WoodExter - Service life and performance of exterior wood above ground - Final report

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SP Sveriges Tekniska Forskningsinstitut

SP Trätek

SP Report 2011:53

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SP Rapport 2011:53

ISSN 0284-5172

ISBN 978-91-86622-83-1

Updated September 3, 2012

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Preface

This report is the conclusion of WoodExter, a WoodWisdom-Net project conducted 2007-2011 with focus on durability and service life issues of wood used in outdoor, above ground constructions. The project was initiated by the European Confederation of Woodworking Industries, CEI Bois, and their initiative Building with Wood, following a feasibility study on wood durability and service life in 2007.

The key outcome of WoodExter is a guidance document "Engineering design guideline for wood in above ground applications" - a practical tool for engineers and architects for design of wood constructions with respect to durability and service life. This represents a breakthrough in design of wood constructions with respect to durability and service life and the approach is based on a similar approach as used in structural design which is familiar to engineers and architects.

We hope that the knowledge generated in WoodExter shall be further developed for the benefit of improved competitiveness of timber as a building material, and to increase the market share of timber in construction and in different commodities. This can be achieved by

- Further research in the field of durability and service life

- Feedback from the use in practice of the Guideline to improve it and take further steps towards introducing performance based engineering design in practice for wood and wood-based building components in outdoor above ground situations

- Intensify standardization work with focus on harmonized test procedures for durability testing as well as methodology for interpretation of early field test results with respect to long-term performance.

The financial support of WoodWisdom-Net (www.woodwisdom.net) and wood industry partnership. Building with Wood is gratefully acknowledged as well as the support from local industrial partners. The WoodExter research partners are thanked for their cooperation and collaboration in this project.

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Key words: service life, exterior wood, exposure, resistance, limit state

Executive summary

WoodExter has successfully delivered against the objectives with the most important contributions as follows:

- The first European technical guideline and practical tool for engineers and architects for design of wooden constructions with respect to durability and service life.

- New, important, knowledge generated, in particular concerning
  - exposure conditions and risk of decay
  - effect of decay on micromechanical properties of wood
  - performance of different coating systems on different wood substrates and in particular chemically modified wood
  - the use and development of a novel technology, quantitative real-time PCR (Polymerase Chain Reaction), qPCR, as a tool for identification and quantification of early decay in wood as well as for studies of colonization pattern of decay fungi in different wood materials
  - mode of action of modified wood against decay fungi
  - evaluation of field trials and the possibilities to predict the expected average service life based on early results from inspections. Further development of the technique is needed, however.

- The development of a proforma for systematic performance assessment of cladding and decking and the extensive database established following the inspection of over 100 buildings carried out by partners. The database will serve as input for testing the model and engineering tool.

- Contributing to kick starting CEN/TC 38 WG 28 Performance Classification.

WoodExter has so far generated nearly 70 publications, and results from WoodExter have been presented at numerous national and international events.

Five young scientists have been engaged in different WoodExter projects as part of their master and doctoral studies. This will be beneficial for future research in the areas of wood durability, wood protection and service life prediction to support the European Research Area and the wood industry sector.

As to **future activities** the following can be foreseen:

- The Guidance document and related software will now be tested in practice on a national level. There are plans for capturing feedback in order to further improve the technique, e.g. by professionals or in future research projects.

- Work on early indicators for decay from various test procedures will continue to give useful input to standardization work within CEN/TC 38 WG 28 and accommodate requirements for performance data expressed in the Construction Products Directive (CPD).

- The proforma for systematic performance assessments of cladding and decking will be further used and tested in practice and improved.

- A number of field tests started within the WoodExter project will continue and generate important data for future assessment and evaluation and input to CEN/TC 38 and CEN/TC 139.

- Research work on micromechanical techniques will continue within the framework of other projects. Together with local chemical and physical properties, the micro-mechanical model can help to enhance the current understanding of effects of fungal decay on the microstructure of wood.

- Research on decay mechanisms linked to climate change and service life will continue in ongoing and new projects. A more global approach is needed to consider the full range of “deterioration resistance causing factors” of wood. In such a global approach, one need to compare exposure-dependent decay patterns and durability mechanisms for different wood species and wood-based materials.

WoodExter organization and support

The European project WoodExter (Service life and performance of exterior wood above ground) was part of the WoodWisdom-Net Research Programme 2006-2011. It was performed during 2007-2011 with the following research partners

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

and the following industrial partners

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

WoodExter was performed in close collaboration with the national projects

WoodBuild, Sweden
EcoBuild, Sweden and Norway
MechWood, Austria
Optiwoodcoat, Belgium

Public funding was received from the WoodWisdom-Net Research Programme, jointly funded by the following national research funding organizations:

Finland :	Tekes - Finnish Funding Agency for Technology and Innovation
Germany:	Federal Ministry of Education and Research (BMBF) / Project Management Agency Jülich (PtJ)
Norway:	The Research Council of Norway (RCN)
Sweden:	Swedish Governmental Agency for Innovation Systems (VINNOVA)
France:	Ministry of Agriculture, General Direction for Forest and Rural Affairs (DGPAAT)
United Kingdom:	Forestry Commission

Additional public funding was received from the Austrian Research Promotion Agency (FFG) and IWT, the Belgian government agency for Innovation by Science and Technology.

Background

The building sector in Europe is under strong pressure to move towards better cost effectiveness, improved quality, higher energy efficiency, improved environmental performance and reduced use of non-renewable resources. Today wood – even if commonly recognised as the most important renewable material in the construction sector – is often overlooked as a building material due to uncertainties associated with its long term performance and sensitivity to moisture.

A key issue for the competitiveness of wood is the possibility to control durability, service life, maintenance and life cycle costs for constructions and components where wood is used.

Traditionally, durability design of wooden components and structures is based on a mixture of experience and adherence to good building practice, sometimes formalised in terms of implicit prescriptive rules. A modern definition of durability is: *The capacity of the structure to give a required performance during an intended service period under the influence of degradation mechanisms*. Conventional durability design methods for wood do not correspond to this definition.

The development of performance-based design methods for durability and service life requires that models are available to predict performance in a quantitative and probabilistic format for intended use condition. The relationship between product performance during testing and in service performance needs to be quantified in statistical terms and the resulting predictive models need to be calibrated to ensure that they provide a realistic measure of service life, including a defined risk level.

Service life estimation methods for wood and wood-based products is an area of research that so far has been given little attention in Europe. Whilst the concept is not new the development has been very slow in comparison with competing materials such as concrete. The best known, and most advanced approach to date is an Australian research programme initiated by Robert Leicester (Wang *et al* 2007) designed to develop performance based engineering design procedures applying a probabilistic approach.

The importance of service life issues are reflected in the Construction Products Directive (CPD) with its six essential requirements, which shall be fulfilled by construction products during a reasonable service life.

A comprehensive feasibility study commissioned by the Building With Wood group within the CEI-Bois Roadmap 2010 initiative to consider the future research and development requirements for wood durability and service life that would support the growth of the sector underpinned the need for further research. There is potential in future European building and construction for an increased competetiveness and use of wood as an environmentally friendly and renewable material providing the durability and linked service life issues are given appropriate attention and the research is brought closer to the needs of the building community.

The core team responsible for preparing the feasibility study was thus encouraged to approach the WoodWisdom-Net with an application for research in the area of wood durability and service life prediction. A consortium with partners described above was established, the application was successful and the WoodExter project started towards the end of 2007.

Wang C-H, Leicester R H, Foliente G C, Nguyen M N (2007). Timber service life design guide. Forest and Wood Products Australia Limited. www.fwpa.com.au

Objectives

The ***main objective*** of WoodExter was, as stated in the original project plan, "to take the first steps towards introducing performance based engineering design in practice for wood and wood-based building components in outdoor above ground situations" with a guidance publication targeted for specifiers, architects and qualified do-it-yourself builders as the key outcome. The vision was to develop a practical tool for design of wood constructions with respect to durability and service life, based on a similar approach as used in structural design which is familiar to engineers and architects. It was decided to focus on decking and cladding, two major end uses for wood as two test case products to rigorously assess the methodology.

Other objectives were:

- to generate new knowledge on:
  - how different climates and end-use situations will affect the performance of wood.
  - the role of surface coatings and their interactions with wood.
  - decay indicators from field tests to produce in-service performance predictions and related input to European standardisation.
  - the effect of decay on micromechanical properties of wood.
  - the use of novel methodologies, quantitative real-time PCR Polymerase Chain Reaction (qPCR), for identification and quantification of early decay and conventional Polymerase Chain Reaction (PCR) for identification of early detection of colonisation by blue stain and mould.

- to develop a systematic approach for performance assessments of cladding and deliver a proforma for that purpose.

Work packages

The overall structure and interrelated links of the WoodExter project is shown in Figure 1 below.

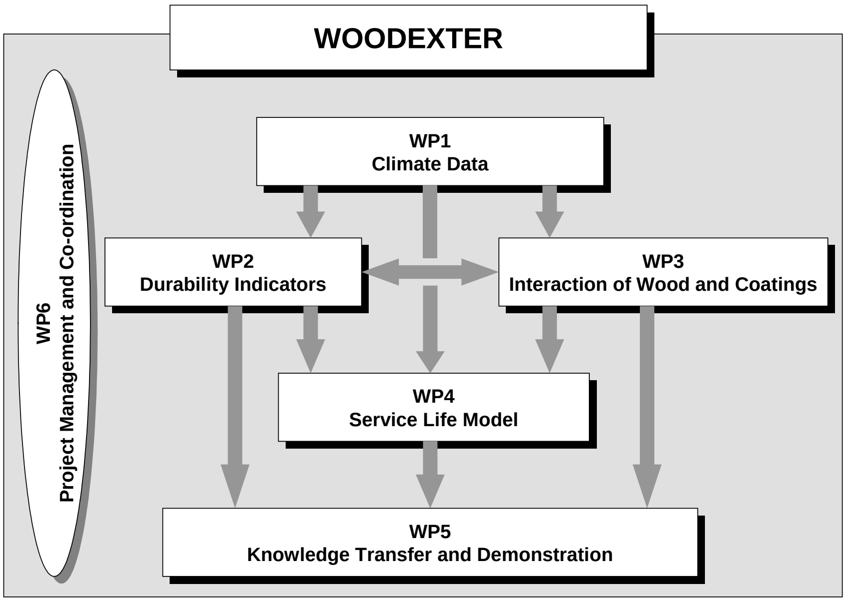


Figure 1. WoodExter structure.

In line with the above presented overall structure, the research approach was divided in four work-packages. Three work packages were directly related to the development of a probabilistic model for the estimation of service life and one work package on modern coating systems with the ultimate aim to provide input to service life model. Two work packages were devoted to knowledge transfer and project management.

Work package 1. Climate data – exposure conditions

The key issue of this WP was the transformation of climatic data into a suitable format to take climate factors affecting the progress of decay into acount. The WP consisted of three major tasks. The first task involved a classification and mapping of main exposure conditions for use class 3 (EN 335) components. The second task involved an experimental set up for the selected applications to investigate the effect of design and detailing on the microclimate. Finally, based on data mainly from the first two tasks, the third task focussed on collaboration with WP 4 on how to apply the model for climatic impact on the service life model.

Work package 2. Durability indicators

This WP dealt with the development of indicators for in-service performance predictions with respect to the progress of decay based on the use of field and laboratory assessment data, as well as experiences from practice. This WP also dealt with further development of a novel methodology, quantitative real-time PCR (Polymerase Chain Reaction) for the quantification of early decay for estimation of service life as well as with the impact of wood decay on mechanical properties - stiffness and strength. Another important part of this WP involved a systematic inventory of cladding and decking made of different wood-based products in service, including modified wood, to clarify causes of degradation. The final task was the interpretation of field trial data to feed into the probabalistic models for predicting service life.

Work package 3. Interaction of wood and coatings – effect on the performance of wood products

This WP was devoted to studies on the interactions between wood substrate and coatings, quantified using laboratory and field trials with selected coatings on various substrates (untreated wood and modified wood). WP 3 also focussed on derivation of performance specifications for specific end uses and review of current evaluation procedures with respect to input to CEN standardisation work.

Work package 4. Risk based engineering methodology for service life design

This WP was the core of the project. Input from WP 1 and WP 2 in the first place, but also WP 3, was used for the development of a model for prediction of service life for the selected applications. Formats for a practical tool for use by engineers and architects were proposed and tested in practice. The WP also included calibration of the model developed against existing data from test procedures and practice.

Work package 5. Knowledge transfer

This WP dealt mainly with the communication of results of the project to stakeholders and other interested parties.

Work package 6. Project management and coordination

This WP covered the project administration, management and coordination of the research activities.

Results

Work Package 1. Climate data – exposure conditions

Task 1.1 Classification of outdoor exposure conditions for Use class 3 to be used for engineering model

The key issue of WP 1 was the transformation of climatic data into a suitable format to take climate factors affecting the progress of decay into account.

Ambient microclimatic conditions, especially moisture conditions, are the most important factors for durability of wood and the classification of use conditions is based on the evaluation of the water exposure during use. Decay is the more severe result of high moisture exposure of wooden materials when the structures are wet for long periods. For start of the growth of decay fungi and decay development, the ambient critical humidity level of the microclimate should be above RH 95 - 100 % and the moisture content of pine sapwood above 25 - 30 %, depending on the temperature and exposure time.

For evaluation the climatic exposure conditions, the empirical wood decay model presented in Task 1.2 was first used for the ERA-40 data for air temperature, humidity and precipitation at 6 hour intervals. ERA-40 is a massive data archive produced by the European Centre of Medium-Range Weather Forecasts (ECMWF). The re-analysis involved a comprehensive use of a wide range of observation systems including, of course, the basic synoptic surface weather measurements. The ERA-40 domain covers all of Europe and has a grid spacing of approximately 270 km.

The decay index mapping for Europe with respect to macro-climate was developed in collaboration with WP 4. The results gave input to WP 4 to evaluate the effect of the macroclimate, and in a first step different climatic exposure areas or zones could be identified: Northern European (north and south), Continental, Atlantic (north, middle and south), Mediterranean zone (wet and dry).

The classification will give relative values for decay risks in different part of Europe (Figure 2). The exposure of horizontal exterior surfaces to solar radiation of Europe was simulated using the average solar radiation values (GW/m^2s) during a 30 year period. The

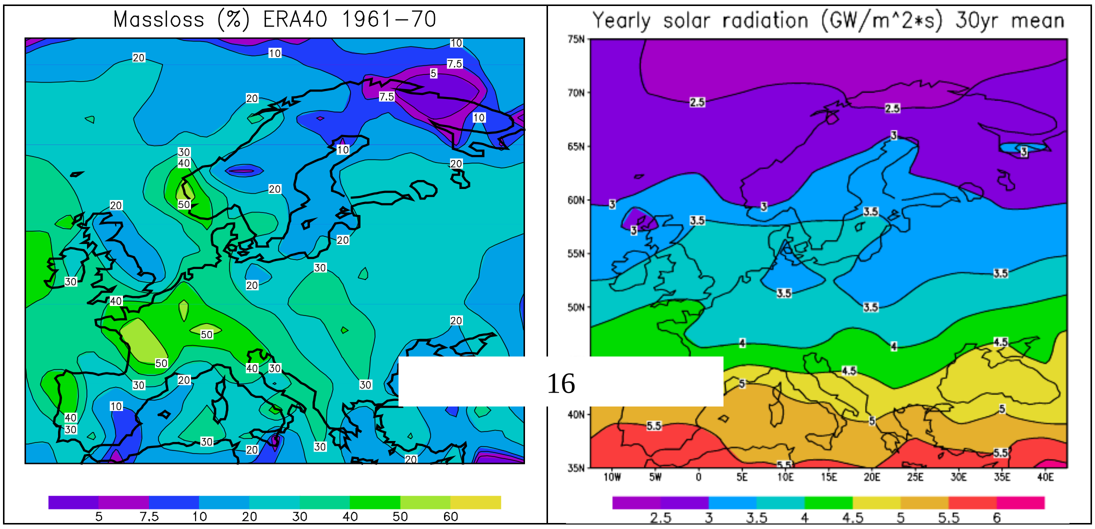


Figure 2. Left: Modelled mass loss (in %) of small pieces of pine wood that were exposed to rain for 10 years in Europe. Right: Simulated solar radiation in Europe.

solar radiation is lowest in North Europe even though the days during summer time are longer. The highest solar radiation was found in Southern Europe (Figure 2).

In the second stage, a dose response model was used to evaluate the climate conditions for selected places in Europe. The effect of climate variability on the risk for decay of wood exposed outdoors was investigated using the performance model. The climate data used was obtained with the computer software Meteonorm (www.meteonorm.com). Desired climate parameters for any place can be obtained with Meteonorm.

Several places in Europe were evaluated (Figure 3). Due to the variation of climate across Europe, relative doses, compared to reference Helsinki = 1.0, between 0.6 (northern Scandinavia) and 2.1 (Atlantic coast in Southern Europe) were obtained. For sites not shown in Figure 3 the (relative) base value of the exposure can be estimated with the help of the methods described above based on climate data from Meteonorm.

A detailed climate characterization for the whole of Europe is very difficult to make and would be very rough and uncertain. However, it should be kept in mind that local variation of climate conditions may lead to different relative doses than shown in the map. Examples could be sites near large lakes – experiencing higher relative humidity, sites at high altitude with lower temperature or with extremely high relative humidity and high rainfalls.

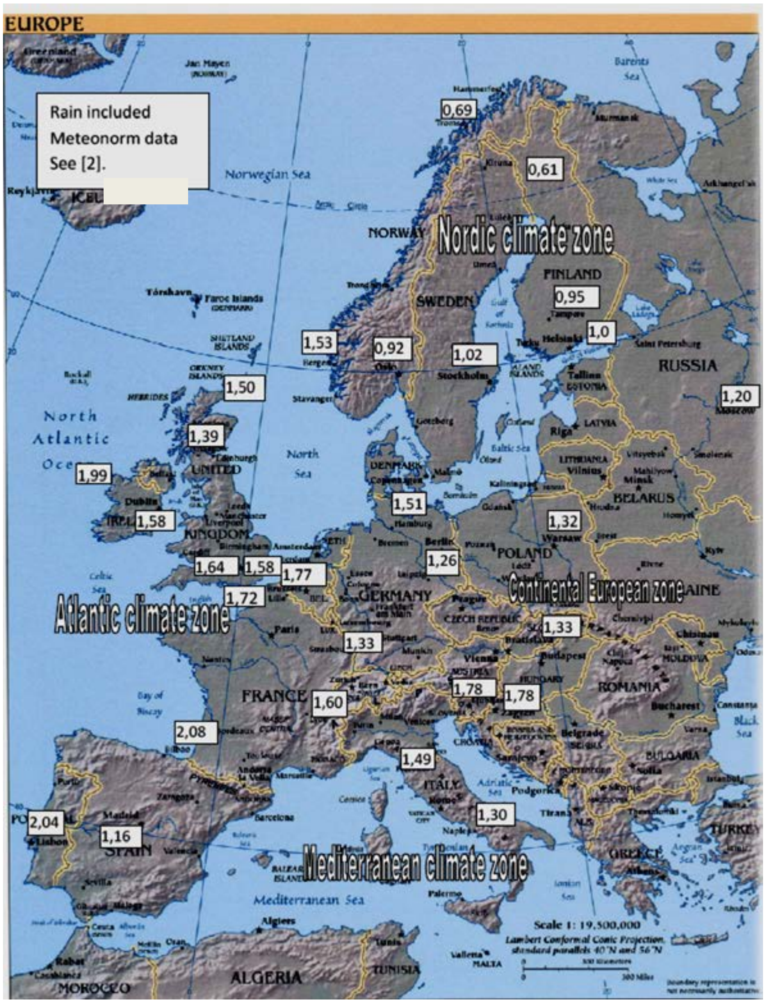


Figure 3. Climate zones in Europe. Numbers shown indicate relative risk of fungal decay.

Task 1.2 a Effect of meso and microclimate conditions for durability of wood

The local exposure for a building at a given geographical site is assumed to be a function of three distinct factors: land topography, presence of adjacent buildings and distance from the sea. The local conditions are described in terms of four classes as shown in Table 1. The categorization in Table 1 is based on the WP 2 experiences from inspections of decking and cladding and the values for the factor k_{s1} have been estimated on the basis of subjective expert judgement. k_{s1} is valid for wood facing the dominating wind direction, since this case gives the most severe exposure. Adjustments for less exposed directions are not made, because the design of e.g. cladding normally does not vary between different walls for the same building.

Table 1. Evaluation of the effect of local conditions.

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

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

On the basis of previous laboratory work on decay development of brown rot in spruce and pine sapwood in different constant relative humidity and temperature conditions a decay model was presented by Viitanen. This model was further developed in WP 1. The model is a time stepping scheme and the climate conditions may be variable. The development of decay is modelled as two consecutive processes:

a) Activation process: This is termed as α parameter, which is initially 0 and gradually grows depending on the air conditions to a limit value of 1. This process is able to recover favorable conditions (dry air) at a given rate (although no experimental evidence of recovery is available).

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

These processes only occur when the temperature is between 0 and 30 ^{0}C and the relative humidity is 95 % or above. Outside these condition boundaries, the activation process may recover, but the mass loss process is simply stopped. The mass loss process proceeds the activation process, when α has reached 1.

Figure 4 shows the impact of different climates on the decay development by using the decay model. The mass loss is much higher in a humid location as Bergen, Norway than in Central France. A cold location in Northern Finland gives no decay during 3 years.

When applying the models for evaluation of service life in certain microclimatic conditions, the great natural variability of materials, structures, different treatments and rganisms should also be taken into consideration. Different types of microbial growth will be found on stone-based and insulation materials than those on wood-based materials. The ageing of material and accumulation of dust and other material on the surface of building materials will change the response of the materials to moisture and biological processes.

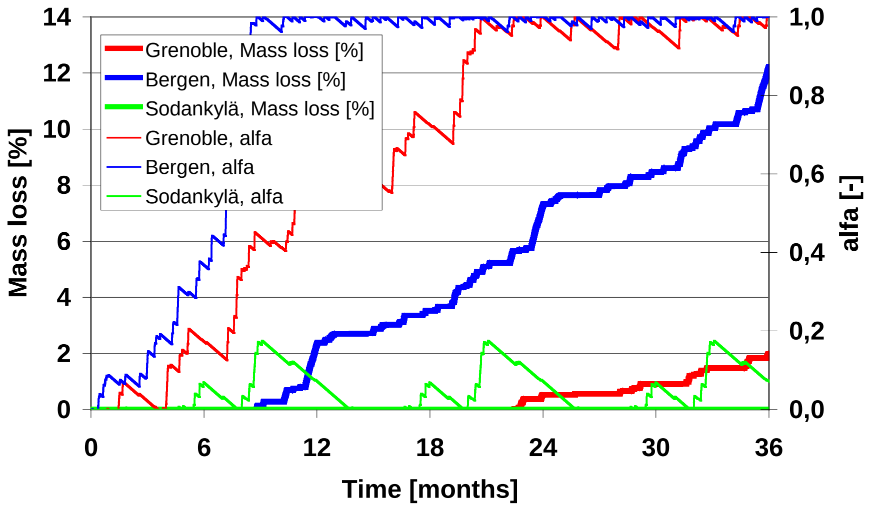


Figure 4. The evaluated risk of decay development and activation parameter during 3 years at different locations in Europe. Alfa means the lag phase of decay development and mass loss the degree of decay during active phase of decay development.

Task 1.2 b Verification experiments on exposure conditions for different climate classes

In order to investigate how the micro-climate is affected by design details and moisture traps three comparative experimental investigations were performed:

- Field trials with different decking designs
- Weathering test with wood blocks, rails and decking
- Weathering test with different types of moisture traps and contact zones

Field trials with different decking designs

FCBA built deckings with three different designs. Decking no. 1 has a conventional design. Decking no. 2 includes improvements of the fixation to reduce moisture ingress and decking no. 3 includes other improvements to avoid water traps, see Figure 5. Two sets of these three objects were made. One was exposed and assessed in Bordeaux, the other one was sent to the University of Göttingen in Germany. Moisture measurements were performed on these uncoated and untreated deckings during 18 months. The aim was to study the influence of design on moisture content.

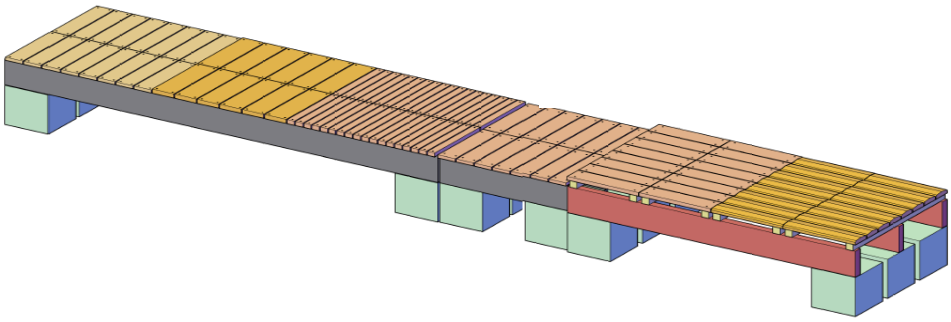


Figure 5. Principal set-up of decking trials.

The measurements for the trials in Göttingen are shown in Figure 6.

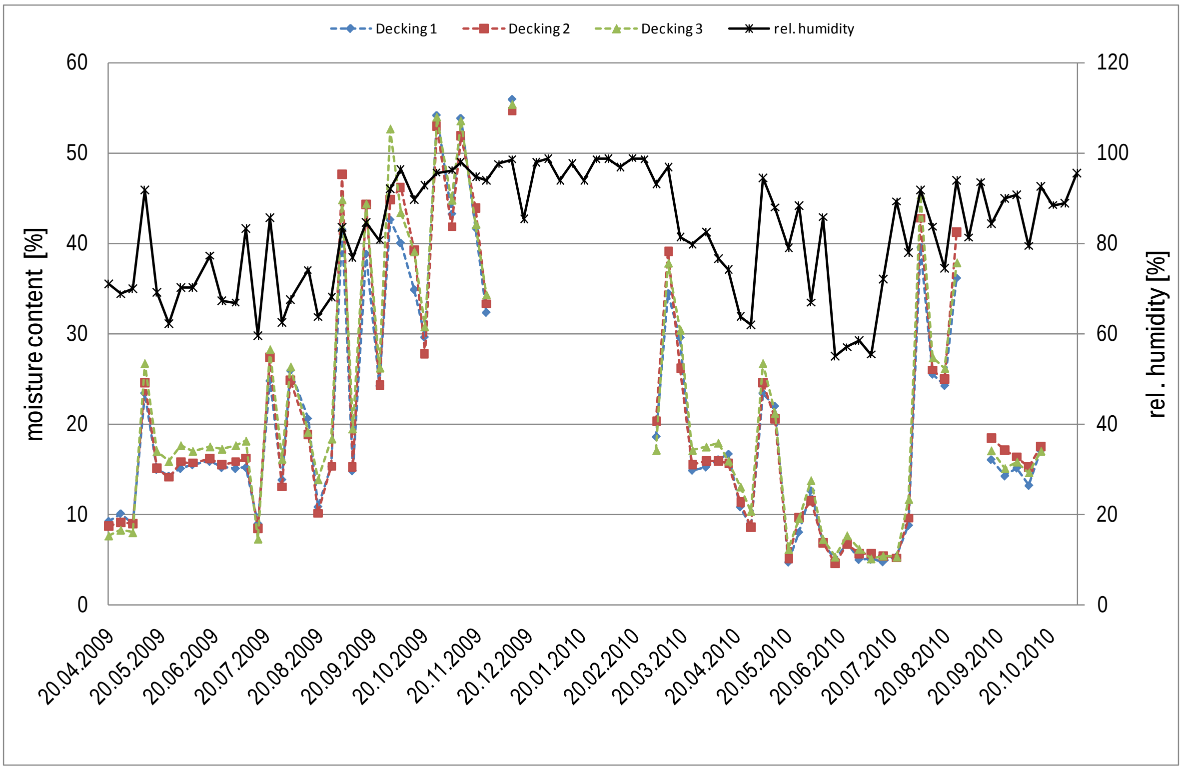


Figure 6. Wood moisture content [%] depending on decking element and RH [%] (mean value from 6 measurement points).

The results of this trial can be summarized as follows:

- The wood moisture content is similar within all decking elements. Differences in moisture content for the three decking designs were low when the measurement was made on the top of the boards. When the rear face is considered, decking no. 3 displayed slightly higher moisture content than decking nos. 1 and 2.

- The construction design of the decking elements did not influence the wood moisture content significantly. For all decking designs the rear face showed higher moisture contents than the top of the boards because the microclimate was different. The rear face was less exposed to sun and air circulation and therefore was more humid.

- This test was not capable to evaluate different drying behavior after rain because measurements were carried out just once a week.

- On the French site results showed that high moisture contents were explained by significant rainfall events. During the test no signs of rot were observed, only blue stain and moulds occurred.

Weathering test with wood blocks, rails and decking

Three test designs were used to evaluate the moisture content of wood species and modified wood in different outside weathering conditions during two years' exposure (November 2008-November 2010) in Göttingen, Germany (Figure 7).

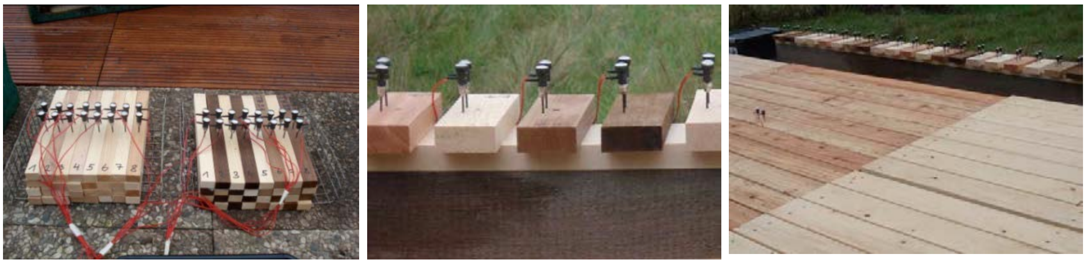


Figure 7.
Test set up for the block test (left), rail test (middle) and decking elements (right).

As expected, there are differences in moisture content between the wood species and test designs. Because temperature is also a critical factor, it was calculated how many days during the 2 years exposure was above critical moisture (20, 25 and 30 and 35 %) and at the same time the temperature was above 3°C (Table 2).

Table 2. Number of days with wood moisture content (MC) above 20, 25, 30 and 35 % and temperature above 3°C.

Test set-up/ Wood species	**Days**				
	In total	**MC >20 % and T >3°C**	**MC >25 % and T >3°C**	**MC >30 % and T >3°C**	**MC >35 % and T >3°C**
Rail test					
Beech	734	517	445	315	52
Spruce	734	444	344	215	80
Pine	734	516	474	386	32
Larch	734	247	67	0	0
Thermally treated pine	734	213	14	0	0
Furfurylated pine	734	515	255	0	0
Block test					
Beech	700	459	392	309	148
Spruce	734	394	310	229	141
Pine	734	481	399	290	62
Larch	700	331	228	54	0
Thermally treated pine	598	354	244	0	0
Furfurylated pine	734	526	210	0	0
Decking element					
Beech	662	375	309	231	93
Spruce	660	318	218	138	47
Pine	566	307	274	229	45
Larch	660	270	121	5	0
Thermally treated pine	566	219	45	0	0
Furfurylated pine	566	300	144	0	0

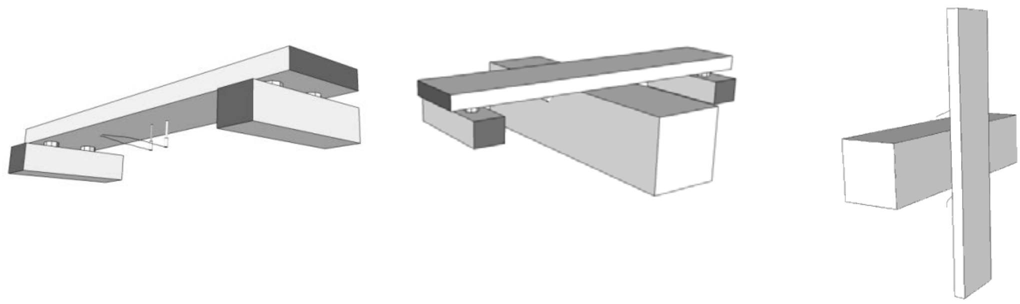
The results can be summarized as follows:

- There are big differences in moisture content of different wood species in various trials.
- The influence of wood species is higher than the test design (block test, rail test, decking element)
- Beech, pine and spruce show in all tests the highest amount of days with moisture content above 25 %

- Modified pine (thermally treated and furfurylated) show in all tests a moisture content lower than 30 %

Weathering test with different types of moisture traps and contact zones
In the third trial the moisture content was monitored continuously during a period of five months in a variety of type details exposed outdoors without protection from the weather in Lund, Sweden, see examples in Figure 8. As reference detail a horizontal board (22x95 mm) of spruce (*Picea abies*) without moisture traps was used.

All details and designs were tested under the same climate exposure to investigate the relative effect depending on the type of detail. Variables investigated were compass orientation for vertical boards, inclination of horizontal boards, cross section dimensions, vertical and horizontal contact with different sizes for the contact areas and size of designed gaps.



a b c

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

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

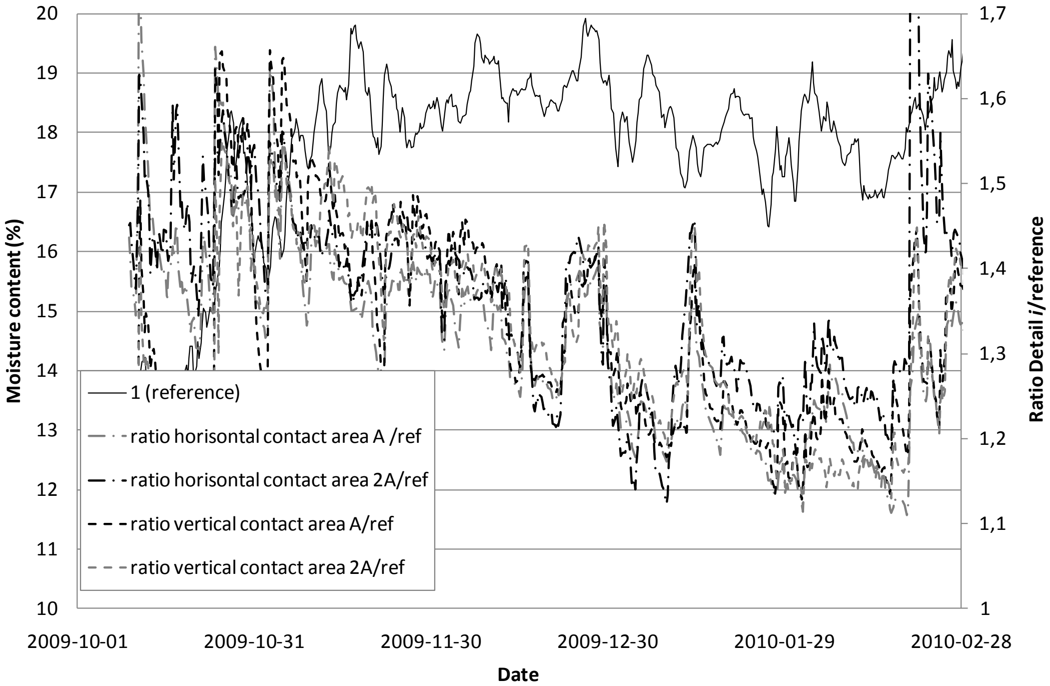


Figure 9. Moisture content for the reference detail (top curve) shown together with the ratios between details with different size and orientation of contact area (side to side grain).

During the first three months of the test period rain occurred frequently and the temperature was between 0 and 10 °C, while the temperature during the last two months was almost always below zero with no precipitation. Figure 9 shows that the moisture content in the contact areas area are 40-60 % higher than in the reference board during the rainy period. Furthermore, no significant influence could be found for orientation or size of the contact zone. For contact zones with end grain/side grain the moisture content was slightly larger, but no effect of orientation was found.

WP 1 Key outcome

- The most significant outcome of WP 1 was the development of a methodology for describing and modelling the effect of climate variability on risk for decay of wood exposed outdoors to be used for engineering tool of service life evaluation.

- Additionally, the knowledge of moisture dynamics and microclimate in contact zones (moisture traps) have increased, based on a number of field trials, and will further increase as results from ongoing tests will be further evaluated.

WP 1 Key publications

Viitanen H. (1996). Factors affecting the development of mould and brown rot decay in wooden material and wooden structures. Dissertation, dep. of forest Products, The Swedish University of Agricultural sciences, Uppsala.

Viitanen H, Peuhkuri R, Ojanen T, Toratti T, Makkonen L (2008). Service life of wooden materials – mathematical modelling as a tool for evaluating the development of mould and decay. Proceedings, COST Action E37 Final Conference. Bordeaux, 29-30 September, 2008

Viitanen H, Toratti T, Peuhkuri R, Ojanen T, Makkonen L (2009). Durability and service life of wood structures and components -State of the art. Proceedings COST Action E25 Workshop Integrated approach to life-time structural engineering. Timisoara, 23-24 October, 2009

Viitanen H, Toratti T, Makkonen L, Peuhkuri R, Ojanen T, Ruokolainen L, Räisänen J (2010). Towards modelling of decay risk of wooden materials. European Journal of Wood and Wood Products. Vol 68. No 3.

Thelandersson S, Isaksson T, Suttie E, Frühwald E, Toratti, T, Grüll G, Viitanen H, Jermer J (2011). Background document for "Engineering design guideline for wood in outdoor above ground applications". Report TVBK-3061, Lund University.

Viitanen H, Toratti T, Makkonen L, Peuhkuri R, Ojanen T, Thelandersson S, Isaksson T, Früwald-Hansson E (2011). Climate data. – Climate conditions in Europe. VTT Working papers 181 (a network report), VTT, Espoo.

Work Package 2. Durability indicators

Task 2.1 Inventory of exterior wood cladding and decking in service

This task was concerned with establishing an inventory of cladding and decking use across the participating partner countries in the WoodExter project. A total of over 100 buildings have been studied across Europe, from the Northern part of Sweden and Finland to the Mediterranean coast and the maritime climate of the United Kingdom. The selection of buildings attempted to meet several simultaneous criteria. The cladding materials and design cover a span of variety, and the status of the claddings cover a range from poorly performing to well-performing. A proforma was completed by building inspection teams across Europe alongside a Guidance Document to establish a degree of consistency of approach.

The task resulted in:

1. input to testing the model developed in WP 4. The model at the core of the project needs real data from construction to be used as a sanity check. The background data and information for examples of cladding on buildings that is performing and meeting both the aesthetic and weather protection functions is needed to input to test the model outcomes. Similarly data from projects where the materials are not performing to expectation are helpful in testing the structure and function of the model (Figure 10).

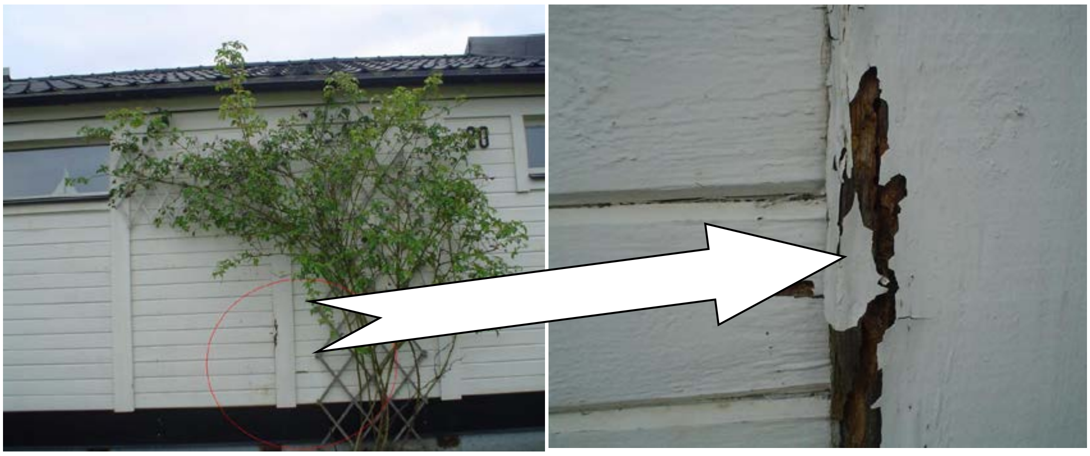


Figure 10. Photo from the cladding inventory. Decay on cladding exposed to the north.

2. informing best practice. Part of the inspections was to consider nationally available best practice literature which many of the project partner organisations author. The inventory will add to the information to revise and improve best practice information and to provide case studies of good practice and understand how it has been achieved. In addition the task has provided an opportunity to present the five key best practice features for cladding that has been launched across Europe (Figure 11) through the project partners. This raises awareness of existing best practice and provides common Europe-wide principles for delivering long lasting exterior wood cladding solutions.

3. a database. The completed proformas and accompanying photographs provide a database for future study and use of long term performance of exterior wood cladding.

Wood cladding – the FIVE keys for extending service life

The collaborative European project WoodExter has agreed on an early set of principles to ensure the maximum service life is delivered for an exterior wood cladding specification. The five key design features will ensure a long service from wood cladding. Further details can be obtained from any of the project partner organizations.

1. Off the ground – cladding to start at least 30 cm above ground level.
2. End grain protection – water ingress is 1000 times quicker along the end grain of wood. End grain protection by capping, design or sealant can provide a key way of restricting moisture ingress into the wood and prolong service life.
3. Ventilation and shedding water – design the cladding to shed water rapidly and to dry rapidly if it becomes wet. Sloping surfaces and a ventilated cavity behind the boards are simple design features to enable this.
4. Coatings play a key role in performance of cladding and must be maintained. An exterior wood coating must be delivered as part of a complete maintenance and care package.
5. No sharp edges – sharp edges on cladding profiles tend to damage easily from impact and if coated provide weak points in the protective coating layer as the film cannot form over the edge.

Figure 11. The five key design actions for extending the service life of exterior wood cladding.

Task 2.2 Micromechanical model to quantify the effect of the degradation mechanisms on mechanical properties of wood

This task was concerned with the quantification of changes in mechanical properties upon fungal decay. Wood decay causes changes in the wood microstructure. This is expressed by a change in oven-dry mass, mass density, moisture content, as well as a change in the relative amount of wood polymers. Consequently, there is a change in macroscopic mechanical properties. This task was concerned with the application of a micromechanical model that allows to predict the changes in the macroscopic mechanical properties based on the microstructural alterations. For the purpose of model verification, an extensive experimental program was carried out, in which changes in chemical and physical properties, as well as corresponding changes in the mechanical behaviour were examined.

The result of the task can be summarized as:

- Transverse stiffness properties (in the radial and tangential direction) were found to be more sensitive to degradation than longitudinal stiffness. This could be shown to be a result of hemicelluloses degradation.
- Ratios of elastic stiffnesses derived from ultrasonic tests revealed different effects of the brown rot and the white rot fungi on the transverse stiffness properties of pine sapwood. The brown rot fungus *Gloeophyllum trabeum* more strongly affects earlywood than latewood, while the white rot fungus *Trametes versicolor* more strongly affects latewood than earlywood.

- The micromechanical model allows prediction of changes in solid wood stiffness properties, based on microstructural alterations, not only in the longitudinal but also in transverse directions.

Task 2.3 a Identification and quantification of early decay for estimation of service life using quantitative real-time Polymerase Chain Reaction (qPCR)

The aim of this sub task was to establish and further develop a novel methodology, quantitative real-time PCR (Polymerase Chain Reaction), for quantification of early decay for estimation of service life of timber.

Wood decaying fungi are a challenge for timber used outdoors. The development of new systems for wood protection is delayed due to long term field testing. It is known that many of the new wood protection systems, e.g. modified wood, are effective against wood decaying fungi. But all the reasons why many of them are working and how fungi colonize different wood materials are still unknown. That is why new accelerated test methods and new methods for early decay identification and quantification of decay fungi are needed. For future use of timber it is important to develop early estimation of service life. Molecular tools have showed to be very useful, but still this approach has been insufficiently utilized within the field of wood protection. One of the advantages of quantitative real time PCR (qPCR) methodology, the focus of this sub task, is to both identify and quantify the decay fungi present in the wood material.

To understand more about wood decay a range of different, interdisciplinary, methods should be used. Hence, within this sub task experts within mycology, molecular biology, chemistry, micro mechanics, wood physics, microscopy and wood technology have cooperated.

Key outcome of the task:

- A novel methodology, quantitative real-time PCR Polymerase Chain Reaction (qPCR) has been further developed as a tool for identification and quantification of early decay in wood, both in laboratory and field samples.
- The method has been used both in laboratory and field trials to study colonization rate and colonization pattern in different wood materials.
- New knowledge with respect to the mode of action of modified wood against decay fungi.
- qPCR has proven to be a useful tool for early estimation of service life of timber.
- New insight has been gained about the correlation between different stages of colonization and the corresponding change in mass loss, chemical composition and micromechanical properties.
- The use of Thermo Gravimetric Analysis (TGA) has proven to be a fast and useful tool for estimation of chemical changes during decay for brown rot fungi.

Task 2.3 b Early detection of ascomycetes on modified woods exposed in the field using specific PCR

The aim of this task was the early detection of fungal attack on the surfaces of modified and unmodified wood after natural weathering. The investigation was carried out by molecular techniques and the development and establishment of genus/species specific PCR for important moulds and sapstain fungi was part of this work. After adaptation of the method, a monitoring of the succession of Ascomycetes on surfaces of modified wood with and without coatings after natural weathering started. The method turned out to be a very useful tool for monitoring the surfaces of wood in service concerning the attacks by moulds and sapstain fungi.

Task 2.4 a Interpretation of field test data for service life prediction

Field testing of wood and wood-based products is so far the most reliable way to get information on performance with respect to durability and expected service life. However, field trials are extremely time and cost consuming. The main objective of this task was to investigate possible correlations between early stages of decay, preferably during the first 5 years, and the actual service life of a wood material. The hypothesis was that such correlations could be used when developing realistic models for service life prediction of wood materials in different applications.

Data from Nordic field trials with more than 20 000 stakes of untreated and preservative-treated wood has been re-analysed and evaluated according to new approaches. The evaluation showed that the average life of stakes in test can be predicted with high precision by using the median (50^{th} percentile) to rating 4 (failure) as the basis for the determination. In the case of the material related to the encircled data point in the graphs below (Figures 12 and 13), the average life time is 14 years, but the time to reach the last rating 4 was 35 years, i.e. the average life could not be calculated until 35 years had passed!. This example shows that by this method, a value of the average life will be obtained in a shorter time than waiting until the last stake in a series has failed.

Further examination of data aimed at finding out how the time to early stage decay correlates with the average life. The approach was to analyze the time in testing needed for the development of decay corresponding to a rating of 1, 2, 3 and 4 according to EN 252. The evaluation also included analysis of the time needed for 5 %, 25 % and 50 % of the stakes in a test to reach the rating of interest. Results clearly showed that the early stages of decay are reflected in the long time performance of the stakes (Figure 13). However, the overall conclusion is that the reliability of predicting the long term performance of wood is lower the earlier in the test the information is extracted.

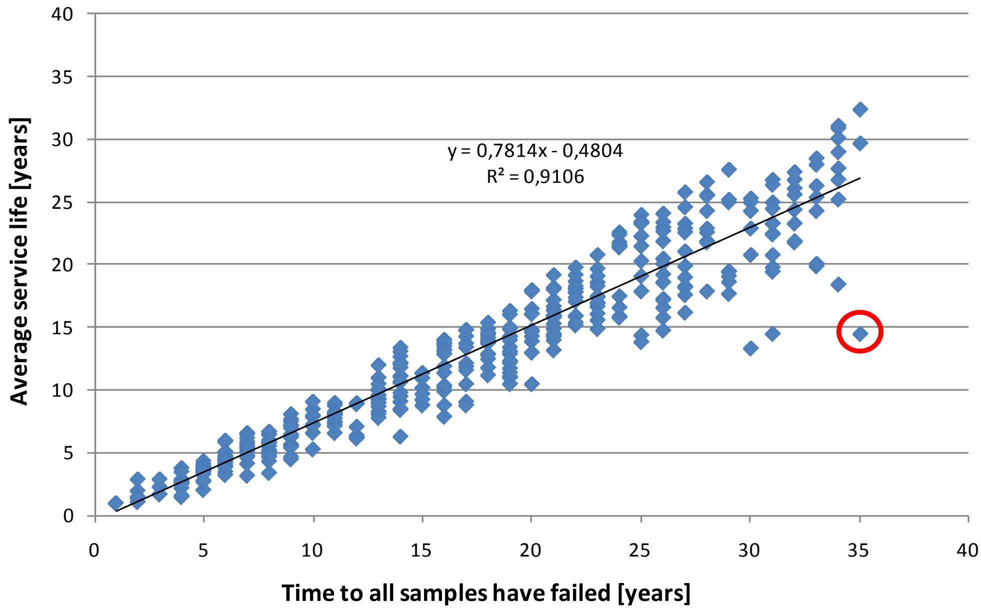


Figure 12. The average life, i.e. the average time until a rating of 4 is reached, plotted against the time until the last stake within a group has reached a rating of 4.

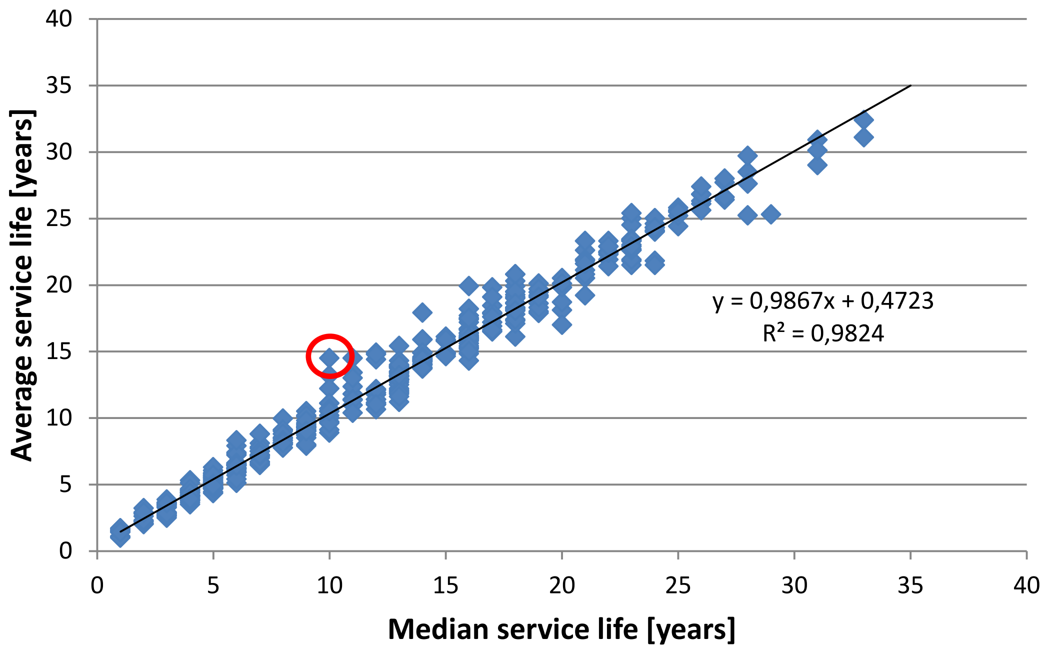


Figure 13. The average time to rating 4 (i.e. average life) plotted against the median service life or 50th percentile to rating 4.

Task 2.4 b Input to standards

Following an initiative by the WoodExter coordinator and other colleagues in CEN/TC 38 a new Working Group (WG 28 Performance Classification) – End use performance of wood products – was established with the following scope: *Guidance on the determination of end use performance of wood products: utilisation and improvement of existing test methods to estimate service life, in order to give input to the harmonised product standards dealing with the durability requirement of the CPD and future CPR.*

The decision was taken at the TC 38 Plenary meeting in November 2008, and the WG had its first meeting in September 2009. Dr Ed Suttie, responsible for WoodExter WP 2, was appointed to convene WG 28.

The task of this group is to consider performance classification for wood products in the context of TC 38 expertise – biological durability. The group has a unique possibility to look at CEN/TC 38 and its work to seek and request information for performance classification. The fundamental needs of service life information in the construction industry provide an opportunity for the group to try and make best use of data available from existing tests.

A significant, if not the most significant, challenge is to be able to predict the performance of products (e.g. window, woodpole, timber deck, structural beam) from tests that by their very nature do not consider the primary influences of service life such as design, exposure and maintenance. TC 38 tests almost exclusively consider only the material, and an idealised material (e.g. preservative treated sapwood), and the primary influence of material resistance not the moisture risk. Termites and insects might present a special case. They have to be present so need to consider the product use location (e.g. South of France) and beyond that we may just accept that the material resistance (durability + permeability) is the only influence. In which case the insect and termite tests should have a high predictive ability and be good at classifying the performance of wood and wood-based materials.

Figure 14. How can early results from field trials be used to predict the performance of a wood product? SP test site in Borås, Sweden.

Design and exposure can be controlled to deliver a wood product that meets a desired service life through elimination of moisture risk. However, it can be difficult to achieve and risks are high of non-conformities (e.g. poor workmanship on installation of the window) which will compromise performance. The third means is the material resistance. Most of TC 38 tests classify the performance of preservative treated wood (the material) not the product. The more complex the construction product the further away from the prediction we get with our tests. The material resistance (and its variability) is a hugely important part of service life modelling so *perhaps we can accept that this is all we will achieve* – but then we must be sure that how we measure material resistance, against which reference products, is appropriate for our needs.

In addition, WG 28 must think from the end user of wood products perspective. The distinction between efficacy and performance is complex and yet subtle. Users understand performance and a helpful structure could be if Tier 1 is efficacy and Tier 2 is the claim for performance (Figure 15). WG 28 recommends that EN 460 becomes the primary user interface and is where performance and service life information may be brought together. EN 599 and EN 350 are where the data from the suite of test methods is manipulated to yield service life information. The test methods in green boxes are the current focus and need to produce good quality data.

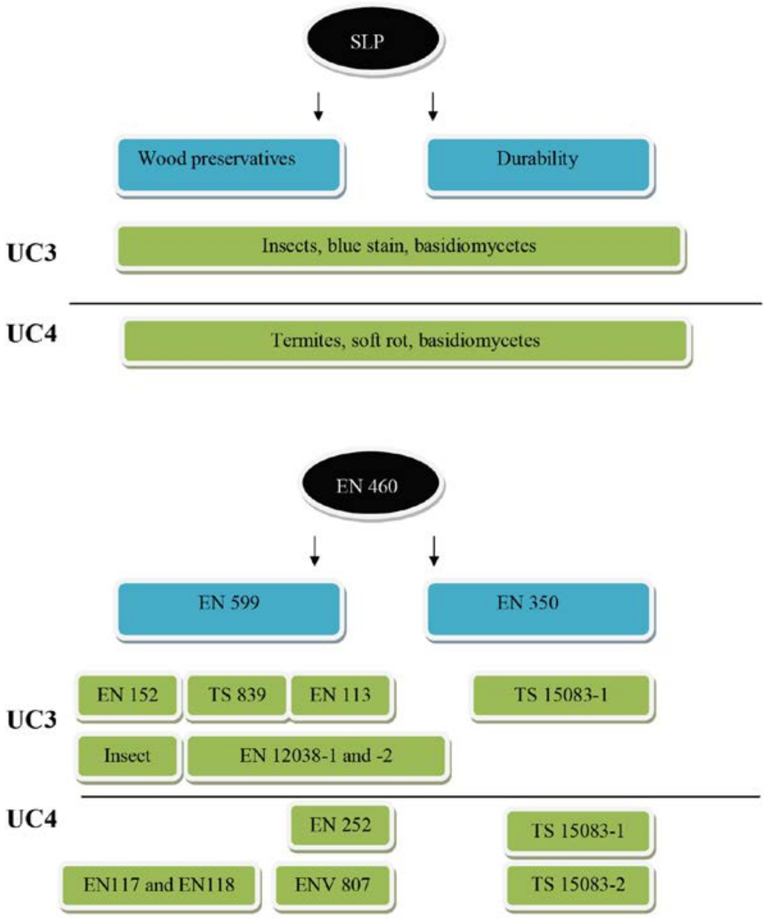


Figure 15. Schematic used by WG 28 to show the tiers in existing CEN TC 38 standards (adapted from J Van Acker).

CEN/TC 38 will be requested for further input from Working Groups on the adaptation and modification of existing standards. It is likley that ensuring quality material resistance data is an output will be the focus of work.

Task 2.5 Extending service life of casting timbers

Re-use of casting timber could be a way of saving timber resources, particularly in countries where most timber for construction purposes has to be imported. The objective of this task was to investigate residual concrete on casting timber re-used four times. Moulds were made of sections of Norway spruce, untreated and treated with a casting oil and a wax formulation applied by a vacuum-pressure process, respectively.

Casting was carried out with concrete of strength class C40/50 with a slump of 120 mm. The concrete was allowed to set for at least ten days before the sections were investigated with respect to residual concrete (Figure 16).

Figure 16. Typical result after the fifth casting.

None of the treatments, wax applied by vacuum pressure treatment or casting oil applied by brushing, resulted in completely residual free wood surfaces after five castings. The best result was obtained with the casting oil. If application by vacuum-pressure ever shall be an attractive alternative to the superficial treatment with casting oil, further improvements of the treatment formulation are necessary. It is hardly realistic to completely avoid residues, but re-use of the casting timber four times should be possible if the residues can be minimized and some scraping can be accepted.

WP 2 Key outcome

The most significant outcome of WP 2 was:

- The development of the proforma for consistent inspections of cladding and the extensive database established following numerous inspections carried out by partners in Austria, Finland, France, Germany, Sweden and the United Kingdom. The database will serve as input for testing the model and engineering tool developed by WP 4, see below.

- New knowledge on how the micromechanical properties of wood are affected by fungal decay and how to apply this knowledge on a micromechanical model that allows prediction of changes in the macroscopic mechanical properties. The micro-mechanical model allows prediction of changes in solid wood stiffness properties, based on microstructural alterations, not only in the longitudinal but also in transverse directions.

- A novel methodology, quantitative real-time PCR Polymerase Chain Reaction (qPCR) has been further developed as a tool for identification and quantification of early decay in wood and has proven to be a useful tool for early estimation of service life of timber. With the help of qPCR new knowledge has been gained with respect to the mode of action of modified wood against decay fungi.

- The use of Thermo Gravimetric Analysis (TGA) has proven to be a fast and useful tool for estimation of chemical changes during decay for brown rot fungi.

- Using PCR technique turned out to be a very useful tool for monitoring the surfaces of wood in service concerning the attacks by mould and sapstain fungi.

- Promising results have been achieved with respect to evaluation of field trials and the possibilities to predict the expected average service life based on early results from inspections. Further development of the technique is needed, however.

- The establishment of a new Working Group (WG 28) within CEN/TC 38, partly as a result of a WoodExter initiative, will put more focus on performance and service life prediction of wood and wood-based materials in standardisation.

WP 2 Key publications

Suttie E, Englund F, Viitanen H, Podgorski, L, Bollmus, S, Grüll G (2011). Inspection proformas and images from buildings in Austria, Finland, France, Germany, Sweden and the United Kingdom. DVD from WoodExter Task 2.1, BRE, Garston.

Suttie E (2011). Task 2.1 Inventory of cladding and decking from building inspections in Woodwisdom-Net project WoodExter. BRE Report 274-243, BRE, Garston.

Anon. (2011). Wood cladding – the FIVE keys for extending service life. SP Info 2011:36. SP Trätek, Borås.

Bader T K, Hofstetter K, Alfredsen G, Bollmus S (2011). Microstructure and stiffness of Scots pine (*Pinus sylvestris* L) sapwood degraded by *Gloeophyllum trabeum* and *Trametes versicolor* – Part I: Changes in chemical composition, density, and equilibrium moisture content. Holzforschung, DOI 10.1515/HF.2011.149.

Bader T K, Hofstetter K, Alfredsen G, Bollmus S (2011). Changes in microstructure and stiffness of Scots pine (*Pinus sylvestris* L) sapwood degraded by *Gloeophyllum trabeum* and *Trametes versicolor* – Part II: Anisotropic stiffness properties. Holzforschung, DOI 10.1515/HF.2011.153.

Bader T K, Alfredsen G, Bollmus S, Hofstetter K (2011). Decrease of stiffness properties of degraded wood predicted by means of micromechanical modelling. IRG/WP 11-40570. Proceedings IRG Annual Meeting, Queenstown, New Zealand, The International Research Group on Wood Protection, Stockholm.

Alfredsen G, Bader T K, Dibdiakova J, Filbakk T, Bollmus S, Hofstetter K (2011). Thermogravimetric analysis for wood decay characterization. European Journal of Wood and Wood Products, DOI 10.1007/s00107-011-0566-7.

Pilgård A, Alfredsen G, Björdal C G, Fossdal C G, Børja I (2011). qPCR as a tool to study basidiomycete colonization in wooden field stakes. Holzforschung 65.

Pilgård A, Alfredsen G, Hietala A (2010). Quantification of fungal colonization in modified wood: Quantitative real-time PCR as a tool for studies on *Trametes versicolor*. Holzforschung 64.

Steitz A, Schmöllerl B, Pfabigan N, Bollmus S, Grüll G (2010). Early detection of colonisation by blue stain and mould on modified wood using PCR technique. IRG/WP 10-10730. Proceedings IRG Annual Meeting, Biarritz, France, The International Research Group on Wood Protection, Stockholm.

Steitz A, Schmöllerl B, Pfabigan N, Grüll G, Gründlinger R (2010). Pilzbewuchs auf modifiziertem Holz - Untersuchung der Pilzabfolge mittels DNA-Analyse. Proceedings Wiener Holzschutztage, 25-26 November 2010, Vienna

Steitz A, Schmöllerl B, Pfabigan N, Bollmus S, Grüll G (2011). Sukzession von Pilzen. Proceedings 4th Mycological Colloquium at the Institute of Wood Technology, 27-28 October 2011, Dresden.

Larson-Brelid P, Brischke C, Rapp A O, Hansson M, Westin M, Jermer J, Pilgård A (2011). Methods of field data evaluation - time *versus* reliability. IRG/WP 11-20466. Proceedings IRG Annual Meeting, Queenstown, New Zealand, The International Research Group on Wood Protection, Stockholm.

Work Package 3. Interaction of wood and coatings – effect on the performance of wood products

Task 3.1 Interaction between wood substrate and coatings

Interactions of wood and coatings were studied in a collaborative approach by the research partners based on a systematic sample plan. This plan included 12 different coating systems, 2 wood species, variations in growth ring orientation, wood density and surface preparation (planed, sanded, sawn) as well as five types of modified wood produced commercially. In total approximately 900 wood panels with selected properties were produced and coated for different experiments. The objective of this work was to study the influence of several types of modification (acetylation, furfurylation, thermal modification) and other parameters of the wood substrates on coatings performance.

Physical properties like water and water vapour permeability, adhesion in dry and wet conditions and UV-light protection were studied in laboratory trials with different methods. A comparison of two methods of assessing the adhesion has shown that the pull-off test is more sensitive than the cross-cut test and gives more information about the influence of the substrate. Under wet conditions adhesion was generally lower than dry adhesion. Compared to the reference, there was no improvement in the dry adhesion due to the different modifications, treatments or variations of the substrates. It was found that by increasing the coating film thickness, the coating permeability decreased and also less solar radiation transmitted through the coating film. This indicates the higher barrier properties of a coating film with higher thickness.

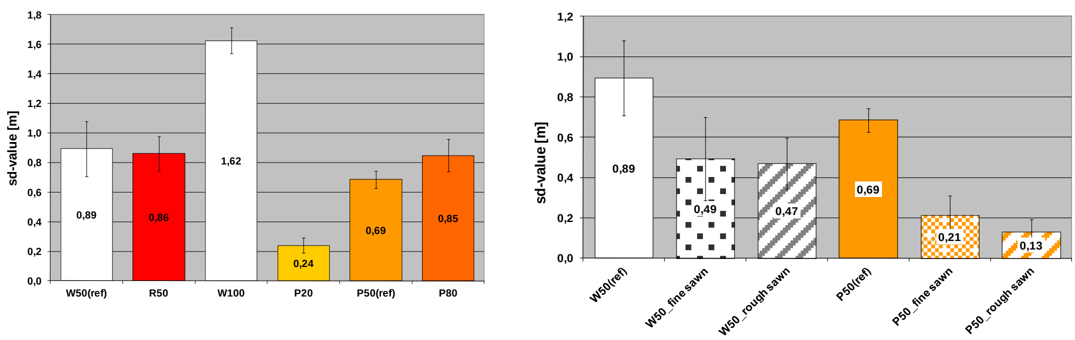


Figure 17. Sd-values for water borne coating systems (left) and different surface preparations (right).

Artificial weathering and 24 months natural weathering at six sites in Europe were carried out with coated panels and uncoated references. In the natural weathering trials data on wood moisture content fluctuations in the panels was recorded and assessed to quantify the influence of coatings systems and exposure sites. This data was partly used to assess the risk of decay of these panels by previously published models. Fluctuations in wood moisture content were influenced by the film thickness, moisture protection and colour of the coating systems used. Degradation phenomena led to decreasing moisture protection of less durable coating systems over time of exposure. Differences between the exposure sites were relatively low, except for the site in the United Kingdom where moisture conditions were higher. The data of wood moisture content gives evidence on coating durability and its moisture protection. It was used to estimate the influence of coatings on durability design for the guidance document "Engineering design guideline for wood above ground applications". It may also contribute to future modelling of decay risk and service life estimation of coated wood constructions on a European level.

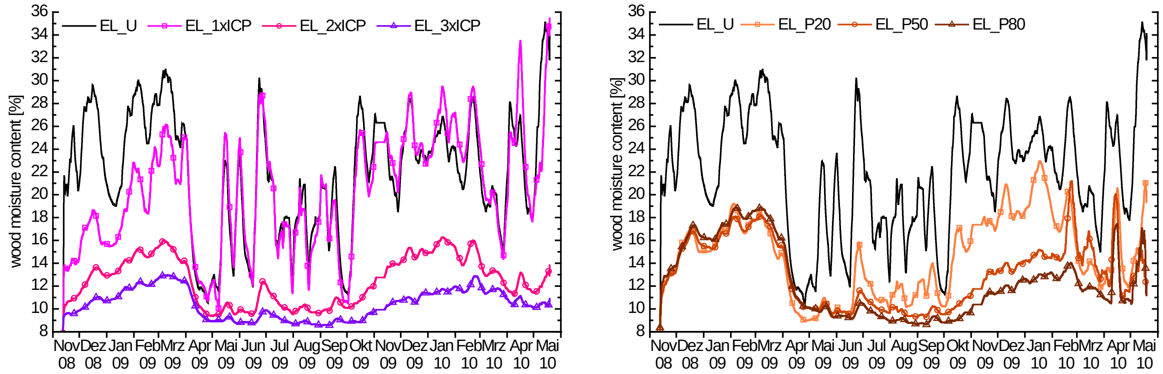


Figure 18. Wood moisture content (smoothed by weekly average) of coated wood panels (coating systems 1x ICP , 2x ICP, 3x ICP, P20, P50, P80, U uncoated reference) measured by electric resistance (EL) at the site in Vienna.

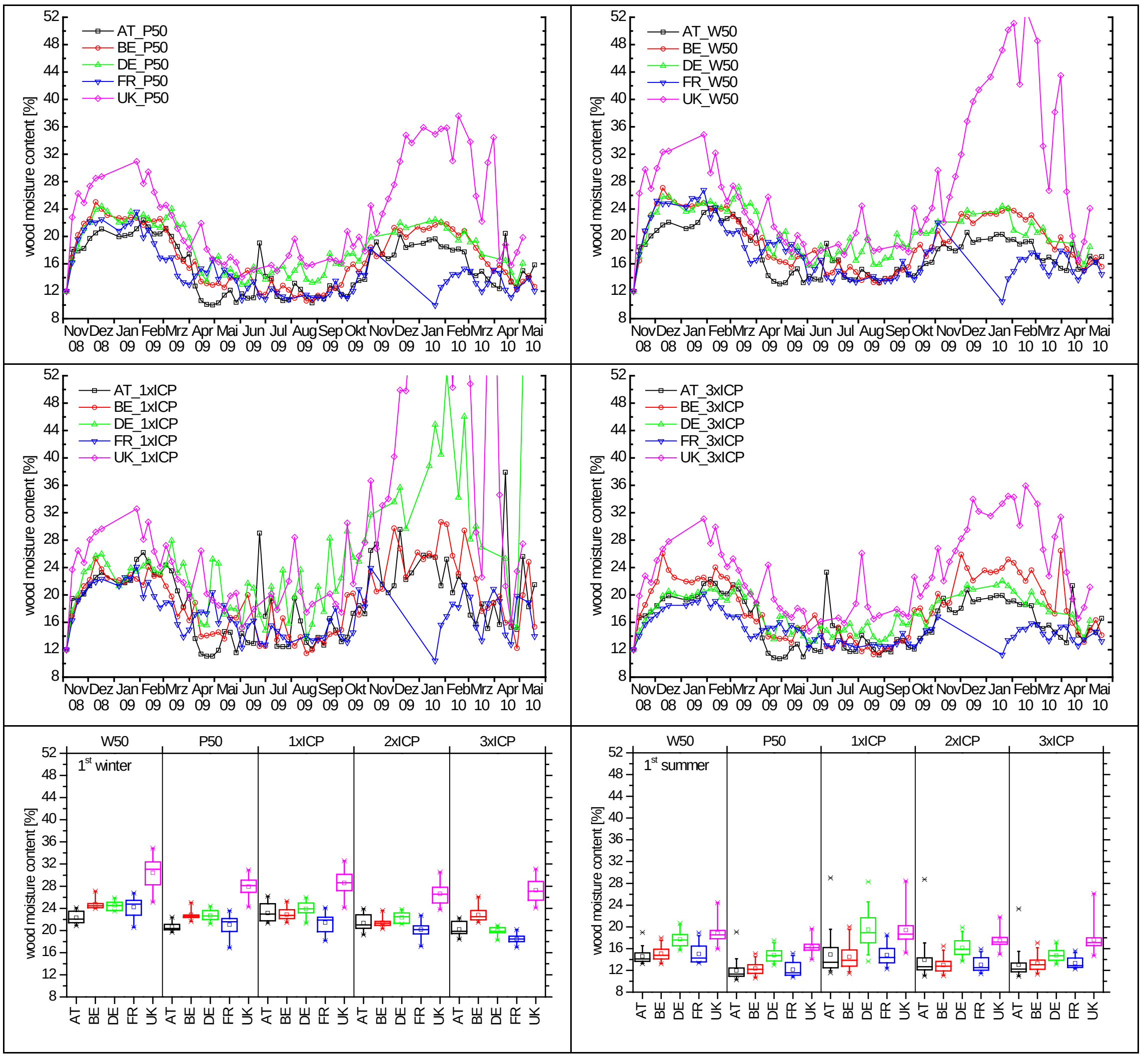


Figure 19. Wood moisture content of coated wood panels (coating systems P50, W50, 1x ICP, 3x ICP) measured by changes in panel mass at five sites in Europe (AT Austria, BE Belgium, DE Germany, FR France, UK) and box plot graphs of 1st winter and 1st summer period.

Results of weathering performance in artificial and natural exposure indicated that on one hand higher film thickness can result in improved durability of the coating and thus longer maintenance intervals but on the other hand very low permeability of the coating can enhance the risk of moisture trapping in the wood at defects or joints. Acetylated radiata pine wood revealed outstanding performance in colour stability and as coating substrate in all weathering trials. The performance of thermally treated pine sapwood was comparable to the unmodified reference. Its colour change was characterised by bleaching. Uncoated furfurylated pine sapwood samples showed strong colour change with extensive bleaching, whereas coated furfurylated wood showed good colour stability. Coated Cr-free preservative-treated pine sapwood showed sensitivity to mechanical defects of the semi-transparent coating film, leading to strong discolouration. These results indicate the possible influence of preservative-treatment on coating performance of semi-transparent stains.

Figure 20. Pictures of uncoated and coated samples with different wood modification methods; unexposed reference (left) and panel after natural weathering exposure (right).

Long term experience was gained from assessment of old weathering trials that were started up to 15 years ago including cladding samples of Scots pine, Norway spruce and thermally modified wood. It was found that the coating system has a great influence on the performance of wood. With two or three layer systems the best performance was obtained and wood species had minor effect on the performance. The wood species had a greater importance in case of "low performing" coatings.

Figure 21. Natural weathering exposure of south west oriented vertical cladding in Vienna.

Task 3.2 Performance specifications for coatings for specific end uses (UC 3)

Definitions of a series of limit states for coating systems on wood were published including aesthetical limits and three levels of durability limits. Film forming coatings can reach two durability limits, i.e. the maintenance interval and the renovation interval. For non film forming coatings there is only one limit state of coating durability where maintenance is needed. Experience on coating durability and maintenance intervals of different wood coating systems was collected among the research partners to gain information on coating durability in real situations and in different regions of Europe. A Top Five list of recommendations to obtain good coating performance on cladding was generated, with an appendix of a few more items with lower priority.

Table 3. Definition of limit states for wood coating systems.

<table>
<tr><th>Limit State</th><th>Film forming coatings</th><th>Non film forming coatings</th><th>State of coating</th><th>Defects</th></tr>
<tr><td rowspan="3">L-E</td><td rowspan="3">Esthetical Limit, Optical Deficiency</td><td rowspan="3">Esthetical Limit, Optical Deficiency</td><td rowspan="3">only optical alteratioins</td><td>change of gloss</td></tr>
<tr><td>change of colour</td></tr>
<tr><td>growth of algae</td></tr>
<tr><td rowspan="6">L-D1</td><td rowspan="6">Maintenance Interval</td><td rowspan="12">Maintenance Interval
=
Renovation Interval</td><td rowspan="6">minor defects that do not require removal of original coating</td><td>reduction of film thickness >50%*</td></tr>
<tr><td>intensive chalking</td></tr>
<tr><td>cracks in coating film
(without discoloration)</td></tr>
<tr><td>cracks in coating by hail impact
(without discoloration)</td></tr>
<tr><td>flaking in single areas
(< 5mm², without discoloration arround flaked area)</td></tr>
<tr><td>superficial mould growth /
blue stain</td></tr>
<tr><td rowspan="6">L-D2</td><td rowspan="6">Renovation Interval</td><td rowspan="6">coating degradation</td><td>cracking</td></tr>
<tr><td>blistering</td></tr>
<tr><td>flaking</td></tr>
<tr><td>hail damage</td></tr>
<tr><td>discoloration around cracks</td></tr>
<tr><td>penetrating mould growth /
blue stain</td></tr>
<tr><td rowspan="3">L-D3</td><td rowspan="3">Decay of Wood</td><td rowspan="3">Decay of Wood</td><td rowspan="3">onset of decay in wood</td><td>brown rot fungi</td></tr>
<tr><td>white rot fungi</td></tr>
<tr><td>wood boring insects</td></tr>
</table>

An overview of present evaluation procedures for coatings on exterior wood on European and national levels was compiled and summarised. The collection of methods was categorised in those assessing weathering performance, moisture related failure and susceptibility to biological attack. A range of well-defined and standardised assessment methods is available from European standardisation. A summarizing report was submitted to CEN/TC 139 WG 2.

Optiwoodcoat

Through WoodExter partner University of Ghent the Belgian research project Optiwoodcoat was connected to WoodExter.

The main topic of Optiwoodcoat was to establish an assessment methodology for wood coating systems with focus on setting requirements for an acceptable system, a wood coating system performing adequately. The results prove that it is not unambiguous to define the minimal and maximal evaluation criteria for a sound wood coating system. Some parameters are ignored in the test set up because there are characteristics described as parameters to be met by the coating producers e.g. blocking and stackability. The research was based on the European (pre)standards for exterior wooden joinery coatings. Coatings were tested on commercial wood frames made of wood species that are frequently used for making windows. Paints were all opaque white systems while translucent stains are brown coloured and semi-transparent.

Outdoor exposure was done using window frames measuring 1 m² outer size. Because of practical reasons no glass was used causing extra stress for the coating system e.g. sharp ridges and water stagnation.

The assessment methodology developed is based on physicochemical weathering (erosion, cracking, flaking,…), moisture dynamics (permeability, adhesion) and biological aspects. Each single laboratory test does not hold the power to predict the performance of a coating system for exterior joinery in a natural weathering trial. However, the combination of the accelerated test results can predict the performance of the wood coating system rather well on a short term base. Incorrect predicted performance can be avoided when including critical laboratory tests and/or by combining the test results in relation to their impact. However, further research is needed to come as such to a more reliable service life prediction.

Taking into account that maintenance intervals should be as long as possible, Table 4 summarizes the test results by means of mandatory tests and matching evaluation criteria.

Table 4. Overview of the test methodologies and matching evaluation criteria for wooden exterior joinery with large maintenance intervals.

	Importance	Outdoor exposure	Laboratory tests
Component 1 - PHYSICOCHEMICAL WEATHERING	*high*	**Natural weathering After 30 months**	**Artificial weathering (WOM) T: 10 weeks O: 14 weeks**
	required	Rating ≤ 4	Rating < 4
	low		**Layer thickness**
Performance assessment on flat elements	*required*		T > 60 µm O > 80 µm
Component 2 – WATER	*high*	**Natural weathering After 12 months**	**Moisture dynamics sorption test: absorption and desorption after 72h**
	required	Rating < 1	ΔMC (%) ≤ 1.5 % or 1.5 < ΔMC (%) ≤ 3 and residual < 70 %
	high		**Adhesion Torque-test dry and wet**
Water damage at sensitive parts (corner joints and sharp edges)	*required*		probability of failure = $e^{-\left(\frac{x}{5.75}\right)^{1.16}}$ x: wet shear stress (MN/m²)) or > 6 MN/m²
Component 3 - BIOLOGY	*high*		**Mould test**
Biological aspects	*required*		Rating ≤ 1

T: translucent system
O: opaque system

Based on the criteria in Table 4 a model to certify finished wooden joinery was drafted in agreement with the involved coating producers and joinery manufacturers. This certification system gives the opportunity to test for different wood species. The project showed that the wooden substrate obviously influences the performance of the wood coating system. Finished dense tropical hardwood containing large vessels performs well. Due to this specific anatomical feature erosion in the vessel lines will occur rather fast, so a regular check up is recommended to avoid severe maintenance procedures (renovation) for the coating system. Finished tropical hardwood species with low densities and finer textures weather at a slower rate, but are more sensitive to water damage. This kind of damage requires a total renovation of the coating system. The old and damaged layers have to be removed in order to replace them. Softwood is in many cases prone to fungal attack.

By defining these three groups of substrates, each with their typical characteristics, a wide range of reference systems is available as base for performance assessment type benchmarking and for certification. Benchmarking gives the opportunity to modify the developed certification system by regular comparison with similar products used in neighbouring countries.

WP 3 Key outcome

- It was shown that by increasing the coating film thickness, the coating permeability decreased and also less solar radiation transmitted through the coating film. During natural weathering fluctuations in wood moisture content were influenced by the film thickness, moisture protection and colour of the coating systems used. Degradation phenomena led to decreasing moisture protection of less durable coating systems over time of exposure. Higher film thickness can result in improved durability of the coating and thus longer maintenance intervals but very low permeability of the coating can enhance the risk of moisture trapping. Acetylated radiata pine wood revealed outstanding performance in colour stability and as coating substrate.

- It was found that the coating system has a great influence on the performance of wood when the condition of coated wood after 15 years outdoor exposure was inspected. With two or three layer systems the best performance was obtained and wood species had minor effect on the performance. The wood species had a greater importance in case of “low performing” coatings.

- Limit states for coating systems on wood were defined including aesthetical limits and three levels of durability limits. Experience on coating durability and maintenance intervals in real situations and in different regions of Europe was gathered and reported. An overview of present evaluation procedures for coatings on exterior wood on European and national levels was submitted to CEN/TC 139 WG 2 together with experimental results form WoodExter WP 3.

- The information received from Optiwoodcoat is useful in the interpretation of the quality of the exterior wooden joinery as a whole. In general the project brought a lot of discernment in the behaviour of coating systems for exterior wooden joinery. The direct collaboration of each joinery producer and one coating producer involved in the project made it possible to accomplish a realistic research focussing on water-borne systems applied on the most common wood species used in Belgium for exterior joinery. The proposed evaluation criteria for critical as well as for non-critical parameters will be used to finalize the STS 52.04.08 'HOUTEN BUITENSCHRIJNWERK - Bescherming en afwerking / MENUISERIES EXTÉRIEURES EN BOIS – Protection et finition'.

WP 3 Key publications

Grüll G, Truskaller M, Podgorski L, Georges V, Bollmus S, Jämsä S, Viitanen H, Jermer J (2010). WOODEXTER Work Package 3 Interaction of wood and coatings – effect on the performance of wood products. Report on Laboratory Results. HFA Report Nr FFG 436.

Podgorski L, Grüll G, Georges G, Truskaller M, Bollmus S (2011). Coating performance on different types of modified wood: natural and artificial weathering results. Surface Coatings International 2011, 4, 139-150.

Grüll G, Podgorski L, Truskaller M, Spitaler I, Georges V, Bollmus S, Steitz A (2010). Performance of selected types of coated and uncoated modified wood in artificial and natural weathering. IRG/WP 10-40510. Proceedings IRG Annual Meeting, Biarritz, France. The International Research Group on Wood Protection, Stockholm.

Grüll G, Truskaller M, Podgorski L, Bollmus S, De Windt I, Suttie E (2010). Moisture conditions in coated wood panels during 18 months natural weathering at five sites in Europe. Proceedings of the 7th International Woodcoatings Congress, 12-13 October 2010, Amsterdam.

Grüll G, Truskaller M, Podgorski L, Bollmus S, Tscherne F (2011). Maintenance procedures and definition of limit states for exterior wood coatings. European Journal of Wood and Wood Products, 69.

Grüll G, Podgorski L, Georges V, Bollmus S, Jermer J (2011). WOODEXTER workpackage 3 Interaction of wood and coatings – effect on the performance of wood products. Report on natural weathering trials. HFA Report Nr FFG 443.

De Windt I, Grüll G, Podgorski L, Bollmus S, Van Acker J (2010). Present evaluation procedures for coatings on exterior wood, Technical Report University Gent.

De Windt I, Grüll G, Podgorski L, Bollmus S, Van Acker J (2010). Present evaluation procedures for coatings on exterior wood. In CTIB-TCHN (2010) Optimalisatie van levensduur, onderhoud en garantie voor toekomstgericht houten buitenschrijnwerk door duurzaam gebruik van water-gedragen afwerkingssystemen. (Optiwoodcoat). Technical report nr 60878.

Dearling T B, Suttie E D (2011). Maintenance and renovation of exterior wood coatings. BRE-Report No 273427, BRE, Garston.

De Windt I, Van den Bulcke J, Van Acker J (2009). Continuous moisture measurement (CMM) to detect failure of moisture resistance. IRG/WP 09-20422. Proceedings IRG Annual Meeting, Beijing, China. The International Group on Wood Protection, Stockholm.

De Windt I, Van den Bulcke J, Van Acker J (2010). Impact of wood species on the performance of exterior wood coatings. IRG/WP 10-40519. Proceedings IRG Annual Meeting, Biarritz, France. The International Research Group on Wood Protection, Stockholm.

Jämsä S, Viitanen H (2010). Performance of coated heat treated Scots pine and Norway spruce after 15 years' outdoor exposure. Proceedings of the 7th International Woodcoatings Congress, 12-13 October 2010, Amsterdam.

Work Package 4. Risk based engineering methodology for service life design

Task 4.1 Probabilistic model for prediction of service life

A general principle for a performance-based service life design model has been as illustrated in Figure 22, utilised as the basis for research under this task. The problem here is described in terms of climatic exposure on one hand and resistance of the material on the other hand. The design model is related to a prescribed limit state, which for the present application has been onset of fungal decay during a service life of 30 years. Since most factors affecting the performance are associated with uncertainty, the probability of non-performance must be assessed so that it can be limited to an accepted maximum level. The advantage with this approach is that exposure can be described as a function of global and local climate, component design and surface treatment in a general way independent of the exposed wood material. Likewise, the resistance of different types of materials can be expressed in terms of response to quantified micro-climate conditions independent of practical design situations.

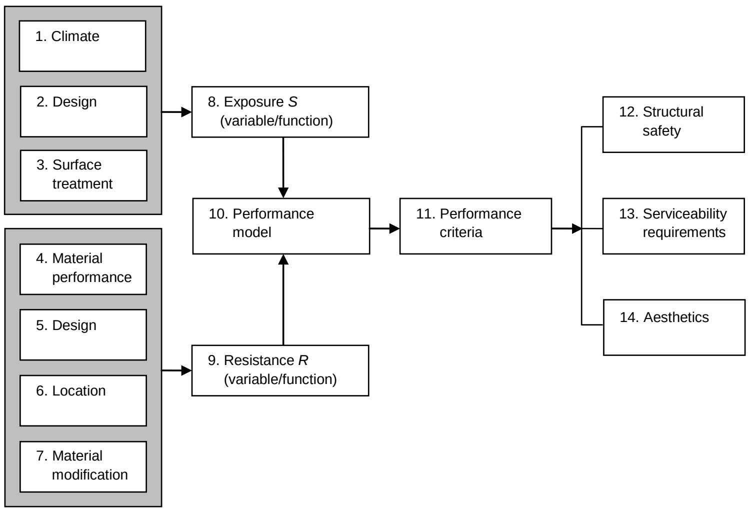


Figure 22. Principle for performance-based service life design of wood elements.

The key element in this approach is the performance model which is needed to evaluate whether the limit state is reached or not under a given micro-climate exposure. The performance model is based on the simple fact that the fungi spores need favourable moisture and temperature conditions during a sufficiently long period of time in order to germinate and grow. A so called dose response model was developed in the project which could be used to evaluate the potential risk of decay. In addition a simple empirical model was developed in the project with the purpose to transform meteorological data in the form of relative humidity and rain to moisture content in a reference board under use class 3 conditions. These models were used to produce the climate maps implemented in the engineering guideline, see Task 4.2 b below. In addition the performance model was used together with experimental data from WP 1 to quantify the effect of design detailing and moisture traps. Also these results were used as input to the engineering design guideline described in Task 4.2 b.

Task 4.2 a Durability design of wooden cladding and decking – an overview of guidelines and information sources

This task aimed at presenting existing information about durability by design, as it is reflected in handbooks, guidelines, scientific reports, manufacturers' recommendations as well as other experience-based design information. The discussion is limited to cladding and decking. A further purpose is to elucidate to what extent the recommendations and guidelines are consistent and if they express different views on important detailing aspects. It should be emphasized that the purpose was not to make a synthesis of all available information and produce yet another, but more comprehensive and indisputable guide.

It is obvious that a large number of publications have been devoted to this theme over the years in many countries. Many of them are directed towards a national group of readers, which means that they are only available in the local language and not translated into e.g. English for a wider audience. It also means that they may reflect national conceptions and traditions to some extent, and it is therefore not to be expected that they all tell the same stories. Furthermore, the target groups of these publications vary from laymen to students and to engineers, and the scope, contents, and structures of the information are quite diverse.

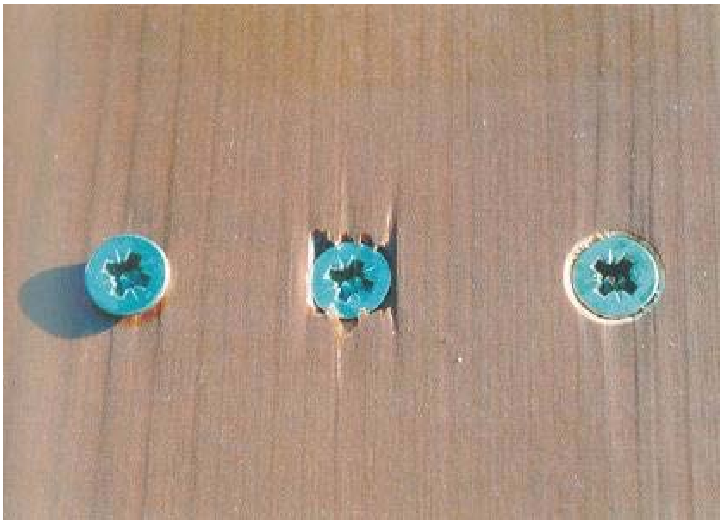


Figure 23. Incorrect and correct depths of screw heads.
Photo from Holzfassaden (2007). Holzforschung Austria.

Task 4.2 b Engineering design model

Joint efforts from research partners of WoodExter have resulted in a breakthrough for design of wood constructions with respect to durability and service life. Thus, the main objective of the project has been fulfilled and a first version of the guidance document "Engineering design guideline for wood in above ground applications" - a practical tool for engineers and architects for design of wood constructions with respect to durability and service life has been issued. The WoodExter approach is based on a similar approach as used in structural design which is familiar to engineers and architects. The expected service life is determined by available data of the resistance and exposure of the timber and expressed in a mathematical formula. Real building case studies have confirmed that this novel approach looks very promising.

Although is not possible to quantify all the factors in the design method on a scientific basis, the work within WoodExter has made it possible to determine a characteristic exposure index for a reference situation by using time series of climate data at different geographical locations (decay index mapping for Europe) together with the performance models for onset of decay for a reference material. Attempts have been made to make a relevant assessment of variability to achieve appropriate safety margins.

The system will give the designer a method to consider climate conditions at the actual site and also to some extent on the meso-level. A simplified way to account for the effect of coatings on exposure has also been introduced.

Figure 24. Key outcome of the task: The first European technical guideline and practical tool for engineers and architects for design of wooden constructions with respect to durability and service life.

One advantage with the system is that the user will have to think about the consequences of violation of the limit state. Another advantage is that in applying the method the designer will go through a check list where he/she becomes aware of the importance of appropriate detailing solutions. Even if the factors describing effects of detailing, contact zones, coating systems and maintenance are difficult to quantify in a reliable way the use of the method should generally lead to better solutions.

Building professionals normally have limited understanding of the concept durability by design for wood. Direct descriptions (pictures) of so called best practice solutions are quite difficult to use because the designer does not understand what happens if the solution is modified, which is most often necessary. As a complement to the guidance publication a special software based on MS Excel has been developed to serve as a practical help for design for durability.

4.3 Verification of design methodology

The purpose of this task was to verify the model against existing data and experience from existing structures by performing so called reality checks.

The elements in the design model or guideline described in 4.2 b were only expressed in relative terms. The tool had to be calibrated to produce a reasonable safety margin against non-performance. The approach at the present level of knowledge was to check if the system will give reasonable results in accordance with generally accepted and known experience. For this reason verification of the guideline against a number of reality checks of cladding on buildings across Europe have been made. Each reality check consists of a case from practice, for which the guideline is applied and where the real service life performance is known. In the reality checks, the interpretation of the guideline was made by the individual providing the information.

The output from the guideline tool agreed with the actual performance on the buildings in the majority of the cases, but not in all cases. One of the main problems is to rate different materials in a correct manner and to cope with the variability of wood materials. For three of the cases where the output from the tool did not agree with what happened in reality, the materials used were species with nominally high natural durability, given that only heartwood is present, which was assumed in the design tool evaluation. Under this assumption the guideline predicted that the design in these three cases should be acceptable implying a service life up to 30 years. Decay occurred however in reality after 6-16 years in these cases. One possible explanation could be that the material contains significant amounts of sapwood, but no information has been available to confirm this. For one case with CCB-treated pine with nominal high durability, the possible presence of non-impregnated heartwood could similarly explain that also this case failed in reality. In general, both heartwood from durable species and treated sapwood involve a risk due to the difficulty to distinguish between heartwood and sapwood in practice.

Task 4.4 Standardisation

This task focused on present development in standardisation works, including analysis of how input to ongoing standardisation works can be provided as well as how present standards can be used in service life design. It resulted in a state of the art overview of standards and ongoing activities in standardisation related to service life issues.

WP 4 Key outcome

The major key outcome of WP 4 was the first European technical guideline and practical tool for engineers and architects for design of wooden constructions with respect to durability and service life. A background document presented a reasonable verification of the guideline, but also a description of uncertainties still valid in service life design of and a compilation of important questions to be addressed in future research.

In addition, a state of the art compilation of standardisation activities in the field of service life prediction as well as an overview of guidelines and information sources related to durability design of wooden cladding and decking were produced.

WP 4 Key publications

Englund F (2010): Durability by design of wooden cladding and decking – an overview of guidelines and information sources. SP Report 2010:38, SP Trätek, Borås.

Thelandersson S, Suttie E, Viitanen H, Jermer J, Isaksson T, Grüll G (2011). Service life of wood in outdoor above ground applications: Engineering design guideline. Report TVBK-3060/SP-Report 2011:15, Lund University.

Thelandersson S, Isaksson T, Suttie E, Frühwald E, Toratti, T, Grüll G, Viitanen H, Jermer, J (2011). Service life of wood in outdoor above ground applications: Engineering design guideline - Background document. Report TVBK-3061, Lund University.

Englund F (2010). Standardization related to Service Life Planning. SP Report 2010:37, SP Trätek, Borås.

Viitanen H, Toratti T, Makkonen L, Thelandersson S, Isaksson T, Früwald E, Jermer J, Englund F, Suttie E (2011). Modelling of service life and durability of wooden structure. Proceedings NSB 2011, 9th Nordic Symposium on Building Physics, 29 May – 2 June 2011, Tampere.

Work package 5 Knowledge transfer

This WP has focussed on communication of results of the project to stakeholders and other interested parties.

Task 5.1 Workshops, seminars and conferences

Results from WoodExter have been presented at the following international conferences:

- COST Action E37 12th workshop, 21-22 April 2008, Heraklion, Greece
- 39th Annual Meeting of the International Research Group on Wood Protection, 25-29 May 2008, Istanbul, Turkey
- 40th Annual Meeting of the International Research Group on Wood Protection, 24-28 May 2009, Beijing, China
- 4th International Building Physics Conference, 15-18 June 2009, Istanbul, Turkey
- 5th Meeting of the Nordic-Baltic Network in Wood Material Science and Engineering, 1-2 October 2009, Copenhagen, Denmark
- COST Action E25 workshop, 23-24 October 2009, Timisoara, Romania
- 41st Annual Meeting of the International Research Group on Wood Protection, 9-13 May 2010, Biarritz, France
- 5th European Conference on Wood Modification, 20-21 September 2010, Riga, Latvia
- 7th International Woodcoatings Congress, 12-13 October 2010, Amsterdam, The Netherlands
- Wiener Holzschutztage, 25-26 November 2010, Vienna, Austria
- XII DBMC, International Conference on Durability of Building Materials and Components, 12-15 April 2011, Porto, Portugal
- 42nd Annual Meeting of the International Research Group on Wood Protection, 8-12 May 2011, Queenstown, New Zealand
- 9th Nordic Symposium on Building Physics, 29 May – 2 June 2011, Tampere, Finland
- 11th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP11), 1-4 August 2011, Zürich, Switzerland
- VI Congreso Nacional Protección de la Madera, 29-30 September 2011, San Sebastian, Spain
- 4th Mycological Colloquium at the Institute of Wood Technology, 27-28 October 2011, Dresden, Germany
- Temadagar om Träskydd, 17-18 November 2011, Kolmården, Sweden.

In addition, WoodExter related material has been presented at approximately 25 national workshops, seminars and information meetings connecting with industry and users of buildings and wood products.

Task 5.2 Publications

WoodExter has generated nearly 70 publications and a list of these can be found in the Annex.

Work package 6 Management

Task 6.1 Management and economy

All partners have been actively involved in and responsible for an efficient management of the project. SP Trätek has been co-ordinating and responsible for contacts and communication with WoodWisdom-Net Programme and BWW Group (CEI-Bois) concerning all administrative issues.

Table 5. Outturn for R&D partners per 28 February 2011 compared to original budget (kEUR).

Partner	Budget (public)	Budget (BWW)	Budget (other)	Budget (total)	Outturn 28 February 2011
SP	183.0	89.5	93.5	366.0	**374.8**
LTH	106.5	60.0	46.5	213.0	**204.2**
BRE	120.0	50.0	30.0	200.0	**200.7**
VTT	150.0	62.5	62.0	274.5	**274.5**
FCBA	100.0	-	100.0	200.0	**235.2**
HFA	100.0	-	110.0	210.0	**267.4**
TUW	22.5	-	7.5	30.0	**30.0**
NFLI	150.0		15.0	165.0	**165.5**
UGOE	128.0	-	-	128.0	**127.9**
UG	-	-	100.0	100.0	**188.7**
Total	**1 060.0**	**262.0**	**564.5**	**1 886.5**	**2068.9**

Task 6.2 Meetings

Meetings of the Steering Committee and Project Management Group were held accordingly:

Steering Committee (SC)

SC 1 4 April 2008 in Brussels
SC 2 3 November 2008 in Paris
SC 3 16 June in Oslo (integrated with PMG 4)
SC 4 24 November 2009 in Vienna
SC 5 23 June 2010 in Espoo
SC 6 1 December 2010 in Göttingen

Programme Management Group (PMG)

PMG 1 19-20 November 2007 in Upplands Väsby
PMG 2 10-11 June 2008 in Garston, Watford
PMG 3 3-4 November 2008 in Paris
PMG 4 15-16 June 2009 in Oslo
PMG 5 23-24 November 2009 in Vienna
PMG 6 22-23 June 2010 in Espoo
PMG 7 30 November-1 December 2010 in Göttingen

Additionally, separate WP meetings have been held when considered necessary and the co-ordinator has attended a number of CEI-Bois BWW meetings for reporting back.

The co-ordinator has attended the following WoodWisdom-Net seminars for introducing and further presentation of results from WoodExter:

- Opening seminar, 12 January 2008 in Berlin
- 2nd WoodWisdom-Net Research seminar, 10-11 November 2009 in Stockholm
- 3rd WoodWisdom-Net Research seminar, 1-2 February 2011 in Paris

Figure 25. Awarded WoodExter poster at WW-Net Seminar in Stockholm 2009.

Conclusions

From the results reported above it can be concluded that WoodExter has succeeded to deliver in accordance with the objectives with the most important contributions as follows:

- The guidance document "Engineering design guideline for wood in above ground applications" and the related software - practical tools for engineers and architects for design of wood constructions with respect to durability and service life.

- New, important, knowledge generated, in particular concerning exposure conditions and risk of decay, performance of coating systems, effect of decay on micromechanical properties of wood and the use of PCR techniques as early indicators of fungal colonization.

- The development of a proforma for systematic performance assessment of cladding and decking.

- Contributing to kick starting CEN/TC 38 WG 28 Performance Classification.

WoodExter has so far generated nearly 70 publications and results from WoodExter have been presented at over 40 national and international events.

Five young scientists have been engaged in different WoodExter projects as part of their master and doctoral studies. This will be beneficial for future research in the areas of wood durability, wood protection and service life prediction to support the European Research Area and the wood industry sector.

The main knowledge generated in WoodExter is the practical tool for engineers and architects for design of wood constructions with respect to durability and service life. After further development and improvements of the tool, including software, there is a potential for new businesses in the wood building sector.

Furthermore, WoodExter has generated improved knowledge on

- Exposure conditions in Europe with focus on decay hazard for wood (decay index mapping).
- The relationship between exposure conditions and risk of decay.
- The influence of sites on coating system performance.
- The influence of wood modification on coating performance and fungal colonization.
- The influence of detailing and coatings on moisture conditions in wood
- Indicators of fungal colonization (qPCR+micromechanical properties +field test evaluation)
- The evaluation of field trials with respect to the use of early results for predicting the long term performance
- A critical analysis of the use of existing CEN standards for informing on service life

As to **future activities** the following can be foreseen:

- The Guidance document and related software will now be tested in practice on a national level. There are plans for capturing feedback in order to further improve the technique, e.g. by professionals or in future research projects.

- Work on early indicators for decay from various test procedures will continue to give useful input to standardisation work within CEN/TC 38 WG 28 and accommodate requirements for performance data expressed in the CPD. There is an urgent need to crosslink laboratory short-term tests with mid-term and long-term field test methods referring to different use and hazard classifications for timber in outdoor use. This should be combined with a data base for collecting service life records from various reliable sources with respect to all relevant deteriorating organisms.

- The proforma for systematic performance assessments of cladding and decking will be further used and tested in practice and improved.

- A number of field tests started within the WoodExter project will continue and generate important data for future assessment and evaluation and input to CEN/TC 38 and CEN/TC 139.

- Research work on micromechanical techniques will continue within the framework of other projects and will focus on changes of mechanical properties on smaller length-scales. Nanoindentation is an experimental technique to measure stiffness properties at the cellular level. Together with local chemical and physical properties, the micromechanical model can help to enhance the current understanding of effects of fungal decay on the microstructure of wood.

- Research on decay mechanisms linked to climate change and service life will continue in ongoing and new projects. A more global approach is needed to consider the full range of deterioration resistance causing factors of wood. In such a global approach, one need to compare exposure-dependent decay patterns and durability mechanisms for different wood species and wood-based materials.

ANNEX
List of publications

1. Articles in international scientific journals with peer review

Alfredsen G, Bader T K, Dibdiakova J, Filbakk T, Bollmus S, Hofstetter K (2011). Thermogravimetric analysis for wood decay characterization. European Journal of Wood and Wood Products, DOI 10.1007/s00107-011-0566-7.

Bader T K, Hofstetter K, Alfredsen G, Bollmus S (2011). Microstructure and stiffness of Scots pine (*Pinus sylvestris* L) sapwood degraded by *Gloeophyllum trabeum* and *Trametes versicolor* – Part I: Changes in chemical composition, density, and equilibrium moisture content. Holzforschung, DOI 10.1515/HF.2011.149.

Bader T K, Hofstetter K, Alfredsen G, Bollmus S (2011). Changes in microstructure and stiffness of Scots pine (*Pinus sylvestris* L) sapwood degraded by *Gloeophyllum trabeum* and *Trametes versicolor* – Part II: Anisotropic stiffness properties. Holzforschung, DOI 10.1515/HF.2011.153.

Grüll G, Truskaller M, Podgorski L, Bollmus S, Tscherne F (2011). Maintenance procedures and definition of limit states for exterior wood coatings. European Journal of Wood and Wood Products, 69: 443-450.

Pilgård A, Alfredsen G, Hietala A (2010). Quantification of fungal colonization in modified wood: Quantitative real-time PCR as a tool for studies on *Trametes versicolor*. Holzforschung 64: 645-651.0

Pilgård, A, Alfredsen, G, Björdal, C G, Fossdal, C G, Børja, I (2011). qPCR as a tool to study basidiomycete colonization in wooden field stakes. Holzforschung 65: 889-895.

Podgorski L, Grüll G, Georges G, Truskaller M, Bollmus S (2011). Coating performance on different types of modified wood: natural and artificial weathering results. Surface Coatings International 4, 139-150.

Viitanen H, Toratti T, Makkonen L, Peuhkuri R, Ojanen T, Ruokolainen L, Räisänen J (2010). Towards modelling of decay risk of wooden materials. European Journal of Wood and Wood Products. Vol 68. No 3.

2. Articles in international scientific compilation works and international scientific conference proceedings with peer review

Thelandersson S, Isaksson T, Häglund M, Frühwald E (2011). Probabilistic methods for performance based service life evaluation of wooden components. 11th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP11), Zurich.

Viitanen H, Peuhkuri R, Ojanen T, Toratti T, Makkonen L (2008). Service life of wooden materials – mathematical modelling as a tool for evaluating the development of mould and decay. Proceedings COST Action E37 Final Conference. 29-30 September 2008, Bordeaux.

Viitanen H, Toratti T, Peuhkuri R, Ojanen T, Makkonen L (2009). Durability and service life of wood structures and components -State of the art. Proceedings COST Action E25 Workshop Integrated approach to life-time structural engineering. 23-24 October 2009, Timisoara.

Viitanen H, Toratti T, Makkonen L (2011). Development of service life model for wooden structures. Proceedings XII DBMC, International Conference on Durability of Building materials and Components. April 12 – 15, 2011, Porto.

Viitanen H, Toratti T, Makkonen L, Thelandersson S, Isaksson T, Früwald E, Jermer J, Englund F, Suttie E (2011). Modelling of service life and durability of wooden structure. Proceedings NSB 2011, 9th Nordic Symposium on Building Physics, 29 May – 2 June 2011, Tampere.

3. Scientific monographs

Forslind I, Salihodzic N (2009). Träfasaders beständighet – utvärdering av en inspektionsmanual (Durability of cladding – Evaluation of proforma for inspections). Univ College of Borås BSc Thesis. (In Swedish).

Schlotzhauer P (2010). Vergleichende Untersuchungen von Fassaden aus thermisch modifiziertem und unmodifiziertem Holz. University of Göttingen BSc Thesis.

4. Other scientific publications, such as articles in scientific non-refereed journals and publications in university and institute series

Alfredsen G, Pilgård A, Hietala A (2008). A step towards a better understanding of fungal colonization of modified wood - QRT-PCR studies. IRG/WP 08-10653. Proceedings IRG Annual Meeting 2008, Istanbul, Turkey. The International Research Group on Wood Protection, Stockholm.

Alfredsen G, Bollmus S, Bader T K, Hofstetter K (2011). Basidiomycete colonization of Scots pine sapwood quantified by qPCR and TGA. IRG/WP 11-10750. Proceedings IRG Annual Meeting 2011, Queenstown, New Zealand, The International Research Group on Wood Protection, Stockholm.

Anon. (2011). Wood cladding – the FIVE keys for extending service life. SP Info 2011:36. SP Trätek, Borås.

Bader T K, Hofstetter K (2010). Pilzabbau von Holz: Quantifizierung des Steifigkeitsverlusts auf Basis von mikromechanischen Überlegungen. Proceedings Wiener Holzschutztage, 25-26 November 2010, Vienna.

Bader T K, Alfredsen G, Bollmus S, Hofstetter K (2011). Decrease of stiffness properties of degraded wood predicted by means of micromechanical modelling. IRG/WP 11-40570. Proceedings IRG Annual Meeting 2011, Queenstown, New Zealand, The International Research Group on Wood Protection, Stockholm.

De Windt I, Van den Bulcke J, Van Acker J (2009). Continuous moisture measurement (CMM) to detect failure of moisture resistance. IRG/WP 09-20422. Proceedings IRG Annual Meeting 2009, Beijing, China, The International Research Group on Wood Protection, Stockholm.

De Windt I, Van den Bulcke J, Van Acker J (2010). Impact of wood species on the performance of exterior wood coatings. IRG/WP 10-40519. Proceedings IRG Annual Meeting 2010, Biarritz, France, The International Research Group on Wood Protection, Stockholm.

De Windt I, Grüll G, Podgorski L, Bollmus S, Van Acker J (2010). Present evaluation procedures for coatings on exterior wood. In CTIB-TCHN (2010) Optimalisatie van levensduur, onderhoud en garantie voor toekomstgericht houten buitenschrijnwerk door duurzaam gebruik van water-gedragen afwerkingssystemen. (Optiwoodcoat). Technical report nr 60878.

Dearling T B, Suttie E D (2011). Maintenance and renovation of exterior wood coatings. BRE-Report No 273427, BRE, Garston.

Englund F (2010). Standardization related to Service Life Planning. SP Report 2010:37, SP Trätek, Borås.

Englund F (2010). Durability by design of wooden cladding and decking – an overview of guidelines and information sources. SP Report 2010:38, SP Trätek, Borås.

Friese F, Larnøy E, Alfredsen G, Pfeffer A, Militz H (2009). Comparison between different decay assessment methods. WSE conference – Nordic Baltic Network in Wood Material Science & Engineering. September 2009, Copenhagen.

Gobakken L R, Mattsson J, Alfredsen G (2008). In-service performance of wood depends upon the critical in-situ conditions. Case studies. IRG/WP 08-20382. Proceedings IRG Annual Meeting 2008, Istanbul, Turkey. The International Research Group on Wood Protection, Stockholm.

Grüll, G (2011). Round Robin. Alternative ICP for EN 927-3 Natural weathering. HFA Report Nr FFG 436.

Grüll G, Podgorski L, Truskaller M, Spitaler I, Georges V, Bollmus S, Steitz A (2010). Performance of selected types of coated and uncoated modified wood in artificial and natural weathering. IRG/WP 10-40510. Proceedings IRG Annual Meeting 2010, Biarritz, France, The International Research Group on Wood Protection, Stockholm.

Grüll G, Truskaller M, Podgorski L, Bollmus S, De Windt I, Suttie E (2010). Moisture conditions in coated wood panels during 18 months natural weathering at five sites in Europe. Proceedings of the 7th International Woodcoatings Congress, 12-13 October 2010, Amsterdam.

Grüll G, Truskaller M, Podgorski L, Georges V, Bollmus S, Jämsä S, Viitanen H, Jermer J (2010). WOODEXTER Work Package 3 Interaction of wood and coatings – effect on the performance of wood products. Report on Laboratory Results. HFA Report Nr FFG 436.

Grüll G, Podgorski L, Georges V, Bollmus S, Jermer J (2011). WOODEXTER workpackage 3 Interaction of wood and coatings – effect on the performance of wood products. Report on natural weathering trials. HFA Report Nr FFG 443.

Isaksson T (2008). Methods for predicting service life for wood. Lund University Report TVBK-3058, Lund University.

Jermer J (2010). Research hits new heights. Timber Trades Journal 7/14 August 2010.

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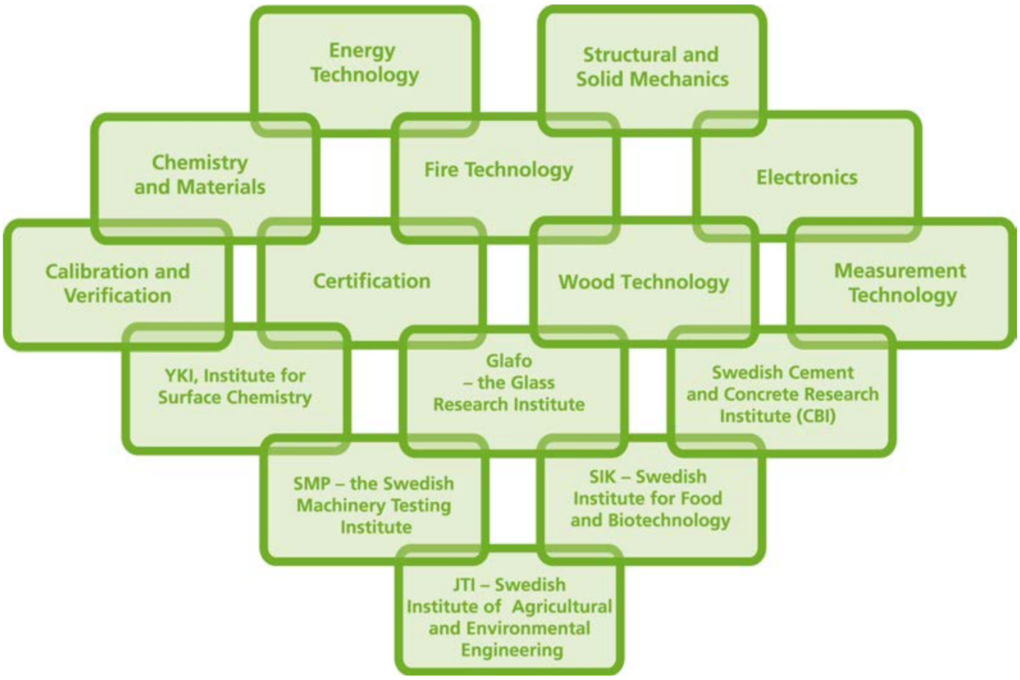

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SP Trätek
SP Rapport 2011:53
ISBN 978-91-86622-83-1
ISSN 0284-5172