakes will perform differently, but this cannot hide the fact that sessile oak decayed faster than pine sapwood in this study.

The overall result from the different in-ground exposure tests is a durability classification that considerably deviates from the European standard EN 350-2 (CEN 1994b), which rates European oak as "durable" (DC2).

3.4 Durability in above-ground exposures

The durability determined in above ground double layer tests also stayed behind the normative reference (CEN 1994b). The progress of decay for the above-ground exposure is shown in Fig. 2 for sessile oak and in Fig. 5 for English oak. Although the mean life of oak heartwood was not yet assessable after 7.5 years of exposure, the preliminary classification on the basis of decay rates clearly revealed DC 4 for all test sites and both oak species (Table 4). All above-ground trials were dominated by white and soft rot, which may explain similar high decay activity compared to the in-ground tests, where white and soft rot occurred exclusively (Augusta 2007, Rapp et al. 2007, Welzbacher and Rapp 2007).

4 Conclusion

The comparative studies on the durability of European oak heartwood revealed significant discrepancies between results from different laboratory tests, field tests and the current European normative durability classification. According to EN 350-2 (CEN 1994b) European oak is a "durable" timber species (DC 2). This could neither be attested in laboratory soil box tests (DC 5) nor in field studies in ground (DC 5) and above ground (DC 4). The soil box tests with different terrestrial microcosms gave a strong indication on the results to be expected in the field, because of similar types of decay organisms involved (i.e. mainly soft and white rot causing fungi). In contrast, the laboratory resistance tests with basidiomycete monocultures were misleading as they suggest classifying European oak as a "very durable" timber.

Though the various field studies showed that the durability of European oak heartwood seems to be fairly overestimated, they could not explain where this overestimation derives from. Looking into the use traditions for oak timber structures may give an answer on this question: Use of big-dimensioned components, careful protection by design, and exposure in adverse environments, e.g. waterlogged foundation piles or window joinery with at least some protection by design. Future studies on the durability of oak should therefore include also timber structures in-service. Case studies and surveys on the quantity of oak timber components with service lives above-average could assist a better understanding of the performance of oak timber under outdoor exposure.

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6.13 Publication XIII: Durability of European oak (*Quercus* spp.) in ground contact – A case study on fence posts in service

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Durability of European oak (*Quercus* spp.) in ground contact – A case study on fence posts in service

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Abstract The durability of European oak (*Quercus* spp.) is under debate for a long time. In contrast to its classification as "durable" timber species according to EN 350-2 (CEN 1994), results from different comparative studies have clearly shown a lower durability, especially for in-ground exposures. To highlight this conflict more detailed, a case study on oak fence posts, which had been in service for 5, 10, 20, 30, and 60 years, was carried out. The posts were examined in terms of decay type and intensity, remaining cross section, wood moisture content, and different characteristics of the adjacent soil. The durability of the oak posts was affected by high variation. Posts prematurely failing after only five years were found as well as posts still serviceable after 60 years. Different findings of the study have the potential to increase the understanding of durability aspects in the future and might be considered for calibration and adaption of field and laboratory test methods in the future: The ground line turned out to be not the most severe exposure for posts, although it is generally assumed to be. Furthermore, no significant negative impact of remaining sapwood portions on the durability of the heartwood was found, but the important role of radial cracks for the initiation of decay became apparent. In this regard further potentially important factors for the in-ground durability are size and shape of timber components.

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Die Dauerhaftigkeit Europäischer Eiche (*Quercus* spp.) im Erdkontakt – Eine Fallstudie an Weidezaunpfählen im Gebrauch

Zusammenfassung Die Dauerhaftigkeit von Eichenholz (*Quercus* spp.) wird seit langer Zeit kontrovers diskutiert. Während es nach EN 350-2 (CEN 1994) als „dauerhaft" (Dauerhaftigkeitsklasse 2) eingestuft wird, haben Ergebnisse vergleichender Studien eine deutlich geringere Dauerhaftigkeit belegt, insbesondere bei Exposition mit Erdkontakt. Um diesen Widerspruch näher zu betrachten, wurde eine Fallstudie an Eichenzaunpfählen durchgeführt, die sich bereits seit 5, 10, 20, 30 und 60 Jahren im Gebrauch befanden. Die Pfähle wurden in Bezug auf Art und Intensität von Fäulnis, Restquerschnitt, Holzfeuchte und verschiedener Charakteristika des umgebenden Bodens untersucht. Die Dauerhaftigkeit der Eichenpfähle war durch eine hohe Variation gekennzeichnet. Frühausfälle nach nur fünf Jahren wurden ebenso beobachtet wie Pfähle, die nach 60 Jahren immer noch gebrauchstauglich waren. Verschiedene Erkenntnisse aus der Studie tragen zu einem besseren Verständnis der Dauerhaftigkeit von Eichenholz im Erdkontakt bei und ließen sich zur Kalibrierung und Anpassung von Labor- und Freiland-Prüfmethoden berücksichtigen. So stellte sich die als besonders kritisch erachtete Boden-Luft-Zone nicht als die Zone mit der stärksten Befallsintensität heraus. Weiterhin ließ sich kein signifikanter negativer Einfluss von Splintholzanteilen auf die Gebrauchsdauer der Pfähle nachweisen; die besondere Rolle radialer Risse in den Pfählen als Ausgangspunkt für Fäulnis wurde hingegen deutlich. In diesem Zusammenhang sei ebenfalls auf die Bedeutung von Dimensionierung und Form von Bauteilen auf die Dauerhaftigkeit im Erdkontakt hingewiesen.

1 Introduction

The timber of European oak (*Quercus robur* L. and *Q. petraea* Liebl.) is an appreciated building material and therefore it has been used since centuries. Its suitability for outdoor applications derives from its proverbial durability (Kollert 1991), and in fact it is classified as "durable" species (durability class 2, DC 2) according to EN 350-2 (CEN 1994). Thus, it is one of the most durable domestic wood species in Europe besides Black locust (*Robinia pseudoacacia* L., DC 1–2) and Sweet chestnut (*Castanea sativa* Mill., DC 2). Archaeological oak findings from Roman times (Haneca et al. 2005) as well as numerous half-timbered oak houses, which have still remained since the 16th century (Schepers 1994) also point to an outstanding durable timber species.

On the other hand, several authors reported on laboratory results indicating an inter-specific variability of European oak durability with remarkable percentages of moderately durable, poorly durable and not durable timber (Ayadi et al. 2001, Aloui et al. 2004, Guilley et al. 2004, Humar et al. 2008). Results from soil bed tests against soft rotting and other soil-inhabiting micro-organisms also led to lower durability classes, e.g. DC 3–4 as reported by Van Acker et al. (2003). Comparative studies by Brischke et al. (2009) revealed significant discrepancies between results from different laboratory tests, field tests and the current European normative durability classification. In laboratory soil box tests as well as in in-ground field tests according to EN 252 (CEN 1990), oak was found to be non durable (DC 5), and even exposed above-ground in double layer tests it was only classified as less durable (DC 4). Soil box tests with different terrestrial microcosms gave a strong indication on the results to be expected in the field, because of similar types of decay organisms involved (i.e., mainly soft and white rot causing fungi). In contrast, laboratory resistance tests with basidiomycete monocultures were misleading as they suggest classifying European oak as a "very durable" timber. Though the various field studies showed that the durability of European oak heartwood seems to be fairly overestimated, they could not explain where this overestimation derives from.

Therefore, in this case study, oak posts, which had been in service between 5 and 60 years, were surveyed to obtain more information on the durability of oak timber under real life conditions. The posts were sampled at five different sites in North Rhine-Westphalia, Germany and assessed with respect to decay and wood moisture content. Furthermore, the in-use conditions were examined in terms of different soil parameters.

2 Materials and methods

2.1 Sites and sampling of the posts

Oak fence posts were examined at five sites (feedlots) in the rural district Gütersloh, North Rhine-Westphalia, Germany, representing previous service lives of 5, 10, 20, 30, and 60 years. Round posts were included as well as splitted and double splitted posts. The geographic characteristics of the sites, and the corresponding number and type of fence posts sampled are summarized in Table 1.

The posts were carefully pulled out of the ground using a vertical hydraulic elevating device. Total length of the posts and depth of burying were determined, afterwards adherent soil was removed. For determination of remaining cross sections and wood moisture content, discs of 20 mm thickness were cut out of the posts at four different section planes (30 cm above ground, at the ground line, 30 cm below ground, and 60 cm below ground, see Fig. 1).

Table 1 Geographic characterization of the sites, corresponding number of posts existent, and number, dimension, and type of posts examined (Standard deviation in brackets)

Tabelle 1 Geografische Charakterisierung der Standorte, zugehörige Anzahl vorhandener Pfähle, Anzahl, Abmessungen und Typ der untersuchten Pfähle (Standardabweichung in Klammern)

		Site 1		Site 2		Site 3		Site 4		Site 5	
Previous service life [a]		5		10		20		30		$60+x$[1]	
Location		Versmold-Bockhorst		Versmold-Bockhorst		Versmold-Bockhorst		Werther-Rotingdorf		Werther-Rotingdorf	
Latitude		52°4′29″		52°5′6″		52°4′29″		52°5′6″		52°5′6″	
Longitude		8°12′2″		8°12′2″		8°12′2″		8°25′16″		8°25′16″	
Altitude [m]		70		70		70		130		130	
Posts existent		44		67		18		66		25	
Posts examined	Round posts	0		1		10		7		3	
	Splitted posts	2		9		2		18		3	
	Double splitted posts	13		10		3		5		9	
	Total	15		20		15		30		15	
Mean length [cm]		189	(4)	190	(9)	195	(5)	174	(16)	168	(16)
Mean length in ground [cm]		70	(6)	86	(6)	71	(4)	71	(16)	49	(16)
Original heartwood cross section [cm^2]		130	(34)	134	(34)	168	(45)	104	(25)	85	(28)

[1] the posts have been in service for at least 60 years

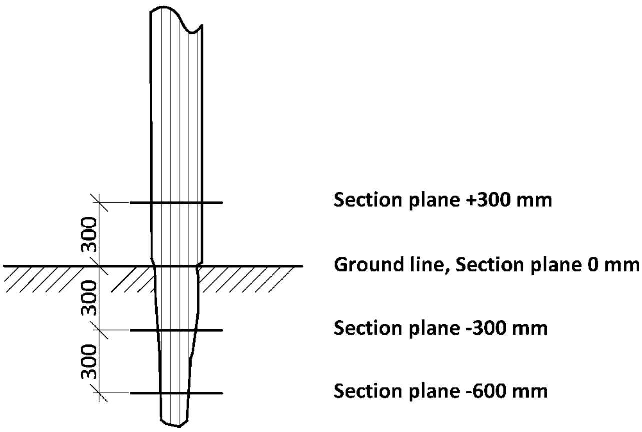

Fig. 1 Cutting schedule of fence posts for determination of remaining cross sections and wood moisture content (all dimensions in mm)
Abb. 1 Schnittplan zur Entnahme von Pfahlscheiben für die Bestimmung von Restquerschnitt und Holzfeuchte (alle Angaben in mm)

2.2 Determination of remaining cross section

The remaining cross section was determined in all four sections of all sampled posts. Therefore, the wooden discs were sanded, scanned and the areas of the original heartwood section (A_{original}) as well as the remaining undecayed heartwood section (A_{existing}) calculated using "Adobe Photoshop CS3" (Fig. 2). As the original heartwood sections were unknown due to different cross shapes and degrees of conicity of the posts, it was reconstructed considering number, width and course of the annual rings in the different section planes. The non-durable sapwood was not considered.

Fig. 2 Determination of remaining cross section. *Grey line*: Reconstructed original heartwood cross section. *Black line*: Remaining undecayed heartwood cross section
Abb. 2 Bestimmung des verbliebenen Restquerschnitts. *Graue Linie*: Rekonstruierter ursprünglich vorhandener Kernholzquerschnitt. *Schwarze Linie*: Querschnitt des verbliebenen, nicht verfaulten Kernholzes

The percentage of the remaining cross section $A_{\text{remaining}}$ was calculated as follows:

$$A_{\text{remaining}} = \frac{A_{\text{existing}}}{A_{\text{original}}} \cdot 100\,[\%]\,.$$

In addition, the prevailing type of decay (white rot, brown rot, or soft rot) was identified for each post and section plane according to EN 15083-2 (CEN 2005).

2.3 Determination of wood moisture content

The wood moisture content was determined according to DIN 52183 (DIN 1977) for the inner and outer part of the heartwood from each section plane at five posts per site. The specimens were weighed (m_u), dried at $103 \pm 2\,°C$ until constant mass, and weighed again (m_0). The wood moisture content (MC) was calculated as follows:

$$\text{MC} = \frac{(m_u - m_0)}{m_0} \cdot 100\,[\%]\,.$$

2.4 Determination of soil parameters

The soil at the different sites was sampled close to those posts which were used for wood moisture measurements to determine its moisture content, water holding capacity, and pH-value. Around each post, four single samples were taken using a sampling tube, which allowed sampling in different depths (0 to −10 cm, −25 to −35 cm, and −55 to −65 cm) corresponding to the section planes 0, −30, and −60 cm. Prior to the analysis, the four single samples were merged to obtain one homogenous and representative total probe per section plane.

To determine the soil moisture content (MC_{soil}) 80–100 g moist soil were weighed (m_u), dried at $103 \pm 2\,°C$ till constant mass, and weighed again (m_0). The soil moisture content was calculated as follows:

$$\text{MC}_{\text{soil}} = \frac{(m_u - m_0)}{m_0} \cdot 100\,[\%]\,.$$

The water holding capacity (WHC) was determined according to ISO 11268-2 (ISO 2000). Therefore, the soil samples were air dried, pounded in a mortar, sieved (mesh size: 2 mm), and put into plastic tubes ($\varnothing = 40$ mm, $l = 10$ cm). The bottom of the tubes was covered with a synthetic grit and a filter paper (MN 640 W, Macherey Nagel, Düren). The filling height was 7 cm. The tubes were dipped in deionised water for 12 h to obtain water saturation of the substrate. Afterwards the tubes were put on a water saturated sand bath for 2 h to drain off. To determine the WHC of the substrate it was weighed (m_u), dried at $103 \pm 2\,°C$ till constant mass, and weighed again (m_0). The WHC was calculated as follows:

$$\text{WHC} = \frac{(m_u - m_0)}{m_0} \cdot 100\,[\%]\,.$$

Table 2 Mean remaining cross section of the posts for the different sites and section planes
Tabelle 2 Mittlerer Restquerschnitt der Pfähle für die unterschiedlichen Standorte und Schnittebenen

Site	Previous service life [a]	Mean remaining cross section [%]				
		+30 cm	0 cm	−30 cm	−60 cm	Minimum[2]
1	5	95.2	90.0	86.9	90.2	84.9
2	10	87.2	78.5	79.1	83.9	71.8
3	20	74.4	53.5	39.3	45.7	34.9
4	30	91.2	74.9	56.1	48.4	42.9
5	$60+x^1$	90.6	73.5	40.9	77.5	40.9

[1] The posts have been in service for at least 60 years.
[2] Refers to the section plane with the least remaining cross section of each post.

Table 3 Percentage of posts in classes of remaining cross section for the different sites
Tabelle 3 Anteil von Pfählen in Klassen des verbliebenen Restquerschnitts für die unterschiedlichen Standorte

Site	Previous service life [a]	Percentage of posts with remaining cross section x [%]			
		$100\% > x \geq 90\%$	$90\% > x \geq 75\%$	$75\% > x \geq 50\%$	$x < 50\%$
1	5	60.0	26.7	6.7	6.7
2	10	5.0	45.0	40.0	10.0
3	20	0.0	0.0	26.7	73.3
4	30	0.0	10.0	50.0	40.0
5	$60+x^1$	0.0	6.7	46.7	46.7

[1] The posts have been in service for at least 60 years.

The pH-value of the soil samples was determined in deionised water as well as in 0.01 molar $CaCl_2$-solution according to ISO 10390 (ISO 2005). After suspending 10 g of each air dried and sieved sample for 2 h in 25 ml of the respective liquid, the pH was measured with a pH-meter (pH-Checker, Hanna Instruments).

3 Results and discussion

3.1 Remaining cross section

Regarding the mean remaining cross section as a measure for the degree of destruction of the posts, a high variation was observed between the different section planes as well as between the different sites and previous service lives, respectively (Table 2). The mean minimum remaining cross section decreased from site 1 (84.9%) to site 3 (34.9%) with increasing previous service life, but was higher at site 4 (42.9%) after 30 years and at site 5 (40.9%) after at least 60 years in service.

Remarkable differences between the differently old posts became obvious when the posts were grouped according to their remaining cross section independent from the section plane. In Table 3 only the section with the smallest remaining cross section was considered: 40% of the posts at site 1 had already lost more than 10% of their cross section due to decay, although they had been in service for only 5 years. In contrast, more than half of the posts at site 5 retained more than 50% of their cross section after at least 60 years in service.

Furthermore it became evident that the section plane with the smallest mean remaining cross section was not the same for the different sites (section 0 cm for site 2; section −30 cm for site 1, 3, and 5; section −60 cm for site 4). Therefore, each post was assigned to one of the following groups with different courses of remaining cross section along the post axis:

- Group 1: Remaining cross section increased from the bottom to the top of the post
- Group 2: Smallest remaining cross section between the ground line and 30 cm below
- Group 3: Remaining cross section decreased from the bottom to the top of the post

The percentage of posts assigned to these three groups can be seen in Table 4. In general, the percentage of posts belonging to group 1 increased with ascending age of the posts. On the other hand, the percentage of posts in group 2

Table 4 Percentage of posts in groups with different courses of remaining cross section along the post axis for the different sites. Group 1: Remaining cross section increased from the bottom to the top of the post. Group 2: Smallest remaining cross section between the ground line and 30 cm below. Group 3: Remaining cross section decreased from the bottom to the top of the post
Tabelle 4 Anteil von Pfählen in Gruppen unterschiedlichen Verlaufs des verbliebenen Restquerschnitts entlang der Pfahlachse für die unterschiedlichen Standorte. Gruppe 1: Restquerschnitt steigt mit der Pfahlhöhe an. Gruppe 2: Geringster Restquerschnitt zwischen der Boden-Luft-Zone und 30 cm darunter. Gruppe 3: Restquerschnitt sinkt mit der Pfahlhöhe

Site	Previous service life [a]	Percentage of posts [%]		
		Group 1	Group 2	Group 3
1	5	20	60	20
2	10	20	65	15
3	20	60	33	7
4	30	67	33	0
5	$60+x^{1,2}$	87	13	0
All		51	41	8

[1] The posts have been in service for at least 60 years.
[2] The depth of burying of the posts in group 1 at site 5 was less than 60 cm.

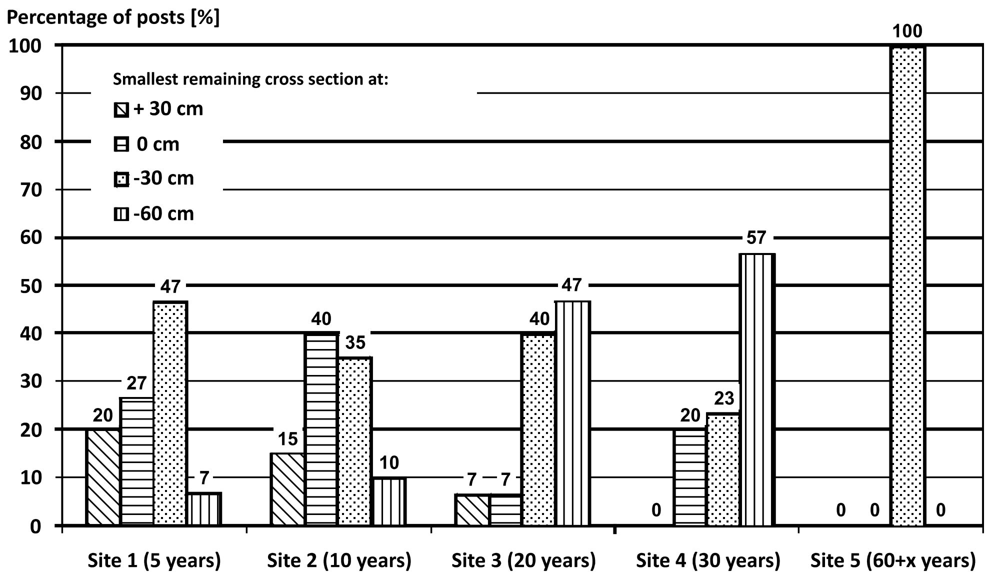

Fig. 3 Percentage of posts with the smallest remaining cross section in different section planes for the different sites
Abb. 3 Anteil von Pfählen mit dem geringsten verbliebenen Restquerschnitt in den jeweiligen Schnittebenen an den unterschiedlichen Standorten

decreased. Group 3 contained the smallest number of posts; at sites 4 and 5 none of the posts followed the criteria of this group. This assignment stands in contrast to the commonly accepted assumption, that the ground line is the most severe exposure for a wooden component in ground contact [De Groot et al. 1979, EN 252 (CEN 1990)], because here, supplies of atmospheric oxygen, soil water and nutrients are plentiful (Levy 1987). In this study only the younger posts (site 1 and 2) were decayed to the highest extent in this zone.

This finding became even more obvious when looking on the distribution of posts with respect to the section plane with the smallest remaining cross section (Fig. 3). The percentage of posts showing the smallest remaining cross section at the deepest part of the post increased with the posts' age. Thus, in most instances posts and poles may fail at the ground line, because at this point the bending moment is maximal, but it is not necessarily the zone of most severe decay.

3.2 Type and distribution of decay

White rot was the dominating decay type at all sites, in many cases in combination with soft rot: It was found on 95.2% of the round posts and on 98.6% of the splitted posts. In contrast, brown rot was detected at only two out of 354 section discs in total. This dominating role of white and soft rot on oak heartwood coincides with its poor performance in laboratory tests with white rot fungi and in terrestrial microcosms with soft rot as main decay type (Brischke et al. 2009).

Remarkable differences in the distribution and dissemination of decay were observed (Table 5 and Fig. 4). In most of the round posts decay started from the sapwood (95.2%), but also from radial cracks (33.3%). Only 4.2% of the posts showed interior rot starting from the heartwood. The main starting points for decay in the splitted posts were radial cracks (98.1%), but in 58.1% of the posts not exclusively, but also from the heartwood.

Table 5 Types of distribution and dissemination of decay in the posts
Tabelle 5 Verteilungs- und Ausbreitungsformen der Fäulnis in den Pfählen

Type of decay distribution	Percentage of posts [%][1]	
	Round posts	Splitted posts
Starting from sapwood	95.2	13.5
Starting from heartwood	4.8	58.1
Starting from radial cracks	33.3	98.1

[1] A post was assigned to one of the groups if at least half of the section discs fulfilled the criteria.

The use of posts that include sapwood portions, which suffer from very low durability, is supposed to be problematic as it may accelerate the infection of the post with wood-destroying organisms. On the other hand, two contradictory assumptions can be made concerning the role of sapwood for fungal infestation: 1. Heartwood will be infected faster, if fungal mycelium is already established in the adjacent sapwood. 2. The sapwood ring acts as a protective barrier, where decay fungi establish themselves, but do not or even very slowly attack the heartwood portions, potentially because sap- and heartwood are susceptible to different decay organisms. Although both hypothesises were not definitively approved, it became evident, that remaining sapwood does not necessarily lead to a shortened service life of the posts, as can be seen from the high percentage of splitted posts with decay starting from the heartwood. As expected, on nearly all round posts decay started from the sapwood, because it was surrounding these posts completely, and only a few showed interior heartwood decay.

Fig. 4 Examples for different types of distribution and dissemination of decay in round posts. *Left*: Decay starting from the sapwood. *Centre*: Decay starting from the central heartwood. *Right*: Decay starting mainly from radial cracks
Abb. 4 Beispiele für die Verteilung und Ausbreitung von Fäulnis in Rundpfählen. *Links*: Fäulnis vom Splintholz ausgehend. *Mitte*: Fäulnis vom inneren Kernholz ausgehend. *Rechts*: Fäulnis überwiegend von radialen Rissen ausgehend

The role of deeper cracks acting as gates for water, fungal mycelium and spores into the wood was often reported for preservative treated wood, where the treated shell frequently breaks up through cracks (e.g. Helsing and Graham 1976, Morrell 1990), but may be transferred also to untreated wood. However, quantitative studies on the meaning of cracks as starting points for decay in untreated wood are rare and do rather indicate that their role is important (Clausen et al. 2001, Augusta 2007).

Insect damage caused by *Phymatodes testaceus* L. was detected on 42.9% of the round posts and on 43.2% of the splitted posts, but was mainly restricted to sapwood portions.

3.3 Wood moisture content and soil parameters

The wood moisture content of the posts generally increased with increasing depth, whereby only slight differences between the interior and exterior fifth of the posts were found (Table 6). Furthermore, the five sites were very similar in terms of the resulting wood moisture content of the posts.

The moisture content of the soil varied between 7.7 and 29.5% at the five sites. At sites 1, 4, and 5 the soil moisture content decreased slightly with the soil depth, but was nearly constant at sites 2 and 3 (Table 7). This finding coincided with the course of the water holding capacity of the soils at the different sites: increasing with soil depth at sites 1, 4, and 5, and nearly constant at sites 2 and 3. The pH values varied between 5.5 and 7.2 in deionised water and between 4.8 and 6.3 in $CaCl_2$-solution. Although the soil moisture values represent only the current status at the sites for one single day, it became obvious for all soil parameters that the differences between the sites were only marginal. The only exception was site 5 showing a high water holding capacity (46–61%), but low soil moisture contents (10–15%).

Table 6 Mean wood moisture content of the interior and exterior fifth of the posts in different section planes for the different sites
Tabelle 6 Mittlere Holzfeuchte im inneren und äußeren Fünftel der Pfähle in den jeweiligen Schnittebenen an den unterschiedlichen Standorten

Site	Previous service life [a]	Mean wood moisture content [%]							
		Interior fifth of the post				Exterior fifth of the post			
		+30 cm	0 cm	−30 cm	−60 cm	+30 cm	0 cm	−30 cm	−60 cm
1	5	21	47	65	83	20	50	92	102
2	10	20	53	73	84	17	54	88	101
3	20	19	34	85	93	17	30	103	118
4	30	18	42	86	110	17	56	107	129
5	$60+x^1$	17	47	97	100	17	42	96	107

[1] The posts have been in service for at least 60 years.

Table 7 Mean moisture content, water holding capacity, and pH of soil surrounding the posts in different section planes and for the different sites
Tabelle 7 Mittlere Feuchte, Wasserhaltekapazität und pH-Wert des Bodens in unmittelbarer Nähe der untersuchten Pfähle in den jeweiligen Schnittebenen an den unterschiedlichen Standorten

Site	Previous service life [a]	Mean soil moisture content [%]			Water holding capacity [%]			pH in deionised water	pH in 0.01 m $CaCl_2$
		0 cm	−30 cm	−60 cm	0 cm	−30 cm	−60 cm	all	all
1	5	22	19	19	50	44	35	7.2	6.3
2	10	14	15	16	44	42	40	5.5	4.8
3	20	20	22	22	50	50	50	5.9	5.2
4	30	28	27	21	49	46	39	6.1	5.5
5	$60+x^1$	15	12	10	61	54	46	5.8	5.3

[1] The posts have been in service for at least 60 years.

Table 8 Interrelationship between the different investigation parameters, expressed as coefficient of determination R^2 for linear smoothing functions, at the different sites

Tabelle 8 Zusammenhang zwischen den verschiedenen Untersuchungsparametern ausgedrückt als Bestimmtheitsmaß R^2 einer linearen Ausgleichsfunktion für die unterschiedlichen Standorte

Site	Previous service life [a]	Coefficient of determination R^2					
		Variable 1					
		Remaining cross section [%]	Remaining cross section [%]	Remaining cross section [%]	Soil moisture content [%]	Water holding capacity [%]	Water holding capacity [%]
		Variable 2					
		Wood moisture content[2] [%]	Soil moisture content [%]	Water holding capacity [%]	Wood moisture content[2] [%]	Wood moisture content[2] [%]	Soil moisture content [%]
1	5	0.0031	0.0093	0.0008	0.0241	0.7161	0.0728
2	10	0.0006	0.1164	0.0359	0.2334	0.0078	0.2478
3	20	0.0783	0.5686	0.3443	0.0792	0.0033	0.1497
4	30	0.5802	0.3546	0.3481	0.6151	0.6927	0.8032
5	$60+x$[1]	0.1008	0.0057	0.0027	0.4509	0.5494	0.6688

[1] The posts have been in service for at least 60 years.

[2] Wood moisture content measured in the interior fifth of the posts.

The complexity of the factors responsible for the intensity of decay at the posts became apparent from the coefficients of determination for potential correlations between the wood moisture content, the different soil parameters, and the remaining cross sections (Table 8). Neither the wood moisture content, nor the soil moisture content and the water holding capacity of the soil were correlated with the degree of decay of the posts ($R^2 < 0.8$). Furthermore, even the soil and the wood moisture content seemed to be independent from each other; the same for the water holding capacity and the corresponding moisture content of the soil. Finally, also no correlation arose between the age of the posts and the remaining cross sections (Fig. 5).

In contrast to in-ground field tests, e.g., according to EN 252 (CEN 1990) it was not possible to assess the extent of decay in terms of strength or mass loss, because the posts in this study were very inhomogeneous in size and shape. Pursuant to the pick test according to EN 252 (CEN 1990), wood specimens are rated with respect to the depth and distribution of decay, which allows at least a calculative comparison with those results (Table 9). Augusta (2007) and Brischke et al. (2009) reported on numerous field tests with European oak heartwood in and above ground. Hereby a steady increase in the mean decay rating was observed till all specimens had failed, which stands in contrast to nearly identical mean remaining cross sections found in this study at sites 3, 4, and 5 after 20, 30, and 60 years in service. Secondly, decay started on oak heartwood immediately after its exposure in the ground without any time lag necessary for leaching of extractives or any other kind of detoxification in field tests (Brischke et al. 2009). This coincides with the unexpectedly early reduction of the posts' cross section at

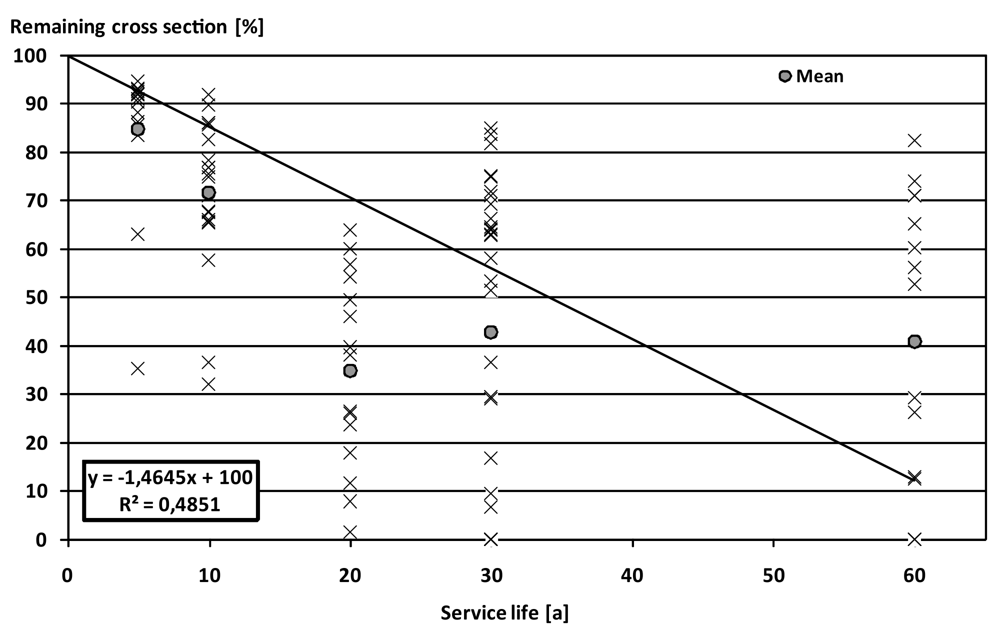

Fig. 5 Interrelationship between remaining cross section and the previous service life of the posts (refers to the section plane with the least remaining cross section of each post)

Abb. 5 Zusammenhang zwischen Restquerschnitt und bisheriger Gebrauchsdauer der Pfähle (berücksichtigt wurde jeweils der minimale Restquerschnitt des Pfahls)

Table 9 Decay rating for in-ground field tests according to EN 252 (CEN 1990) and corresponding remaining cross sections of specimens
Tabelle 9 Abbaubewertung für Eingrabeversuche nach EN 252 (CEN 1990) und entsprechende Restquerschnitte der Prüfkörper

Decay rating after EN 252 (CEN 1990)	Description	Remaining cross section of specimen x [%]
0	No attack	$x = 100$
1	Slight attack	$100 > x \geq 88$
2	Moderate attack	$88 > x \geq 67$
3	Severe attack	$67 > x \geq 48$
4	failure	$48 > x$

site 1 of this study after only 5 years in service (Table 2, Fig. 5).

The extremely long service life of many posts at site 4 and 5 seemed to stand in contrast with results of field tests according to EN 252 (CEN 1990), where the mean service life of oak specimens did not exceed 8 years (Brischke et al. 2009), but may be explained by the differences in size. There is still a controversial discussion about the influence of size and shape of a wooden component on its durability: While in above ground exposures bigger sized components seem to be compromised due to their lower capability to dry out after wetting (Sell 1980), opposite effects are discussed for timber in ground contact: Leicester et al. (2005) have shown that the impact of leaching of water soluble extracts or preservatives as well as the superficial degradation by bacteria is less pronounced for bigger components. As in this study also remarkable decay was observed on posts after only 5 years in service, a general rule for the impact of size or cross section of a component cannot be framed.

4 Conclusion

The durability of oak and the service life of the posts, respectively, were affected by high variation. Posts prematurely failing after only five years were found as well as posts still serviceable after 60 years. Thus, a definite service life of oak posts to be expected in ground contact was not indicated, and it seemed that the posts' service life is not simply correlated with one of the soil parameters examined or the wood moisture content, respectively. On the other hand, different peculiarities were observed and quantified: It was clearly shown that the ground line, where moisture and oxygen conditions should be ideal for many fungi, was not at all the most critical part of the posts; in fact it was 30 cm below the ground line. Furthermore no significant negative impact of remaining sapwood portions on the durability of the heartwood was found, but the important role of radial cracks for the initiation of decay became apparent. In summary, it became obvious that case studies can seriously contribute to a better understanding of decay processes and the reasons for wood durability. In regard to this potential, important factors for the in-ground durability are size and shape of timber components, which have not adequately been considered so far. For service life prediction of timber components in general and for oak wood in particular further surveys seem to be worthwhile and should include also above ground exposures. For calibration and adaption of field and laboratory test methods valuable hints can be expected when aiming at a methodology as close to reality as possible.

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6.14 Publication XIV: Durability of oak timber bridges – Impact of inherent wood resistance and environmental conditions

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Durability of oak timber bridges – Impact of inherent wood resistance and environmental conditions

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ABSTRACT

Premature failure of timber construction can have dramatic consequences, at worst threat to human life or physical condition. Timber components might perform unexpectedly poor due to insufficient protection by misuse, design, low work execution level, or due to low resistance of the material in use. However, information about the material resistance of prematurely failed structures is usually lacking. Therefore this study aimed on developing a method to display the relationship between damages occurring on structures in service and the resistance against wood-destroying fungi of the material used.

Drilling cores taken from wooden structures were found to have the ability to serve as specimens in laboratory decay test when compared to standard specimens. Therefore, drilling cores were sampled from different components of six timber bridges in Hannover, Germany, made from English oak (*Quercus robur* L.). The cores were submitted to the white rot fungus *Trametes versicolor* and to soft rot fungi in terrestrial microcosms. The determined mass losses due to fungal decay were compared with the level of damage of the studied bridge components. The results indicated that the material-inherent resistance was responsible for damages rather than poor details of the construction. The methodological approach might be used to provide further knowledge about the relationship of timber in service and under ideal laboratory test conditions.

1. Introduction

1.1. Reasons for premature failure of timber structures

For millennia timber is an important building material and used for many different applications. More than 5000 years ago, first timber bridges were built spanning the river Nile (Gerold, 2001). Compared to synthetic materials like metal alloys or polymers, the natural grown wood is a heterogeneous raw material, with varying properties also within one wood species. Finally, the structure and thus corresponding material properties vary also within one tree and consequently within one piece of wood, which needs to be considered in particular for structural use of timber. Premature failure of timber construction can have dramatic consequences, at worst threat to human life or physical condition. Timber components might perform unexpectedly poor due to insufficient protection by misuse, design, low work execution level, or due to low resistance of the material in use.

If wood is used outdoors the impact of physical and biological agents lead to biodegradation, which determines the service life of timber structures (e.g. Brischke, 2007). Irrespective strong efforts during recent years, in particular in the public sector, to enhance wood protection by design, premature failure of timber structures can occur after a couple of years in service. Approximately 1% of transmission poles failed after a period of less than 10 years in service (DHMV, 2008), although usually 30 years service life is expected (e.g. Bollmus et al., 2012). In contrary, wooden components and commodities can reach surprisingly long service lives as reported by Willeitner (2005) and Brischke and Rolf-Kiel (2010). The reasons for high variation of service life of timber construction are manifold, but might be constrained to exposure in terms of moisture and temperature loads on the one hand and material-inherent resistance on the other hand. More recently Larsson-Brelid et al. (2011), Brischke et al. (2012) and Bollmus et al. (2012) reported on partly dramatic differences in resistance of wood in dependence on the

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respective exposure situation, but also under nearly identical environmental in-use conditions.

Unexpectedly low durability of wood and wood-based products is a potential source of danger as well as an additional expense factor. Furthermore premature failure prohibits a precise service life prediction and thus accurate planning in the building trade. Against this background further research on the reasons for premature failure of timber components are needed, preferably based on in situ studies of real structures in service.

Numerous standard and non-standard procedures to determine resistance or durability of wood exist (Gobakken and Viitanen, 2004). They all have in common that specimens of certain shape and dimension need to be taken for exposure to wood-destroying organisms. Usually this requires destruction of at least parts of the structure in question, which is a criterion for exclusion. Consequently, a new method of sampling and testing the resistance of wood was sought, which allowed non- or at least semi-destructive testing. Therefore drilling cores should be taken from structures in service and submitted to modified standard laboratory durability tests.

1.2. Durability of European oak (Quercus robur and Quercus petraea)

Oak trees (*Quercus* spp.) play an important role for people in various countries for several centuries. European oak (*Q. robur* and *Q. petraea*) forests offered food for animals and humans as well as firewood and building material (Rüffer and Kätzel, 2006). Oak timber was appreciated because of its hardness, strength and proverbial durability (Kollert, 1991). Archaeological oak findings from Roman times can still be made (Haneca et al., 2005), but also studies on 800 years old foundation poles and planks (Böttcher, 1989) point to an extraordinarily durable timber species. On the other hand oak timber structures failed surprisingly after only a few years in service. Schulz (1976) reported on oak railway sleepers, which were exposed in the tropical climate of Liberia showing signs of decay after 1–2 years and failed partly after four years. More recent studies on oak fence posts confirmed the high variation of natural durability (Brischke et al., 2010). A case study on fence posts revealed premature failures of oak after only 5 years in service, while other posts were still serviceable after more than 60 years exposure in ground (Brischke and Rolf-Kiel, 2010).

At present European oak is classified as "durable' (durability class DC 2) according to EN 350-2 (1994). However, numerous studies lead to the assumption that its durability is overestimated and results from laboratory and field test studies showed partly significantly lower durability (e.g. Augusta et al., 2005; Brischke et al., 2010). Oak was partly found to be "non-durable' (DC 5) when exposed in ground and "less durable' (DC 4) when exposed above ground (Brischke et al., 2010). Also results from laboratory tests with unsterile soils (terrestrial microcosms TMC) led to classify oak as "non-durable'. In contrast, laboratory tests with pure cultures of different basidiomycetes came to a durability classification between DC 1 ("very durable') to DC 3 ("moderately durable') (Wälchli, 1973, 1976; Bellmann, 1988; Van Acker et al., 1999, 2003; Guilley et al., 2004; Humar et al., 2008).

However, results from standardized laboratory tests are not necessarily transferable to real service conditions, results from field tests are characterized through real climatic conditions and a variety of potential decay organisms present at the test site assuring more realistic results.

To overcome the gap between idealized test conditions of laboratory experiments and the often unacceptably high variation of parameters under real life situations, this study aimed on "quasi in situ' resistance tests. Exemplarily, six oak timber bridges were examined in terms of decay and other damages. Drilling core samples were taken from a variety of differently attacked components and submitted to modified standard durability tests in the laboratory. Real life condition of structural members and their resistance determined under defined test conditions will be compared.

2. Materials and methods

This study aimed on developing a method to display the relationship between damages occurring on structures in service and the resistance against wood-destroying fungi of the material used. Therefore in a first step the suitability of drilling cores for durability tests was examined. In a second step drilling cores were taken from oak timber bridges and submitted to durability tests with pure cultures of basidiomycetes and terrestrial microcosms.

2.1. Suitability of drilling cores for decay tests

2.1.1. Specimen preparation

Wooden cores were taken from boards, which were 30 mm in thickness, with a battery-operated tenoning drill with an outer diameter of 20 mm. The diameter of the cores was 10 mm. To assure the suitability of drilling cores as test specimens comparative decay tests were conducted with the following alternative specimen types as shown in Fig. 1: discs (5 (ax.) × 30 × 30 mm^3) as used for screening tests with a low ratio between axial and non-axial wood tissue, blocks with a volume similar to the cores (10 (ax.) × 10 × 30 mm^3), and stakes of 100 (ax.) × 5 × 10 mm^3 according to CEN/TS 15083-2 (2005). All specimens were free of knots, cracks and other defects.

Reference specimens were cut from European beech (*Fagus sylvatica* L.). In total 363 specimens were submitted to decay tests against different basidiomycetes and in terrestrial microcosms. Table 1 gives an overview about the distribution of specimens on the different tests.

2.1.2. Durability tests with basidiomycetes

To examine the suitability of using drilling cores to determine the durability of wood the different oak and beech specimens were submitted to durability tests according to CEN/TS 15083-1 (2005). The following test fungi were used

- *Coniophora puteana* (Schumacher ex Fries), Karsten (Strain BAM Ebw.15),
- *Trametes versicolor* (Linnaeus) Quélet (Strain CTB 863A),
- *Donkioporia expansa* (Desm.) Kotlaba & Pouzar.

The specimens were put in incubation jars (105 mm ∅ × 80 mm), where the test fungi have been cultivated on malt agar filled to a height of approximately 5 mm. After steam sterilization the specimens were placed on stainless steel washers. The incubation period was 12 weeks.

Mass loss (ML) by fungal decay and wood moisture content after incubation (u_i) were determined. Therefore all specimens were oven-dried before and after incubation at 103 °C for 24 h till constant mass and weighed to the nearest 0.001 g. Mass loss and wood moisture content were determined according to the following equations:

$$u_i = \frac{m_i - m_0}{m_0} \times 100 \quad (1)$$

u_i = wood moisture content after incubation in %
m_i = mass after incubation in g
m_0 = oven dry mass in g before incubation

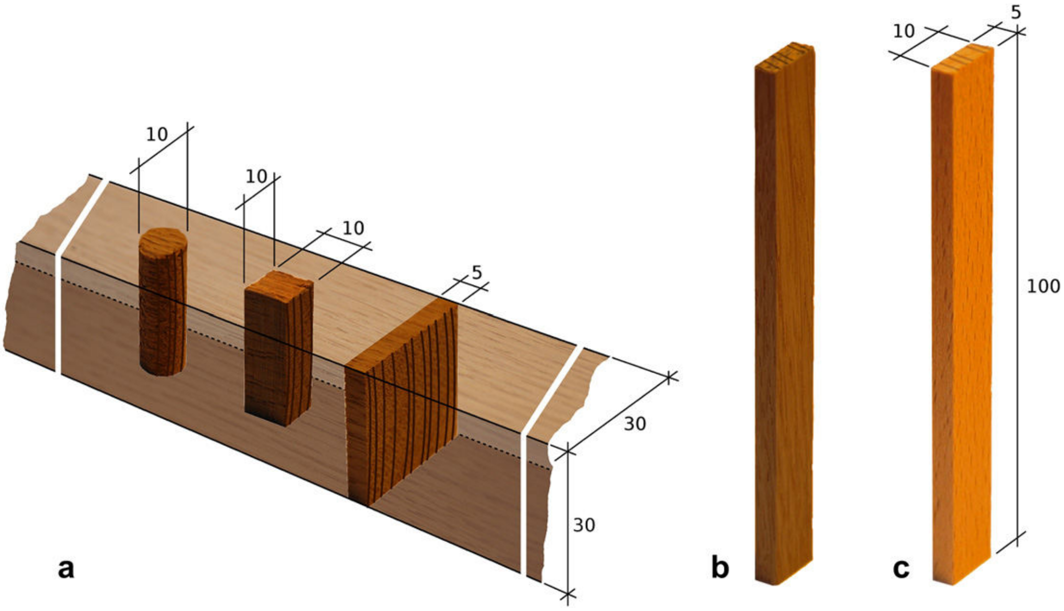


Fig. 1. Specimen types used for comparative decay tests. a) Sampling of axially matched drilling cores, blocks, and discs from an English oak lattice. b) Stake-shaped test specimen of English oak. c) Moisture control specimen of beech. All dimensions in mm.

$$ML = \frac{m_0 - m_{i,0}}{m_0} \times 100 \quad (2)$$

ML = mass loss in %
$m_{i,0}$ = oven-dry mass after incubation in g
m_0 = oven dry mass before incubation in g

2.1.3. Durability tests with terrestrial microcosms

In addition to durability tests with basidiomycetes, drilling cores were submitted to unsterile soil in terrestrial microcosms according to CEN/TS 15083-2 (2005). Therefore soil from the test site in Hannover–Herrenhausen was used at 95% of its water holding capacity. The four different specimen types were exposed to the soil according to the standard and thus buried to 4/5 of their length and stored at 27 ± 2 °C and 70 ± 5% RH for 24 weeks. Mass loss (ML) by fungal decay and wood moisture content after incubation (u_i) were determined as described above and calculated according to Eqs. (1) and (2).

2.2. Oak timber bridges

2.2.1. General description

Elements from six pedestrian timber bridges were selected for this study according to the following criteria:

- Identical/similar type of construction and design to allow comparison
- Semi-destructive sampling only on non-load-bearing elements (handrails, interties, and posts) to assure remaining stability of the construction
- Components made from European oak (*Quercus* spp.) without biocidal treatment
- Documented history/known previous service life

Table 1
Number of replicates used for different decay tests and dimension of different specimen types.

Wood species	Specimen type	Dimension in mm (ax. × rad. × tang.)	Number of replicates *n*			
			Basidiomycetes tests			TMC[d]
			C.p.[a]	*D.e.*[b]	*T.v.*[c]	
Beech	Drilling core	10 ø × 30	11	11	11	12
	Block	10 × 10 × 30	11	11	11	12
	Disc	5 × 30 × 30	11	11	11	12
	Virulence disc	5 × 30 × 30	6	6	6	–
	Test stake	100 × 10 × 5	–	–	–	12
	Reference stake	100 × 10 × 5	–	–	–	60
English oak	Drilling core	10 ∅ × 30	12	12	12	12
	Block	10 × 10 × 30	12	12	12	12
	Disc	5 × 30 × 30	12	12	12	12
	Virulence disc	5 × 30 × 30	6	6	6	–
	Test stake	100 × 10 × 5	–	–	–	12
Sum			69	69	69	156

[a] *C.p.* = *Coniophora puteana*.
[b] *D.e.* = *Donkioporia expansa*.
[c] *T.v.* = *Trametes versicolor*.
[d] TMC = Terrestrial microcosms.

All bridges were located in the municipal area of the capital city of Hannover, Lower Saxony, Germany. The previous service life of the bridges varied between four and 10 years (see Table 2). The bridges were open deck bridges with filled rod balustrade made from English oak. The principal construction is shown in Fig. 2.

2.2.2. Evaluation of timber bridges and sampling procedure

On every bridge a set of $n = 12$ drilling cores was taken from a sound intertie acting as reference component. Additional sets of drilling cores each consisting of 12 cores were taken from other elements (e.g. handrail or post), which were also assessed as "sound', as well as from elements showing signs of fungal infestation or decay. The conditions of the bridge structural components were therefore rated according to a rating scheme between 0 (no attack) and 3 (severe attack) modified after EN 252 (1990). Since none of the examined components failed, the rating 4 (failure) did not occur.

As illustrated in Fig. 3 the conditions of the respective elements were assessed according to different criteria: occurrence of cracks, growth of algae and lichen and surface strength or softening through fungal decay respectively. Fungal decay was assessed using a pick test according to EN 252 (1990) and served as main criteria for selection of non-sound samples. Furthermore, the whole constructions as well as the diverse details were inspected visually and documented. Finally, each set of 12 replicate drilling cores was split into two subsets, one submitted to durability tests against basidiomycetes and one exposed in terrestrial microcosms.

The cores were drilled with a battery driven drilling device (moment of force = 96 Nm), which was gripped in a modified drill rig allowing for fast fixation on the bridge element. The maximum length of the drilling cores was 55 mm with a diameter of 10 mm. In those elements, which were more than 55 mm in length, the cores were broken out, which reduced their length to 30–40 mm. For the subsequent durability tests all cores were therefore reduced to 30 mm length. All drilling cores were taken orthogonal to the grain of the respective member. They were free of defects such as knots and visible cracks. The resulting drilling holes on the bridge members were tightly closed through gluing in wooden dowels (diameter 20 mm) made from recent oak using weather-proof polyurethane glue to avoid water trapping and consequently the initiation of decay. Afterwards, the surface was sanded.

In total 227 drilling cores were taken from the three different parts of the bridge railing. Table 2 gives an overview about the sampling of cores at the different bridges.

2.2.3. Durability tests with drilling cores

One half of the drilling cores were submitted to durability tests against basidiomycetes according to CEN/TS 15083-1 (2005). The test was limited to the most aggressive test fungus, which was *T. versicolor* (Linnaeus) Quélet (Strain CTB 863A) in previous tests with different specimen types. The incubation period was again 12 weeks.

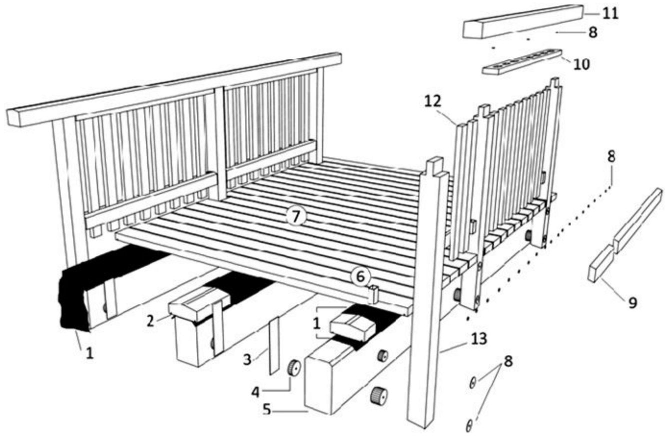


Fig. 2. Composite drawing of oak timber bridges. 1: Cover (foil), 2: Frame rail with beveled surface and drip edge, 3: Mounting panel, 4: Distance washers, 5: Principal beam, 6: Fixation of intertie, 7: Decking with drip edge, 8: Flat washer, 9: Intertie with drip edge, 10: Pilot drilled plank to fixate web members, 11: handrail, 12: Web member, 13: Post with drip edge.

The second half of the specimens was used for durability tests against soft rot and other soil-inhabiting micro-organisms in terrestrial microcosms according to CEN/TS 15083-2 (2005). The natural durability was determined according to the scheme of CEN/TS 15083-1 (2005).

3. Results and discussion

3.1. Resistance of different specimen types

No significant differences in relative mass losses were found between the three specimen types (Table 3). In no way the mass loss obtained with the drilling cores differed from the other specimen types. However, partly drastic differences in relative mass loss were found as expected between beech and oak, but also between the three test fungi. Highest mass loss was obtained by the white rot fungus *T. versicolor* on oak and beech and by the brown rot fungus *C. puteana* on beech specimens. The mean relative mass losses were above 30%. In contrast, mass losses below 5% were provoked by *C. puteana* on oak and by *D. expansa* on oak and beech.

After 24 weeks exposure in terrestrial microcosms the mean mass losses of oak specimens were between 16 and 28%, whereby stake-shaped specimens showed significantly less mass loss (Table 3). However, no significant differences in mass loss were observed between drilling cores, cubes and discs made from both, beech and oak.

Based on these findings, drilling cores were considered as useful alternative to small standard specimens in comparative laboratory durability tests and therefore used for further experiments within

Table 2
Name, year of origin, number and distribution of drilling core samples of the different oak timber bridges.

Component	Marienwerder (2001)	Stöcken (2001)	Kirchrode I (2005)	Kirchrode II (2005)	Wülfel (2006)	Limmer (2007)
Intertie reference	13	12	12	12	12	12
Intertie[a]	–	12	–	12	–	–
Post	13	13	12	–	–	15[b]
Post[a]	13	14	13	–	–	–
Handrail	12	–	–	–	12[c]	–
Handrail[a]	13	–	–	–	–	–
Sum	64	51	37	24	24	27

[a] Element more severe decayed than reference.
[b] Reference to identical elements of other bridges.
[c] First taken as reference, but severe decay was detected subsequently.

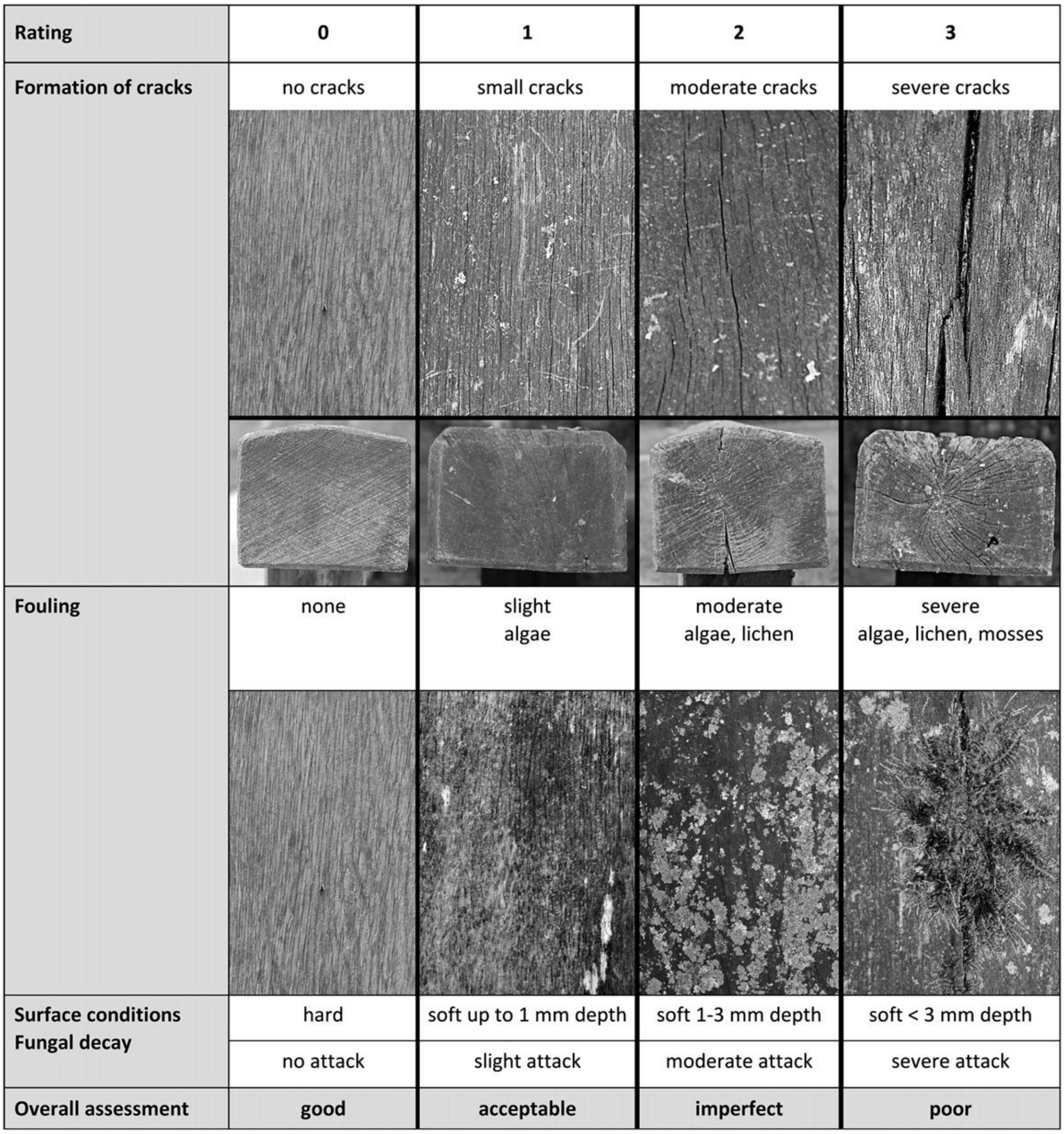


Fig. 3. Rating scheme and description of criteria for the assessment of structural bridge elements in terms of formation of cracks, growth of algae, lichen, and mosses, and surface strength or softening through fungal attack, respectively.

Table 3
Relative mass loss by attack of soil-inhabiting micro-fungi obtained in terrestrial microcosms (TMC) on differently shaped oak and beech specimens after 24 weeks of exposure.

	Mean mass loss [%] (standard deviation)			
	Drilling cores	Cubes	Discs	Stakes
Beech				
D. expansa	2.8 (0.7)	0.9 (0.3)	0.7 (0.3)	– –
C. puteana	54.3 (15.5)	40.2 (24.8)	41.0 (21.1)	– –
T. versicolor	44.4 (5.6)	42.5 (6.1)	44.9 (4.3)	– –
TMC	25.0 (3.2)	25.1 (7.8)	33.1 (9.4)	20.1 (1.2)
English oak				
D. expansa	1.8 (0.5)	1.0 (0.4)	0.6 (0.2)	– –
C. puteana	1.9 (0.9)	0.3 (0.3)	0.5 (0.1)	– –
T. versicolor	34.2 (5.1)	31.5 (4.1)	33.1 (3.4)	– –
TMC	26.9 (4.4)	21.7 (4.2)	27.7 (4.2)	16.2 (2.2)

this study. The increased ratio between specimen surfaces, in particular end grain surfaces, and specimen volume, is considered to have a negative effect on wood resistance in laboratory decay tests (Willeitner, 1982; Kleist, 2000). The accessibility of wood for water and decaying organisms is supposed to be increasing. However, these effects might be negligible for comparative studies based on worst case test conditions. In any case no negative effect of the drilling process, e.g. through heat induction or compression of wood tissue, was detected when comparing cores and cubes with high end grain portions. Finally, *T. versicolor* turned out to be the most aggressive out of the three fungi on oak and was therefore used exclusively in further tests.

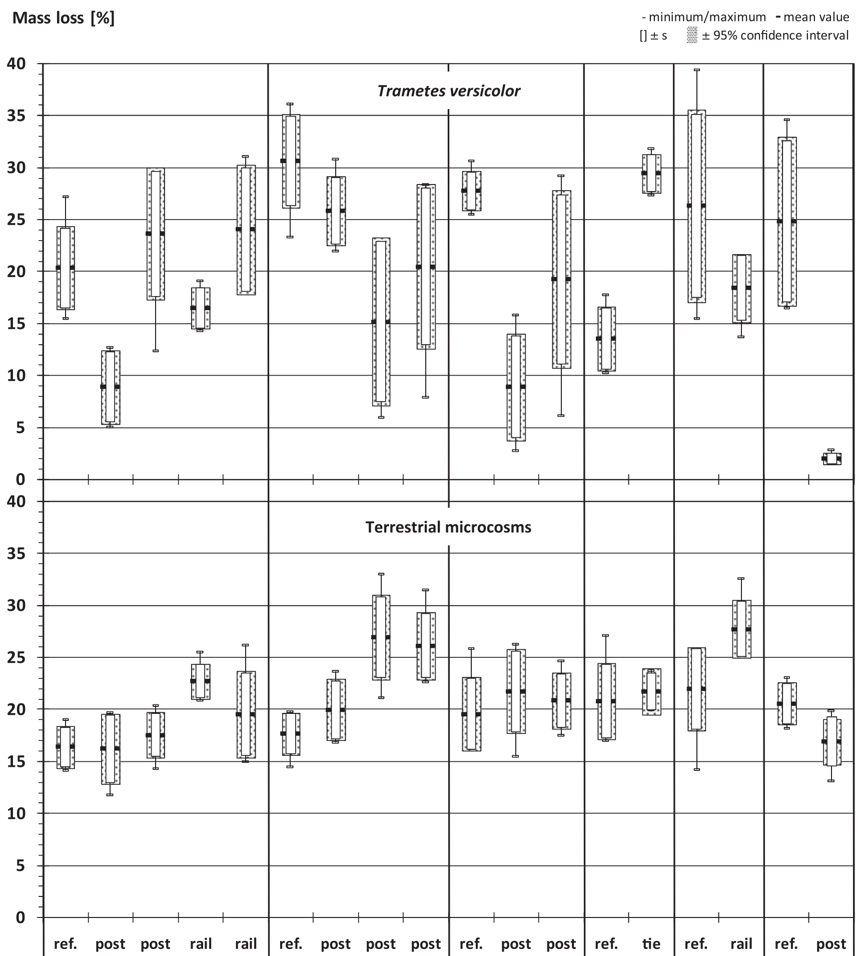
3.2. Durability against white rot fungus *T. versicolor*

Mean mass loss by *T. versicolor* after eight weeks of incubation was between 2% (post, “Limmer”) and 31% (intertie reference, "Stöcken'). Fig. 4 gives an overview about the results of the durability test against white rot and the corresponding rating of the bridge components, from which the cores have been taken. In general, cores taken from components with higher ratings (poor conditions) suffered from higher mass losses by *T. versicolor*. However, with respect to their high variation the results need to be interpreted carefully. When comparing mass losses of identical components from the same bridge 75% of the components differed significantly from each other, e.g. posts and handrails from the bridge in "Marienwerder'.

Surprisingly, cores from the reference interties showed generally high mass losses above 20%, which might be explained by the high surface-volume ratio of the interties. On the one hand it might increase leaching of extractives, which leads to reduced resistance. On the other hand the higher re-drying potential of such small sized components did most likely lead to better assessment of the overall conditions (Meyerhofer and Sell, 1979; Augusta, 2007; Mehlich, 2009). This coincides with the finding that there were no significant differences in mass loss by *T. versicolor* among 90% of the intertie samples. Only the reference intertie cores from "Kirchrode II', which were slightly burnt on the outer surface through drilling, showed less mass loss (18%).

The most significant difference was found for the cores from a post of the "Limmer' bridge (mean mass loss 2%). Furthermore this sample showed the overall lowest wood moisture content after incubation ($u_i = 67\%$), which is most likely attributed to a comparatively high number of thyllosis, which have a decisive effect on the permeability of oak wood (Chatonnet and Dubourdieu, 1998).

Furthermore, remarkable little mass loss was obtained with cores from handrail in "Wülfel', which is in contrast to rating this component as "severely attacked' (rating 3). The damage itself is illustrated in Fig. 5a and b. Fruiting bodies of the common jelly spot fungus (*Dacrymyces stillatus* Nees:Fr.) were found as well as corresponding brown rot decay with cubic breaks (Fig. 5c–e). Thus, the discordance between lab test result and observation in practice is a consequence of two different decay types, on the one hand brown rot on the handrail and on the other hand the white rot test fungus *T. versicolor*. Furthermore, *D. stillatus* caused a decay pocket, which was several centimeters deep indicating that an interior rot has been established earlier. A previous service life of only six years suggests that a complex of various parameters led to the severe brown rot attack on the handrail: the high decay rate of *D. stillatus* (Seifert, 1983; Huckfeldt and Schmidt, 2006), the predominant tangential tree ring orientation, which should be avoided (Sandberg, 2005), consequently the



Formation of cracks	1	1	1	2	3	1	2	1	2	0	0	0	1	3	1	2	0	0
Fouling	1	1	2	2	3	1	1	1	1	1	1	1	1	1	1	1	2	1
Fungal decay	1	1	1	1	2	1	1	1	2	0	1	2	0	0	1	3	1	1
	Marienwerder 2009					Stöcken 2001				Kirchrode I 2005			Kirchrode II 2005		Wülfel 2006		Limmer 2007	

Fig. 4. Mean mass loss of drilling cores exposed to *T. versicolor* after eight weeks of incubation and exposed in terrestrial microcosms after 12 weeks of exposure taken from different bridge components and corresponding rating of component conditions according to different evaluation criteria (ref. = reference intertie).

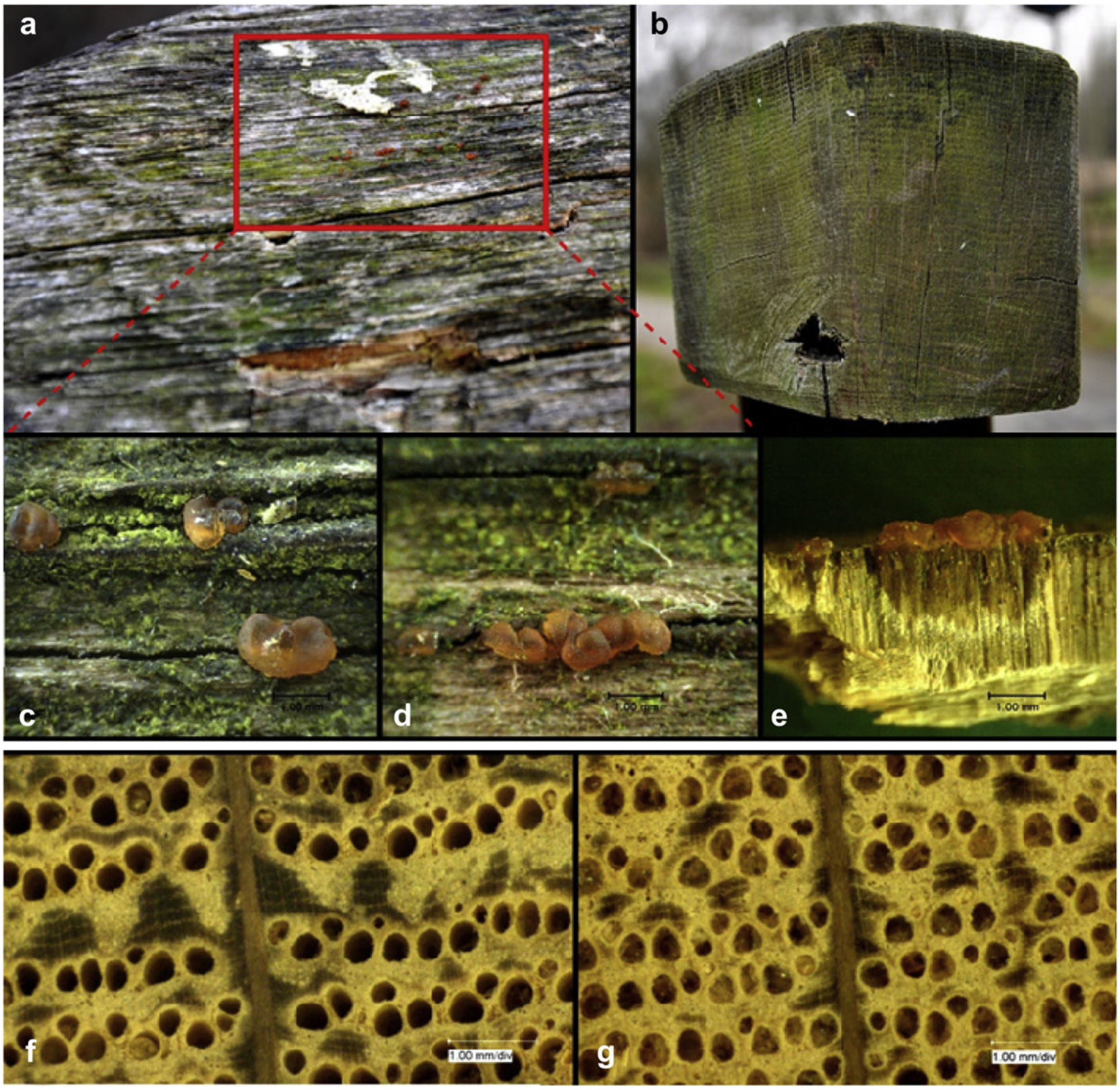


Fig. 5. Handrail in "Wülfel': a) Fruiting body and cubic cracking, b) Rot pocket on the end-grain, c) to e) Fruiting body (*Dacrymyces stillatus*), f) Very few thyllosis (handrail), g) Moderate thyllosis (reference intertie).

formation of deep cracks, and relatively sparsely formed thyllosis in the vessels of the oak heartwood as shown in Fig. 5f and g.

In summary the results from laboratory durability tests against the white rot fungus *T. versicolor* indicated that the different conditions of the studied bridge components are related to differences in resistance of the oak timber used rather than differences in quality of design and workmanship.

3.3. Durability in terrestrial microcosms

Mean mass loss obtained in terrestrial, microcosms after twelve weeks of exposure was between 16% (post, "Marienwerder') and 28% (handrail, "Wülfel'). This handrail was the only component rated as "severely' attacked, which in contrast to the white rot tests coincided with high mass loss due to soft rot decay in the TMC. Furthermore, mean mass loss of all reference interties was below 22%, which also coincides with the visual assessment of the components. However, the reason for better performance of the references in TMCs stayed unclear.

In contrast to the tests with *T. versicolor*, no general coincidence was found between mass loss obtained in TMCs and the actual conditions of the bridge components, which might be explained by the principally different exposure situation. All examined bridge components were exposed above ground without exception, while the TMC represents a wide range of in-ground organisms. For instance the post of the bridge in "Limmer' showed only 2% mass loss by *T. versicolor*, and revealed 17% mass loss in TMCs, which is still little compared to the other components and can be explained by intense formation of thyllosis. In general, the variation of mass loss within a subset of drilling cores from one component was significantly smaller in TMC tests compared to the durability tests against *T. versicolor* (Fig. 4).

The different conditions and decay patterns represented by the two durability tests are furthermore illustrated in Fig. 6, where mean mass loss of the different components obtained in both tests were correlated with each other. It became obvious that no clear relationship can be established between the two different "exposure conditions' as reflected by the tests.

Since the components examined in this study were out of ground contact, the results from the durability tests against *T. versicolor* were considered as relevant.

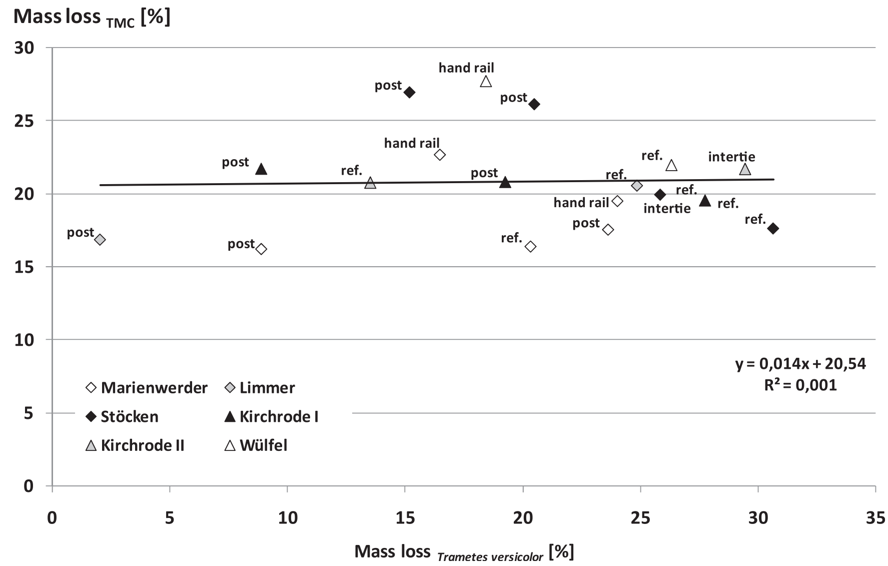


Fig. 6. Correlation between mean mass losses of drilling cores from oak timber bridge components obtained in durability tests against *Trametes versicolor* and against soft rot and other soil-inhabiting micro-organisms in terrestrial microcosms (TMC).

4. Conclusions

The use of drilling cores for durability tests against wood-destroying basidiomycetes and in unsterile soil was found to be feasible. Sampling drilling cores served as semi-destructive alternative and allowed to take higher number of replicates from the same construction element at an acceptable level of damage.

The durability tests against *T. versicolor* pointed on the variation in resistance of English oak against white rot. In contrast, the results from TMCs revealed less variation, which shows the impact of inoculum potential on the resistance of wood.

Although no correlation was found between the mass losses obtained in the two different tests, a clear relationship between mass loss by *T. versicolor* and the actual components conditions became apparent. Thus, damages of the various bridge components should be considered as consequence of varying resistance of the wood in use, rather than poor detailing and imperfect protection by design. Despite the overall good condition of the examined bridges, not all constructive measures led to an increased service life as shown by various examples of decay and other damages. Most remarkable weak points were posts with direct contact to decking boards, wooden washers, and other details leading to water traps.

Further studies will be needed to establish more reliable relationships between the resistance of wood in laboratory decay tests and the in-service performance of real components and structures. Therefore it is recommended to consider structures and assemblies showing premature failure as well as those with significantly higher previous service lives. Further wood species and test fungi should also be considered.

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6.15 Publication XV: Intrasite variability of fungal decay on wood exposed in ground contact

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Intrasite variability of fungal decay on wood exposed in ground contact

C. Brischke*, S. Olberding, L. Meyer, T. Bornemann and C. R. Welzbacher

Timber exposed in the ground faces most severe conditions in terms of exposure to wetting and fungal decay in the terrestrial environment, therefore wood durability tests are often conducted in test fields preferably ensuring the occurrence of all relevant decay organisms. One can also expect differences in decay within an individual field test site due to localised distribution of certain organisms. Therefore, relevant decay parameters were examined on the newly prepared in-ground test field in Herrenhausen, Hannover: Scots pine sapwood and European beech were exposed to record distribution of decay types, decay intensity and soil parameters. Soft and white rot were found to be dominating. Significant differences of the intrasite variability of decay intensity were observed between wood species and over time. In contrast, differences in decay intensity by different rot types were small. It was concluded that spatial differences in decay intensity were due to localised established fungal flora.

Keywords: Brown rot, Decay rate, Field test, Service life, Soft rot, White rot

Introduction

Timber structures in ground contact are exposed to conditions that promote decay by a large number of decay types. Generally, the moisture conditions in soil provoke a continual decay hazard to wood, since wood moisture content in contact with the soil is normally well above fibre saturation. In natural forests, the high decay potential under in-ground conditions is the basis for cycling of matter, i.e. the decomposition of deadwood, and is therefore beneficial in terms of releasing nutrients necessary for new growth in living trees. In contrast, when timber in service is exposed in ground contact (UC 4), decay intensity leads to shorter service lives compared to exposing the same timber in situations above ground (UC 3).

Wood durability is traditionally tested in the ground. In so called 'graveyard tests', wood specimens of standard cross-section are buried to at least half of their length and exposed to natural microflora including soil inhabiting fungi and bacteria. Based on this principle, different standardised test methods are well established in numerous countries around the world (e.g. ASTM 2006, CEN 1989, GB/T 1992). Furthermore, laboratory decay tests have been developed which include exposure of wood to unsterile soil taken from the field (CEN 2001, 2005; Edlund 1998).

While it is without controversy that exposure in ground is the most severe environment for timber with the exception of marine testing, recently there has been debate about variations of in-ground decay potential and how this needs to be considered when assigning service lives. For instance, the latest version of the European standard EN 335-1 (CEN 2006) now recognises two subclasses (4·1 and 4·2) referring to different levels of severity within UC 4 (contact with ground or fresh water). However, the specific differences between the subclasses, which had previously been considered as one class, are not described in the standard. Solely a higher moisture induced decay risk is indicated for subclass 4·2.

Numerous studies have reported on the factors that influence wood durability in the ground: soil moisture content has a direct influence on wood moisture content and depends itself on the climatic conditions as well as on the soil substrate (Rahman and Chattopadhyay 2007). While high wood moisture contents (above fibre saturation) generally promote decay as do high temperatures, stagnant water has the opposite effect (Augusta 2007). Optimum conditions for decay can therefore be expected from warm, moist, but well ventilated soils. Furthermore, pH value, salinity, chemical composition and the amount of available nutrients play an important role on the decay intensity of a field as they determine the fungal flora, which can be established in the ground (Rayner and Boddy 1988; Schmidt 2006; Rahman and Chattopadhyay 2007). Decay rates strongly depend on the decay type, whereby soft rot, which can be found frequently in the ground, is normally considered to develop more slowly than white and brown rot. Consequently, in-ground test fields are known to provide different dominating decay types, e.g. brown rot in the 'old field' at Simlangsdålen (Sweden), but soft rot and tunneling bacteria in Ultuna (Sweden), and soft rot in Viikki (Finland), Tåstrup (Denmark) and Sørkedalen (Norway) as reported for these Nordic fields by Edlund (1998) and Edlund and Nilsson (1998). For determining wood durability and the

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1 Satellite picture of in-ground test field (red rectangle) in Herrenhausen, Hannover, Germany (Google 2011), and surrounding

relative protective effectiveness of wood preservatives, it is recommended that in-ground tests are undertaken at a minimum of three different test fields to include the full range of potential decay organisms (e.g. CEN 1989; Edlund and Nilsson 1998; Augusta 2007; Brischke *et al.* 2009). Beyond this biological parameter, the site specific decay potential depends on numerous physical and chemical factors, which have been intensively examined in the past (Nilsson and Daniel 1990; Johnson and Thornton 1991; Edlund *et al.* 2006; Brischke *et al.* 2009). As reported by Edlund (1998), differences in decay activity and intensity can be expected between fields which are located close to each other and presumably one can expect differences within one test field due to certain organisms being established locally. However, data on the intrasite variability of decay intensity are not readily available and variations in decay influencing soil factors within a field site have not been quantified in relation to the decay patterns before. The aim of this study was therefore to examine all factors known to influence wood decay on a newly prepared in-ground test field at Leibniz University Hannover: Scots pine sapwood (*Pinus sylvestris* L.) and European beech (*Fagus sylvatica* L.) specimens were exposed to record distribution of decay type and intensity and various soil parameters were examined.

Experimental methods

Test field: physical data

Wood specimens were exposed on the new in-ground test field at Leibniz University Hannover, Institute of Vocational Sciences in the Building Trade in Herrenhausen, Hannover, Germany (geographic coordinates: 52°23′42·21″N; 9°42′06·95″E). The field is at an elevation of 50 m above sea level and has a total area of ~244 m^2 (Fig. 1). The field was surrounded by small trees and bushes to the north, west and south sides. Before the tests, the area was an old garden containing a variety of herbs, flowers and small bushes. Bushes and older roots of trees had been removed from the field before smaller herbs and grass were mulched down to a depth of ~20 cm, which represented fresh biomass added to the ground. Afterwards, the whole area was planed using a rotary cultivator, and after initialisation of the durability tests the grass was regularly cut between the test specimens. Climate data for the Herrenhausen site are given in Table 1.

An area of $21{\cdot}8\times 11{\cdot}2$ m^2 was allocated to in-ground field tests and this was divided into segments according to the scheme given in Figs. 2 and 3. The requirements of EN 252 (CEN 1989) for testing wood preservatives in ground contact served as basis for the layout. In total 1818 test positions with a minimum distance of 30 cm between each were arranged in 18 rows separated by 60 cm to allow for grass cutting and inspection. Before starting long term durability testing at this site, the decay activity of the test field soil was examined within this study to assure an adequate interpretation of future test results.

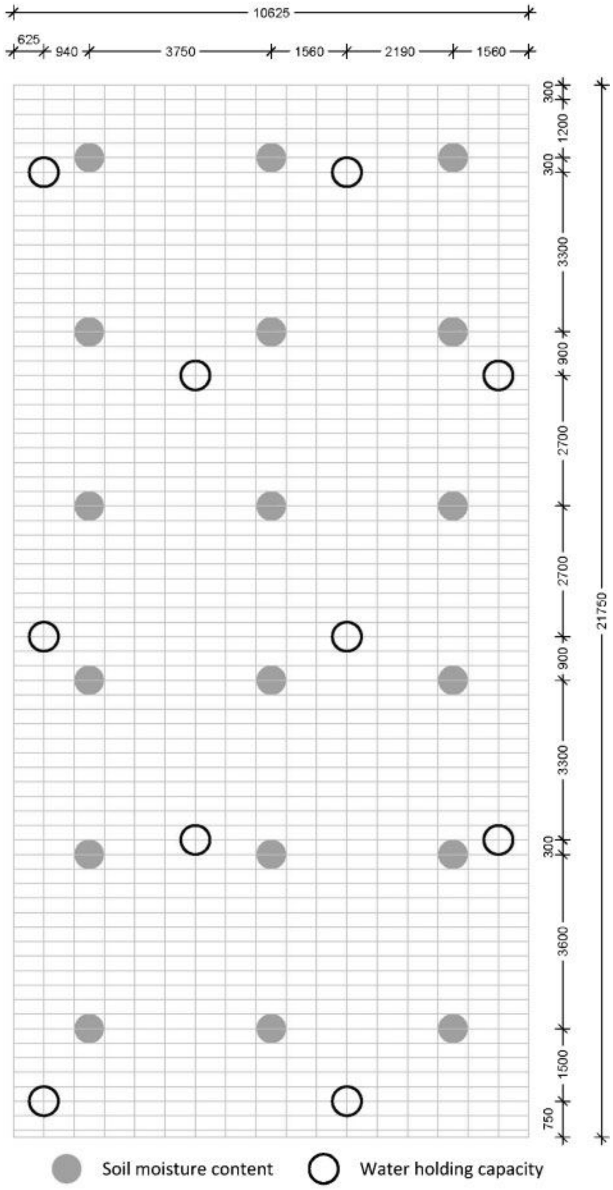
Test field: soil analyses

Determination of water holding capacity

The initial water holding capacity of the field soil was determined according to ISO 11268-2 (ISO 2000). Soil samples were taken at 10 measuring points on the field at

Table 1 Climate data for the site Herrenhausen, Hannover, Germany, determined by the Institute of Meteorology and Climatology (Hannover)

	Air temperature/°C			
Period	Annual	January	July	Rain sum/mm
1980–1999	10·2	…	…	662
2000–2009	10·7	3·0	19·5	661
June 2008–June 2011	10·7	0·4	20·6	640



2 Position plan of ground contact test field with segmentation into test positions and location of sampling positions for soil analyses (all dimensions in mm)

0–5 cm and 20–25 cm depth (Fig. 2). The soil samples were air dried and sieved (2 mm mesh). Afterwards the soil was inserted into PE cylinders of 4 cm diameter. The bottoms of the cylinders were covered with a fine polymer grid and filter paper (MN 640W, 70 mm). All cylinders were placed in a vat for 12 h, which was filled with water to a height 1 cm above the soil filling height of 7 cm. After water soaking of the soil the cylinders were placed on a water saturated sand bath for 2 h to allow unbound water to drain. The soil samples were then weighed wet and after oven drying at 105°C and the water holding capacity of the soil calculated according to equation (1).

Calculation of water holding capacity (WHC, %)

$$\mathrm{WHC}=\frac{m_s-m_0}{m_0}\times 100 \quad (1)$$

where m_s is mass of water saturated soil sample (g) and m_0 is mass of dry soil sample (g)

Determination of soil moisture content

The soil moisture content was determined initially and at monthly intervals from March 2009 and for the remaining exposure period at different measuring points on the field (Fig. 2). The soil substrate was taken at 0–5 cm and 20–25 cm depths with a cone penetrometer. The soil samples were weighed before and after oven drying at 105°C and the moisture content was determined according to equation (2).

Calculation of soil moisture content h (%)

$$h=\frac{m_h-m_0}{m_0}\times 100 \quad (2)$$

where m_h is mass of wet soil sample (g) and m_0 is mass of dry soil sample (g)

Determination of pH value and analyses of carbon, nitrogen and sulphur content

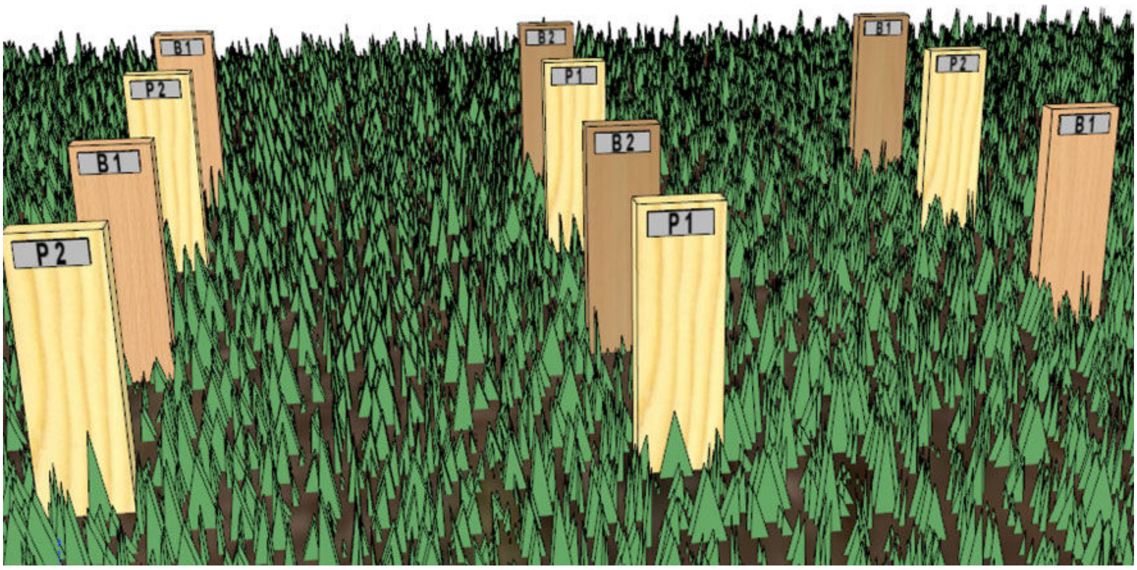
Subsamples of soil from the WHC tests were used to determine soil pH and the content of carbon, nitrogen and sulphur. For determining pH, 10 g of the sieved soil substrate were added to 0·01 mol $CaCl_2$ and deionised water respectively. After 2 h, the pH was determined with a pH meter. Analyses of carbon, nitrogen and sulphur were conducted at the Institute of Soil Science, Hannover, using an elemental analyser (Vario EL). Hereby, the soil samples were heated at 1150°C and based on the exhaust gases the content of carbon, nitrogen and sulphur was determined.

Wood specimens

For initial decay tests 500×50×25 mm specimens were used for the in-ground field trials according to EN 252 (CEN 1989). Specimens were cut from European beech (*Fagus sylvatica* L.) and Scots pine sapwood (*Pinus sylvestris* L.), which are considered to be 'non-durable' according to EN 350-2 (CEN 1994). The specimens were consistent in growth rate and matched to avoid substrate differences. A first set of specimens (×171 beech, ×162 pine) were exposed immediately after completion of the test field in June 2008. To further examine a potential positive effect of accumulated biomass in the ground on the decay intensity, a second set of specimens (×171 beech, ×162 pine) was exposed 1 year later in June 2009. The test rows were filled alternately with pine and beech specimens; the second set of specimens was set in the gaps between the first set of specimens. Thus, a uniform grid pattern was obtained, where both wood species were distributed almost homogenously across the total field as can be seen from Fig. 2.

Exposure and decay assessment

According to EN 252 (CEN 1989) the specimens were buried in the ground to half of their length and evaluated with respect to decay four times a year using the rating scheme offset out in EN 252 (CEN 1989), i.e. 0=no attack, 1=slight attack, 2=moderate attack, 3=severe attack and 4=failure. Therefore, the specimens were removed from the ground and depth and distribution of decay were assessed with the help of a so called 'pick-test' using a sharp pointed knife. In cases where severe decay was present, a manual impact bending test was applied to the specimens. The rating scheme is illustrated in Table 2. In addition, the specimens were visually inspected for the presence of brown rot, white rot, soft rot and wood destroying insects. Furthermore,



3 Position of specimens: P1, Scots pine sapwood exposed in the first year; P2, Scots pine sapwood exposed in the second year; B1, beech exposed in the first year; B2, Beech exposed in the second year

samples were taken from specimens for microscopic diagnosis according to CEN/TS 15083-2 (CEN 2005) to determine the type of decay if necessary.

The results of the decay ratings were used to determine the intensity of decay in terms of decay rate (decay velocity) according to equation (3). To assess the decay intensity distribution within the field independently from the wood species the relative decay rate was also determined (equations (4) and (5)). Therefore, the decay rate of a single specimen was related to the mean of all specimens of the same wood species and set exposed at the same time. Thus, this relative value can be between 0 and ∞.

Calculation of decay rate v (per year)

$$v = \frac{R}{t} \quad (3)$$

where R is decay rating according to EN 252 (CEN 1989) (0–4) and t is exposure time (year)

Calculation of relative decay rate v_r

$$v_r = \frac{v_i}{v_{mean}} \quad (4)$$

where v_i is decay rate for a single Scots pine or beech stake (per year) and v_{mean} is mean decay rate for all Scots pine or beech stakes (per year).

Calculation of mean decay rate v_{mean} (per year)

$$v_{mean} = \frac{\sum_{i=1}^{n} v_i}{n} \quad (5)$$

where v_i is decay rate of specimen i (per year) and n is number of replicates.

Results and discussion

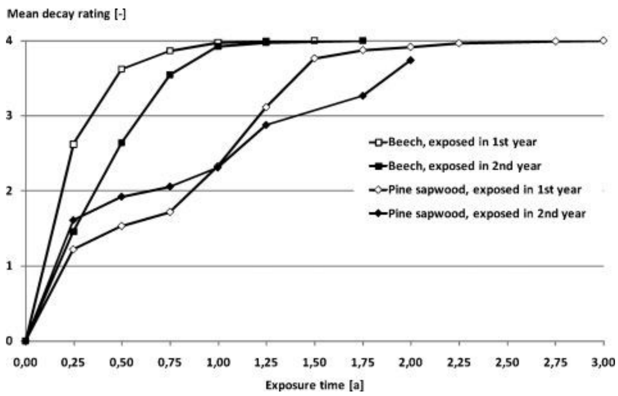
Decay intensity

Decay proceeded rapidly for both wood species, but was faster in beech, which failed completely after 1·5 and 1·75 years respectively (Fig. 4). The pine sapwood specimens survived one more year, this correlates with findings from laboratory terrestrial microcosm tests as reported by Mieß (1997) and van Acker *et al.* (1999). However, the decay of the stakes planted at the beginning of the second year was not consistently faster or slower than the decay of the stakes planted at the beginning of the first year, and so it appears that the additional biomass added to the soil when the site was established did not have any exceptional short term effect (Fig. 5). While the decay rate of the second set of beech specimens was lower than those exposed in the first year, the decay rate of Scots pine sapwood specimens increased from the first to the second year. Furthermore, considerable variation in decay intensity was found within the test field for both species for specimens exposed for both time intervals.

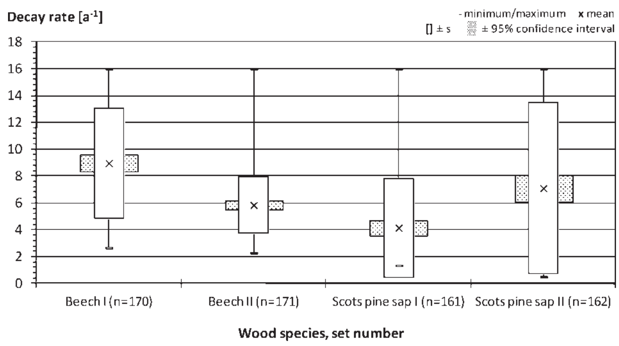
The decay intensity – expressed as relative decay rate v_r – has been determined separately for both wood species. The corresponding mapping for selected exposure intervals is shown in Figs. 6 and 7. For Scots pine exposed in the first year, no clear spatial differentiation became visible, but several 'hot spots' with up to five

Table 2 Rating scheme according to EN 252 (CEN 1989) for evaluation of wood specimens exposed in ground

Rating	Description	Definition
0	Sound	No evidence of decay, discoloration, softening or weakening caused by microorganisms
1	Slight attack	Limited evidence of decay, no significant softening or weakening up to 1 mm depth
2	Moderate attack	Significant evidence of decay, with areas of decay (softened or weakened wood) from 2 to 3 mm depth
3	Severe attack	Strong evidence of decay, extensive softening and weakening, typical fungal decay at large areas from 3 to 5 mm depth or more
4	Failure	Sample breaks after a bending test



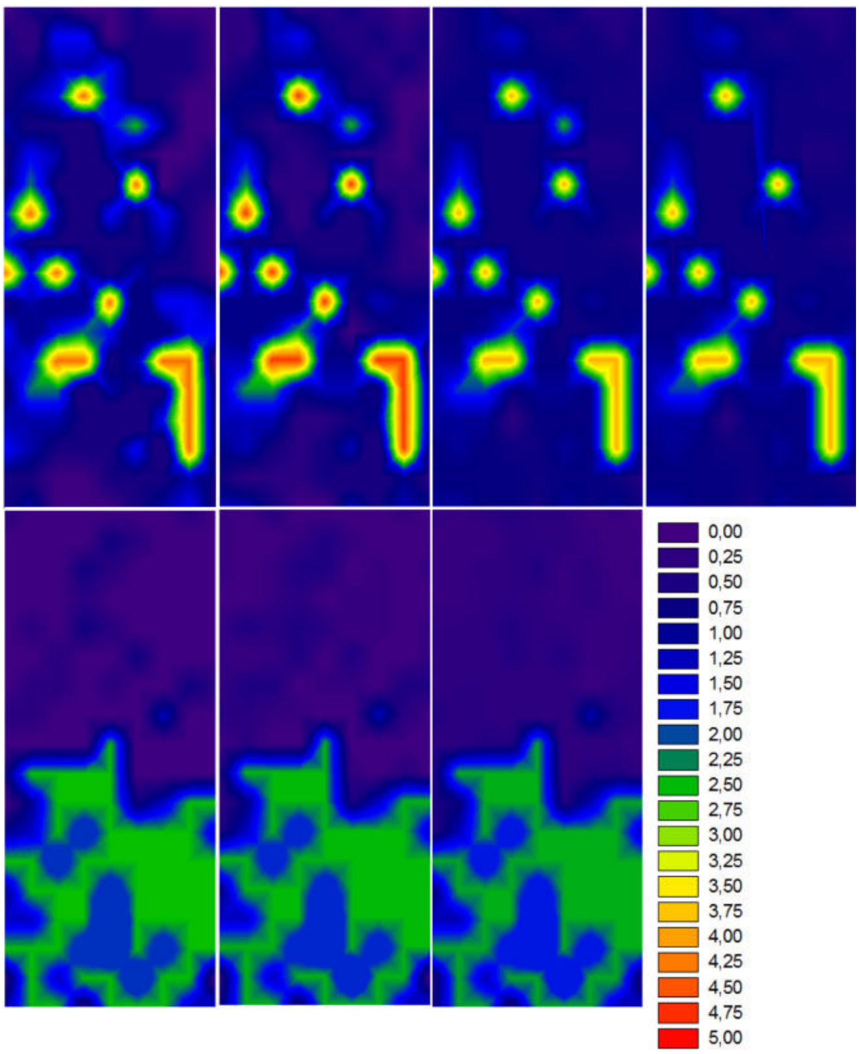
4 **Mean decay rating according to EN 252 (CEN 1989) over exposure time for beech and Scots pine sapwood specimens exposed in June of the first and second years after setting up of the test field in Herrenhausen, Hannover**



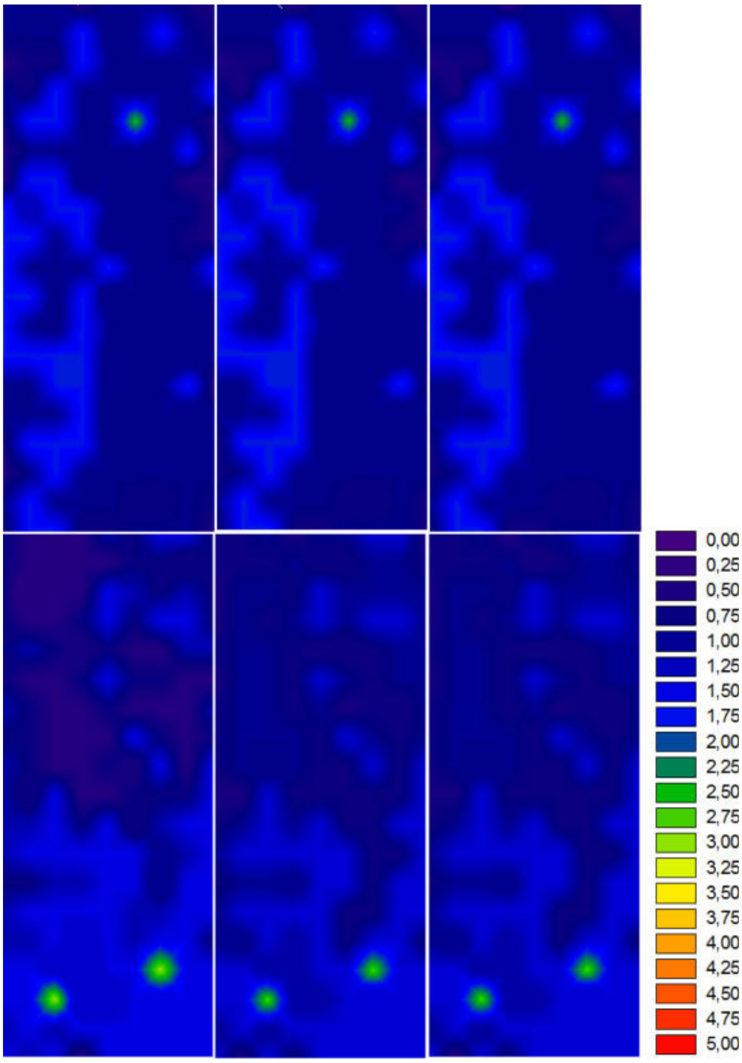
5 **Decay rates for beech and Scots pine sapwood specimens exposed in June of the first and second years after setting up of the test field in Herrenhausen, Hannover**

times higher decay intensity compared to the average intensity have been identified. The general distribution of decay intensity remained over the whole exposure period for specimens exposed in the first year. However, a completely divergent decay intensity distribution was obtained for the second set of specimens, which led to a clear differentiation between the northern part (low intensity) and the southern part (high intensity; up to v_r=3) of the test field. No 'hot spots' emerged.

In contrast to pine sapwood, the rate of decay of beech was higher and a more homogenous distribution in decay intensity was observed (Fig. 7). However, while the first set of specimens revealed no clear distribution pattern at all, the decay intensity for the second set of



6 **Intrasite variation of decay intensity expressed as relative decay rate v_r for Scots pine sapwood on the test field in Herrenhausen, Hannover. Top: specimens exposed in the first year; from left to right: results after 0·5, 1·0, 2·0 and 3·0 years. Bottom: specimens exposed in the second year; from left to right: results after 0·5, 1·0 and 2·0 years**



7 Intrasite variation of decay intensity expressed as relative decay rate v_r for beech on the test field in Herrenhausen, Hannover. Top: specimens exposed in the first year; from left to right: results after 0·5, 1·0 and 1·5 years. Bottom: specimens exposed in the second year; from left to right: results after 0·5, 1·0 and 1·75 years

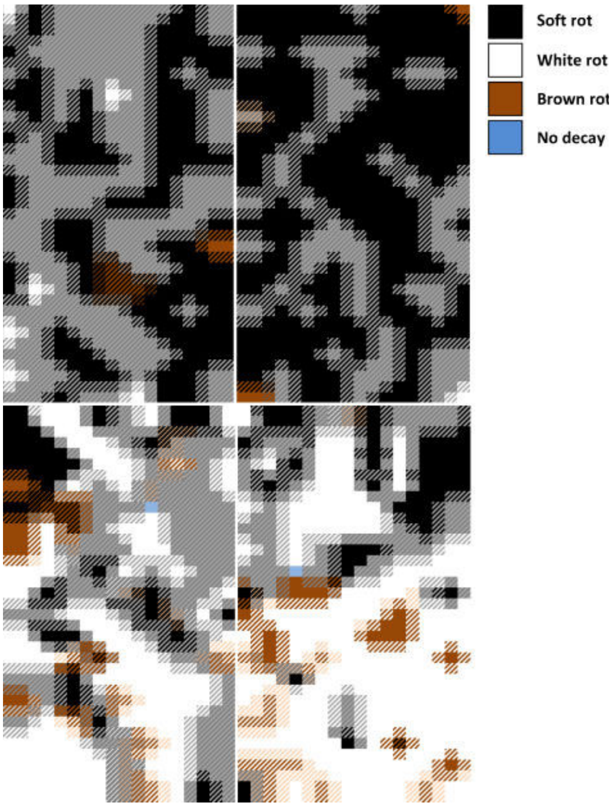
beech specimens was higher in the southern part of the field as was observed for pine sapwood. Only two small spots (single specimens) caused by soft rot in the southern part of the field demonstrated far higher decay intensity.

Decay type distribution

The three main fungal decay types, brown, white and soft rot, were found on specimens of both wood species, but varied significantly in frequency and spatial distribution in the field (Fig. 8 and Table 3). Therefore, the different decay types present in each of the stakes were determined after failure or at the time of last assessment of the specimens respectively. In general, while decay of beech was dominated by soft rot, decay of pine sapwood was mainly caused by white rot. However, a significant number of samples showed different decay types in the same specimen. Thus, combinations of soft and white rot were frequently observed, but also brown rot with or without additional white and soft rot were found on both species. In addition, the brown rot *Leucogyrophana* spp. was detected on numerous pine specimens (as observed by Huckfeldt 2009a), often in conjunction with larvae and occasionally adult wood borers (Fig. 9).

In general, no significant differences between the decay rates of different decay types were observed due to high variation of decay progress between specimens, spatial distribution of the different decay types (Fig. 8) and the combined occurrence of more than one decay type on the same specimen. Furthermore, it became evident that the wood species also had a significant effect on the decay intensity. While white rot on pine tended to result in faster decay, beech wood suffered a similar rate of decay from all decay types. The general ranking of decay velocity ‘brown rot>white rot>soft rot’, as previously reported (e.g. Savory and Carey 1979; Huckfeldt and Schmidt 2006; Augusta 2007; Huckfeldt 2009b), was not confirmed in this study. In contrast, white and soft rot had the potential to cause decay rates up to 10 rating steps per year.

A more detailed analysis of the decay intensity distribution with respect to the different decay types also indicated the predominant role of white rot on pine sapwood. The most pronounced hot spots were found for the first set of pine sapwood specimens (see Fig. 6). In total, 13 specimens showed decay rates of 16 rating steps per year, which corresponds to a relative decay rate of 3·88 (cf. red orange areas in Fig. 6), whereby 12 specimens suffered from white rot, partly associated



8 **Intrasite variation of decay types in the test field in Herrenhausen, Hannover. Top: beech specimens after 1·5 years exposed in the first year (left) and after 1·75 years exposed in the second year (right). Bottom: pine sap after 3·0 years exposed in the first year (left) and after 2·0 years exposed in the second year (right). Hatching and mixed colors indicate combined presence of more than one decay type**

with soft rot, and only one showed soft rot exclusively, none of them revealed brown rot. Second, the clear south–north differentiation of the field, which could be observed for the second set of pine and beech specimens (Figs. 6 and 7), was not evident through the distribution of decay types (Fig. 8).

Soil parameters

Most soil parameters, which were measured initially and during the test period, showed only marginal differences within the field and were therefore not useful to explain the observed differences in decay intensity (Table 4). Only the water holding capacity and the corresponding soil moisture content were found to be correlated with the decay intensity within the field. As shown in Fig. 10, WHC and moisture gradient were found to vary between the northern and the southern part of the field. In general, the moisture content was slightly higher in the layer close to the surface, where there are higher amounts of organic matter from previous use were available and the WHC was therefore also higher. Significant differences in pH and carbon, nitrogen and sulphur content were not found in samples from different locations across the site. Differences in decay intensity could therefore be attributed in part to moisture differences of the soil. In addition, the decay intensity variation is likely to depend on the in-ground microflora at certain locations in the field.

Conclusions

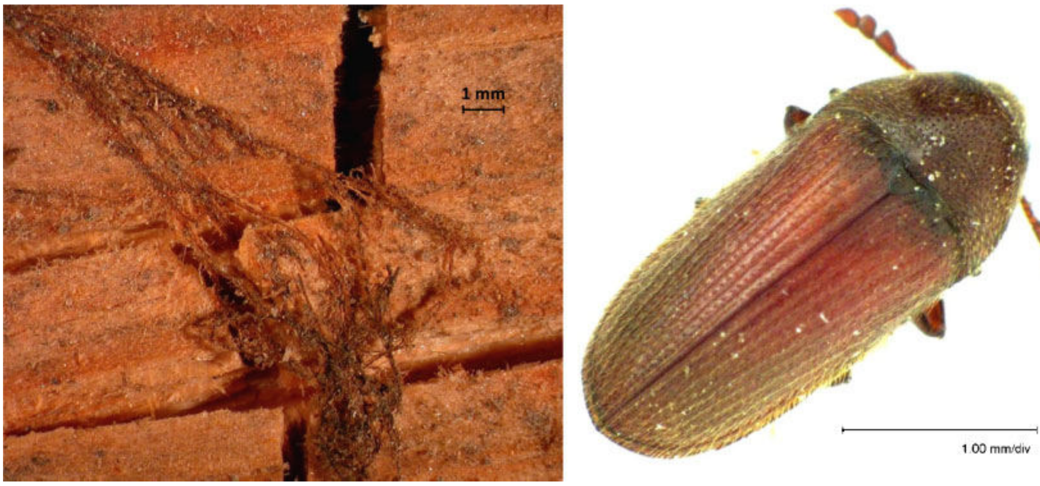
Soft rot and white rot are the dominant decay types in the newly established in-ground test field in Herrenhausen, Hannover. Initial decay trials showed intrasite variability which should be considered when conducting in-ground tests. For wood durability testing, it is essential to expose wood to a broad range of decay organisms. In terms of fungal decay, this means to assure the presence of the three decay types – brown, white and soft rot. It is necessary to include several test sites with different dominating decay types. Most likely, one will not find all three decay types on the same test site showing equal inoculum potential.

As the assessment showed for the Herrenhausen site, it can furthermore easily happen that small areas with high decay intensity of a certain type can be included or excluded; therefore, randomised distribution of test specimens needs to be assured even on a relatively small site.

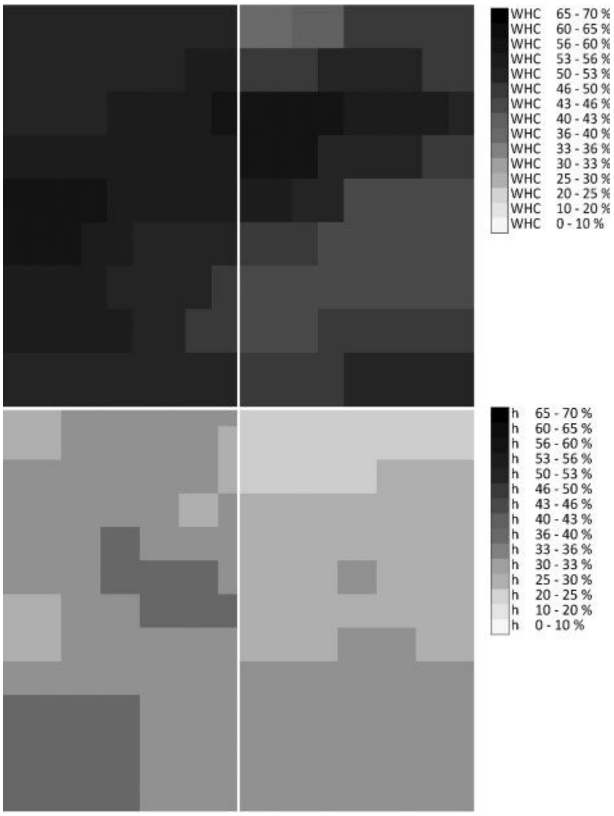
With rising soil moisture content, the speed at which decay progresses also increased. Furthermore, this study shows a time factor needs to be considered in case of newly cultivated test fields to account for different succession steps. The succession itself depends on various further factors, e.g. availability of nutrients, soil moisture regime, vegetation and maintenance measures. Periodic inspections of the field with respect to prevailing decay types and decay activity will be helpful for interpreting the test results.

Table 3 Frequency and corresponding decay rates for different decay types occurring on pine sap and beech wood specimens exposed in the first (1st set) and second years (2nd set): standard deviation in parentheses

		Occurring rot type						
		White rot	Soft rot	Brown rot	White+ soft rot	White+ brown rot	Brown+ soft rot	All rot types
Pine sap, 1st set	Σ	61	24	4	53	6	4	8
	v_{mean}/per year	5·1 (4·4)	3·3 (3·0)	3·0 (0·7)	3·8 (3·6)	3·8 (0·5)	4·0 (0·7)	2·7 (0·2)
Pine sap, 2nd set	Σ	86	26	10	27	10	1	1
	v_{mean}/per year	10·5 (6·6)	1·9 (1·4)	4·9 (2·3)	2·0 (1·3)	8·2 (4·7)	8·0	2·0
Beech, 1st set	Σ	6	72	1	88	0	3	0
	v_{mean}/per year	7·6 (1·1)	9·4 (4·2)	8·0	8·9 (4·1)	…	4·0 (0·0)	…
Beech, 2nd set	Σ	1	114	2	53	0	0	1
	v_{mean}/per year	8·0	5·5 (2·2)	5·6 (3·4)	6·6 (1·8)	…	…	3·2



9 Decay organisms identified on the test field in Herrenhausen, Hannover Left: strands of brown rot causing *Leucogyrophana* spp. found on numerous pine sapwood specimens (photo: Huckfeldt 2009a). Right: wood boring *Anobiidae*



10 Intrasite variation of WHC and soil moisture content *h* on the test field in Herrenhausen, Hannover. Top: WHC in 0–5 cm depth (left) and 20–25 cm depth (right). Bottom: soil moisture content in June in 0–5 cm depth (left) and 20–25 cm depth (right)

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Table 4 Range of various soil parameters (mean value in parentheses)

Soil parameter	0–5 cm depth	20–25 cm depth
Water holding capacity/%	43–67 (53)	38–59 (49)
Soil moisture content in March/%	19–44 (32)	11–26 (21)
Soil moisture content in June/%	14–39 (23)	6–16 (10)
Soil moisture content in September/%	4–21 (14)	4–17 (8)
pH H_2O	5·7–7·1 (6·4)	5·7–7·4 (6·6)
pH $CaCl_2$	5·0–6·4 (5·6)	4·8–6·7 (5·8)
Carbon content/%	2·1–3·7 (3·0)	1·2–3·9 (2·4)
Nitrogen content/%	0·14–0·25 (0·20)	0·07–0·25 (0·16)
Sulphur content/%	0·03–0·04 (0·04)	0·02–0·05 (0·03)

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6.16 Publication XVI: Durability of wood exposed in ground – Comparative field trials with different soil substrates

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Durability of wood exposed in ground – Comparative field trials with different soil substrates

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ABSTRACT

The durability of wood in ground contact is influenced by various factors such as substrate quality, climate and micro flora of the soil, which should consequently be considered for service life prediction of wooden components used in ground. In particular the impact of horticultural soil management and melioration measures demand consideration. Therefore this study aimed on comparing the impact of different soil substrates on the performance, service life, and finally durability of different European grown wood species.

Specimens of Scots pine sapwood (*Pinus sylvestris* L.), Norway spruce (*Picea abies* Karst.), Douglas fir (*Pseudotsuga menziesii* Franco), European beech (*Fagus sylvatica* L.), and English oak (*Quercus robur* L.) were exposed to six different soil substrates: field soil, fertilized field soil, a turf – field soil mix, bark mulch covered field soil, silica sand, and gravel. Furthermore specimens were partly embedded in concrete. Mini stake specimens ($8 \times 20 \times 200$ mm^3) and standard stake specimens ($25 \times 50 \times 500$ mm^3) were exposed in parallel at the field test site in Hannover-Herrenhausen, Germany, to allow also for identifying effects of the specimen size and volume.

After 4.5 years of exposure the decay rates differed significantly between field soil containing substrates and those containing no natural soil substance. In general decay proceeded slowest in concrete followed by sand and gravel. The effect of adding turf, fertilizer and bark mulch to the field soil was negligibly small. Concrete embedding as protective measure performed well during the first 2–3 years, but showed increasing decay rates afterwards. In comparison, the decay process was often similar between substrates, once decay has started. In all soil substrates decay was dominated by soft rot followed by white rot.

The average lifetime of the mini stake specimens was remarkably shorter compared to the standard specimens indicating a potential to shorten test durations. However, the use of mini stakes involved practical problems and led to some extent to an underestimation of wood durability. The meaning of different soils and specimen types, independent of other site influences, for service life prediction and durability assessment of wood is discussed and the need for further studies on this topic is highlighted.

1. Introduction

Wood is frequently used outdoors with and without ground contact. In particular for structural use the durability of wood needs to be considered for service life planning and life cycle assessment. One of the most severe exposures is the in-ground exposition, which is therefore often used for testing the durability of wood (e.g. EN 252, 1989; GB/T 1992; ASTM, 2006). Furthermore, also some laboratory decay tests include exposure to unsterile soil taken from the field (ENV 807, 2001; CEN/TS 15083-2, 2005; Edlund, 1998). Fungal cellar tests and the terrestrial microcosms are furthermore considered as cross-linking elements to real outdoor exposure in ground and therefore named "semi-field tests" (Stephan et al. 2000; Venäläinen et al. 2012).

The durability of wood in ground contact is influenced by various factors such as substrate quality, climatic conditions and micro flora of the soil. Numerous studies have reported on such influence factors: soil moisture content directly influencing wood moisture content and depends itself on the climatic conditions as well as on the soil substrate (Rahman and Chattopadhyay, 2007). While high wood moisture contents (above fibre saturation) generally promote decay as do high temperatures, dammed-up

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water has the opposite effect (Augusta, 2007). Optimum conditions for decay can therefore be expected from warm, moist, but well ventilated soils. Furthermore pH value, salinity, chemical composition, and the amount of available nutrients play an important role on the decay intensity of a field as they determine the fungal flora (Råberg et al. 2013), which can be established in the ground (Rayner and Boddy, 1988; Schmidt, 2006; Rahman and Chattopadhyay, 2007).

Decay development depends on the decay type, whereby soft rot, which can be found frequently in the ground, is known to develop more slowly than white and brown rot. In-ground test fields are therefore known to provide different dominating decay types, e.g. brown rot in the 'old field' of Simlangsdålen (Sweden), but soft rot and tunnelling bacteria in Ultuna (Sweden), and soft rot in Viikki (Finland), Tåstrup (Denmark), and Sørkedalen (Norway) as reported for these Nordic fields by Edlund (1998) and Edlund and Nilsson (1998). Beyond this biological parameter, the site-specific decay potential depends on numerous physical and chemical factors, which have been intensively examined in the past (e.g. Nilsson and Daniel, 1990; Johnson and Thornton, 1991; Edlund et al. 2006; Brischke et al. 2013). Thus, differences in decay activity and intensity can be expected between fields (Edlund, 1998), but also within one test field (Wakeling, 2006; Brischke et al. 2013) and should be considered. Furthermore the impact of horticultural soil management and melioration measures demand consideration (Rapp et al. 2007).

Therefore this study aimed on comparing the impact of different soil substrates on the performance, service life, and finally durability of different European grown wood species. Typical melioration measures such as fertilization and increasing the water holding capacity through admixture of turf and mulch covers as well as alternative foundation substrates have been used for comparative durability field tests in ground contact. Modifications of pure natural top soil were used to reflect situations, which are common in landscaping and gardening. Furthermore, alternative ways of embedding wooden structures for exposure in ground contact were considered, such as sand and gravel having lower water holding capacities compared to natural top soil (Rapp et al. 2007). The influence of concrete embedding on the durability of wood palisades and piles is controversially discussed since the 1980s (Murphy, 1984; Leightley and Willoughby, 1985), and no reliable information is available, if concrete collars do negatively or positively affect service life of wood. Therefore, stakes embedded in concrete were also included in this trial.

2. Materials and methods

2.1. In-ground durability tests

In-ground wood durability tests were performed at a test site in Hannover-Herrenhausen, Germany. Specimens of Scots pine sapwood (*Pinus sylvestris* L.), Norway spruce (*Picea abies* Karst.), Douglas fir (*Pseudotsuga menziesii* Franco), European beech (*Fagus sylvatica* L.), and English oak (*Quercus robur* L.) were exposed to six different soil substrates: field soil, fertilized field soil, a turf – field soil mix, bark mulch covered field soil, silica sand, and gravel. Therefore, excavations with an area of 6–10 m^2 and a depth of 0.5 m were filled with the different substrates. Furthermore, specimens were partly embedded in concrete. A description of the different soil types is given in Table 1.

Mini stake specimens (8 × 20 × 200 mm^3) and standard stake specimens (25 × 50 × 500 mm^3) according to EN 252 (1989) were exposed in parallel in all soil substrates. For each parameter combination $n = 10$ replicates were used. Standard and ministake specimens as well as the different wood species were exposed in alternating order (Fig. 1 and Fig. 2).

Table 1
Description of soil substrates used for durability tests.

Soil type	Description
Field soil	Top soil from in-ground test field in Hannover-Herrenhausen
Mulch	Field soil covered with approx. 4 cm bark mulch
Field + turf	Field soil and turf mixed 50:50
Fertilized soil	Field soil; 40–60 g/m^2 added three times per year. Fertilizer contained 5.5% nitrate nitrogen, 6.5% ammoniac nitrogen, 18% phosphate, 17% potassium oxide, 2% magnesium oxide, 0.02% boron, 0.01% zinc
Sand	Silica sand; grain size approx. 0.5–3.0 mm
Gravel	Gravel: grain size approx. 16–32 mm
Concrete	Specimens concreted (Portland cement) in PVC tubes (d = 100 mm, l = 300 mm (EN 252) and l = 180 mm (mini-stakes) to half (EN 252 stakes) or 2/3 of their length (mini-stakes)

Specimens were evaluated with respect to decay every 3 months according to the rating scheme of EN 252 (1989), i.e. 0 = no attack, 1 = slight attack, 2 = moderate attack, 3 = severe attack and 4 = failure (Table 2). The original EN 252 rating scheme has been adopted for assessing mini-stake specimens. Assuming that their remaining cross section for the different rating steps should be the same as those of the standard specimens, the maximum depth criterion has been reduced (Table 2). In addition, the specimens were visually inspected for the presence of brown rot, white rot, soft rot, and wood-destroying insects. Furthermore, samples were taken from specimens for microscopic diagnosis according to CEN/TS 15083-2 (2005) to determine the type of decay if necessary.

Since not all specimens in all soil substrates failed yet, the median service life of the specimens was considered for preliminary durability classification instead of the average service life. According to EN 350-1 (1994) x-values were determined by relating the median service life of the tested timber to the median service life of the reference species Scots pine sapwood. Durability classes DC were derived from the x-values according to the scheme shown in Table 3.

2.2. Determination of soil parameters

The initial water holding capacity of the field soil was determined according to ISO 11268-2 (2012). Soil samples were air dried

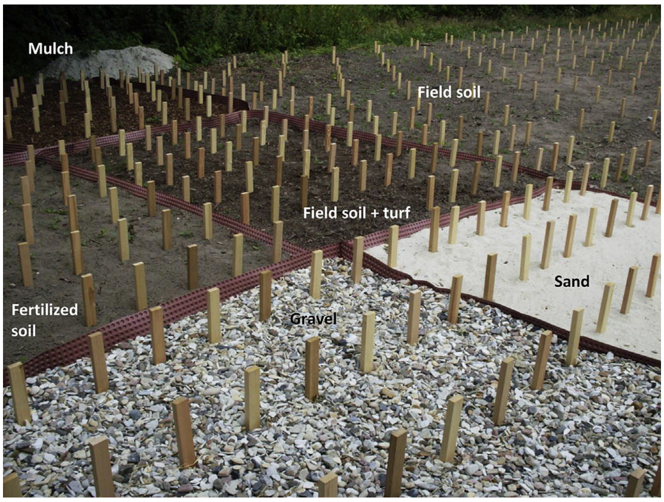

Fig. 1. Lots with different soil substrates on the test field in Hannover-Herrenhausen.

Fig. 2. Alternating order of mini stake and standard specimens according to EN 252 (1989).

and sieved (2 mm mesh). Afterwards the soil was filled in PE cylinders of 4 cm diameter. The bottom of the cylinders was covered with a fine polymer grid and filter paper (MN 640 W 70 mm). All cylinders were placed in a vat for 12 h, which was filled with water to a height 1 cm above the soil filling height of 7 cm. After water soaking of the soil the cylinders were placed on a water saturated sand bath for 2 h to allow spare water to run out. The soil samples were then weighed before and after oven-drying at 105 °C and the water holding capacity of the soil was calculated according to Eq. (1).

$$\mathrm{WHC} = \frac{m_s - m_0}{m_0} \cdot 100 \qquad (1)$$

WHC = water holding capacity in %,
m_s = mass of water saturated soil sample in g,
m_0 = mass of dry soil sample in g

Small portions of the soil samples used for WHC tests were used to determine soil pH and the content of carbon, nitrogen, and sulphur. For determining the pH 10 g of the sieved soil substrate were added to 0.01 mol calcium chloride ($CaCl_2$) and deionized water respectively. After 2 h the pH was determined with a pH metre. CNS analyses were conducted at the Institute of Soil Science, Hannover, using an elemental analyzer (Vario EL). Hereby the soil samples were buried at 1150 °C and based on the exhausting gases the content of C, N, and S was determined.

3. Results and discussion

3.1. Decay rates

The decay rates differed for all wood species between the various soil substrates as shown in Figs. 2 to 7 for standard test specimens. In general, decay proceeded faster in the field soil containing substrates. Apart from English oak, all specimens had failed after 4.5 years of exposure in field soil, fertilized soil, mulch and the turf-soil mix. However, none of these substrates provoked highest decay uniformly on all wood species, which coincides with findings of Rapp et al. (2007) and Brischke et al. (2008). No significant effect of fertilization or admixture of turf on the decay progress became evident. As can be seen from Table 4 the water holding capacity of the field soil was increased drastically by adding turf, which might have led to higher wood moisture content and thus higher moisture-induced decay potential of the soil. However, a significantly accelerated decay progress was not observed in the turf-soil mix.

The effect of covering the ground with bark mulch is controversially discussed. On the one hand leachable extractives of bark might have an inhibitory effect on fungi similar to growth inhibition of weed in gardening. On the other hand a lot of biomass and humus is introduced to the soil, which might increase activity of wood-destroying fungi (Schwab, 1996). Furthermore, mulch cover also reduces soil temperature fluctuations, reduces evaporation of soil water, and influences the level of some nutrients (Pickering et al. 1997; Pinamonti, 1998; Teasdale and Mohler, 2000). In this study neither a positive nor a negative effect of mulch cover on decay activity of the soil was detected.

In contrast to the field soil containing substrates exposure in pure sand, gravel and concrete led to an inhibition of fungal decay for a period of up to three years. For instance, Douglas fir exposed in concrete showed no signs of decay before the third year (Fig. 6). This time lag before onset of decay tended to be longest for concreted samples, followed by specimens exposed in sand and gravel as can be clearly seen from the mean decay ratings for beech wood (Fig. 3). However, once started decay proceeded similarly to that in field soil containing substrates. This has also been observed by Brischke et al. (2008) on Scots pine sapwood and English oak mini-stakes, but was confirmed in this study with bigger-sized

Table 2
Mini stake and standard specimens according to EN 252 (1989) in alternating order.

Rating		Definition	EN 252 stakes			Mini-stakes		
			Maximum decay depth	Minimum intact cross section		Maximum decay depth	Minimum intact cross section	
			[mm]	[mm^2]	[%]	[mm]	[mm^2]	[%]
0	No attack (sound)	No evidence of decay, softening or weakening caused by micro-organisms	0	1250	100	0	160	100
1	Slight attack	Limited evidence of decay, no significant softening or weakening up to certain depth	1	1104	88	0.5	133	83
2	Moderate attack	Significant evidence of decay, with areas of decay (softened or weakened wood) up to certain depth	3	836	67	1	108	68
3	Severe attack	Strong evidence of decay, extensive softening and weakening, typical fungal decay at large areas up to certain depth	5	600	48	2	64	40
4	Failure	Sample breaks after a (impact) bending test	50	0	0	20	0	0

Table 3
Durability classes according to EN 350-1 (1994) based on x-values calculated as relative median (in brackets: as relative mean) service lives of the specimens exposed in different soil substrates.

Durability class	Description	x-value
1	Very durable	$x > 5$
2	Durable	$3 < x \leq 5$
3	Moderately durable	$2 < x \leq 3$
4	Less durable	$1.2 < x \leq 2$
5	Non-durable	$x \leq 1.2$

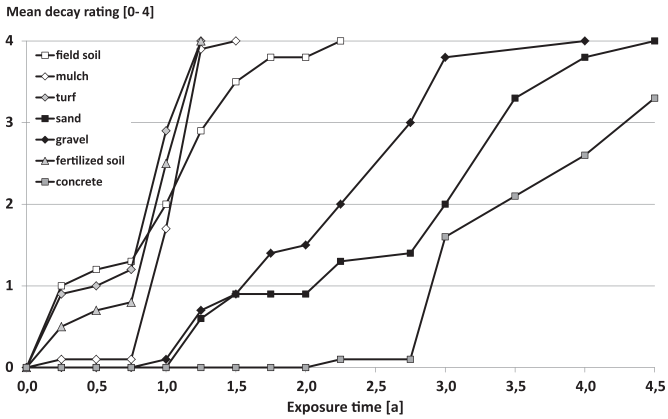

Fig. 4. Mean decay rating for Norway spruce specimens over time during exposure in different soil substrates.

standard specimens only for beech and English oak. In addition to the initial time lag the three tested softwoods showed lower progress of decay as indicated by the lower gradients of the decay rating curves (Figs. 4–6). Rapp et al. (2007) assumed that for smaller mini-stakes after three years' exposure the better performance of wood in sand will not necessarily persist over time and might be compensated by comparatively high decay activity once decay fungi are established. However, results from this study clearly show that the advance of decay inhibition in the nutrient-poor substrates can be maintained over time and can in some cases even increase. Nevertheless, such positive effects might diminish when biomass is brought into the soil (substrate) as shown by Brischke et al. (2013) for field soil enriched with shred fresh garden plants.

Gravel as a substrate did not lead to reduced decay rates compare with sand. The decay activity in gravel was clearly higher than in sand (Figs. 3 and 4, and Fig. 6). An inhibitory effect of the lower water holding capacities of sand and gravel (Table 4) was not observed. The strongest increase in decay rate was observed for the concreted samples of all wood species, which came along with sudden failure of many specimens. Apparently, moisture increased in the embedded part of the stakes, and it seems likely that favourable conditions for decay can be established rapidly leading to failure within one assessment interval – in extreme within three months. Similar observations have been made by Baecker (1993) and Rapp et al. (2007), who found only temporary protection through polyethylene sleeves applied on untreated timber. In practice such water traps should be avoided as well as direct contact between wood and concrete, for instance through bituminous interfaces.

The overall decay rating for all soil types was highest for beech, followed by Scots pine sapwood and Norway spruce. The durability of English oak and Douglas fir depended on the substrate: Best performance up to now has been shown by Douglas fir in sand and concrete. Since it was not possible to determine the mean or median service life of the specimens for all wood species in all substrates (Table 5), the durability classification shown in Table 7 should be seen as preliminary. However, the highest durability (lower durability classes DC) was found for English oak (DC 2). Douglas fir turned out to be 'non-durable' (DC 5) in the field soil containing substrates, which was to some extent surprising, because other authors found higher durability of Douglas fir exposed in ground, for instance DC 4 (Rapp et al. 2010; Van den Bulcke et al. 2013). Nevertheless it can be expected that Douglas fir will reach higher durability in sand, gravel and concrete. The prevailing decay type in all soil substrates was soft rot followed by white rot. This dominating role of soft rot in various soil types is also supported by Nilsson and Daniel (1990), Wakeling (1992), Edlund (1998), and Brischke et al. (2013).

3.2. Impact of specimen size

Besides standard specimens according to EN 252 (1989) mini-stake specimens have been used for the durability tests. The mini-stake format allows preparation of test specimens from smaller wood portions, which can be helpful for instance when pure Scots pine sapwood is required. Furthermore they are supposed to decay faster and allow for shorter test duration to save time and costs for testing. On the other hand one might have reasonable doubts that results from the two specimen types are

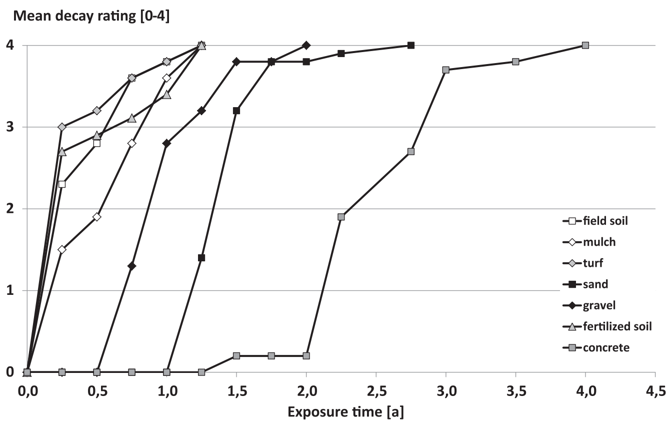

Fig. 3. Mean decay rating for Scots pine sapwood specimens over time during exposure in different soil substrates.

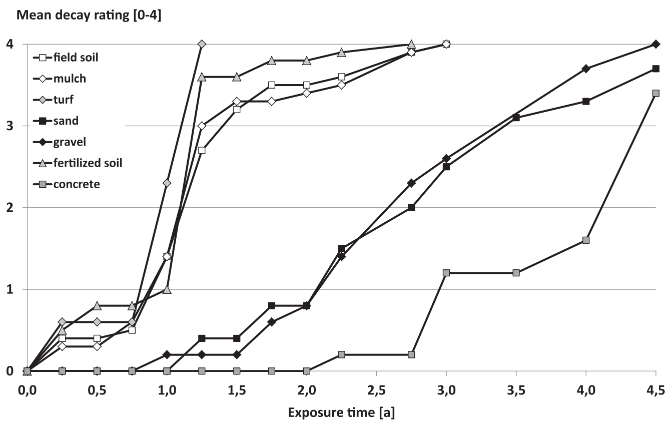

Fig. 5. Mean decay rating for Douglas fir specimens over time during exposure in different soil substrates.

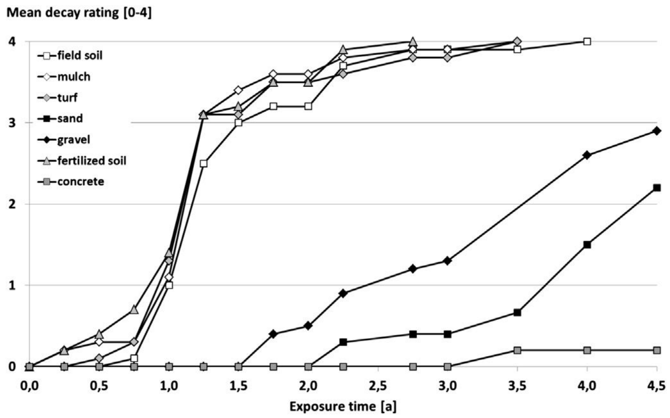

Fig. 6. Mean decay rating for English oak specimens over time during exposure in different soil substrates.

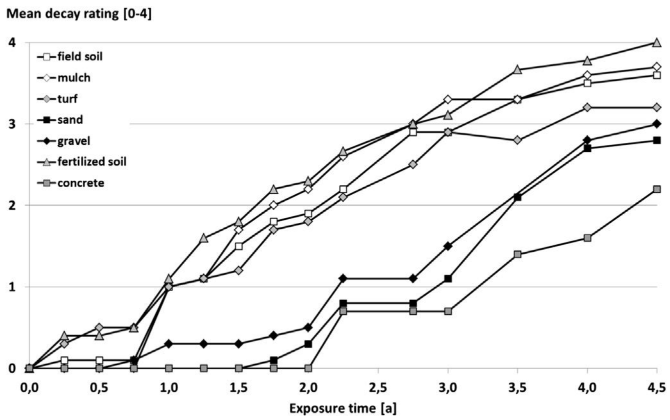

Fig. 7. Relationship between decay ratings of standard specimens (EN 252, 1989) and mini-stake specimens made from Douglas fir after exposure in different substrates (dashed line: ideal correlation).

comparable. Different authors pointed on the potential impact of the specimen dimension on decay rates and resulting performance of wood exposed in ground (Leicester et al. 2005; Augusta, 2007; Brischke and Rolf-Kiel, 2010). Different theories may explain a higher durability of bigger dimensioned poles, such as the reduced vulnerability to leaching of biocidal components or the formation of a protective outer barrier, e.g. wood decayed by soft rot fungi, which does not or even very slowly attack the inner portions of the structure (Brischke and Rolf-Kiel, 2010). This study aimed therefore on comparing both specimen types in terms of decay progress. To make the resulting decay ratings comparable as such, the rating

Table 4
Soil parameters (mean values).

Soil type	Field soil	Pure mulch	Pure turf	Field + turf	Sand	Fertilized soil
WHC [%]	48.2	*n.a.*	*n.a.*	103.1	25.1	54.9
pH H_2O	6.0	5.5	3.4	4.6	6.6	5.1
pH $CaCl_2$	5.2	4.5	2.8	3.9	5.9	4.3
Carbon content [%]	2.30	20.95	52.81	9.48	0.01	2.90
Nitrogen content [%]	0.16	0.38	1.19	0.28	0.02	0.18
Sulphur content [%]	0.03	0.07	0.19	0.06	0.01	0.04
CN ratio [-]	14.5	55.5	44.4	29.9	31.1	15.5

n.a. = not available.

Table 5
Median and mean (in brackets) service lives of EN 252 (1989) standard specimens in different soil substrates (in years).

Soil type	Beech	Scots pine sapwood	Norway spruce	Douglas fir	English oak
Field soil	0.8 (0.7)	1.3 (1.3)	1.5 (1.6)	1.5 (1.9)	4.0 (*n.a.*)
Mulch	1.0 (1.0)	1.3 (1.2)	1.3 (1.7)	1.3 (1.7)	4.0 (*n.a.*)
Field + turf	0.8 (0.7)	1.3 (1.2)	1.3 (1.2)	1.3 (1.8)	*n.a.* (*n.a.*)
Fertilized soil	1.0 (0.9)	1.3 (1.2)	1.3 (1.5)	1.3 (1.7)	3.5 (3.6)
Sand	1.5 (1.8)	3.5 (3.4)	3.0 (*n.a.*)	*n.a.* (*n.a.*)	*n.a.* (*n.a.*)
Gravel	1.3 (1.4)	3.0 (3.1)	4.0 (3.6)	*n.a.* (*n.a.*)	*n.a.* (*n.a.*)
Concrete	2.8 (2.9)	3.5 (*n.a.*)	4.5 (*n.a.*)	*n.a.* (*n.a.*)	*n.a.* (*n.a.*)

n.a. = not available.

Table 6
Median and mean (in brackets) service lives of mini-stake specimens in different soil substrates (in years).

Soil type	Beech	Scots pine sapwood	Norway spruce	Douglas fir	English oak
Field soil	0.5 (0.6)	1.0 (0.8)	1.3 (1.2)	1.3 (1.4)	1.6 (1.7)
Mulch	0.5 (0.6)	1.1 (1.0)	1.3 (1.3)	1.3 (1.6)	2.8 (2.5)
Field + turf	0.8 (0.8)	1.0 (1.0)	1.0 (1.1)	1.5 (1.6)	2.3 (2.3)
Fertilized soil	0.6 (0.7)	1.0 (1.0)	1.5 (1.3)	1.3 (1.3)	1.5 (1.7)
Sand	1.9 (1.9)	4.0 (*n.a.*)	4.0 (3.9)	*n.a.* (*n.a.*)	*n.a.* (*n.a.*)
Gravel	1.4 (1.5)	2.1 (2.4)	2.8 (3.0)	*n.a.* (*n.a.*)	4.0 (*n.a.*)
Concrete	2.8 (2.5)	2.8 (2.6)	2.8 (2.7)	2.8 (2.8)	2.8 (*n.a.*)

n.a. = not available.

Table 7
Durability classes according to EN 350-1 (1994) based on x-values calculated as relative median (in brackets: as relative mean) service lives of the specimens exposed in different soil substrates.

Soil type	Beech	Scots pine sapwood	Norway spruce	Douglas fir	English oak
Field soil	5 (5)	5 (5)	5 (4)	5 (5)	2 (*n.a.*)
Mulch	5 (5)	5 (5)	5 (4)	5 (5)	2 (*n.a.*)
Field + turf	5 (5)	5 (5)	5 (5)	4 (5)	*n.a.* (*n.a.*)
Fertilized soil	5 (5)	5 (5)	5 (4)	5 (5)	2 (2)
Sand	5 (5)	5 (5)	5 (*n.a.*)	*n.a.* (*n.a.*)	*n.a.* (*n.a.*)
Gravel	5 (5)	5 (5)	4 (5)	*n.a.* (*n.a.*)	*n.a.* (*n.a.*)
Concrete	5 (5)	5 (5)	4 (*n.a.*)	*n.a.* (*n.a.*)	*n.a.* (*n.a.*)

n.a. = not available.

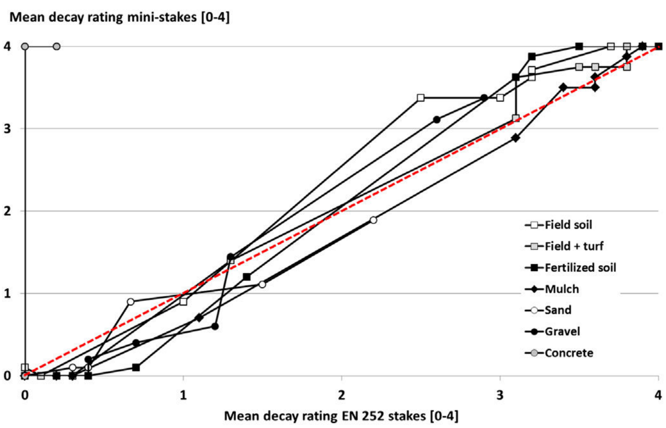

Fig. 8. Relationship between decay ratings of standard specimens (EN 252, 1989) and mini-stake specimens made from English oak after exposure in different substrates (dashed line: ideal correlation).

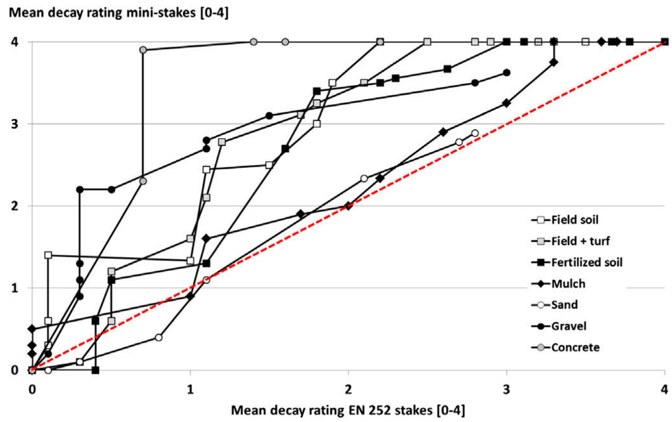

Fig. 9. Relationship between decay ratings of standard specimens (EN 252, 1989) and mini-stake specimens made from English oak after exposure in different substrates (dashed line: ideal correlation).

scheme of EN 252 has been adopted with respect to the remaining cross section of the specimens as shown in Table 2.

In most cases decay proceeded more rapidly in mini-stake specimens compared to standard stakes (Table 6). However, in some cases the decay rates were very similar. A direct comparison has been made and is exemplarily shown for Douglas fir (Fig. 8) and English oak (Fig. 9). While decay ratings for Douglas fir were consistent to a large extent, the decay rating of English oak mini-stakes was worse in almost all cases. Since in particular English oak is most likely suffering from small dimensions, it was not surprising that the mini-stakes caused an underestimation of its durability

Besides their limited potential to provide realistic information about durability some practical problems of using mini-stakes became apparent: Due to their littleness mini-stakes had been dug out by rabbits and other animals. Furthermore the assessment is more difficult compared to bigger specimens not at least, because it is not possible to conduct an impact bending test in the field.

4. Conclusions

The impact of different soil substrates on the durability and thus resulting service life of timber was well demonstrated in this study. However, only marginal differences in durability were found between natural top soil containing soil substrates. In contrast, exposure in sand, gravel and concrete led to a remarkable inhibition of decay. Concrete embedding as protective measure performed well during the first 2–3 years, but showed increasing decay rates afterwards. For practical applications one can furthermore expect that failure of components such as posts will occur more suddenly indicating a higher risk of accidents. In summary, the results pointed on the need for maintaining nutrition-poor foundation substrates. If organic litter is allowed to agglomerate in sand or gravel their positive effect will be diminished. In contrast, it became not apparent that modifications of pure natural top soil, which are commonly used as melioration measures in landscaping and gardening, revealed remarkable differences in decay rates. An increased fungal hazard shall not be expected through fertilization or the use of mulch covers and turf.

In terms of testing the durability of wood one can conclude that soil melioration measures do not provide any acceleration of the test as long as the field test soil is active as such. The average lifetime of the mini stake specimens was remarkably shorter compared to the standard specimens indicating a potential to shorten test durations. However, the use of mini stakes involved practical problems and led to some extent to an underestimation of wood durability. For instance the durability of oak wood suffers from small-sizing of poles and posts. Therefore mini-stake tests might be rather considered as screening tests. Quite in contrast, the effect of component dimension should be further addressed including also full-size elements such as posts and poles.

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6.17 Publication XVII: Potential impacts of climate change on wood deterioration

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Potential impacts of climate change on wood deterioration

C. Brischke* and A. O. Rapp

Climate changes were discussed in many disciplines during recent years. The discussion mainly focused on three aspects: the significance of climate changes, anthropogenic sources for climate changes and finally potential consequences on ecological and economical patterns. This study concentrates on potential impacts of global warming and corresponding moistening on the durability of wooden building components. From experimental test set-ups in the field, climatic data, wood temperature and wood moisture content were used for mathematic modelling of decay. On that basis, a first attempt is made to quantify the influence of climate changes on wood decay rates for various scenarios. It became obvious that warming and humidification will lead to significantly reduced service lives of wooden building components. The quantity of climate induced changes strongly depends on the geographical position and the present climate. Differences between climatically divergent places are shown exemplarily for the sites Uppsala, Freiburg, Portsmouth, Bordeaux and Zagreb.

Keywords: Climate scenarios, Decay, Double layer test, Global warming, Material climate, Moisture monitoring, Wood moisture content, Wood temperature

Introduction

Significant climate changes were observed for many parts of the world as well as in a global manner. Although there is still a lively discussion about potential reasons and causalities, neither they have an anthropogenic or natural origin (e.g. Seinfeld and Pandis 1998; Parmesan 2006); the climate change itself becomes evident in various phenomena (IPCC 2007). Different weather observations such as extreme precipitation events or long lasting drought periods have been considered to be the expression of global long term climate changes. Direct consequences of global warming, e.g. the increased melting of polar and glacier ice and corresponding rising tide scales, have often been highlighted (e.g. Alley *et al.* 2005). It is evident that such drastic meteorological alterations can have major impact on human life with respect to ecological and economical aspects (Hanson and Weltzin 2000; Holmgren *et al.* 2001; Smith *et al.* 2001; Alley *et al.* 2005; Parmesan 2006; Bonan 2008). In principal, each chemical, physical or biological reaction and each other moisture and temperature induced process are potentially affected by changes of these climate parameters, but have not necessarily been examined in terms of significant impact on human beings. Within the building trade, the question of durability is tightly connected to the respective environmental conditions of a building. This can be seen from corrosion of metals, carbonation of concrete, and in particular from biological decomposition of organic materials, such as wood.

Service life of wood based products is limited by its durability, which can be regarded as a material property and is caused by chemical and physical constitution of untreated, modified or preservative treated wood. Besides this material inherent resistance, the service life of wood is influenced by environmental conditions, which are more or less favourable for decay organisms. Hereby the climate plays an important role, but different climate levels need to be distinguished: The macroclimate, which is described by the weather data of a certain site, the mesoclimate, which is described by influences provoked at the site (e.g. shading, wind breaks), and the microclimate which reflects the situation at and within the construction (surface conditions). The climate inside the material has a decisive influence on decay of wood. Therefore, the 'material climate' determined by wood moisture content and wood temperature and their dynamics should be considered for estimation of decay hazards in first instance (Brischke *et al.* 2006; Gobakken and Lebow 2010).

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

This study aims on prognosticating potential impacts of climate changes on the durability of timber structures and thus on the service life of wooden building components. From experimental test set-ups in the field

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1 Double layer test rig with upper specimen layer shifted by 25 mm horizontally to lower layer: specimens are separated with bitumen foil from chromium–copper–boron (CCB) impregnated support beams

spread over Europe, climatic data, wood temperatures, wood moisture contents and decay rates recorded for several years were correlated and used for mathematic modelling of decay (Brischke *et al.* 2010; Brischke and Rapp 2010). On that data basis, a first attempt is made to quantify the influence of global warming on wood decay rates for different regions and scenarios, valid for wood in both modern and historical structures.

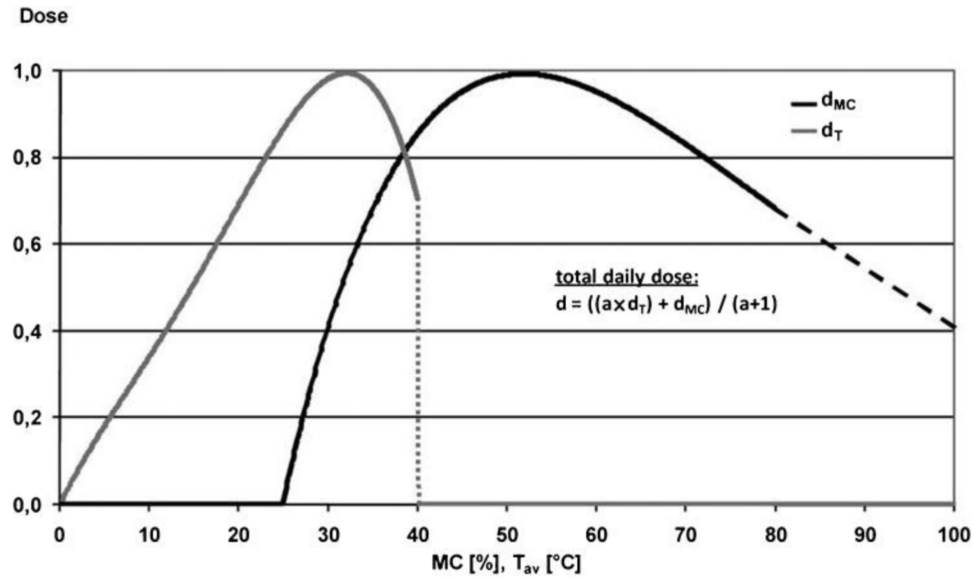
Experimental methods

Field trials in different climates

Horizontal double layer field trials were conducted with Scots pine sapwood (*Pinus sylvestris* L.) and Douglas fir heartwood (*Pseudotsuga menziesii* Franco) at 28 different European test sites, which were selected to provide a range of climate regimes. The trials ran between 2000 and 2008 with exposure times between 4 and 8 years. The original objective of the experiments was to establish a data base for modelling decay and thus the service life of wooden components on the basis of moisture and temperature data. A detailed description of the trials and their background is given by Brischke and Rapp (2010).

The test rigs consisted of specimens ($500\times50\times25$ mm) placed horizontally in two layers and exposed above ground (Fig. 1) producing a decay risk corresponding to European use class 3 (EN335-1; European Committee for Standardization 2006). The whole test set-up formed a closed deck ($73\times65\times21$ cm), similar to a poorly designed terrace flooring, and was placed on paved ground or horticultural foil to avoid the growth of grass. All specimens were monitored in terms of wood moisture content (MC), wood temperature and the progress of fungal decay. Therefore, they were assessed yearly by using the so called 'pick-test' and rating the extent and distribution of decay according to EN252 (European Committee for Standardization 1990) as: 0 (sound), 1 (slight attack), 2 (moderate attack), 3 (severe attack) or 4 (failure).

Climate data at all sites were available from official weather stations, where measurements of daily precipitation and average daily temperature were recorded. At

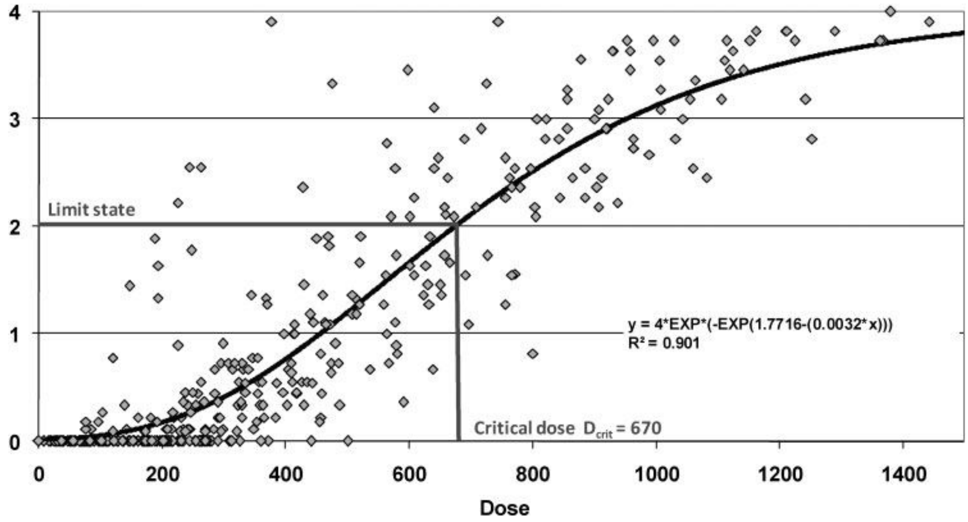


2 Relationship between MC and daily moisture induced dose d_{MC}, and between average wood temperature T_{av} and daily temperature induced dose d_T respectively (dashed black line: MC>80% did not occur; therefore, curve progression is uncertain)

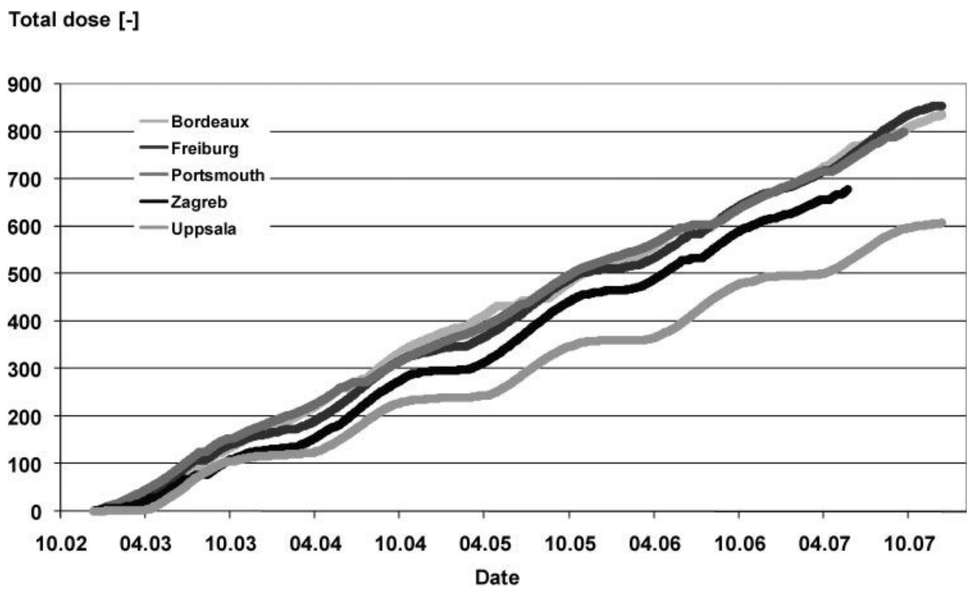
Table 1 Characteristic data of exposure sites

Test site	Uppsala* Sweden	Portsmouth† UK	Freiburg‡ Germany	Bordeaux* France	Zagreb‡ Croatia
Height above sea level, m	7	1	302	4	123
Average air temperature, °C	6·8	11·6	12·1	14·0	10·7
Sum of precipitation, mm	579	667	911	798	910
Begin of exposure	05/2001	04/2001	07/2000	01/2001	08/2002
End of exposure	09/2008	09/2008	09/2008	09/2008	10/2008

*Average of 2000–2006.
†Average of 2002–2006.
‡Average of 2000–2005.



3 **Relationship between dose and mean decay rating according to EN252 (European Committee for Standardization 1990) of Scots pine sapwood and Douglas fir heartwood specimens exposed at 28 different field test sites (each dot represents mean decay rating for one wood species at one exposure site at a certain time of exposure; black line: Gompertz smoothing function): determination of critical dose D_{crit} for service life estimation of wooden components based on limit state 'mean decay rating=2 (moderate decay)'**



4 **Accumulated doses (total doses) on Scots pine sapwood for five chosen exemplary sites**

some sites, additional test rigs were exposed in shade boxes and in a tropical greenhouse to provoke modifications in terms of the microclimate and to promote the conditions for decay. To calculate exemplarily the possible effect of global warming and moistening on decay in Europe, the sites Uppsala, Portsmouth, Freiburg, Bordeaux and Zagreb with their recorded material climates were chosen (Table 1).

Estimation of site specific decay potentials

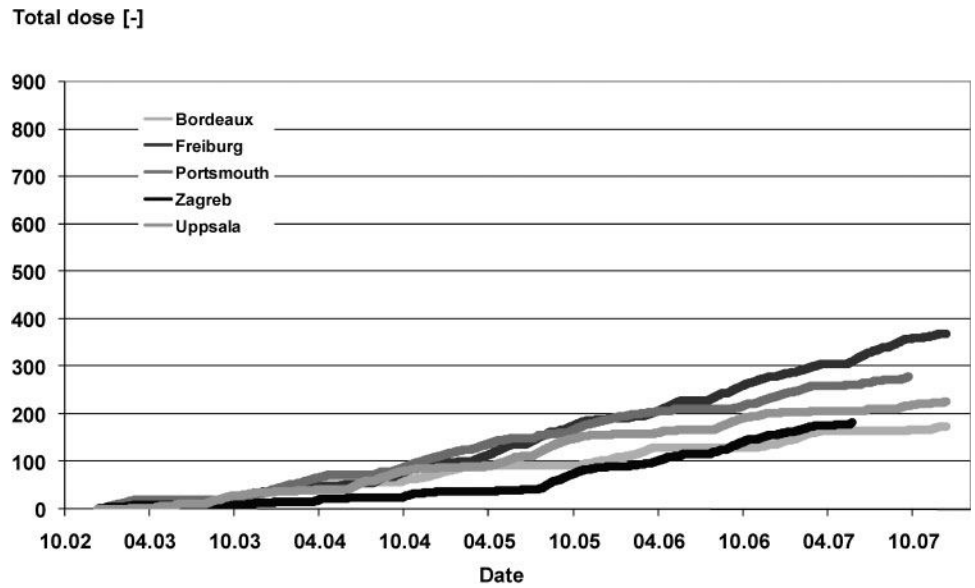
For estimation of site specific decay potentials and how they are affected by potential global climate changes dose–response functions were used. Coming from results of the long term field trials at different sites, a mathematical relationship was established between moisture and temperature induced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

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

(i) is a combination of a MC induced component and a temperature induced component
(ii) can be cumulated over the respective exposure intervals
(iii) can be correlated with the decay ratings in form of the response.

The following relationship between MC and daily moisture induced dose d_{MC}, and between average wood temperature T_{av} and daily temperature induced dose d_T respectively, were found after computed optimisation (Fig. 2).

The daily dose was accumulated and correlated with the corresponding decay ratings for the different exposure intervals and test sites. The sigmoid course of the



5 Accumulated doses (total doses) on Douglas fir heartwood for five chosen exemplary sites

dose–response relationship was fitted with a Gompertz function (cf. Fig. 3). Based on the method of least squares for the dose–response function, all variables of the daily dose functions (d_{MC} and d_T) were optimised using MS Excel Solver. The following side conditions were considered: the total daily dose of days with a maximum temperature above 40°C, with a minimum temperature below −1°C, or with a MC below 25% was set as 0.

MC induced daily dose d_{MC} is

$$d_{MC} = 6.75\times10^{-10}\mathrm{MC}^5 - 3.50\times10^{-7}\mathrm{MC}^4 + 7.18\times10^{-5}\mathrm{MC}^3 - 7.22\times10^{-3}\mathrm{MC}^2 + 0.34\mathrm{MC} - 4.98, \text{ if } \mathrm{MC}\geq 25\% \quad (1)$$

where MC is the daily moisture content.

Temperature induced daily dose d_T is

$$d_T = -1.8\times10^{-6}T^4 + 9.57\times10^{-5}T^3 - 1.55\times10^{-3}T^2 + 4.17\times10^{-2}T, \text{ if } T_{min} > -1^\circ\mathrm{C} \text{ and } T_{max} < 40^\circ\mathrm{C} \quad (2)$$

where T_{Av} is the daily average wood temperature, T_{min} is the daily minimum temperature and T_{max} is the daily maximum temperature.

Daily dose d is

$$d = (ad_T + d_{MC})/(a+1), \text{ if } d_T > 0 \text{ and } d_{MC} > 0 \quad (3)$$

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

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

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

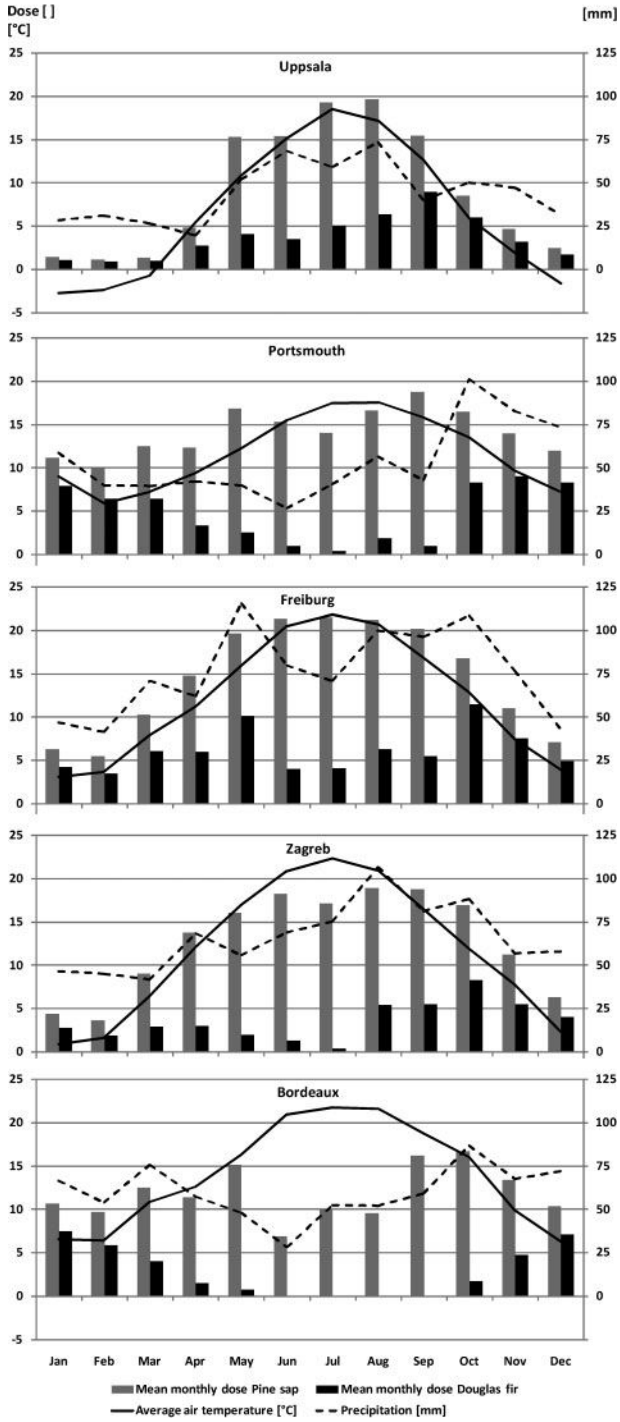
where D is the total dose.

Service life estimations for wooden components were conducted to demonstrate the potential effect of global warming and moistening on wood durability. Therefore, a critical dose was determined according to the dose–response function in Fig. 3. The following assumptions were made: mean decay rating=2, corresponding to moderate fungal decay, was set as limit state. Any decay rating above this limit state means that the serviceability is no longer given. According to equation (4), a critical dose D_{crit}=670 is needed to be summed up to reach the limit state. Finally, in the following, the expected service life was considered to be the quotient of the critical dose D_{crit} and the mean annual dose D_a.

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

		Annual dose* after warming of				Expected service life [*a*] after warming of†			
Wood species	Site	0 K	1 K	2 K	3 K	0 K	1 K	2 K	3 K
Pine sapwood	Uppsala	121·4	135·9	149·3	162·6	5·5	4·9 (−11%)	4·5 (−19%)	4·1 (−25%)
	Portsmouth	159·9	168·9	177·4	185·7	4·2	4·0 (−5%)	3·8 (−10%)	3·6 (−14%)
	Freiburg	170·9	182·5	192·3	201·0	3·9	3·7 (−6%)	3·5 (−11%)	3·3 (− 15%)
	Bordeaux	167·1	176·1	183·9	191·3	4·0	3·8 (−5%)	3·6 (−9%)	3·5 (−13%)
	Zagreb	135·4	146·1	156·5	167·0	4·9	4·6 (−7%)	4·3 (−13%)	4·0 (−19%)
Douglas fir	Uppsala	45·1	54·4	63·5	72·4	14·8	12·3 (−17%)	10·5 (−29%)	9·3 (−38%)
	Portsmouth	61·3	66·6	71·7	76·8	10·9	10·1 (−8%)	9·3 (−15%)	8·7 (−20%)
	Freiburg	73·6	81·9	89·4	96·2	9·1	8·2 (−10%)	7·5 (−18%)	7·0 (−23%)
	Bordeaux	34·9	38·9	42·7	46·3	19·2	17·2 (−10%)	15·7 (−18%)	14·5 (−25%)
	Zagreb	38·7	43·8	49·2	54·3	17·3	15·3 (−12%)	13·6 (−21%)	12·3 (−29%)

*Average of the years 2003–2007.
†In brackets: percentage reduction of expected service life compared with scenario without global warming.



6 Seasonal distribution of moisture contents and temperature induced doses of pine sapwood and Douglas fir heartwood at five chosen exemplary sites

Expected service life ESL is

$$\mathrm{ESL} = D_{\mathrm{crit}}/D_{\mathrm{a}}[a] \quad (5)$$

where D_{crit} is the critical dose to reach decay rating 2 and D_{a} is the mean annual dose. a = years.

Results and discussion

Dose development over time: seasonal and wood species specific differences

From the recorded material climate (wood moisture content and wood temperature) at the different sites, the daily dose was calculated as described above (Fig. 2). The cumulated daily dosages are plotted for Scots pine sapwood in Fig. 4 and for Douglas fir heartwood in Fig. 5. The different slopes of the curves mean different doses per year, translating to different decay potentials at the different sites. The steeper the slope, the higher the decay potential.

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

Comparing the dose distribution over the whole year makes the oppositional response on increasing moisture or temperature conditions between pine sapwood and Douglas fir even more evident (Fig. 6). While pine sapwood retained the highest dosages during the summer months in Uppsala and Freiburg, the summer in Bordeaux was obviously too dry for decay even on pine sapwood; here the dose maxima were in spring and early autumn, but a minimum in June. This trend is clearly in line with rainfall distribution in Bordeaux, so that the favourable temperatures during summer had a negative effect as they accelerate the drying of wood. In contrast to this, at the Uppsala and Freiburg sites, wood moisture content was sufficiently high for decay during the whole year, which led to a temperature induced increase of monthly dosage in summer.

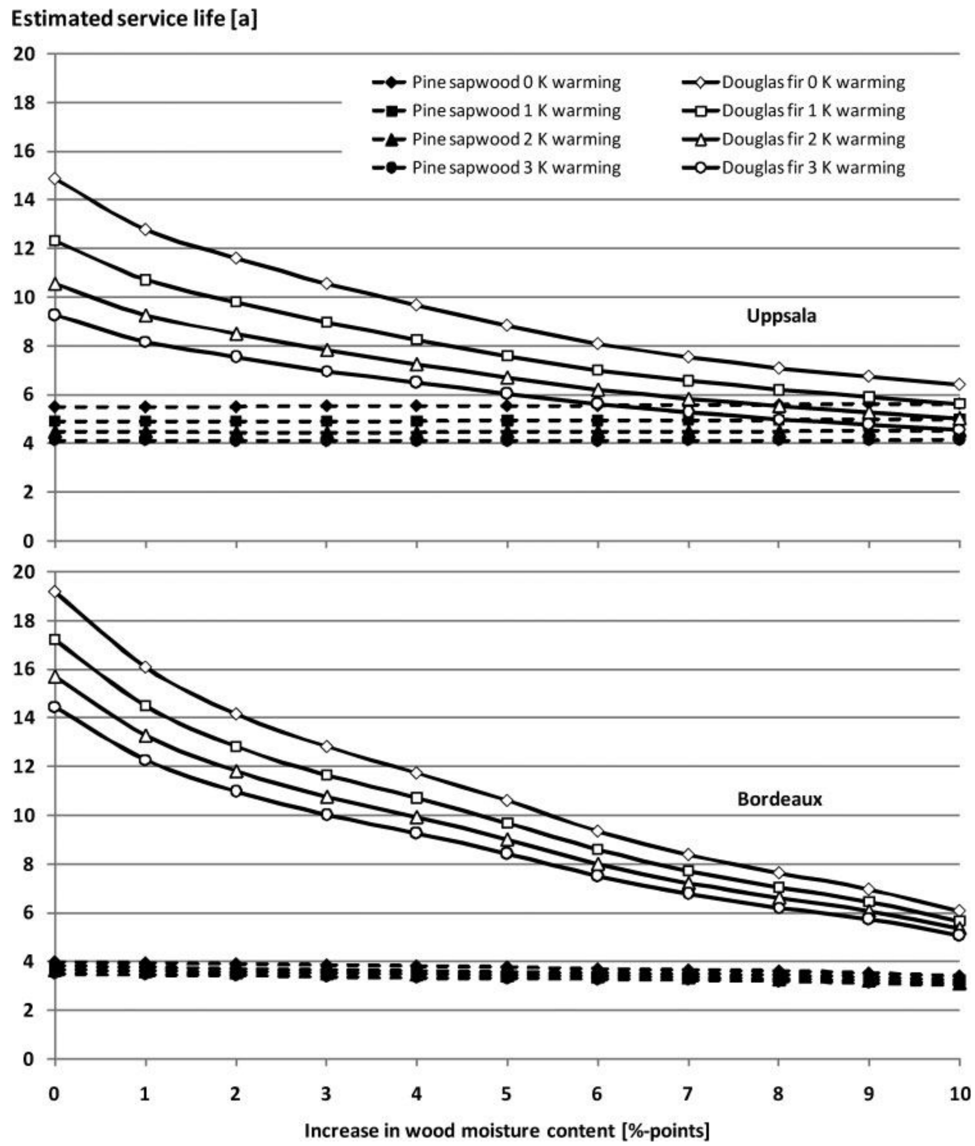
For the more refractory Douglas fir, the seasonal dose distribution differed significantly from pine sapwood. At all sites, minimum dosage was observed in summer apart from the Uppsala site, where high precipitation during summer led to a sufficient moistening of the Douglas fir. Thus, the monthly dose increased during the summer to obtain a maximum in September. In Portsmouth and Bordeaux, it became evident that the moisture content plays the dominating role for decay susceptibility of Douglas fir. At both sites, the winter temperatures had been moderate to warm: in combination with higher rainfalls, the dose rose in winter to reach maxima between November and January.

Impact of global warming

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

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

(i) humidity as well as wood moisture content were not affected



7 Estimated service lives of pine sapwood and Douglas fir specimens prognosticated for various levels of moistening and warming in Uppsala (top) and Bordeaux (bottom)

(ii) increase in air temperature led to identical increase in wood temperature
(iii) temperature increased homogenously, e.g. by 1 K for every single day, corresponding to an increase of average temperature by 1°C.

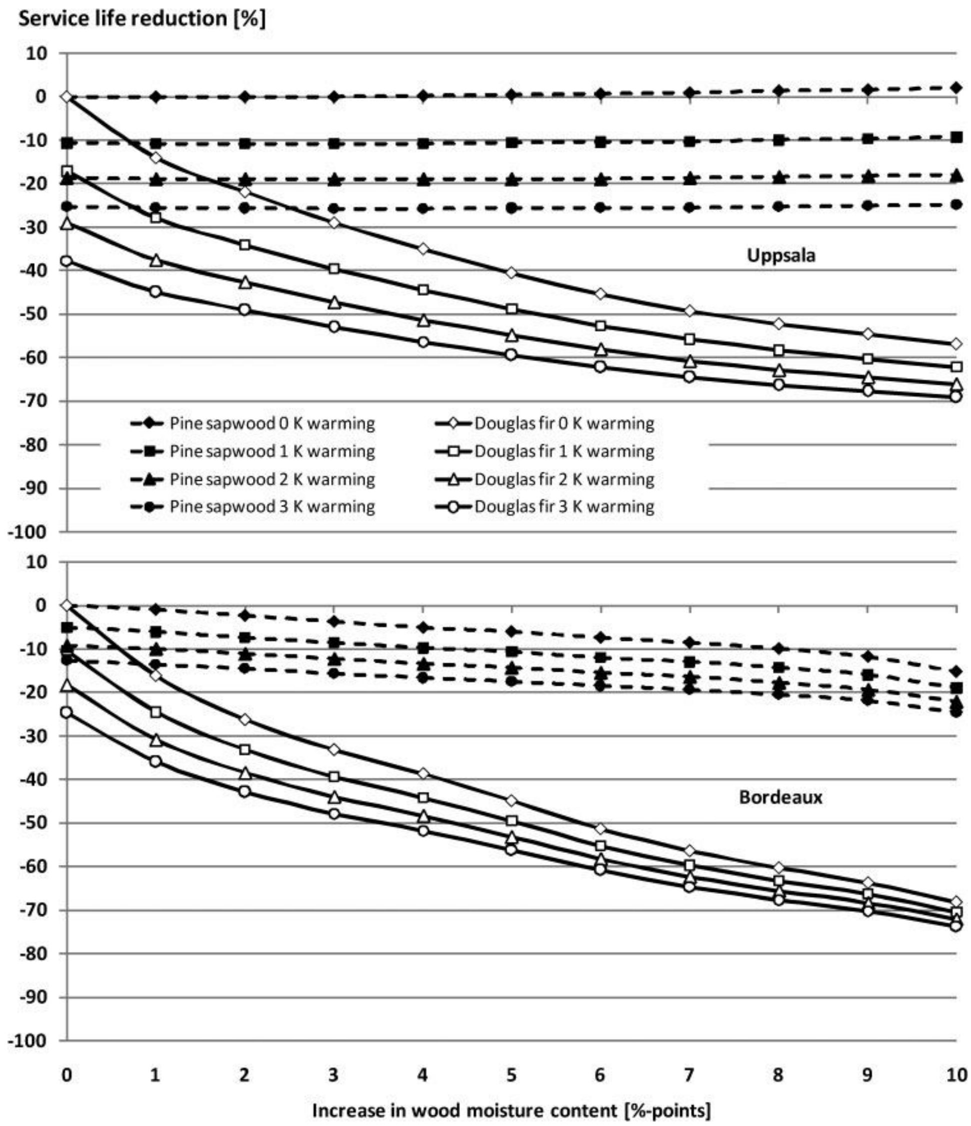
A homogenous warming by only 1 K led to a reduction of the expected service life between 5 and 11% for Scots pine sapwood and 8 and 17% for Douglas fir. The percentage reduction of service life was higher for the more durable Douglas fir heartwood, which can be explained by its moisture dynamics again.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

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

Furthermore, various reports (MPI-M 2006; IPCC 2007) allow the assumption that global warming comes along with increasing rainfalls in many parts of the world; at least this can be expected for northern parts of Europe (IPCC 2007), whereas other areas, e.g. the Mediterranean, will be more likely affected by drought. Generally, the precipitation amount tends to increase in humid climate zones and decreases in arid climate zones.

In the following, the impact of increased precipitation is prognosticated in terms of an increase in moisture content combined with different levels of global warming for comparison of the two most divergent sites Uppsala and Bordeaux (Figs. 7 and 8). Therefore, the following assumptions were made:

(i) increasing rainfalls and corresponding higher air humidity are reflected by increased wood moisture contents
(ii) increase in air temperature led to identical increase in wood temperature
(iii) temperature and wood moisture content increased homogenously, e.g. by 1 K or/and 1% for every single day.



8 Service life reductions of pine sapwood and Douglas fir specimens prognosticated for various levels of moistening and warming in Uppsala (top) and Bordeaux (bottom)

The two wood species responded significantly different on the climate change scenarios applied. While there was only a very slight effect of the moistening on pine sapwood, the expected service life of Douglas fir was dramatically reduced with increasing moisture.

In cold and relatively dry Uppsala, the estimated service life of pine sapwood was not affected at all, while in Bordeaux, an increase in MC by 10% points led to a service life reduction of 15%. In contrast, the maximum calculated moisture increase of 10% points led to service life reductions between 57 and 68% for Douglas fir. As expected, the service life of Douglas fir was more reduced with increasing MC in Bordeaux compared to Uppsala, where temperature is the most limiting factor, not moisture. This again coincides with the finding that the temperature increase has a stronger effect in Uppsala than in Bordeaux.

However, for both sites, the moisture dependent service life reduction decreased with higher moisture contents. Considering the worst case scenario applied in this study, i.e. +3 K and +10% MC, which still reflects current assumptions on global warming for the next 100 years (IPCC 2007; Meehl *et al.* 2007), the service life of Douglas fir would be reduced by 69% in Uppsala and by 74% in Bordeaux.

Conclusions

For this first attempt to estimate the magnitude of the influence of global warming on decay, a certain rise of temperature (1–3 K) and wood moisture content (1–10% points) was assumed and used for mathematical modelling based on the dose–response function after Brischke *et al.* (2010). However, in order to get a realistic value for a certain place, it is necessary to translate the complex prognosticated climatic changes for that place more precisely into daily changes of wood MC and wood temperature. For instance, it can be expected that an increase of 1 K during the summer is of less influence than having the same temperature increase in spring, autumn or winter. Also an increase in precipitation during the cold season has less influence on decay than during the season when the temperatures are favourable for decay. Future work is therefore needed not only to improve dose–response relationships (material climate–decay functions), but also to understand the links between mesoclimate and material climate. To achieve useful algorithms considering the relationship between weather parameters and material conditions, an interdisciplinary approach including experts in meteorology will be needed.

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7 ANNEX

Peer review publications

Brischke C, Borcharding T, Mengel U (2015) *Subjective sensation of color differences – determination of thresholds in depending on color tones and resolution.* Restoration of Buildings and Monuments 21: 21-27

Brischke C, Melcher E (2015) *Performance of wax impregnated timber out of ground contact – results from long-term field testing.* Wood Science and Technology 49: 189-204

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