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In-ground and above-ground service life prediction for timber reusability- Progressing towards circular construction

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Abstract: The increasing demand for and consumption of wood requires special attention in order to keep the wood industry sustainable. Therefore, timber reuse is presented as a solution to control the demand side. Unfortunately, the perception of timber decay poses a major barrier for reuse practices. Therefore, this article presents a factorised service life prediction model for wooden components that aims to promote their reuse. The model is based on the Australian service life prediction model, Timberlife, and the European CLICK*design* model's dose-response model. It predicts the potential for reuse of timber components based on their expected and remaining service life. To determine the service life, the model includes factors that differentiate between wood species, soil characteristics, regional climate and how the investigated components are connected to other components. The presented model focuses on in-ground and above-ground fungal decay and is limited to northwestern Europe. Opportunities for further research include, e.g., a further investigation of the soil characteristics' influence on decay, and evaluating the lag time for regions outside northwestern Europe. The presented service life prediction model can increase awareness and support a circular construction industry.

Keywords: wood decay, timber reuse, service life prediction, circular construction

Word count: 6494

List of abbreviations

CE	Circular Economy
D_{Rd}	resistance dose
NDT	Non-Destructive Test
$k_{climate}$	parameter considering the region where the wood is exposed
$k_{connection}$	parameter considering the type of connection to other components
$k_{contact}$	parameter considering the type of contact to other components
$k_{position}$	parameter considering the position of the components in the greater structure
k_{soil}	parameter considering the soil type in which the wood is exposed
$k_{thickness}$	geometric parameter
k_{width}	geometric parameter
k_{wood}	parameter corresponding to the durability of the used wood species
SPH	Scots Pine Heartwood
SPS	Scots Pine Sapwood
t_{lag}	time until the onset of decay
$U_{wood,a\text{-}g}$	above-ground decay rate
$U_{wood,i\text{-}g}$	in-ground decay rate
UV	ultraviolet
ξ	parameter expressing the organic material concentration in the soil

1 Introduction

The concept of a Circular Economy (CE) was proposed as a solution to mitigate the depletion of earth's resources (D'Amato et al., 2020) and can be summarised in the 4R principle - Reduce, Reuse, Recycle, Recover - signifying the desired order of the value retention of products and materials, and this on three levels - the micro-, meso- and macro-scale (Anastasiades et al., 2020; Kirchherr et al., 2017). When these three levels are considered for the building industry, the scale of the component/material represents the micro-scale, the entire building/construction itself fits within the meso-scale, and the macro-scale considers eco-cities, or in other words, the general CE (Pomponi and Moncaster, 2017).

Research in the field of circular construction has focussed on materials recycling (e.g. Akanbi et al., 2018; Gálvez-Martos et al., 2018; Huang et al., 2018; Jiménez-Rivero and García-Navarro, 2017) or more explicitly recycling through reverse logistics (e.g. Chileshe et al., 2018; Hammes et al., 2020; Li et al., 2018; Wijewickrama et al., 2021). Improving the environmental profile of construction materials and components by incorporating waste streams from other production processes has also gained attention (e.g. Asim et al., 2021; Marvila et al., 2021; Mendes et al., 2019; Mohan et al., 2021).

However, the reuse of construction components is considered a higher-value process in a CE and is of particular importance because it is environmentally more beneficial than recycling materials, as was proved in several studies through life cycle assessment (e.g. Buyle et al., 2019; Cruz Rios et al., 2019; Joensuu et al., 2022; Xia et al., 2020). Unfortunately, when it comes to timber construction, it is much easier to transport all reclaimed wooden components from a demolition site straight to a heat and power plant for energy recovery rather than sorting, cleaning and treating it for reuse or recycling (Jarre et al., 2019). However, in Europe, tree growth periods vary from 30 to 100 years (Ramage et al., 2017) before they can be harvested to obtain timber for construction/structural components. On the other hand, buildings undergo structural changes every 5 to 50 years (Brand, 1994; Rinke and Pacquée, 2022). Hence, the timber rotation period will rarely be matched when all demolition wood is merely incinerated after a first use cycle. Mitchell (2022) explains that wood is brought forward as a solution to counter the high environmental impact of the concrete industry as well as a means for the required energy transition, leading to an estimated annual consumption increase of 3.1% during the next 30 years. The question is where this additional requirement for wood will be sourced, because existing plantations are insufficient and land availability for additional plantations is scarce. Hence, natural forests will be plundered even more (Mitchell, 2022). This will lead to an unsustainable timber construction industry as early as 2023 (ITTO, 2021). An entirely new balance will need to be sought between deforestation and timber supply and demand. Hence, promoting the reuse of timber components may help in decreasing the demand side in this equation. Yet, designers' reluctance to reuse construction components remains a major barrier (Anastasiades et al., 2022, 2021; Cruz Rios et al., 2019, 2015; Densley Tingley et al., 2017; Finch et al., 2021; Iacovidou and Purnell, 2016; Rameezdeen et al., 2016). This reluctance is a consequence of several aspects: quality and safety risks (due to material deterioration) when reusing a component, lack of support from customers, and lack of procedures for component reuse leading to higher costs and time requirement (Anastasiades et al., 2023b).

Deterioration of wood is mainly caused by organisms and is affected by the wood moisture content and temperature (Viitanen, 2011). When the moisture content exceeds the cell wall saturation (approximately 25 to 30%), fungal decay can occur (De Belie et al., 2000; Teles and Do Valle, 2001; Viitanen, 2011) and cause severe biodegradation (e.g. brown rot and white rot). Insects (De Belie et al., 2000; Teles and Do Valle, 2001; Viitanen, 2011) and bacteria (Ramage et al., 2017; Rashidi et al., 2021; Viitanen, 2011) also cause biodegradation. In addition, wood is prone to physical deformation. Creep occurs in response to a permanently applied load and is exacerbated by moisture and temperature (Granello and Palermo, 2019; Holzer et al., 1989). Warping may occur due to differential shrinkage (De Belie et al., 2000; Rashidi et al., 2021; Viitanen, 2011). Damage can also occur through mechanical wear; for instance, applying an excessive load can induce buckling (Franke et al., 2015; Hassan Ali et al., 2014; Rashidi et al., 2021). In addition, the choice of connection (e.g. nails instead of screws) can cause damage during deconstruction, which influences reusability (Akanbi et al., 2018; Graf, 2020; Guy et al., 2005; Sandoli et al., 2021). In conclusion, the deterioration of timber affects its reuse possibilities. Currently, various non-destructive tests (NDTs) to assess the residual wood properties are available on the market: pin penetration, resistance drilling, ultrasound, acoustic emission, stress wave velocity, etc. (Yu et al., 2020). However, these tests are costly, require time and do not provide the necessary accuracy. As mentioned before, it is cheaper to use demolition wood for energy recovery, but this is the least desirable option in a CE.

Apart from reusing timber from end-of-life structures, it is important to consider the timber components' lifecycle already in the design phase of a building. Circularity indicators like the Material Circularity Indicator (Ellen MacArthur Foundation and Granta, 2019) account for reuse of components in the considered construction as well as the reusability of components in the end-of-life phase. However, reusability is never formalised into a reusability analysis. Circularity indicators just assume components to be reusable when they are detachable. Material deterioration is never considered. Therefore, Anastasiades et al. (2023a) proposed a reusability check that considers not only design variables like the connections between components but also compares the actual service life of these components with the building's design service life. In addition, for more accuracy, they proposed the development of service life prediction models for this reusability analysis (Anastasiades et al., 2023a).

The European projects WoodExter (Jermer, 2012), WoodBuild (Isaksson et al., 2014), DuraTB (Pousette et al., 2017) and PerformWOOD (Kutnik et al., 2014) focussed on timber service life prediction. As a follow-up to these research projects, the online timber service life prediction module CLICK*design* (Suttie et al., 2020) was launched recently. The background equations of CLICK*design* are shared in several publications (Alfredsen et al., 2021; Blocken and Carmeliet, 2004; Brischke et al., 2021b, 2021a; Isaksson et al., 2013; Marais et al., 2021, 2020; Niklewski et al., 2018, 2021a, 2021b; Niklewski and Fredriksson, 2021; van Niekerk et al., 2022, 2021). The model considers an inherent decay resistance factor (different per wood species), and a wood moisture content factor that depends on the climate, the environment where the wooden component is located and how it is connected to other components. Using these factors, a resistance dose before the onset of decay is determined for each wood species. However, the model requires certain finite element modelling software for moisture content prediction which is not freely available, as well as complex environmental data that are not straight-forward to interpret and retrieve. In addition, the model only provides the service life until the onset of decay. However, partially decayed wood can still be reusable before turning to the option of recycling it into strand boards. Currently, the most extensive, readily available timber service life prediction model, also referenced in WoodExter and PerformWOOD, is Timberlife (Wang et al., 2006). However, Timberlife is an Australian model and many parameters thus consider the Australian climate and Australian standards, as explained in the Timberlife manuals (Forest and Wood Products Australia Ltd, 2022). Hence, it may not be applicable for a European context (van Niekerk et al., 2021).

Timber service life prediction models may contribute in raising awareness of the reusability of timber components so reuse opportunities may be identified, ultimately increasing the timber reuse rate. In addition, they may facilitate the easy and quick separation of non-reusable from potentially reusable timber components before turning to NDTs. Hence, they can optimise the testing process, reduce the number of NDTs and thus help mitigate the barrier of the required time and costs that is linked to component reuse. However, as the currently available models are not sufficient, applicable or usable, this research focusses on the development of a timber service life prediction model for the European context.

2 Model approach

As mentioned above, Timberlife is the most extensive, readily available timber service life prediction model. However, it is an Australian model and many parameters thus consider the Australian climate and Australian standards, as explained in the Timberlife manuals (Forest and Wood Products Australia Ltd, 2022). Hence, it may not be applicable for a European context (van Niekerk et al., 2021). It will therefore be translated to the relevant European standards, such as EN 350, EN 335, EN 252, EN14081-1 and EN 1995 (CEN, 2019, 2016, 2015, 2014, 2013). In addition, data available in the scientific literature are used to make the required alterations and to test the model. The current study is limited to fungal decay in above-ground and in-ground conditions. Decay caused by insects in outdoor or indoor conditions, and decay due to marine borers (underwater) is not considered in this study. In addition, bacteria only cause minor decay (Brischke et al., 2006) and are therefore also not considered. Corrosion of connections and UV irradiation can occur, but they primarily discolour timber elements and do not complicate reusability in terms of performance (Rashidi et al., 2021). Lastly, mechanical damage is not considered, because this is primarily a consequence of accidental damages, a sloppy execution or a flawed design.

The presented service life prediction model can be used for solid timber components where the timber is either made of an unmodified wood species, or modified by means of impregnation or thermal treatment. The model cannot be used for wood fibre reinforced composites. In addition, historical and archaeological timber falls outside the scope of this research. For such components, efforts should be focussed on extending their service life in their original historical context.

The results of the model are presented by means of a performance-over-time function as described in the ISO 15686-2 (International Organization for Standardization, 2012). The performance is expressed by means of the rating system provided by the European standard EN 252 (CEN, 2014). The EN 252 rating depends on the decay depth and the attacked surface, which is measured during visual inspection. The EN 252 rating system considers a decay depth in mm for standard-sized test specimens of 25×50 mm in cross section. This decay depth is translated into a percentage using the specimen's thickness of 25 mm so the system can be used for other component sizes, as shown in Table 1. In this translation of the EN 252 rating system, a possible size-effect is neglected.

Table 1: rating system EN 252 with a new corresponding reuse recommendation

Rating	Reuse recommendation	Decay	Attacked surface [cm²]	Decay depth [%]
0	Structural reuse possible	No attack	≤ 0	0
1	Structural reuse possible after removal of attacked surface for composting/energy recovery	Slight attack	≥ 10	12
2	Non-structural reuse possible after removal of attacked surface for composting/energy recovery	Moderate attack	≥ 10	33
3	Recycling possible after removal of attached surface for composting/energy recovery	Severe attack	≥ 25	52
4	Composting/energy recovery	Failure	-	100

Note that in Table 1 also a new reuse recommendation is proposed for each rating. Hence, the reuse recommendation advises a reuse potential until rating 2. A higher rating coincides with too much decay. Therefore it is safer to assign the wood portion that has not (yet) decayed to a recycling stream, rather than a reuse stream. In this way, the timber service life prediction model allows to objectively determine the reuse potential of timber components, based on the decay rate and corresponding EN 252 rating.

3 Service life prediction methodology

The service life prediction methodology as an indicator for timber reuse considers in-ground and above-ground fungal decay. Fungi require sufficient oxygen, which implies that timber located 600 mm below ground is rarely attacked. Secondly, nutrients are required and are most of the time provided by timber (Wang et al., 2006). Finally, the temperature range should be between 0°C and 65°C, with an optimum between 20°C to 35°C (Leicester, 2001; Wang et al., 2006). These boundaries are only applicable to the most common fungi. It is important to point out that only these limits are considered in what follows.

The methodology is based on the decay rate. This is the speed, expressed in mm/year, at which fungal decay progresses along the thickness of the considered timber component. The decay rate depends on the environmental specifications, design specifications and the wood's durability. The basic methodology to assess the decay rate was adopted from Timberlife

(Wang et al., 2008a). The reader is referred to these manuals for the full methodology. Only the parts to which alterations were presented, are discussed.

3.1 In-ground service life prediction model

The in-ground decay rate $U_{wood,i\text{-}g}$ is determined through a climate parameter $k_{climate}$ and a wood parameter k_{wood}, as proposed in Timberlife (Wang et al., 2008a), supplemented with a newly introduced soil parameter k_{soil}, see Eq. (1).

$$U_{wood,i-g} = k_{climate} \cdot k_{wood} \cdot k_{soil} \left[\frac{mm}{year}\right] \tag{1}$$

With:

- $k_{climate}$: a parameter considering the region where the wood is exposed
- k_{wood}: a parameter corresponding to the in-ground durability of the used wood species
- k_{soil}: a parameter considering the soil type in which the wood is exposed

To calculate $k_{climate}$ for in-ground elements, the simplified Leicester model (also used in Timberlife) is used (de Freitas et al., 2010). This model (Leicester et al., 2003) calculates $k_{climate}$ from the mean annual temperature and precipitation, and the number of dry months. Note that this method can be used to obtain $k_{climate}$ for any region.
The subsequent parameter, k_{wood}, corresponds to the wood's durability. Wang et al. (2008a, 2008c) determined the values for k_{wood} through testing. Subsequently, they distinguished values for sapwood (softwood and hardwood), and for heartwood according to the Australian durability classes (Wang et al., 2008b, 2008a). However, the European (CEN, 2016) and Australian (Council of Standards Australia, 2005) durability classes do not match exactly. In addition, a subdivision according to the durability classes is not very nuanced. In this respect, CLICK*design* offers a different approach. Here, the durability of the different wood species is approached with a dose-response model (Alfredsen et al., 2021; Brischke et al., 2021a, 2021b). The idea is that each wood type can resist a certain exposure dose before the onset of decay. This critical dose was determined for many different wood types, including treated ones. Subsequently, these critical doses were weighted with Norway spruce (*Picea abies*) as a reference to eliminate climate dependency and test variables affecting the values (Alfredsen et al., 2021; Brischke et al., 2021a, 2021b). The obtained weighted dose was termed the resistance dose D_{Rd}. Note that in Timberlife a lag time, t_{lag} is calculated, which is in fact equal to the time until the onset of decay. Hence, t_{lag} corresponds to the resistance dose D_{Rd}. In addition, t_{lag} is a function of the decay rate $U_{wood,i\text{-}g}$, which in its turn is a function of k_{wood}, see Eq. (2). Hence, in the following, a methodology is proposed to correlate D_{Rd} with k_{wood}.

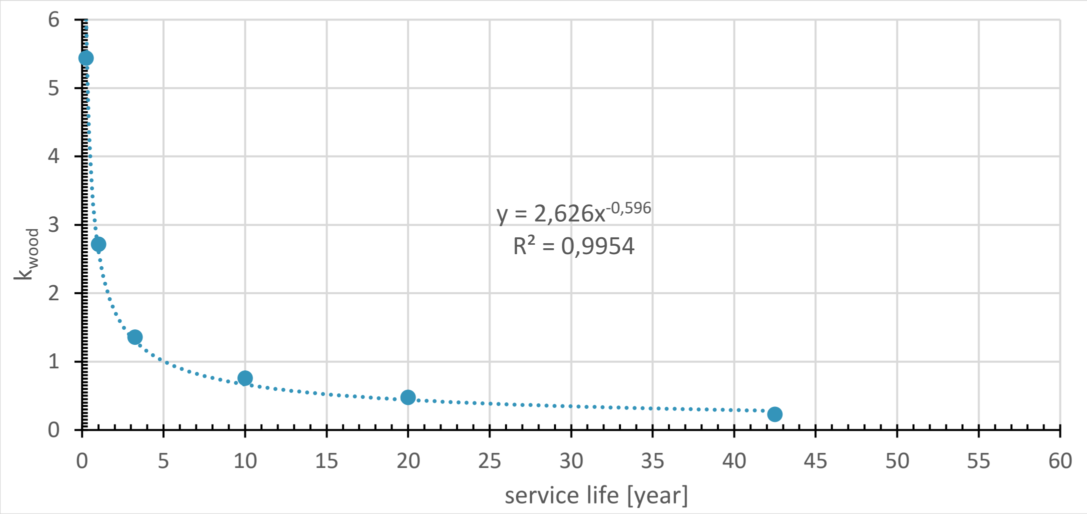
$$\left.\begin{array}{c} t_{lag} \leftrightarrow D_{Rd} \\ \&\ t_{lag} \leftrightarrow U_{wood,i-g} \leftrightarrow k_{wood} \\ \Rightarrow k_{wood} \leftrightarrow D_{Rd} \end{array}\right\} \tag{2}$$

First, the Australian values for k_{wood} are plotted against the average service life corresponding to the Australian durability classes (Table 2). This shows that the k_{wood} values follow a distinct trend which can be formalised into a regression curve with an equation as shown. Note that here the service life is defined as the life expectancy until failure of a test specimen.

In order to correlate this to the list of resistance doses obtained from CLICK*design* (Suttie et al., 2020), it is assumed that the least durable heartwoods can also have a k_{wood} that corresponds to the ones for sapwood. Now, each resistance dose should be plotted against the corresponding service life. Therefore, the service life of a few reference species is determined (Table 3). The chosen references are the minimum and the maximum resistance doses which are correlated to a service life at respectively the lower end and the higher end of the spectrum. Norway spruce heartwood was chosen because it was used as reference to obtain the resistance dose. European beech (*Fagus sylvatica*) and Scots pine (*Pinus sylvestris*) heartwood (SPH) were chosen as reference species on either side of Norway spruce, mainly because of the available field data. When looking more closely at the data in Table 3, it becomes clear that it is difficult to find a trend in the relation between D_{Rd} and the service life. Therefore, the data are split into two sets: minimum-Norway spruce and Norway spruce-maximum. The obtained regression curves and equations are also shown. The resistance doses obtained from CLICK*design* can be translated to a list of k_{wood} factors using the regression curves in Table 2 and Table 3.

Table 2: in-ground and above-ground values for Australia for k_{wood} obtained from Wang et al. (2008a,b)

	Type	**Durability**	**Service life [years]**	**Mean service life [years]**	**k_{wood}**
in-ground	Heartwood	Class 1	>25	42.5	0.23
		Class 2	15–25	20	0.48
		Class 3	5–15	10	0.76
		Class 4	1.5–5	3.25	1.36
	Sapwood	Hardwood	0.5–1.5	1	2.72
		Softwood	0–0.5	0.25	5.44



	Type	**Durability**	**Service life [years]**	**Mean service life [years]**	**k_{wood}**
above-ground	Heartwood	Class 1	>40	60	0.50
		Class 2	15–40	27.5	0.62
		Class 3	7–15	11	1.14
		Class 4	1–7	4	2.20
	Sapwood	/	0–1	0.5	6.52

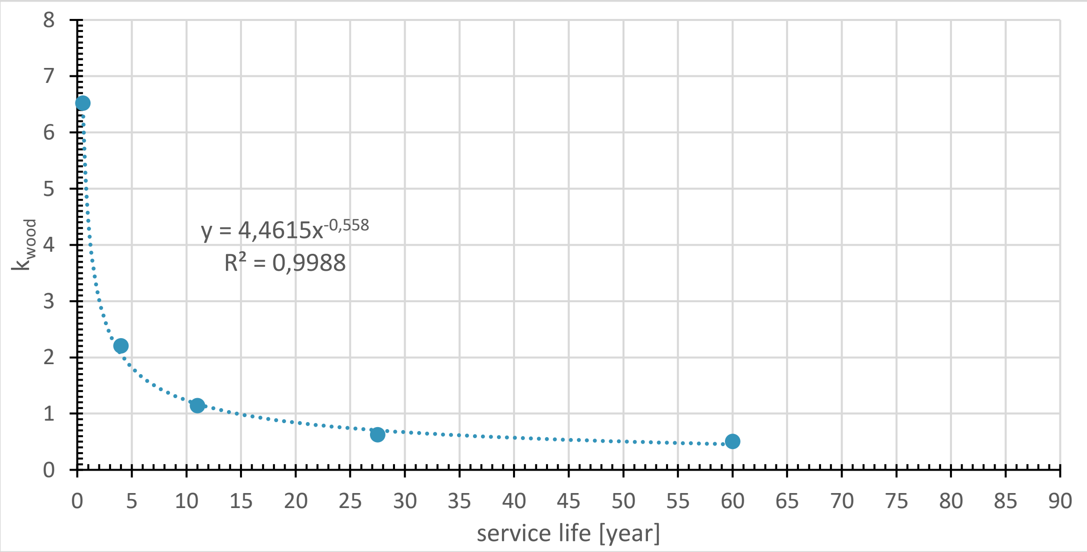
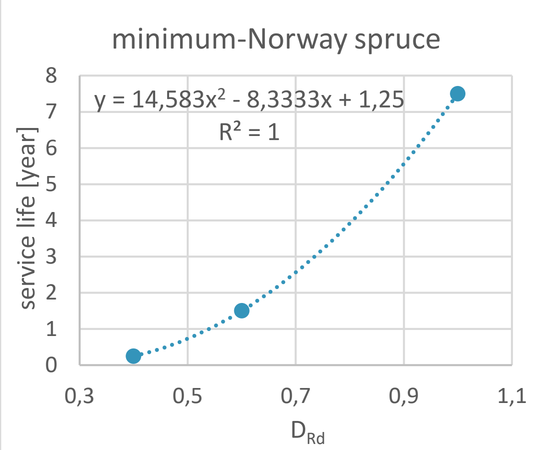
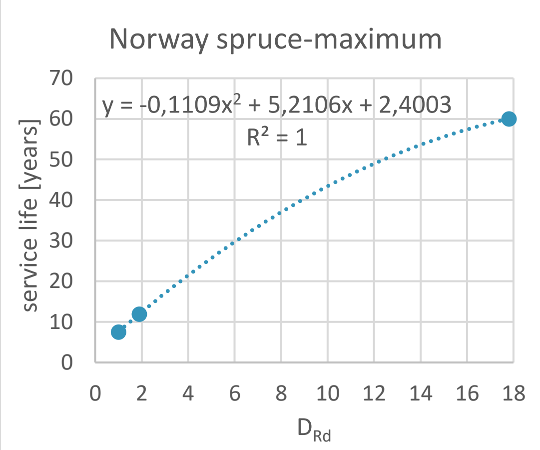


Table 3: in-ground and above-ground reference species to correlate D_{Rd} to k_{wood}

	Species	D_{Rd} [-]	Service life [years]
in-ground	minimum	0.4	0.25
	European beech	0.6	1.5
	Norway spruce	1.0	7.5
	Scots pine heartwood	1.9	11.9
	maximum	17.8	60.0

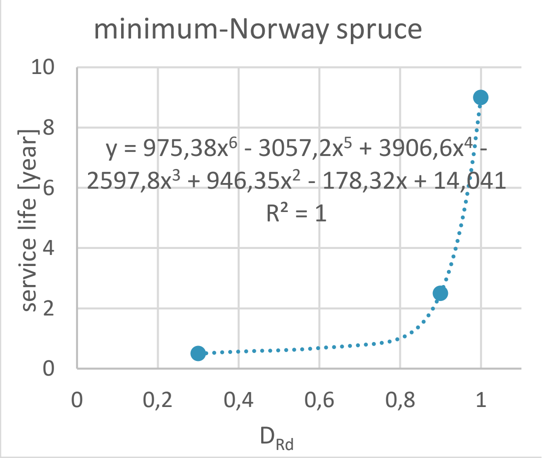
in-ground

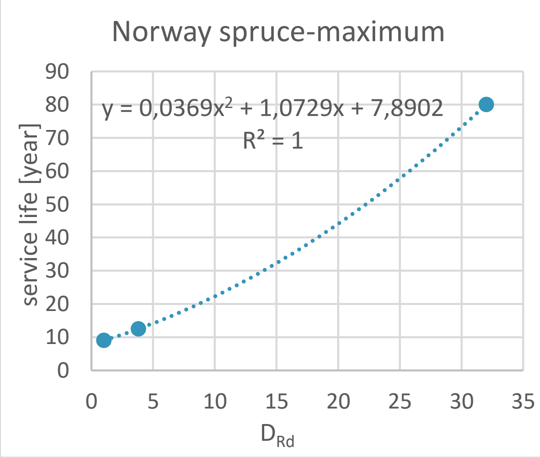




	Species	D_{Rd} [-]	Service life [years]
above-ground	minimum	0.4	0.5
	European beech	0.6	2.5
	Norway spruce	1.0	9.0
	Scots pine heartwood	1.9	12.5
	maximum	17.8	80.0

above-ground





Brischke et al. (2014) investigated the decay rates in different soil types for European beech, Norway spruce, Douglas fir heartwood (*Pseudotsuga menziesii*), English oak heartwood (*Quercus robur*), and Scots pine sapwood (SPS). The investigated soil types were field soil covered with mulch, field soil mixed with turf, fertilised soil, field soil, sand and gravel, and all test plots were laid out on a field in Hannover, Germany. The water holding capacity, acidity, and carbon, nitrogen and sulphur content were determined for the different soil types (Brischke et al., 2014). Interestingly, the test results showed little relation between the decay rate and the mentioned soil characteristics. However, two groups of soil were clearly distinguished in which all wood species performed very similarly: soils with a high concentration of inorganic material - sand and gravel - and soils with a high concentration of organic material - all the other soil types. The latter had significantly higher carbon and nitrogen concentrations than the inorganic soils. The major difference in induced decay between the soil types was the lag time which was much shorter for the soils with a high concentration of organic material. Also the actual decay rate - signified by the slopes of the measurement curves - differed slightly for the two groups of soil types. Comparing the measurements by Brischke et al. (2014) with the original Timberlife model, indicated that there were two major problems: the calculated lag time was too high and the predicted decay rate was too slow. Hence, the equation for the lag time, t_{lag}, was adjusted and a new factor k_{soil} that considers that differences in soil characteristics may result in different decay rates, was introduced in the decay model.

An Australian experiment suggested the need for other equations for t_{lag} (Nguyen et al., 2008). Hence, following an iterative process of fitting values, Timberlife's equation for t_{lag}, Eq. (3), was replaced by a more general expression shown in Eq. (4). In this, ξ is a factor that depends on the soil's concentration of organic material. It was found that the lower boundary of ξ for soils with a high concentration of organic material equals 1.0. The upper boundary for soils with a low concentration of organic material equals 4.5.

$$t_{lag} = 5.5 \cdot U_{wood,i-g}^{-0.95} \tag{3}$$

$$t_{lag} = \xi \cdot U_{wood,i-g}^{-0.95} \tag{4}$$

Similarly, for k_{soil} a lower limit of 3.0 was found for soils with little organic material, and an upper limit of 4.0 for soils with a lot of organic material.

In the comparison in Figure 1, the adjusted equations for t_{lag} and factors k_{soil} are implemented to determine the calculated curves. The accuracy of the model is presented as well and shows a normal distribution along the diagonal. Note that in this representation of the results, the values for Douglas fir were not included, because here the prediction model deviates far from the measurements. Presumably, this is because a different type of rot may have occurred. Further in this study it is shown that Douglas fir reacts very differently to white and brown rot. However, the different types of rot were not investigated by Brischke et al. (2014). The model also does not consider this difference in rot because not every wood species shows this different behaviour.

The questions to be asked are which concentrations of organic material reflect the lower and upper boundaries of ξ and k_{soil}, and how is the progression between them. Therefore, the obtained service life prediction model was compared with the test results presented by Meyer et al. (2014). They performed in-ground decay tests for English oak heartwood and SPS on German test sites in Hamburg, Hannover and Trenthorst (Meyer et al., 2014) (Figure 2). Unfortunately, no further insights were obtained, because the test results in Hannover and Trenthorst corresponded to soils with a high organic concentration, while those in Hamburg corresponded to soil with a low organic concentration. No relationship with the measured carbon contents could be established, and the nitrogen contents were not measured.

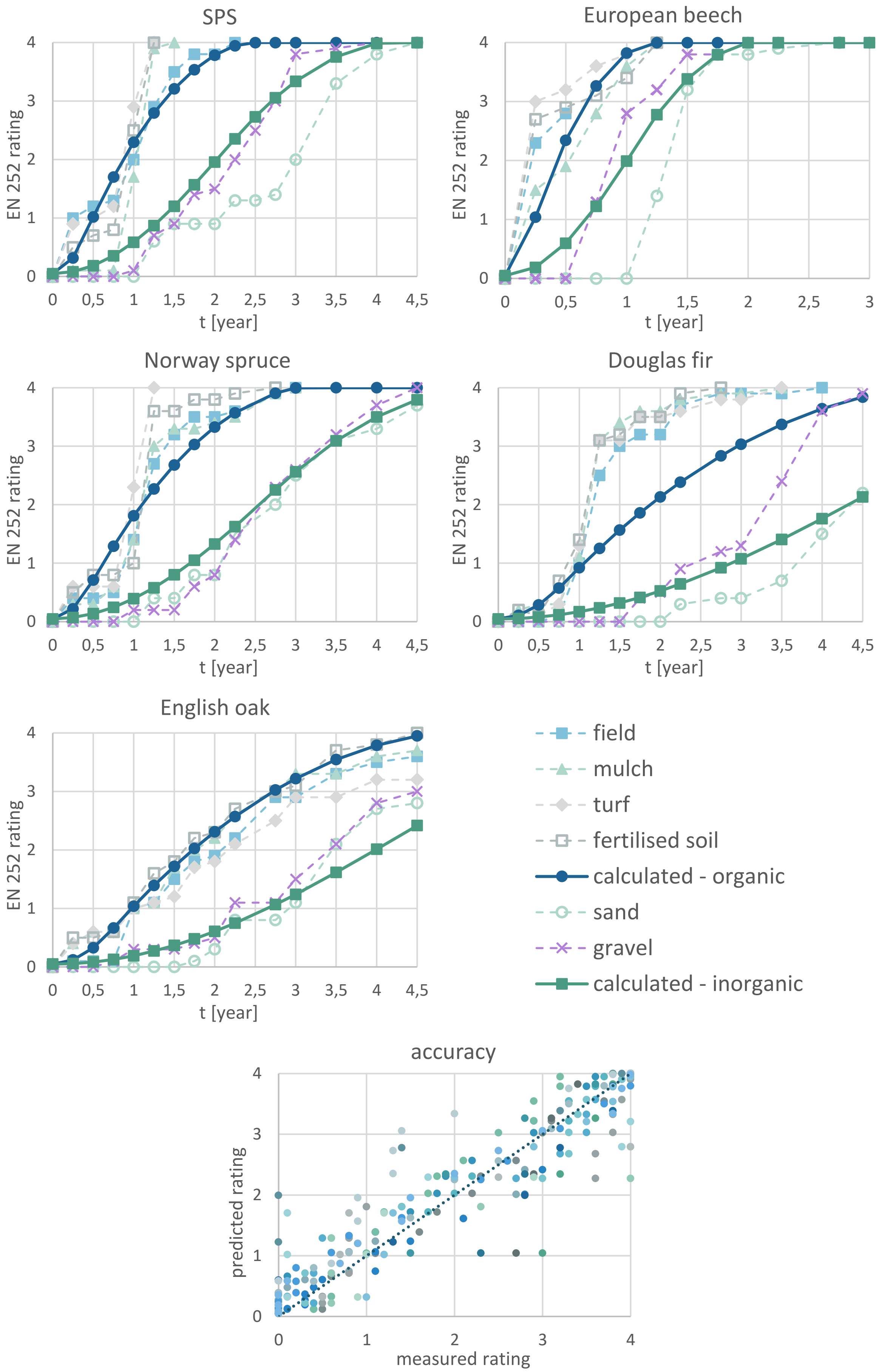


Figure 1: comparison between the test results of Brischke et al. (2014) and the in-ground prediction model for different wood species. At the bottom the accuracy is presented.

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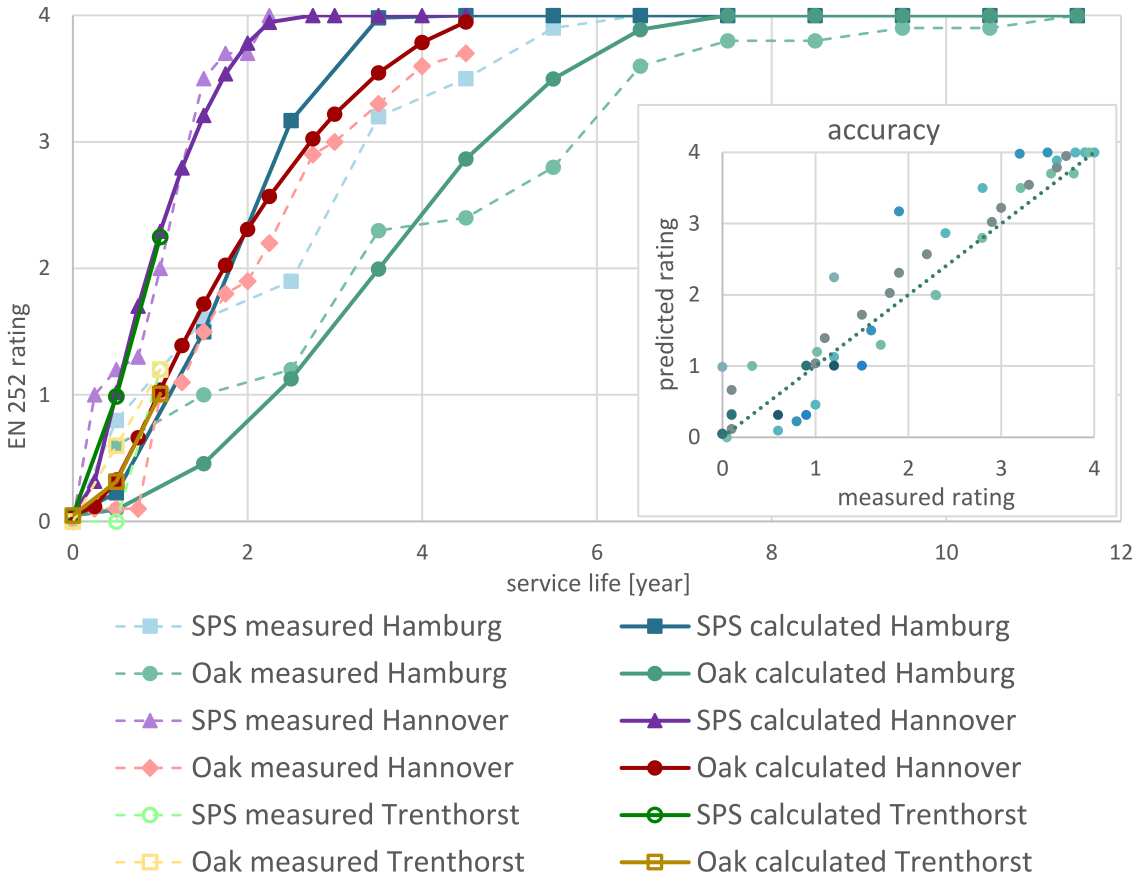

Figure 2: comparison between the test results of Meyer et al. (2014) and the in-ground prediction model, including the accuracy of the model.

3.2 Above-ground service life prediction model

Fungal decay of above-ground elements is influenced by the wood species, climate conditions, paint layers, connections, the element's dimensions and the geometry of the structure it is a part of. Hence, the above-ground decay-rate $U_{wood,a\text{-}g}$ is determined through Eq. (5) (Wang et al., 2008c).

$$U_{wood,a-g} = k_{wood} \cdot k_{climate} \cdot k_{paint} \cdot k_{width} \cdot k_{thickness} \cdot k_{connection} \cdot k_{contact} \cdot k_{position} \left[\frac{mm}{year}\right] \quad (5)$$

With:

- k_{wood}: a parameter corresponding to the above-ground durability of the used wood species
- $k_{climate}$: a parameter considering the region where the wood is exposed
- k_{paint}: a parameter that considers a paint layer
- k_{width}: a geometric parameter
- $k_{thickness}$: a geometric parameter
- $k_{connection}$: a parameter considering the type of connection to other components

- $k_{contact}$: a parameter considering the type of contact to other components
- $k_{position}$: a component considering the position of the component in the greater structure

The reader is referred to Wang et al. (2008c) for the full methodology to determine the different factors in Eq. (5). In the following, only the factors that were altered, are discussed. The parameter k_{wood}, corresponds to the wood's above-ground durability. Because wood moisture performance is different for in- and above-ground conditions, specific resistance doses D_{Rd} for above-ground decay were determined as well (Alfredsen et al., 2021; Brischke et al., 2021a, 2021b). The same methodology as for in-ground decay is followed to correlate D_{Rd} to k_{wood}. First, the Australian values for k_{wood} are plotted against the average service life corresponding to the Australian durability class, as shown in Table 2. The reference species to correlate D_{Rd} to k_{wood} are shown in Table 3. The relation between D_{Rd} and the service life, and corresponding regression curves are shown in Table 2 and Table 3. Using these regression curves, the list of resistance doses obtained from CLICK*design* can again be translated to a list of k_{wood} factors.

Wang et al. (2008b) found that $k_{climate}$ only depends on the number of rainy days D (Wang et al., 2008c), at least for Australia. This is contradictory to the generally accepted Scheffer index (Brischke and Selter, 2020; Carll, 2009) which depends on both precipitation and temperature. For the moment, Timberlife's methodology is retained. The remaining k-factors in Eq. (5) can be adopted from Timberlife.

Meyer-Veltrup et al. (2017) performed an extensive investigation of Scots pine sapwood and heartwood, European beech, Norway spruce, and English oak in different set-ups on a site in Hannover, Germany. Several wood sizes were used for the different set-ups (Meyer-Veltrup et al., 2017). These results were supplemented with additional unpublished test results from the same investigation. Comparisons between these measurements and the presented service life prediction model indicated that some amendments were necessary: the lag time equation in Timberlife again yields results which are too high, and the $k_{contact}$ parameter needed to be adjusted. Hence, Timberlife's equation for t_{lag}, Eq. (6), is replaced by one that is applicable in at least northwestern Europe, Eq. (7).

$$t_{lag} = 8.5 \cdot U_{wood,a-g}^{-0.85} \tag{6}$$

$$t_{lag} = 4.0 \cdot U_{wood,a-g}^{-0.85} \tag{7}$$

Parameter $k_{contact}$ changes depending on the type of contact. It differentiates between non-contact, flat contact and embedded contact. The value for flat contact was adjusted from 0.6, as defined in Timberlife, to 0.8, as derived from the comparison with the test results of Meyer-Veltrup et al. (2017). The comparison of the service life predictions with the results of Meyer-Veltrup et al. (2017) are shown in Figure 3. The adjusted t_{lag} and $k_{contact}$ were implemented here for the service life predictions. The accuracy plot again shows a normal distribution along the diagonal, indicating a good fit.

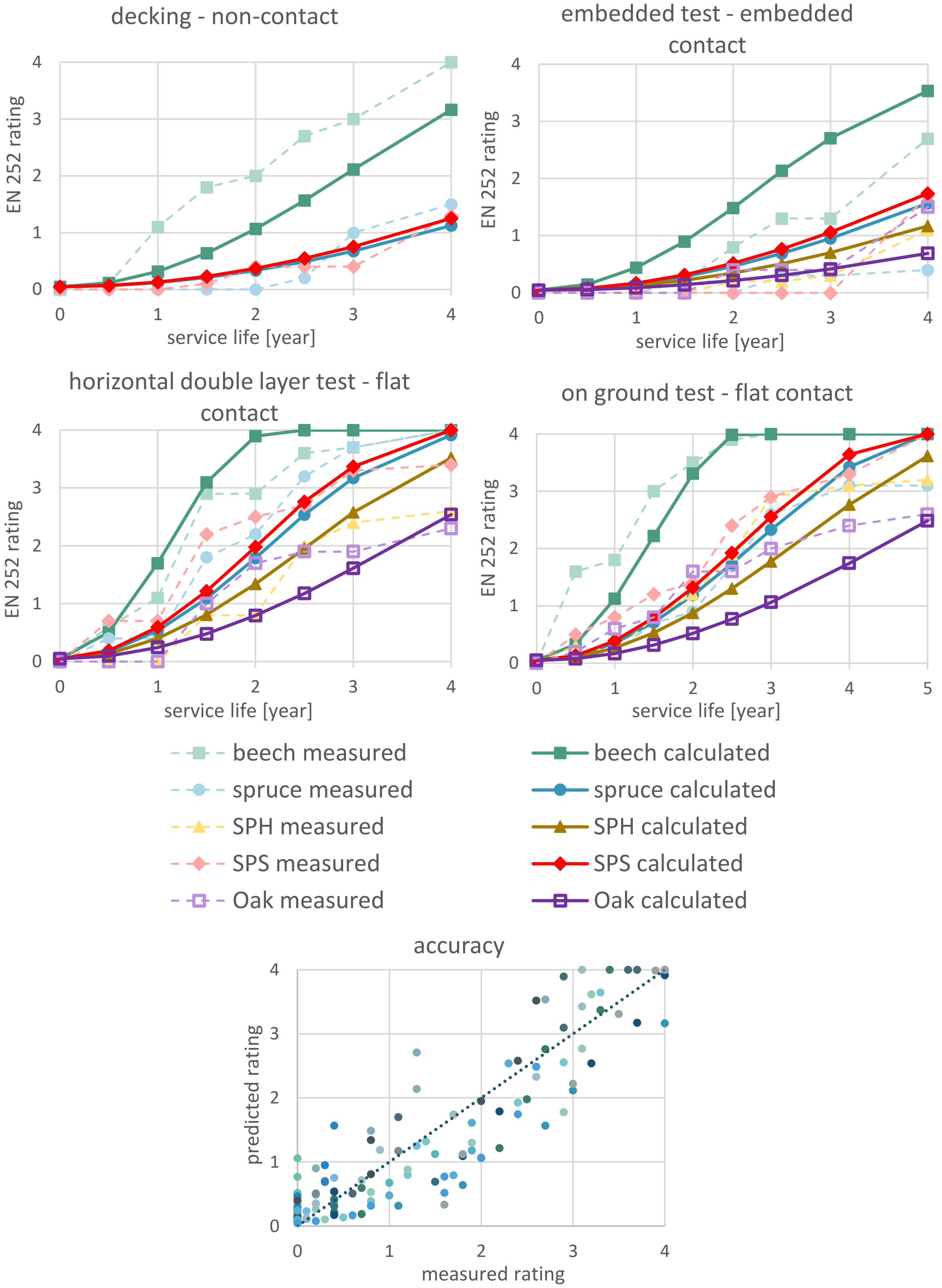

Figure 3: comparison between the test results of Meyer-Veltrup et al. (2017) and the above-ground prediction model. At the bottom the accuracy is presented.

In order to test whether Timberlife's approach for $k_{climate}$ remained valid in Europe, the model was compared to the study of Brischke and Rapp (2008) in which a similar setup was tested on 23 different sites in Europe. The setup was a decking test consisting of Douglas fir heartwood and Scots pine sapwood planks with cross section 25×50 mm (Brischke and Rapp, 2008). Comparing these measurements with the presented service life prediction model indicated that Timberlife's $k_{climate}$, which is based solely on the annual number of rainy days, did not yield good results for all test sites. A closer study revealed that this was particularly the case for the sites where some monthly average temperatures were below 0°C. However, Timberlife's methodology to calculate $k_{climate>0}$, can be retained when monthly average temperatures were always higher than 0°C. This is an interesting observation, because the average monthly temperatures in Australia are always higher than 0°C. Hence, this confirms the approach of Wang et al. (2008b).

For the sites with some average monthly temperatures below 0°C, a different approach is needed. Considering that in this case, the temperature cannot be neglected, there were a few possibilities. First, the $k_{climate}$ of the in-ground decay, or a derivation from it, was tested for above-ground decay. However, after several iterations of different derivations, this led to a dead end. Alternatively, the Scheffer index could be used to determine a new equation for $k_{climate}$. The Scheffer index yields values between 23.88 and 62.77 for the 23 test sites in the investigation of Brischke and Rapp (2008). After several iterations of curve fitting, eventually, a suitable equation was found that provided good results. Hence, Eq. (8) can be used to calculate $k_{climate<0}$ when monthly average temperatures are below 0°C. Interestingly, this equation did not yield good results where average monthly temperatures are all above 0°C, which again confirms the approach of Wang et al. (2008b). Hence, a differentiation is made between $k_{climate<0}$ and $k_{climate>0}$. A selection of the comparison is shown in Figure 4. The accuracy plot again shows a normal distribution along the diagonal. Note that in these test results, Brischke and Rapp (2008) also investigated the occurrence of brown rot or white rot. This is analysed further in the model verification.

$$k_{climate<0} = 0.18 \cdot Scheffer^{0.6} \tag{8}$$

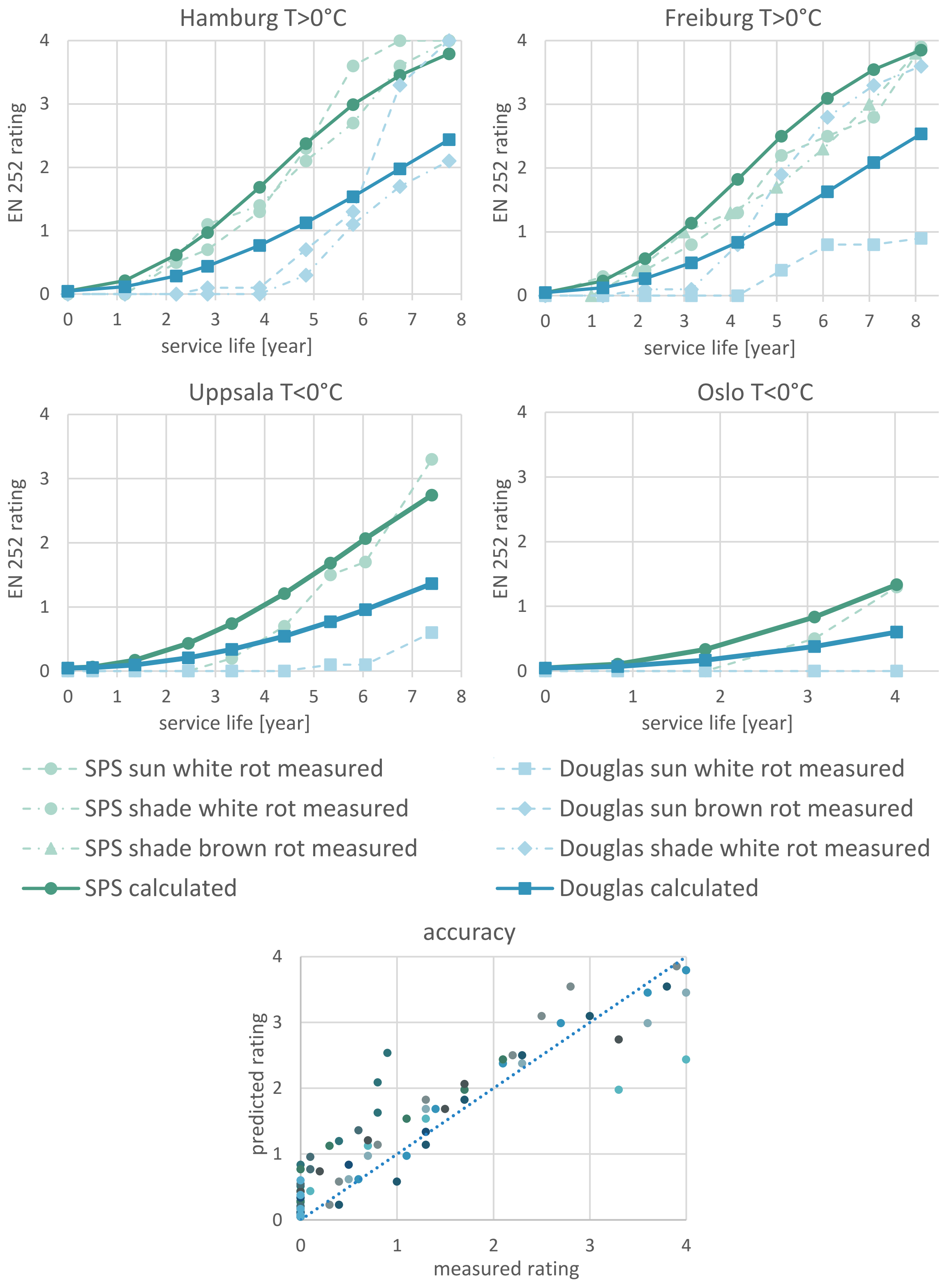

Figure 4: comparison between the test results of Brischke and Rapp (2008) and the above-ground prediction model. At the bottom the accuracy is presented.

4 Model verification and discussion

The in-ground and above-ground service life prediction models were verified using additional test data. Their performance is each time discussed by comparing them to the original Timberlife model. In addition, aspects that should be investigated further are identified

4.1 In-ground model verification

The service life prediction model was verified by comparison to the in-ground test results of European beech, Norway spruce, SPS, SPH and English oak heartwood on a site in Hannover, Germany performed by Meyer-Veltrup et al. (2017). The stakes used had a standard-sized cross section of 25×50 mm (Meyer-Veltrup et al., 2017). This set of test results is supplemented with additional, unpublished test results from the same investigation, using 8×20 mm mini-stakes and 50×50 mm double-sized stakes. No soil characteristics were available for this site, so the same was assumed as in Meyer et al. (2014). The used parameters are shown in Table 4. Note that no resistance dose is available for Scots pine sapwood. Hence, the k_{wood} value was determined with the case studies presented in Brischke et al. (2014) and Meyer et al. (2014). The results for the model verification are shown in Figure 5. By means of comparison, a simulation with the original Timberlife methodology is shown in Figure 6.

Table 4: parameter values for the in-ground and above-ground model verification

	Parameter	**Specification**	**value**	**value Timberlife**
in-ground	$k_{climate}$	Hannover	1.42	1.42
	k_{wood}	Scots pine sapwood	1.00	5.44
		Scots pine heartwood	0.60	1.36
		European beech	2.06	1.36
		Norway spruce	0.79	0.76
		English oak	0.51	0.23
	ξ	high organic material content	1.0	/
	k_{soil}	high organic material content	4.0	/
Above-ground	$k_{climate}$	Hannover	1.62	1.62
		Reulbach	1.27	1.47
		Stuttgart	1.56	1.56
		Garston/Liverpool	1.82	1.82
		St. Märgen	1.49	1.72
		Ghent	1.72	1.72
		Hinterzarten	1.40	1.71
	k_{wood}	Scots pine sapwood	1.40	6.52
		Scots pine heartwood	1.09	2.20
		European beech	2.68	2.20
		Norway spruce	1.31	1.14
		Douglas fir	0.86	2.20
		English oak	0.79	0.50

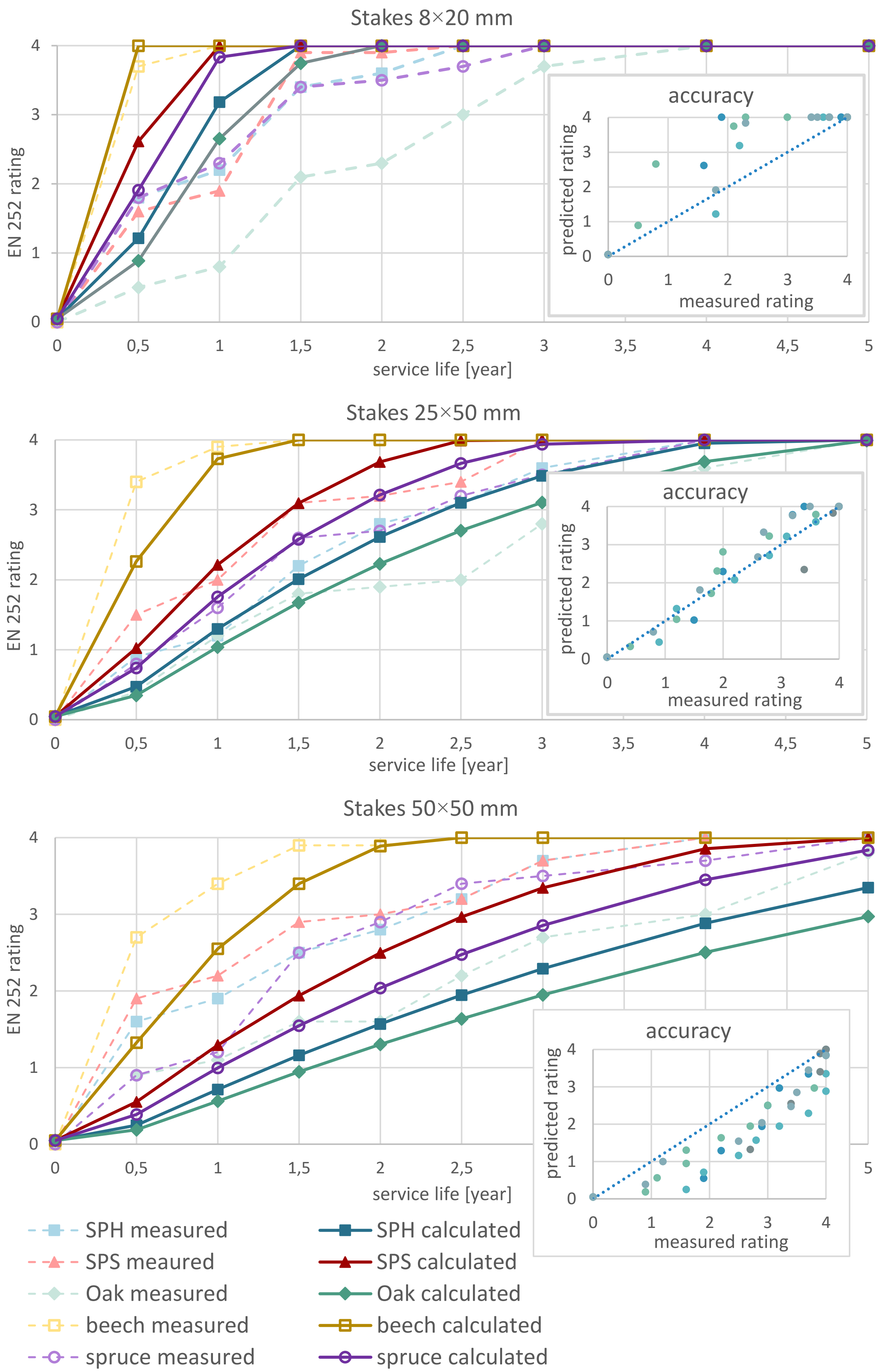

Figure 5: in-ground model verification with test results of stakes of different dimensions obtained from Meyer-Veltrup et al. (2017), including the accuracy of the model.

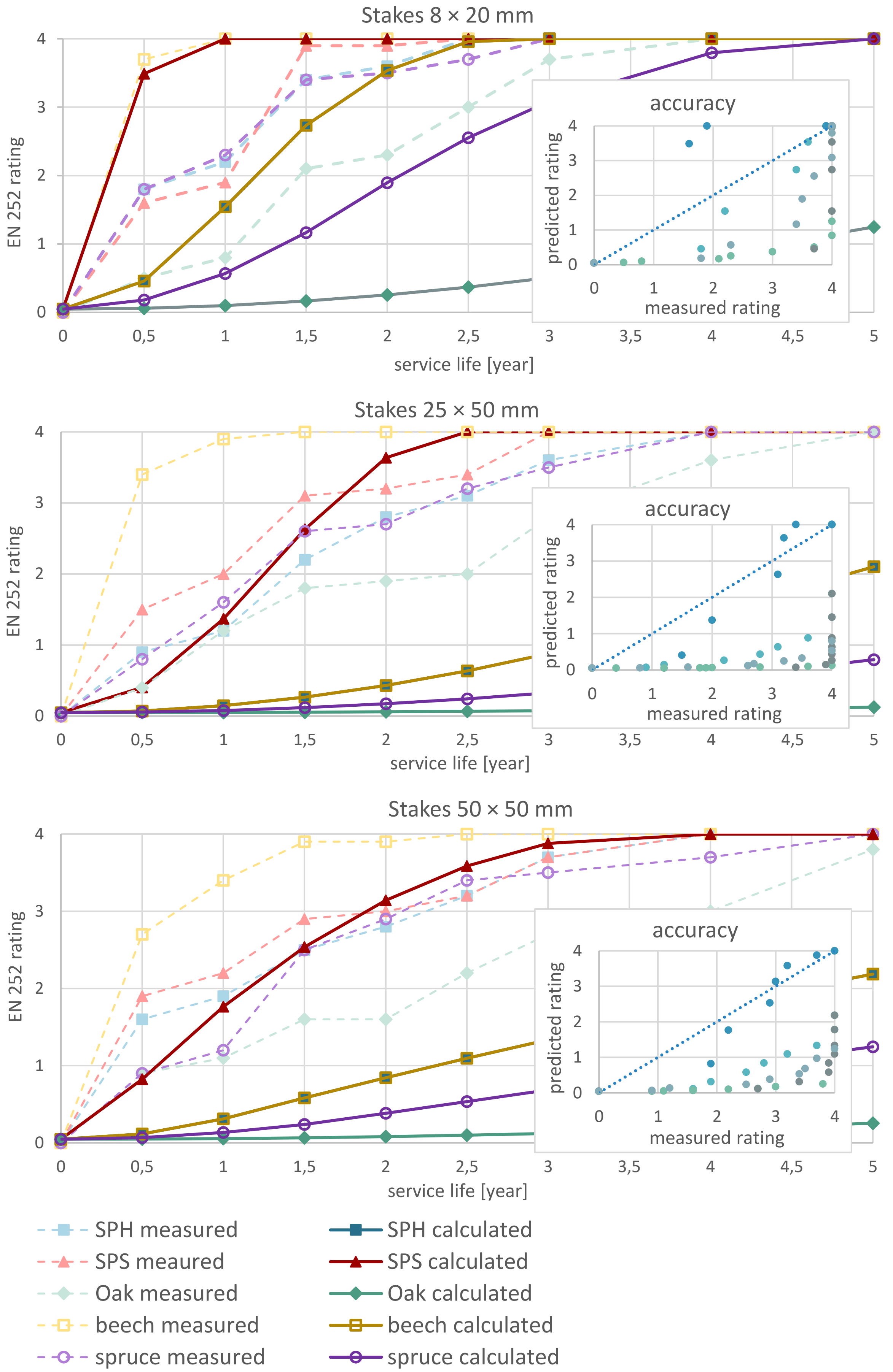

Figure 6: in-ground Timberlife model comparison with test results of stakes of different dimensions obtained from Meyer-Veltrup et al. (2017), including the accuracy of the model.

A comparison between Figure 5 and Figure 6 shows that the accuracy of the model has increased significantly by combining the dose-response model with k_{wood}, adding the new factor k_{soil} and adjusting the lag time equation. Nevertheless, the limitations of k_{wood} must be acknowledged. Wood is a natural material and may thus behave unpredictably because large variations of wood properties can occur in one species (Council of Standards Australia, 2005). Nevertheless, the results in Figure 5 show that the service life prediction model performs well for the standard-sized stakes of 25×50 mm. The measured curves and calculated curves clearly followed the same path, which is also observed in the normal distribution of the accuracy plot. However, the prediction model consistently underestimated the rating for the mini-stakes, while the rating is consistently overestimated for the double-sized stakes for the different wood species. Again, this is observed in the accuracy plot where the majority of the datapoints are in both cases on one side of but parallel to the diagonal. This may be due to the simplification of the EN 252 rating system in Table 1 which does not consider a size-effect. This could be investigated further. However, it should be emphasised that the rating is an interpretation of the decay. The model performed well for the standard-sized components, which means that the actual decay was accurately estimated.

In addition, due to the absence of a large-scale test comparing many different test sites, it was not possible to further verify the obtained k_{soil} and t_{lag}. Neither could the progression between them be determined. However, the available test results do indicate a possible link with the soil's nitrogen concentration as an indicator for organic material. This is also attested in the literature (den Ouden et al., 2010; van der Wal et al., 2007; White, 2006). Further research will in any case be required to test this hypothesis and determine a threshold for the nitrogen concentration.

4.2 Above-ground model verification

The above-ground service life prediction model was verified using more test results from the previously described extensive investigations by Meyer-Veltrup et al. (2017) and Brischke and Rapp (2008). The used parameters are shown in Table 4. Note again that no resistance dose was available for SPS. Hence, the k_{wood} value was determined with the case studies presented in Meyer-Veltrup et al. (2017). The results for the model verification (Figure 7 and Figure 9) show that the above-ground prediction model performed well, attested by the normal distribution of the results along the diagonal in the accuracy plot. By means of comparison, a simulation with the original Timberlife methodology is shown in Figure 8 and Figure 10. This shows again the significant increase in accuracy of the presented model due to the proposed new k_{wood}, lag time equation, $k_{contact}$ and $k_{climate<0}$. However, the high natural variability of wood properties, including its biological durability, needs to be pointed out again. Nevertheless, the measured and calculated curves clearly follow the same path in the comparisons with the different test set-ups in Meyer-Veltrup et al. (2017).

The prediction model does not differentiate between a fully exposed and shaded environment. Nevertheless, there is not always a big difference in the measured results. The test results of

Brischke and Rapp (2008) showed that only a large difference in decay was observed when this coincided with a different type of rot. The test results showed that SPS reacted very similarly to both brown and white rot, whereas Douglas fir heartwood decayed much faster when brown rot became dominant. Interestingly, the presented model's prediction was located in the middle between the two. For SPS, the predicted curve was each time located very close to the measured results. This not only confirmed the adjusted methodology to determine $k_{climate}$, but also confirmed the derived value of k_{wood} for SPS.

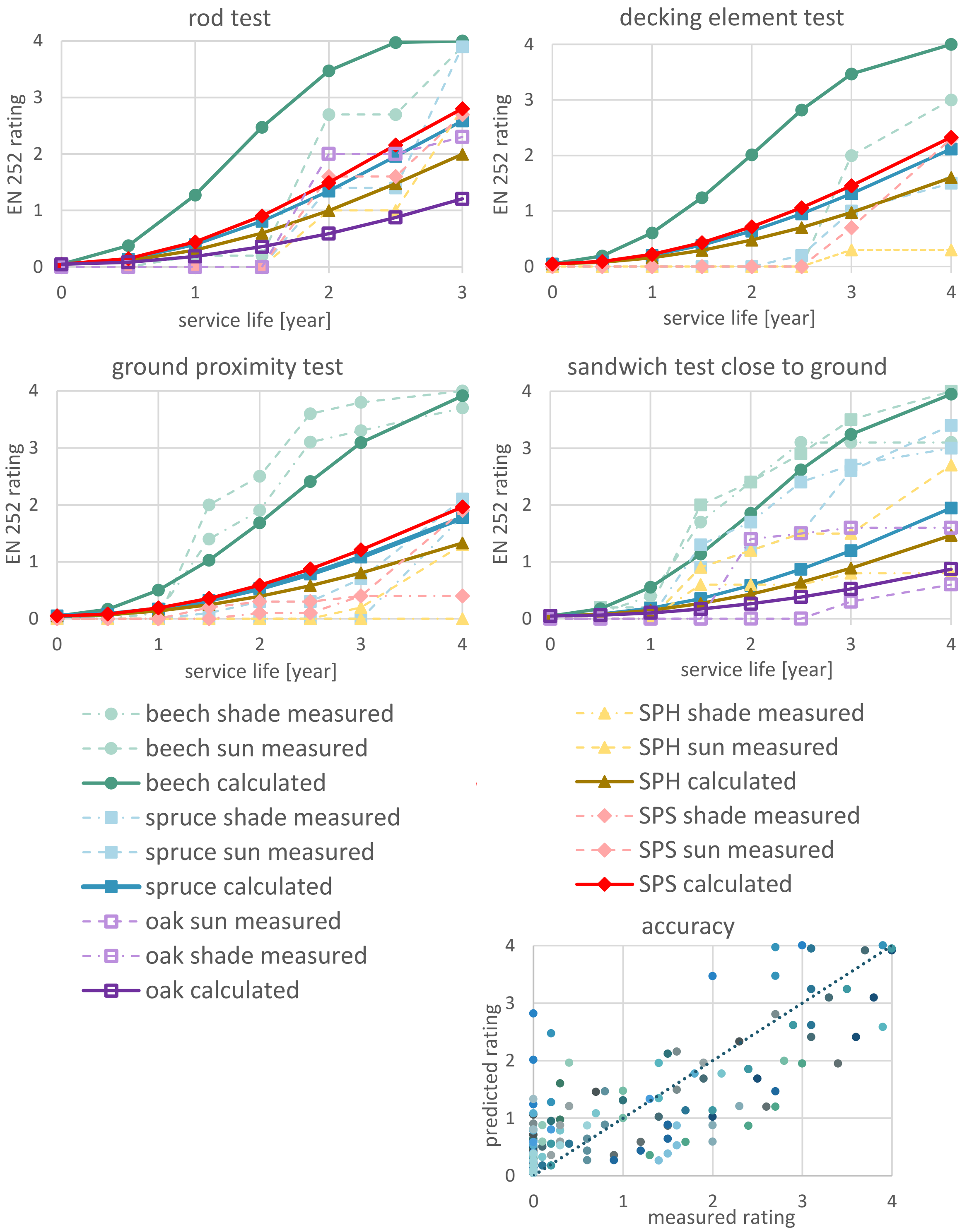

Figure 7: above-ground model verification with test results from Meyer-Veltrup et al. (2017). At the bottom the accuracy is presented.

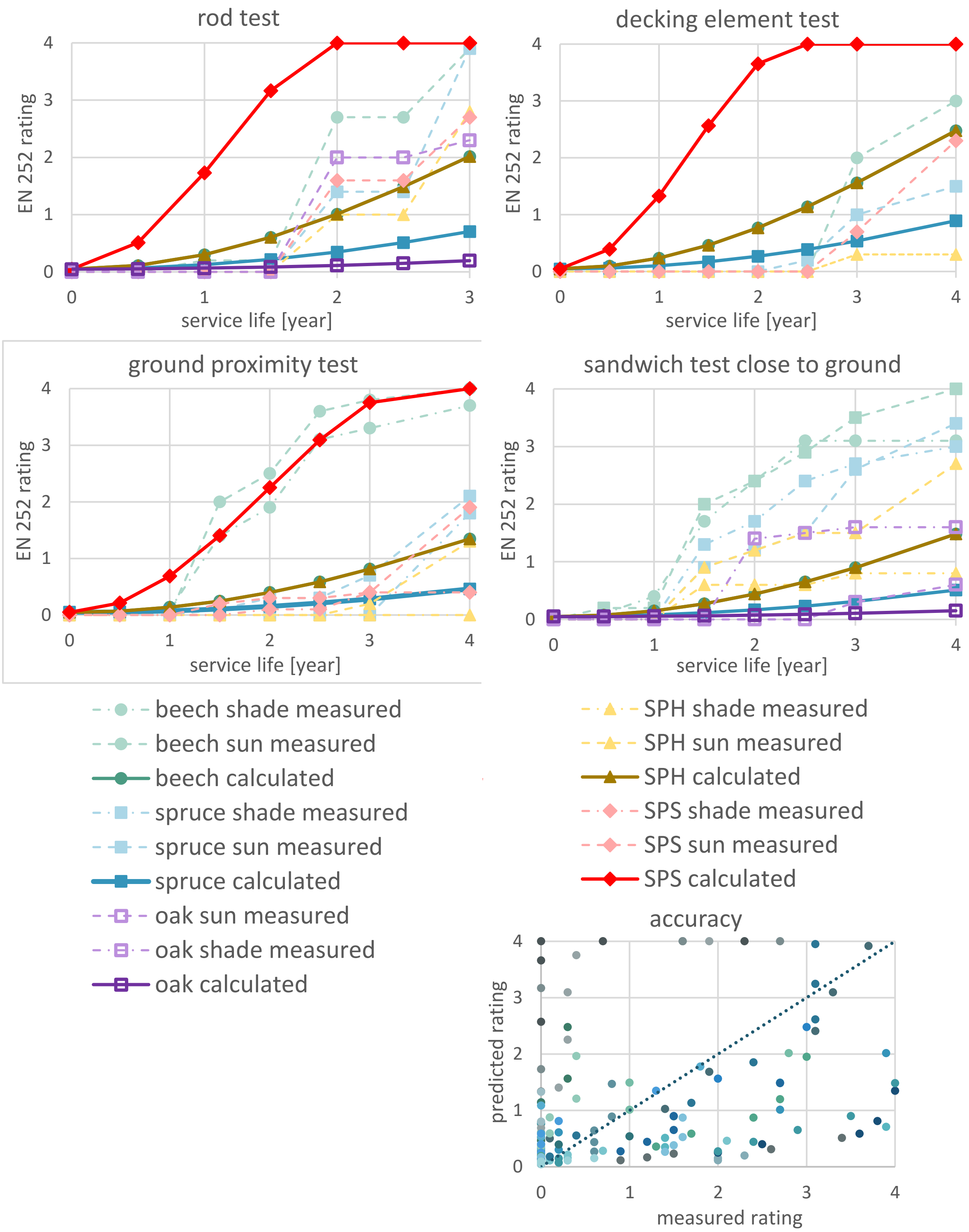

Figure 8: above-ground Timberlife model comparison with test results from Meyer-Veltrup et al. (2017). At the bottom the accuracy is presented.

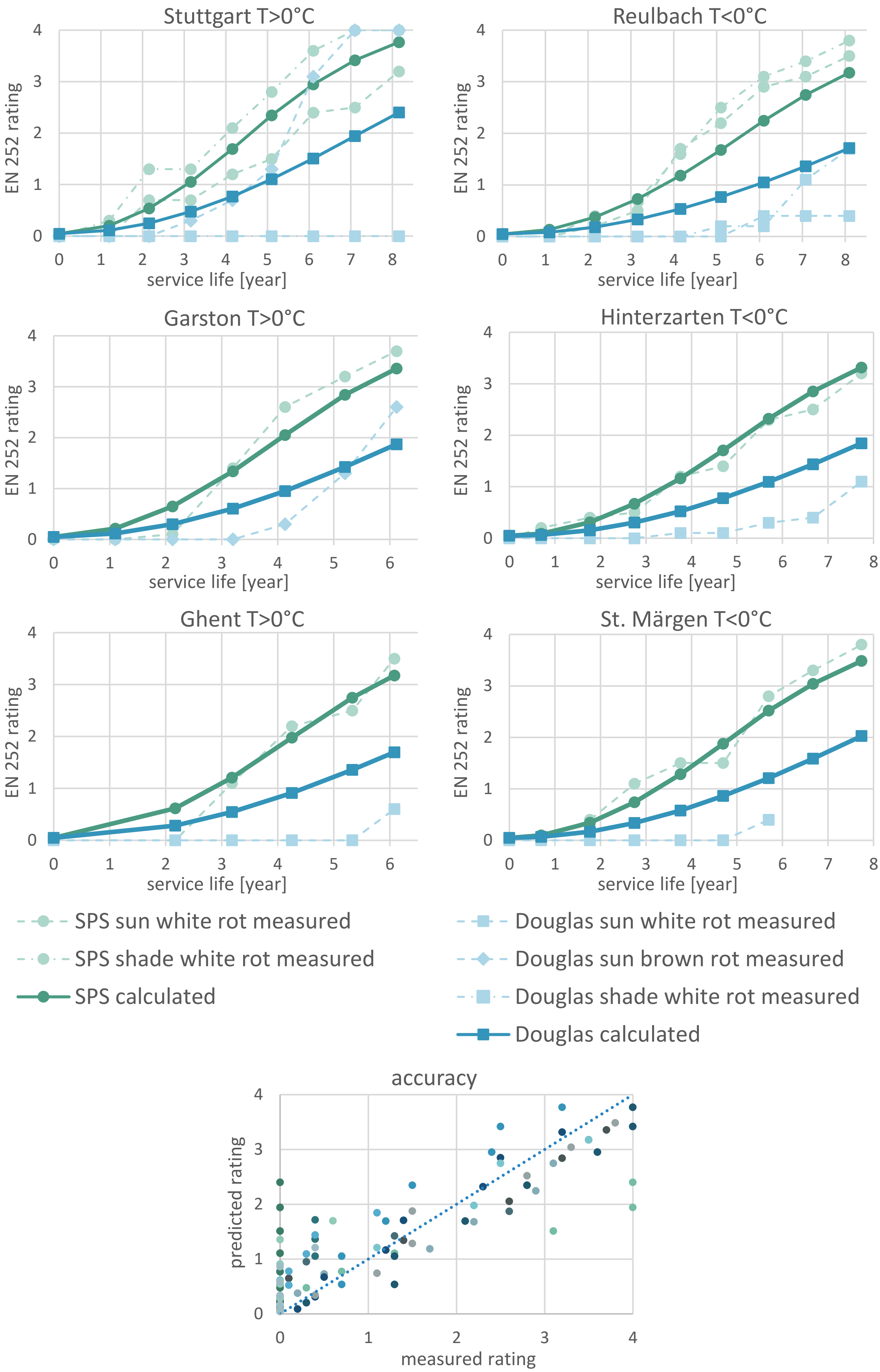

Figure 9: above-ground model verification with results of a decking test in different locations from Brischke and Rapp (2008). At the bottom the accuracy is presented.

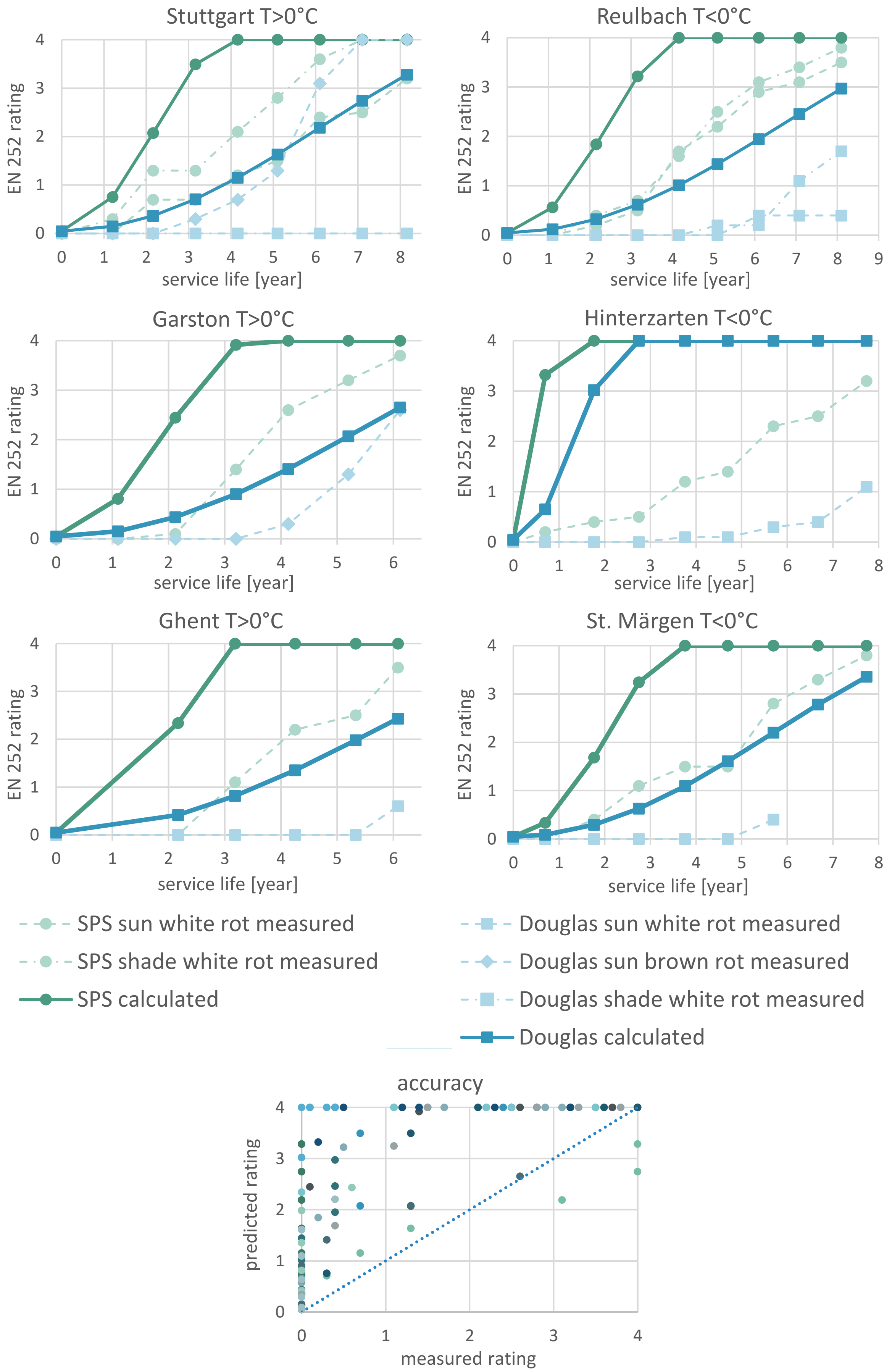

Figure 10: above-ground Timberlife model comparison with results of a decking test in different locations from Brischke and Rapp (2008). At the bottom the accuracy is presented.

Interestingly, the defined procedure to calculate $k_{climate>0}$ and $k_{climate<0}$ did not yield good results for two test sites. What differentiates these two sites is that, unlike the others, they are south of the Alps. Hence, these sites have a Mediterranean climate, which is very different from the other sites. The test results showed that decay started much faster in these sites. Presumably, either the lag time is different here, or the test wood was of poor quality. In any case, changing the lag time to Eq. (9) could apply to both sites. However, this needs to be investigated further with more tests south of the Alps. In addition, it should be investigated what determines the lag time so it can be more easily determined - calculated - for different regions and climates.

$$t_{lag} = 1{,}0 \cdot U_{wood,a-g}^{-0.85} \tag{9}$$

5 Conclusion

The reuse of timber components needs to be promoted to keep the wood construction industry sustainable. To overcome the quality barrier of reusable components, this paper presents a service life prediction model, serving as a reuse potential indicator. The timber service life model allows to objectively determine the reuse potential of timber components based on the decay rate and corresponding EN 252 rating. In this way, it can separate non-reusable from potentially reusable components. Hence, the presented model can help reduce the number of needed quality tests, and corresponding costs, and consequently benefit the reuse of wooden components.

The presented model is a translation of the Australian service life prediction model Timberlife, combined with the dose response model of the European CLICK*design* model. It is limited to in-ground and above-ground fungal decay and to an application area of north-western Europe, possibly all regions in Europe north of the Alps. Table 5 gives an overview of the presented changes to refine the obtained results and to extend the area of application of the model. In addition a few opportunities for further research are defined, these are shown in *italics*.

Table 5: overview of the amendments in the service life prediction model and opportunities for further research

k-factor	**In-ground**	**Above-ground**
k_{wood}	A methodology is presented to correlate the resistance dose D_{Rd} to k_{wood}. This allows to differentiate the service life prediction between different wood species, rather than crude durability classes. The same methodology can be applied to both in-ground and above-ground D_{Rd} and k_{wood} values.	
	Even though the results of the model verification are good, the correlation could be refined and extended with more wood species in the future when more test data are available.	

k_{soil}	A new factor was introduced to consider that different soil characteristics influence the decay rate. An upper and lower limit was determined for soil with respectively a high and low concentration of organic material.	N/A
	The hypothesis that k_{soil} could be a function of the soil's nitrogen concentration should be further investigated when more test data from different locations are available.	
$k_{climate}$	Timberlife's methodology is adopted.	Timberlife's methodology is adopted for regions with mean monthly temperatures higher than 0°C. For regions with mean monthly temperatures below 0°C a new method based on the Scheffer index is presented to calculate $k_{climate}$.
	With more test data from different regions, the methods to determine $k_{climate}$ for both in-ground and above-ground should be investigated and evaluated further.	
t_{lag}	A variable factor ξ is introduced in the equation to calculate the lag time. An upper and lower limit for ξ was determined for soil with respectively a low and high concentration of organic material.	The equation to calculate the lag time was adjusted. This corresponds to earlier findings in literature that the lag time calculation may differ depending on the region.
	Possibly, the soil's nitrogen concentration may be an indicator based on which ξ can be determined. This will, however, require more test data to verify this further.	*Again more test data are required to further investigate the lag time for other regions than northwestern to northern Europe. A few of the available test data came from more southern regions with a Mediterranean climate, indicating that the lag time is presumably different here.*

The presented service life prediction model can increase awareness of the potential of and necessity for timber reuse. Hence, it is a building stone in the progression towards a truly circular construction industry.

CRediT author statement

Kostas Anastasiades: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – Original draft, Visualization **Hanne Bielen:** Conceptualization, Formal analysis, Investigation, Writing – Original draft **Gianni Cantré:** Conceptualization, Formal analysis, Investigation, Writing – Original draft **Amaryllis Audenaert:** Conceptualization, Validation, Writing – Review & editing, Supervision **Johan Blom:** Conceptualization, Validation, Writing – Review & editing, Supervision

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