Estimating the (remaining) service life of timber bridges

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by

Jeroen van de Loo

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Author
Jeroen van de Loo - 4250451
Master track: Structural Engineering
Specialization: Structural Mechanics

Graduation committee

Drs. W.F. Gard,	Technische Universiteit Delft
Prof.dr.ir J.W.G. van de Kuilen,	Technische Universiteit Delft
Dr. ir. P.C.J. Hoogenboom,	Technische Universiteit Delft

TU Delft

Preface

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Jeroen van de Loo, Delft, January 2013

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Introduction

1.1. Background

Timber as a building material is enjoying a significant revival the last few decades. With environmental awareness and sustainability becoming larger parts of the social debate by the day, timber becomes for architects and their clients more and more an interesting alternative for steel and concrete. Timber is, in contrast to steel and concrete, a renewable resource that extracts CO2 from the air when it grows only to release this when the wood is burned or breaks down biologically. Timber is therefore considered a CO2 neutral construction material which makes it the perfect material for developers and policy makers to anticipate on the current trend in which CO2 emissions are considered as one of the main causes of climate change. The increasing popularity of timber can for instance be seen from the fact that high rise buildings are no longer exclusive to steel and concrete, seeing the 85 meter tall timber building Mjøstårnet in Norway, completed in 2019, and the construction of a 73 meter high timber-concrete residential building in Amsterdam, which is expected to be completed in 2021.

For bridges however the trend seems to be the other way around. The Netherlands counts a lot of smaller pedestrian and bicycle bridges made out of timber. These timber bridges are often associated with lots of maintenance works and a low service life compared to for instance steel and concrete bridges. It is for this reason that municipalities, who often have to deal with low maintenance budgets, choose to replace their timber bridges at the end of their service life by steel or composite alternatives, which are believed to have a much lower need for maintenance during their life time.

Despite this current trend it can however be expected that in the near future we will also see a revival of timber as a construction material in bridge constructions. Rijkswaterstaat, the organisation responsible for the Dutch infrastructure and waterways, is currently investigating the application of more timber in the Dutch road- and waterworks [3]. Their intention of using more timber has for instance already led to the construction in 2008 of two timber traffic bridges crossing the N7 motorway in Sneek, see figure 1.1.

Figure 1.1: One of the two timber traffic bridges in Sneek [1]

The increased interest in timber as a construction material by for instance Rijkswaterstaat has been greatly influenced by the recent climate objectives set out by the Dutch government. The goal to reduce the CO2 emissions with 49% in 2030[6] can for municipalities be a good motivation for an increased use of the CO2 neutral timber as an alternative to steel and concrete in their building plans, like the construction of new bridges.

With the current national and international emphasis on reducing the CO2 emissions it seems only a matter of time before these emissions will be a significant factor in the material choice for new bridge designs. However the fact that timber is prone to biological deterioration when it is exposed to weather conditions, and the amount of maintenance and the relatively low service life that goes with it is still making municipalities to often choose for other materials such as steel and composites.

These preconceptions about the life span and maintenance of timber bridges do not always have to be true. When well designed and maintained, timber bridges can reach excellent life spans [2] [7]. In order for timber, as a bridge material, to be fully considered as a worthy alternative for steel and concrete it is important to obtain better insight in its potential life span and in its total costs relative to these other materials.

1.2. Problem statement

There are numerous phenomena that are of influence of the service life of a structural component. Table 1.1 gives a list of the most common phenomena according to the Dutch norm NEN-ISO 15686-1 [2]. This master thesis focuses only on the last item on this list: Biological agents. The reason for this is that the general conception about timber in outside use is that the service life is mainly influenced by biological decay, e.g. wood rot.

Table 1.1: List of agents that can affect the service life of construction components according to NEN-ISO 15686-1 [2].

Nature	**Class**	**Examples**
Mechanical agents	Gravity	Snow loads, rainwater loads
	Forces and imposed or restrained deformations	Ice formation, expansion and contraction, land slip, creep
	Kinetic energy	Impacts, sand storm, water hammer
	Vibrations and noises	Tunnelling, vibration from traffic or domestic appliances
Electromagnetic agents	Radiation	Solar or ultraviolet radiation, radioactive radiation
	Electricity	Electrolytic reactions, lightning
	Magnetism	Magnetic fields
Thermal agents	Extreme levels of fast alterations of temperature	Heat, frost, thermal shock, fire
Chemical agents	Water and solvents	Air humidity, ground water, alcohol
	Oxidizing agents	Oxygen, disinfectant, bleach
	Reducing agents	Sulphides, ammonia, agents of combustion
	Acids	Carbonic acid, bird droppings, vinegar
	Alkalis (bases)	Lime, hydroxides
	Salts	Nitrates, phosphates, chlorides
	Chemically neutral	Limestone, fat, oil, ink
Biological agents	Vegetable and microbial	Bacteria, moulds, fungi, roots
	Animal	Rodents, termites, worms, birds

Because of biological decay, the condition of timber elements decreases over time till the point where the element is deteriorated so much that it does not fulfil its structural and/or aesthetic purpose any more. When designing a new (or assessing an existing) timber bridge it is therefore of importance to know how this deterioration will develop over time so that the (remaining) service life can be determined or a maintenance plan can be made.

1.3. Research questions

The goal of this thesis will be to review a number of models that can predict the development of structural decline due to biological decay over time, and to check the validity of the models by applying it on a number of existing timber bridges.

Main research question:

> **How can the (remaining) service life of a timber bridge in the Netherlands be estimated by using models that take into account biological decay and can these models be validated or improved by applying them on a number of case studies?**

Sub-questions:

- **To what deterioration phenomena are timber bridges in the Netherlands exposed?**
  Degradation of outdoor timber elements can have multiple biological causes such as varying moisture content, bacteria and funghi, insects, or marine borers. In case of glulam beams also de-lamination can occur. In this research only the main degradation causes for timber elements in the Netherlands will be taken into account.

- **What service life models can be used to estimate the service life of timber bridges in the Netherlands?**
  Several approaches already exist for modelling the behaviour of timber in outdoor applications. The goal is to find (or create) the method that is best suited for estimating the service life of timber bridges in the Netherlands.

- **What is, based on earlier stated models, the estimated service life of a number of timber bridges in the Netherlands and how do these estimations relate to the actual conditions of these bridges?**
  The applicability and reliability of the found models will be tested on a number of case studies.

1.4. Research methodology

Part I: Literature Study
A literature study will be done to present theoretical background on timber bridge design and degradation phenomena for outside timber elements and current state-of-art on service life modelling of timber bridges.

Part II: Comparison of service life models
The service life methods found in the literature study will be reviewed in order to find a method best suited to estimate the service life of timber bridges in the Netherlands.

Part III: Reality checks
The service life of a number of timber bridges in the Netherlands will be estimated using the modelling method(s) found in part II.

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I

Part I: Literature Study

2

Timber - the material

Chapter about timber as a building material. Mostly about the degradation hazards for timber used outside, natural durability and preservation measures.

2.1. Timber

Variety in tree species, etc. etc.

Hardwoods and Softwoods

Trees are divided into two major botanical groups: gymnosperms and angiosperms [1]. The wood that comes from gymnosperms is called softwood while the wood from angiosperms is called hardwood. The difference between the two groups can be found in the cell structure, the leaves (needle-like leaves for softwoods and broad leaves for hardwoods), the mechanical properties and the natural durability against biological decay. In general hardwoods have higher natural strength properties and higher natural durability than softwoods although within both groups these properties vary widely between species, trees and even within a tree itself [7].

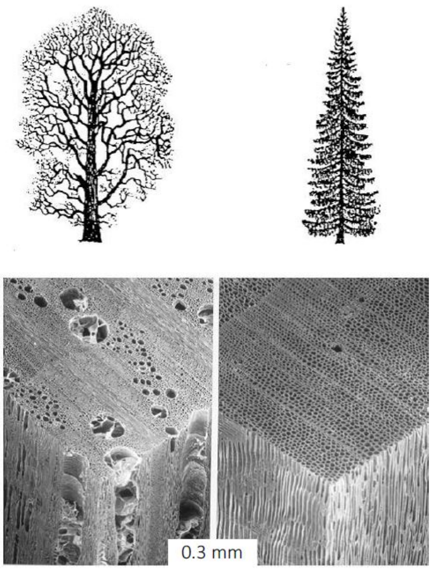


Figure 2.1: Growth patterns and microscopic structures. Left: oak (Hardwood). Right: spruce (Softwood) [1]

Heartwood and sapwood

Within a tree itself wood can be divided into two zones: the heartwood and the sapwood. The heartwood, which is located in the centre of the cross section, generaly only consists of dead cells while in the sapwood, the outer zone, also living cells are present. Heartwood can usually be distinguished from sapwood due to its darker colour, see figure 2.2. Within a tree the properties of the wood differ between the two zones, the natural durability of heartwood is usually much higher than that of sapwood for instance [1].

Figure 2.2: Cross section of a tree with a clear distinction between the darker heartwood and the lighter sapwood [14]

Wood products

For a structural timber element a number of fabrication choices are available. The earliest timber bridges were made of solid timber elements [10]. The length and cross sectional size of these elements are however limited and thus starting from the beginning of the 19th century people started combining smaller solid timber laminations in order to create beams of bigger lengths and cross sections. At first this combining was done by using mechanical fasteners, creating mechanically laminated timber, and later adhesives became a popular way to connect the laminations and create glue laminated timber, also known as glulam [7]. Below follows a short description of these three timber materials. All these types can either be made out of hardwoods or softwoods.

Solid timber

Solid sawn timber elements are cut from logs and their size is thus limited to the tree size of the specific wood species used. Due to the limited cross sectional size, bridges made out of solid timber elements are usually made out of a number of closely spaced solid timber beams with a limited span [10].

Glulam

Glulam elements are made out of multiple layers of timber laminations glued together to form a new larger solid cross section, see figure 2.3. Glulam beams are very well suitable for when large spans need to be crossed, and thus large cross sections are needed, and when curved beams are asked, for instance at arch bridges [12].

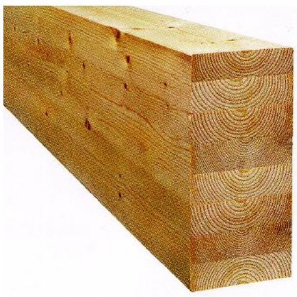


Figure 2.3: Example of a glulam beam [1].

Mechanically laminated timber
Mechanically laminated timber elements are comparable to glulam elements, but istead of glue they use mechanical fasteners, such as dowels, to combine the laminations into one solid cross section [7].

Moisture content
Wood is a capillary-porous material with a hygroscopic cavity system which means that it is able to absorb moisture from the surrounding air. The moisture content of wood, u, is calculated using formula 2.1 [1]. Oven dry means that the wood contains no water and thus has a moisture content of 0%.

$$u = \frac{m_u - m_{dtr}}{m_{dtr}} * 100 \tag{2.1}$$

where

u	:	Moisture content of the wood
m_u	:	Mass of the moist wood
m_{dtr}	:	Mass of the wood in oven dry condition

Being hygroscopic, wood is able to absorb and discharge moisture from the surrounding air. For each air temperature T in combination with an air humidity ψ a corresponding moisture content applies which is called the equilibrium moisture content ω. This equilibrium moisture content level is reached within the wood after a certain amount of time.

Starting from the oven dry condition, the first water that is absorbed by the wood is called bound water, since it bounds to the cell walls by hydrogen bonds. The point at which the cells cannot bind any more water is called the fibre saturation point. This point varies between wood species but on average this point is reached at a moisture content of 28% [1]. The water that is absorbed after this point is called free water.

The moisture content has an influence on the mechanical properties of wood and is a key factor in the swelling and shrinking of wood and the development of wood deteriorating processes such as moisture induced cracking and the growth of moulds and fungi.

2.2. Degradation hazards
Wood that is used in outdoor applications, and is thus exposed to weather conditions, is vulnerable for a number of degradations, both biological and non-biological.

Moisture
Due to being exposed to rain, snow and changing temperature and humidity the moisture content in outdoor wooden elements constantly changes. In a timber cross section, the moisture content in the centre changes in a lower pace than the moisture content in the outer zones. Because of this unequal deformations want to occur over the cross section which then leads to the development of internal stresses [8]. When these moisture induced stresses become larger than the strenght of the timber perpendicular to the grain they will lead to the development of cracks, see figure 2.4.

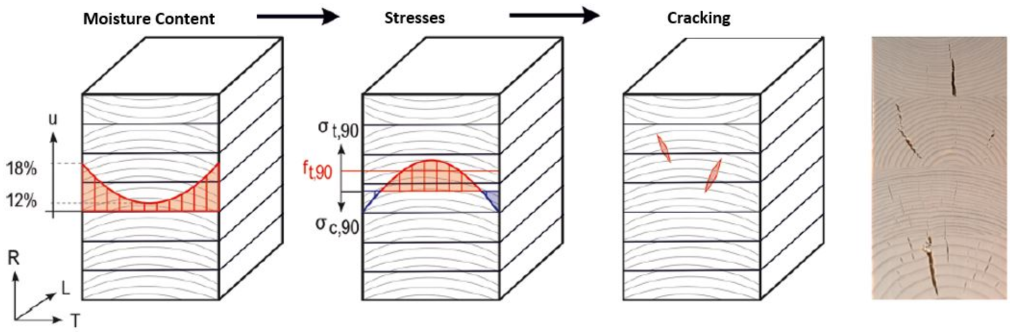


Figure 2.4: Moisture and stress distribution and the development of cracks in a timber cross section due to adsorption [6]

Besides causing stresses in the wood, moisture is also a key factor in the development of biological wood decaying organisms such as funghi and moulds. Most of these organisms thrive on a relatively high moisture content. Koch et al. [10] state that a moisture content above the fibre saturation point should be avoided in timber elements since fungal decay could start developping. This also applies for when lower moisture contents around 20 to 25 percent are present for an extended period of time.

Fungi and bacteria

Wood deteriorating fungi come in two main groups: Wood destroying fungi and wood staining fungi [1]. Wood staining fungi mainly affect the wood aesthetically by discolouration while wood destroying fungi can greatly influence the strength and mass of the wood in a negative way. The development of fungi is related to a couple of factors like nutrients, water content, temperature, oxygen and PH-level. Eliminating one of these factors from the wood is therefore the often used method to protect the wood from biologial decay, for instance by keeping moisture away [3].

Wood destroying fungi

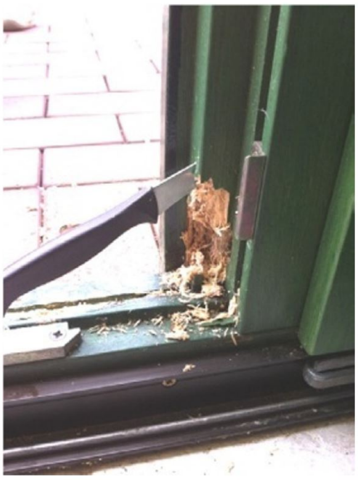
There are three types of wood destroying fungi: brown rot, white rot and soft rot. They differ from each other in exterior appearance and the way they decompose the wood.

Brown-rot fungi grow inside the cell cavities of the wood from where they predominantly break down the cellulose while they lignin stays more or less intact. Due to the cellulose breaking down the wood loses its strength and mass. It also gives the wood a dark brown colour and causes the wood to crack in a deep cubic cracking pattern, see figure 2.5. Most brown-rot fungi attack preferably softwoods, whilst hardwoods are more frequently attacked by white- and soft-rot fungi [1] [3].

Figure 2.5: Typical example of wood degraded by brown rot [1]

White-rot fungi degrade both the cellulose and the lignin in wood. Wood attacked by white rot has a bleached colour and becoumes fibrous in texture, see figure 2.6a. In all white rot types, the wood strength properties are reduced to a lesser extent than in brown-rotten wood, since at the same mass loss, lesser cellulose is consumed, and it does not come to cracking or cubical rot [11].

The third type of rot, soft rot, degrades the cellulose, hemicellulose and the lignin inside the wood [11]. Soft rot often develops at wood that has a constantly high wetness, for instance around the water line of poles supporting bridges, see figure 2.6b. Soft rot often leads to erosion of the timber surface [2].



(a) White rot [3]

(b) Soft rot and its eroding effect [2].

Figure 2.6: Examples of white- and soft rot

Wood staining fungi
Moulds grow on the wood surface and cause no or only little damage to the wood componetnts such as lignin or cellulose. This results in discolouration of the wood surface while the wood physical features of the wood remain intact. Nevertheless, mould development is usually a sign that the conditions (temperature and humidity) are favourable for the growth of other more dangerous fungi. Also moulds can cause health problems, especially when growning in indoor environments [1] [11].

Blue stain fungi grow on the wood surface but are also able to penetrate deeply into the wood. Just like with moulds the strength properties of the wood are hardly affected but the presence of blue stain indicates that the growth of worse fungi can follow.

Insects

2.3. Natural durability

Durability here is used in the sense of the resistance of wood against wood decaying organisms and thus the ability to fulfill its (load bearing) function for the intended service life. The durability of wood is often increased by impregnation of chemicals, wood modification and/or paints and coatings. However wood from itself already has a certain resistance against biological deterioration which is called the natural durability. The natural durability ranges greatly between wood species. In general Hardwoods have higher natural durability than softwoods but even within these groups the differences between species are big. Even within a tree itself there are large differences since heartwood has a much higher natural durability than sapwood.

For most common tree species the natural durability has been assessed during tests in laboratories and in the open air. As a result from these tests the wood species are distributed into different durability classes, which in the Netherlands are specified in the European standard EN 350:2016. In this norm the durability against wood-decay organisms of various wood species is ranked into durability classes. It is however stressed that the durability ranking gives no guarantee for the performance of the wood in service since for this many other factors have an influence, such as the principles of good design, climate conditions and maintenance. The natural durability of wood against wood destroying fungi is ranked in a five grade scale, see table 2.1. These durability classes only refer to the heartwood. The sapwood is always regarded as not durable, unless tests have proven otherwise [4].

Table 2.1: Durability classes (DC) of wood and wood-based materials for attack by decay fungi as described in the European standard EN 350:2016 [4]

Durability class	Description
DC 1	Very durable
DC 2	Durable
DC 3	Moderately durable
DC 4	Slightly durable
DC 5	Not durable

2.4. Material protection

When used for outdoor applications the natural durability of the wood does not always provide sufficient resistance against decay organisms for the intended service life. In order to still be able to use these wood species in outdoor conditions they need to somehow be protected. For this it is first important to know what circumstances lead to the biological deterioration of wood.

In the Netherlands the main type of wood decaying organisms are different sorts of fungi. For these fungi to develop, the following five conditions need to be met [2]:

1. **A nutrition source needs te be present.** For wood deteriorating organisms the wood is the nutrition source. The presence of other nutrition sources such as dirt can speed up the growth process.
2. **Sufficient oxygen needs to be present.** The fungi do not grow in places with low amounts of oxygen, for instance below the water level.
3. **Enough moisture need to be present over a longer period of time.** As already stated in section 2.2, wood deteriorating organisms are usually unable to develop in wood with a moisture content below 20 percent.
4. **The wood needs te have the right temperature.** The right temperatures vary per fungi type. In general however the Dutch climate is one in which fungi can develop easily.
5. **No substances that are toxic to fungi must be present.** The natural durability of wood species is partly based on by the tree itself produced toxic substances. These substances are partly able to leach away from the wood with water and so the natural durability can decrease over time.

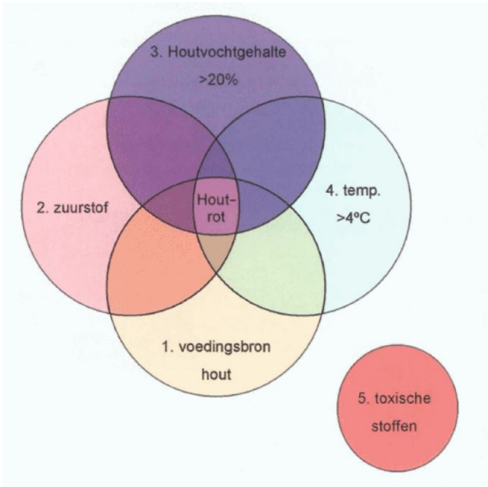


Figure 2.7: Conditions for the development of wood deteriorating Fungi [2].

To prevent biological deterioration from developping only one of these five conditions needs be excluded. Conditions 1 and 4 cannot be prevented when using timber in the Dutch climate. Condition 5 is often made use of by impregnating wood with preservatives which contain substances that are toxic to the deteriorating organisms. Conditions 2 and 3 can be taken into account in the detailing.

Preservatives

Chemical wood preservatives can be be applied with different impregnation techniques. In the early days of wood preservation the main preservatives used were chromated copper arsenate (CCA), pentachlorophenol (PCP) and creosote. However since the 1990s the use of these preservatives has been restricted or banned in most of the EU member states due to health reasons [1]. Nowadays for heavy duty outside application there are two main types of products available, copper-amine based preservatives and creosote. However in the EU creosote as a preservative is under pressure and the allowed use of creosote is limited.

Preservation Techniques
Brushing, dipping, Preasure treatment

Wood modification

Acoya bridge in Sneek (acetylated wood).

Protective design

Wood can be protected by assuring that either decay organisms have no access or physical prerequisites for such organisms are inhibited. This means moisture, temperature and oxygen levels are kept below minimum or above maximum for activity or even survival of the respective organisms [2]. Another part of protective design is the selection of building materials that are adequate for the environment the structure will be in.

This makes the choice for the wood specie with sufficient natural durability also part of protective design.

As stated earlier, biological wood degrading organisms need a moisture content above 20% to be able to develop in the wood [10]. One of the main goals of protective design is thus to keep the moisture level constantly below this level in order to make the growth of fungi unlikely. For this 'moisture protection' usually three rules are followed [1]

1. Keeping water away from the structure
2. If the first is not possible, removing water from the structure as fast and effective as possible by providing sufficient drainage and ventilation measures.
3. Make sure that wood species with sufficient natural durability are used when permanent humidification cannot be prevented.

Also the way that wood is treated during the construction process is part of protective design. If possible the wood should be installed at the equilibrium moisture content present in the building so that only seasonal variations in humidity have to be taken into account. When no care is taken here, the wood will be prone to cracking after installation.

Below are a few design principles which protect the timber and can make a significant difference to the life expectancy of components. In section 3.3 a number of protective design measures especially for timber bridges are discussed.

End grain protection
Water is particularly liable to infiltrate wood in the grain direction. An important protective measure is thus to cover the end grain surfaces so that no water can penetrate, see figure 2.8.

Figure 2.8: End grain protection. Left, timber bridge in Spain without end grain protection of severely decayed main beam. Right, end grain metal covers of projecting exterior beams. [2]

Seperate timber from wet materials

Timber should be isolated from the ground and from moisture retaining materials or wet surfaces by either an impermeable damp proof membrane or, preferably, by providing sufficient air gaps to prevent absorption or capillary action [12]. Examples shown in figures 2.9 and 2.10.

Figure 2.9: Protection from ground contact. Left, pedestrian bridge with pillars in direct contact with ground. Right, pedestrian bridge in Galicia, Spain, with concrete fundaments and loadbearing pillars separated from the ground. [2]

Figure 2.10: Ventilation measures, avoiding direct contact with wet walls. Left, end of beam in direct contact with wet wall. Right, physical separation between end of beam and wet wall that allows drying of wood. [2]

Avoid water traps

To avoid water traps, the following points should be incorporated in the design:

- Sufficient slope to horizontal surfaces to prevent water lying on the surface.
- Drainage to ensure that junctions between exposed components and connections do not become water traps

Figure 2.11: Water draining and avoidance of water trapping. Left, decking with good details design to allow dripping rainwater and space between two boards to avoid water accumulations. Right, hand rail in Kristineberg, Sweden: Declined surface but gap between two elements with potential for water trapping. [2]

Figure 2.12: Protection from water accumulation. Left, decking with no correct design due to contact board to board. Right, decking well designed thanks to a good separation between boards that avoid water accumulations. [2]

Protect timber from wetting

Protecting the timber from wetting can for instance be achieved by placing (metal) covers on top of beams like in figure 2.13. Wetting of the timber can also occur due to splashing, of which an example is shown if figure 2.14.

Figure 2.13: Effect of covers. Left, end grain joint on railing without cover protection. Right, fence post with traditional copper cover to protect joint area. [2]

Figure 2.14: Protection from splash water. Left, wetting of cladding made from thermally modified wood in north Spain due to splash water — growth of moulds and disfiguring fungi. Right, cladding in north Spain with correct detail design to avoid splash water. [2]

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3

Timber bridges

Some introductory text about timber bridges. Benefits of timber bridges [7]:

- High strenght to weight ratio (for strength parallel to grain)
- Use of prefabrication
- Quick assembly (easy lifting of large components)
- Aesthetics (natural appearance)
- Sustainability (Renewable material, positive CO_2 balance)

In the following sections of this chapter first a subdivision of timber bridges will be made on the basis of the main structural type, the timber products used, and the type of deck. After that a number of connection systems often used in timber bridge design will be described and linked to the structural types in which they can often be found. In the last section the actions on timber bridges that are prescribed by Eurocode 1 will be discussed.

3.1. Types of timber bridges

In this section three important characteristics of timber bridges are discussed, namely the the structural type, the wood product and the deck type. For each characteristic a number of different options are described that will often be encountered in present-day timber bridges. Another important characteristic, the connection system, will seperatly be discussed in section 3.2.

Main structural system

In this research, four main bridge types are distinguished: beam bridges, truss bridges, arch bridges and suspended bridges. Per type a short description will be given below.

Beam bridges

Beam bridges generally are the simplest and most common type of timber briges [10]. For relatively small spans they usually consist of a number of longitudinal beams that are simply supported on both ends of the crossing. For larger crossings one or more extra intermediate supports might be needed, see figure 3.1. With beam bridges the deck is usually placed on top of the main beams and can thus, if designed properly, protect these main beams against weather conditions such as rain [7].

Figure 3.1: Two examples of beam bridges, both located in Arnhem. A single span bridge (left) and a bride with multiple spans (right) [6].

Truss bridges

The main structural system of a truss bridge usually consists of two trusses that are composed of a top and a bottom chord which are connected by diagonals and posts which leads to a lot of connection points. When placed above the top chord, the deck could protect the trusses against rain. However in most cases, where the clearance below the bridge is of importance, the deck is placed at the height of the bottom chord and thus provides no protection to the main load bearing elements, see figure 3.2.

Figure 3.2: Two examples of truss bridges. In the left picture the deck is placed somewhere halfway the top and bottom chords. The right picture shows a timber bridge near Harderwijk where the deck is positioned at the bottom chord. Also noticable here are the steel cross beams providing lateral stability to the top chord. [3].

Arch bridges

Modern timber arches are usually made of glulam beams that are curved in the factory after which they are transported to the building site. The bridgedeck can be placed at the top or at the bottom of the arch, or somewhere in between. This choice is often dictated by the local environment of the bridge [5]. In the design of an arch bridge the choice is often made between a two hinged arch, with two hinged supports, and a three hinged arch with an extra hinge at the top [10], see figure 3.3.

Figure 3.3: A bridge for pedestrians and cyclists consisting of two timber arches crossing the N18 at Lichtenvoorde (left)[6] and a timber arch bridge near Kopenhagen, Denmark (right)[13]. A close look at the connection at the top suggests that this is a three hinged arch.

Suspended bridges

Suspended bridges can be divided into two different types, namely the suspension bridge and the cable-stayed bridge, see figure 3.4. Altough they are differnt types of load bearing systems they are both characterised by a deck that is supported by steel cables which transfer the forces to two or more towers or masts (for cable stayed bridges only one tower or mast could already be sufficient).

Figure 3.4: Timber cable stayed bridge at Harderwijk for cyclists and pedestrians (left)[13] and a timber suspension footbridge near Arnhem (right) [6].

Deck

- Simple deck boards
  - Slijtlaag
  - Antislip strips
- Composite deck
- Laminated panels
- Timber-concrete composite
- Open deck - waterproof deck

3.2. Connections

For timber bridge constructions, a so called "durable" connection design is of vital importance when aiming for an optimal service life. Badly designed timber bridges that have failed too soon because of biological decay are often found to have failed due to badly designed details with respect to moisture control. For connections it is important to follow the general rules concerning moisture that are previously discussed in section 2.4.

Figure 3.5 shows a number of common details used in jetty constructions that are prone to biological deterioration. These details are also often encountered in smaller timber bridges. The details are described below [2].

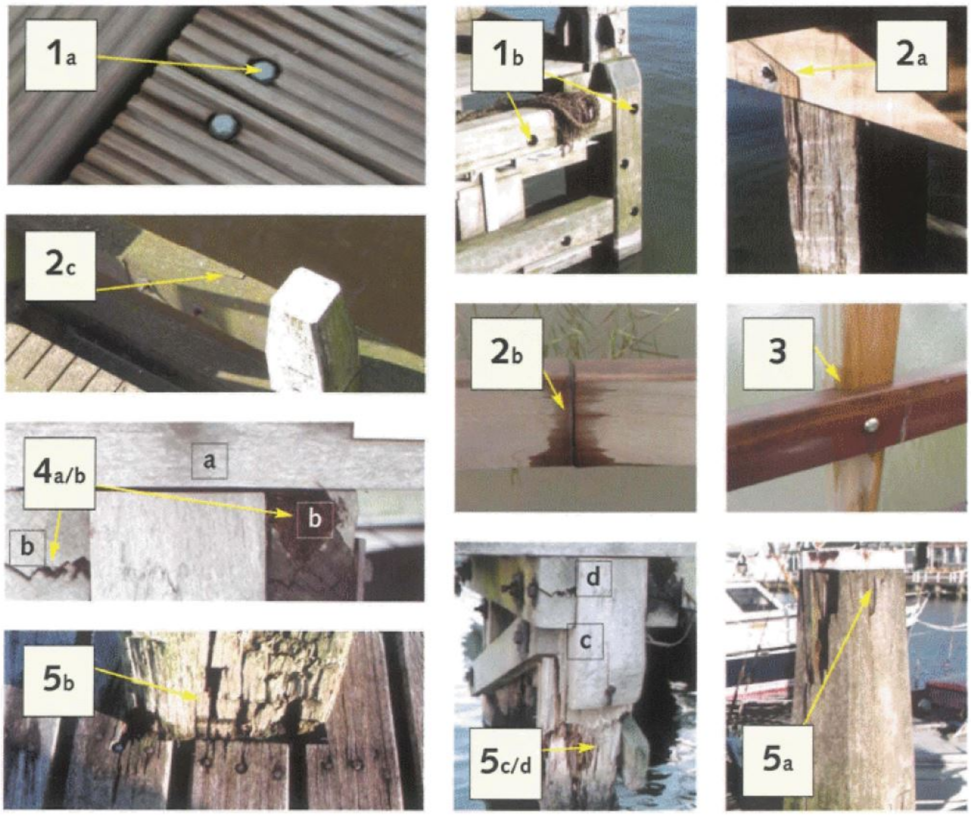

Figure 3.5: Examples of critical details of jetties [2].

1. Milled holes for countersunk bolts
The problem with milled holes needed for bolts is that additional end grain surfaces are created. Especially in case of deck boards this will cause an increased moisture intake when water remains in the holes.

2. Transverse joints
Connections used to increase the length of a timber element. Also in this case the problem is the presence of end grain surfaces. When these surfaces are placed too close to each other a capillary plane is created in which water will be sucked, as can be seen in figure 3.5 2b.

3. Rails with mortise joints
Also here capillary planes are created in which moisture will be sucked in.

5. Poles
Poles have three main places that are prone to biological deterioration. The end grain surface at the top of the pole, 5a, at the level of the decking, 5b, and at the waterlevel, 5c.

These critical details and their durable alternatives are further discussed in the next paragraph.

3.3. Protective design

In section 2.4 the main principles of protective design for timber elements has been discussed. In this section a couple of typical protective design measures for timber bridges are shown. As stated in section 2.4 the main goals are to keep water away from the structure and provide sufficient drainage and ventilation to allow for quick drying when water does reach the timber elements.

The effect of protective design measures has been studied in Germany by Koch et al. [10]. In Germany the main structural timber elements of bridges are often structural-protected against precipitation and moisture ingress. In order to show that well protected timber bridges are able to compete with steel and concrete alternatives in terms of durability, Koch at al. initiated a monitoring program to evaluate the efficiency of these structural protective measures. For the structural-protected timber elements of nine bridges, equiped with measurement systems, the moisture content and ambient climate conditions were measured for 2 years. So far, after measuring one bridge for one and a half year and eight bridges for half a year, the results show that the average moisture level of all nine bridges does not exceed the 20 percent limit. Therefore the conclusion can be drawn that structural-protective measures can keep the moisture level of timber bridge elements below the critical level and can thus increase the service life of timber bridges by preventing the growth of decay fungi.

End grain protection

As already stated in section 2.4, an important aspect of protective design is the covering of end grain surfaces of beams and posts. Figure 3.6 shows two pictures of timber bridge posts, one with an open end grain surface and one with the end grain surface covered. The cover should still allow for ventilation of the end grain surface so that any water that gets trapped below is able to escape [2].


Figure 3.6: Left picture shows an example of a bridge post with unprotected end grain surface. On the right a similar bridge post is shown where the end grain surface is covered to prevent water adsorption. (Both bridges located in Pijnacker)

Water trapping

As stated in section 3.2, water getting trapped in cappilary planes, like in figure 3.5 example 3, should be avoided. An example of how to avoid this is shown in figure 3.7 on the left. With the use of spacers between the two wood surfaces, water and dirt have no change of accumulating between the surfaces and it provides ventilation so that the wood dries faster when wet.

Figure 3.7: Left, railing joint usign spacers to create a gap between the railing post and main beam for drainage and ventilation. Right, railing joint susceptible for water trapping. (Both bridges located in Pijnacker)

Vegetation

Vegetation on or close to timber elements leads to a long term high moisture content in combination with oxygen. These conditions, which are ideal for the development of fungi, lead to an accelerated deterioration of the timber close to the vegetation. Therefore a situation like in figure 3.8 should be avoided.

Figure 3.8: Example of vegetation growing around a timber pole

Cladding and covers

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Figure 3.9: Fully protected timber arch bridge located in Lohmar, Germany, build in 2014. The main structural timber elements (arches and main girders made from glue laminated spruce) are protected by titanium zinc covers on top and cladding made from larch on the sides [11]

Roofs

The new generation of timber bridges – durable by protection - Antje Simon

3.4. Codes and standards

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3.5. Mechanical loads on timber bridges

Pedestrian and cyclist bridges

In Eurocode 1-2: *Traffic loads on bridges*, the following vertical actions on cycle- and footbridges that need to be taken into account in the design are given:

- a uniformly distributed load, $q_{fk} = 5kN/m^2$,
- a concentrated load, $Q_{fwk} = 7kN$ (Dutch National Annex),
- loads representing service vehicles, Q_{serv}.

Also a horizontal force, Q_{flk}, needs to be taken into account equal to the bigger of the following two values:

- 10 per cent of the total load corresponding to the uniformly distributed load,
- 60 per cent of the total weight of the service vehicle, if relevant.

Road bridges

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3.6. Timber bridge inspection

Points for attention when inspecting a timber bridge (following from previous chapters):

- Blue stain fungi indicate that the right conditions for the growth of food destroying fungi are present.
- For constructions above water, wood deteriorating fungi develop at places where moisture can accumulate and ventilation is limited. At these places brown- and/or white-rot will develop.
- Soft rot occurs at timber poles at the heigth of the waterline.
- Rotten wood can at the wood surface be recognised by being white and soft (in case of white rot) or brown and brittle (in case of brown rot).
- White rot mainly appears in hardwoods, while brown rot mainly appears in softwoods.
- The presence of vegetation on or close to timber elements can lead to accelerated deterioration of the timber.

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II

Part II: Service life models

4

Model descriptions

4.1. Japanese factor method

In a study done by Honda and Araki [4], the service life of 72 timber bridges was estimated using a model, based on the factor method, developed by the Japanese Society of Civil Engineers [8].

The JSCE model estimated the service life using the following formulas:

$$ESL = 15 * Y \tag{4.1}$$
$$Y = P * E * S * D * C + M \tag{4.2}$$

In which:

ESL	:	is the estimated service life in years.
15	:	is the reference service life.
P	:	is a factor accounting for the wood specie used.
E	:	is a factor accounting for the climate conditions .
S	:	is a factor accounting for the structural design.
D	:	is a factor accounting for any decay preventing detailing applied.
C	:	is a factor accounting for any decay preventing execution measures used.
M	:	is a factor accounting for any maintenance done.

The reference service life of 15 years is based on experience and counts for the following situation: a girder bridge with a timber deck, made out of cedar with no preservative treatment, situated in an average (Japanese) climate, no use of a roof or any other decay preventing detailing, standard execution process and without any maintenance. In this situation all the factors are equal to 1.

Honda and Araki found, after a first evaluation of 12 timber bridges, that the ESL prediction from formula 4.4 becomes off for bridges with a service life larger than 16 years. Therefore they proposed the following exponential function for the service life estimation with a maximum service life of 50 years, see also figure 4.1:

$$ESL = 7.0\ e^{0.73Y} \ \leq \ 50 years \tag{4.3}$$

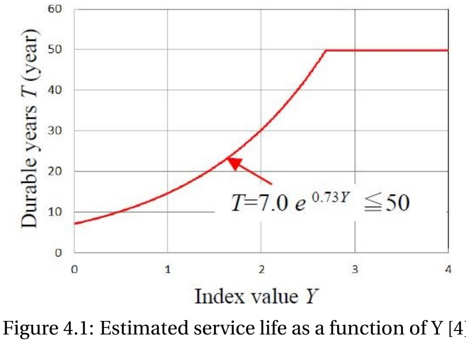


Figure 4.1: Estimated service life as a function of Y [4].

Factor values

The factors and their formulas are set out in table 5.2. The lists with values for the different factors and sub-factors are shown in table 4.3.

Table 4.1: Factors and sub-factors [4]

Factors		Sub-factors	Formulas
P	P1:	Durability of the wood	$P = P_1 + P_2 * P_3$
	P2:	Permeability of the preservative	
	P3:	Method of preservative treatment	
E	E1:	Regional climate conditions	$E = E_1 * E_2$
	E2:	Local climate conditions	
S	S1:	Existence of a roof	$S = S_1 * S_2 * S_3 * S4$
	S2:	Location of deck	
	S3:	Main structural style	
	S4:	Deck style	
D	d:	Prevention of decay (structural)	$D = d$
C	c:	Prevention of decay (execution)	$C = c$
M	m:	Conservation action	$M = \sum(N * m)$
	N:	Frequency	

For factor P1 a number of often used wood species for timber bridges in Japan were ranked based on their weather resistance, which was found from field pile tests. Factor P2 ranks the same wood species based on their permeability, or the ability to absorb preservatives.

Factor E1 is the factor that takes into account the regional climate conditions. In the model developed by the JSCE this climate factor is only a function of the mean annual temperature of the region relative to the national mean annual temperature which is equal to 15.5 degrees Celsius, see table 4.2. Figure 4.2 shows a map of the different climate regions of Japan. The other climate factor, E2, describes the local climate conditions with respect to moistness. For this there are two options: a general local environment or a moist local environment. From the obtained literature it is not clear what exactly is understood with a 'moist' environment.

Table 4.2: Determination of the climate factor E1 [4] [8].

E1:	1.2	1.1	1.0	0.9	0.8
$R_T = T_L / T_A$	$R_T \leq 0.74$	$0.74 < R_T \leq 1.0$	$1.00 < R_T \leq 1.16$	$1.16 < R_T \leq 1.25$	$1.25 < R_T$
T_L = annual mean temperature at bridge location T_A = National (Japanese) annual mean temperature (15.5 deg)					

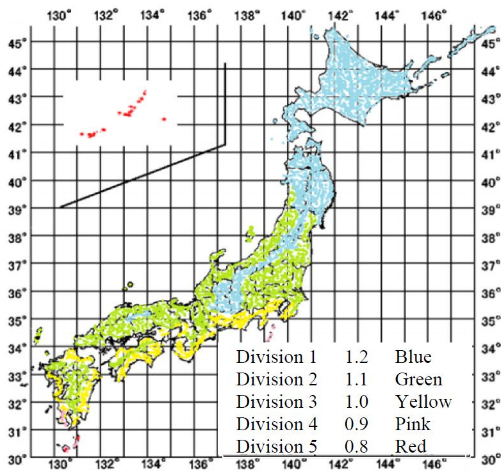


Figure 4.2: Map of Japan showing the different climate regions for factor E1 [4].

Table 4.3: List of values for the different factors [4] [8].

P_1 : Timber specie	
Cypress, Bongossi (Azobe), Zelkova, Japanese cypress, chestnut	1.5
Cedar, bay pine, Larch	1.0
Fir, red pine, Black pine	0.9
Todomatsu, Ezomatsu, Camphor tree	0.8

P_2 : Permeability of preservative	
Japanese Cypress	1.1
Cedar, bay pine, fir, Red pine, black pine	1.0
Cypress, zelkova, larch, Scots pine, Todomatsu	0.9
Chestnut, bongoshi, Kunugi, camphor tree	0.8

P_3 : Preservative treatment	
Pouring and a surface treatment	1.0
Pouring treatment	0.6
Surface treatment	0.3
No preservative treatment	0

E_1 : regional climate	
Climate region 1	1.2
Climate Region 2	1.1
Climate Region 3	1.0
Climate Region 4	0.9
Climate Region 5	0.8

E_2 : Local climate	
General local environment	1.0
Moist local environment	0.7

S_1 : Presence of roof	
With roof	2.0
Without roof	1.0

S_2 : Location of deck	
Deck on top	1.0
Half trough deck	0.8
Trough deck	0.8

S_3 : Main structural type	
Girder bridge	1.0
Arch bridge	0.9
Slab bridge	0.8
Truss bridge	0.7

S_4 : Deck style	
Steel plate deck, rc deck	1.8
Timber deck (with pavement)	1.5
Timber deck (without pavement)	1.0

d : Decay prevention (Structural)	
Prevention of decay specially considered in design	1.3
Standard design	1.0

c : Decay prevention (execution)	
Prevention of decay specially considered during execution	1.2
Standard Execution	1.0

M : Maintenance	
- Re-preservation of main girder with anti-decay coating. - Replacement of decayed elements	0.3
No maintenance	0.0

The factors $S_1 - S_4$ take into account the structural design of the bridge. Historical examples show that roofs are an excellent way to extend the service life of timber bridges. Therefore factor S1 takes into account the presence or absence of a roof. The reason of factor S2 is similar. When the deck is placed on top of the main girders it protects these girders against the weather conditions. The values for S3 are based on the amount and type of connections and elements that belong to the different structural types. A truss bridge has, relative to a girder bridge, a lot of joints and is thus more likely to retain water and development of decay is more likely. Factor S4 is based on the water tightness of the deck and again has to do with the protection of the underlying timber elements against water.

Factor D depends on whether decay preventing detailing has been incorporated into the bridge design. It does not rank the detailing but it just takes into account whether it has been applied yes or no.

Factor C depends on whether decay preventing measures have been applied during the execution of the bridge. These are measures such as protecting timber elements from rain by covering them up.

Reality checks

The prediction formula was set with the use of 12 timber bridges that got closed or removed because of timber decay. Since for these bridges the actual service life time was known, they could be used to calibrate the prediction formula , see table 4.4.

Factor method ISO 15686

The main principle of the Japanese method, multiplying a reference service life with a number of factors, is similar to the factor method described in the ISO 15686 series [13]. With this method an Estimated Service Life (ESL) can be calculated by multiplying a Reference Service Life (RSL) with a number of factors, as shown in equation 4.4 [5].

$$ESL = RSL * A * B * C * D * E * F * G \tag{4.4}$$

The values of the factors A-G need to be determined per element or structure and depend on certain conditions such as the material quality, the protection against weather conditions and the outdoor (or indoor) climate.

In a more general way the ISO 15686 factor method can be formulated as follows:

$$ESL = f(RSL, A, B, C, D, E, F, G) \tag{4.5}$$

Table 4.4: Expected and actual service life of 12 existing timber bridges. [8]

Bridge name	Bridge outline	Y value	Expected years	Actual years	Remarks
A: bridge Hokkaido Takikawa	Beimatsu, surface treatment, Arch Bridge (wood floor version)	1.1	17	17	bridge closed
B: bridge Hokkaido Takikawa	Beimatsu, surface treatment, Cable-stayed bridge (wood floor version)	1.2	19	17	Road Closed
K: bridge Kamo City, Niigata Prefecture	Sugi, no preservative treatment, Girder bridge (steel floor version)	1.4	21	22	Removed
N: bridge Toda City, Chiba Prefecture	Bongossi, no preservative treatment, Lower path truss bridge (wooden floor)	1.2	18	16	Road Closed
Q: bridge Karuizawa Town, Nagano Prefecture	Larch, surface treatment, Nakaji style ramen bridge (wooden floor)	1.8	28	24	Removed
R: bridge Shizuoka Prefecture Shimada City	Sugi, no preservative treatment, Girder bridge (wood floor version)	1.0	15	15	Road Closed
T: bridge Shizuoka Prefecture Shizuoka City	Sugi, no preservative treatment, Girder bridge (wood floor version)	1.5	23	20	Road Closed
Y: bridge Fukuyama City, Hiroshima Prefecture	Beimatsu, surface treatment, Lower path truss bridge (wood floor version)	0.7	11	13	Removed
AD: Bridge Kitawa-gun, Ehime Prefecture	Bongossi, no preservative treatment, Lower path truss bridge (wood floor version)	0.8	13	10	Removed
AJ: Bridge Oita City, Oita Prefectur	Bongossi, no preservative treatment, Lower arch bridge (wood floor version)	1.1	16	13	Removed
F: bridge Hokkaido	Larch (presumed), surface treatment, Girder bridge (Co floor version)	2.7	41	68	In service, but reinforced.
G: bridge Hokkaido	Larch (presumed), surface treatment, Girder bridge (Co floor version)	2.7	41	68	In service, but reinforced.

4.2. Australian decay rate method

Another model that estimates the service life of outdoor timber elements was developed in Australia during an extensive research funded by FWPA (Forest and Wood Products Australia). The research resulted in a technical guide [11] that addresses, among others, service life estimations of timber elements in multiple situations such as in-ground and above-ground decay. Other outcomes of the research are: a draft proposal for an Australian standard which provides calculation procedures for assessing the remaining structural adequacy of timber elements [14], an educational software called 'TimberLife' that provides detailed estimates of service life performance for an extensive range of hazards, and seven detailed technical reports documenting the durability and service life estimation models.

The reports give service life estimation models for a number of deterioration hazards that timber elements are subjected to in Australia. For this thesis the two main interesting hazards are in-ground and above-ground fungal attack which are handled in ManualNo3: Decay in ground contact, and ManualNo4: Decay above ground [19] [3].

Service Life

The model is based on the assumed idealised development of decay shown in figure 4.3. This development of decay is characterised by two parameters: a decay rate, r (in mm/year), and a time lag, t_{lag} (in years). In the technical guide two limit states are considered:

- **Onset of decay**: This service life refers to an estimate of the mean time taken for the decay to develop to a depth of 2 mm.
- **Need for replacement**: Refers to an estimate of the mean time taken for the decay to develop to a depth of 10 mm.

The decay depth after t years is given as:

$$d_t = \begin{cases} ct^2, & \text{if } t \leq t_{d0} . \\ (t - t_{lag})r, & \text{if } t > t_{d0} . \end{cases} \tag{4.6}$$

in which

$$t_{d0} = t_{lag} + \frac{d0}{r} \tag{4.7}$$

$$c = \frac{d0}{t_{d0}^2} \tag{4.8}$$

The decay lag, t_{lag} in years, is assumed to function of the decay rate r:

$$t_{lag} = 8.5r^{-0.85} \tag{4.9}$$

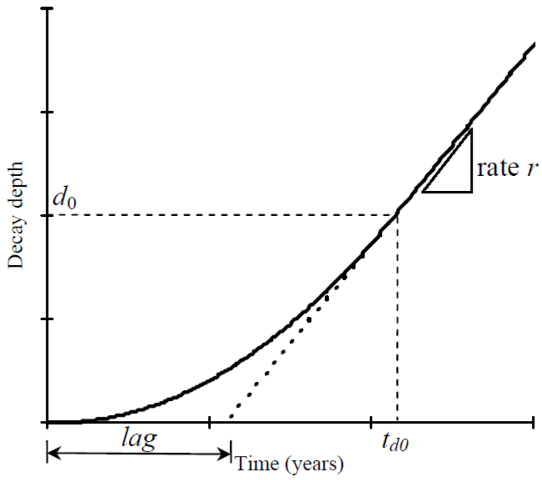


Figure 4.3: Idealised progress of the decay depth over time [3].

For a given time lag t_{lag} and decay rate r, and assuming that $d_0 = 5mm$, the service life for the two earlier mentioned limit states can be determined as follows:

$$L_S = \left(t_{lag} + \frac{5}{r}\right)\sqrt{\frac{2}{5}} \qquad \text{(onset of decay)} \tag{4.10}$$

$$L_R = t_{lag} + \frac{10}{r} \qquad \text{(replacement)} \tag{4.11}$$

Both functions are derived from equation 4.6 assuming that $d_0 = 5mm$ and using $d = 2mm$ for the onset of decay and $d_0 = 10mm$ for replacement.

Design calculations

Part of the research was a proposal for a new Australian standard that will provide design procedures for dealing with timber decay [14]. In the proposal for this standard, called AS1720.5 - Timber Service Life Design Code, the design decay depth is to be determined as follows:

$$d_{design} = d * (1 + \alpha V_d) \tag{4.12}$$

In which:

d : is the mean decay depth for a chosen design life time, calculated using equation 4.13, which is a simplified version of equation 4.6, see also figure 4.4.

V_d : is the coefficient of variation of d. The in the proposal recommended value of V_d is 2.0.

α : is a specified parameter related to the target reliability level. The proposed values are:

- $\alpha = 0.8$ for normal consequences of element failure.
- $\alpha = 0.4$ for low consequences of element failure.
- $\alpha = 0.1$ for serviceability considerations.

$$d = \begin{cases} 0, & \text{if } t \le t_{lag} . \\ (t - t_{lag})r, & \text{if } t > t_{lag} . \end{cases} \tag{4.13}$$

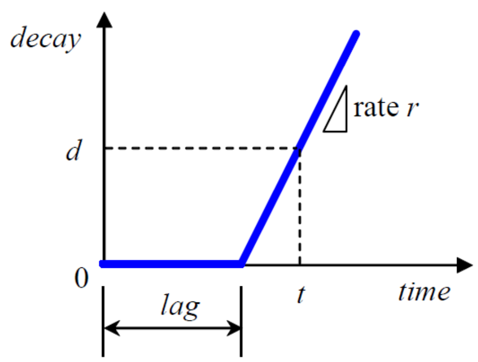


Figure 4.4: Simplified progress of the decay depth over time [14].

Decay rate r

The decay rate r for a certain timber element surface is calculated as the product of a number of factors that account for the timber specie, geometry and environmental factors:

$$r = k_{wood} k_{climate} k_p k_t k_w k_n k_g \tag{4.14}$$

In which:

k_{wood}	:	is a wood parameter,
$k_{climate}$	:	is a climate parameter,
k_p	:	is a paint parameter,
k_t	:	is a thickness parameter,
k_w	:	is a width parameter,
k_n	:	is a fastener parameter
k_g	:	is a geometry parameter.

It should be noted that the decay rate r is determined for one **surface** of a timber element. For example: for a simple timber board supported on both ends, the top surface, which is the most exposed to the weather conditions, will have a higher decay rate than the bottom surface and thus the decay rate r should be separately determined for both surfaces.

Wood parameter k_{wood}

The value for the wood parameter k_{wood} depends on the durability class in which the used timber specie is ranked. The durability ranking followed is the one set out in the Australian standard AS 5604. The values corresponding to the classes are shown in equation 4.15.

$$k_{wood} = \begin{cases} 0.50, & \text{for durability class 1.} \\ 0.65, & \text{for durability class 2.} \\ 1.15, & \text{for durability class 3.} \\ 2.20, & \text{for durability class 4.} \\ 6.52, & \text{for sapwood.} \end{cases} \tag{4.15}$$

Climate parameter $k_{climate}$

Figure 4.5 shows a map of Australia divided into four different climate areas. Each zone has its own value for the climate parameter $k_{climate}$, see equation 4.16.

$$k_{climate} = \begin{cases} 0.40, & \text{for zone A.} \\ 0.50, & \text{for zone B.} \\ 0.65, & \text{for zone C.} \\ 0.75, & \text{for zone D.} \end{cases} \tag{4.16}$$

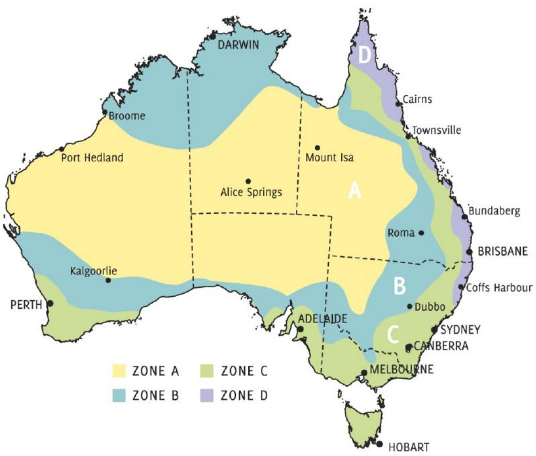


Figure 4.5: Map of Australia divided in four climate zones [3].

Based on tests, the following relationship was found between $k_{climate}$ and the annual rainfall duration t_{rain}:

$$k_{climate} = \begin{cases} 0.15 t_{rain}^{0.50}, & \text{if } t_{rain} \text{ is in days per year.} \\ 0.03 t_{rain}^{0.50}, & \text{if } t_{rain} \text{ is in hours per year.} \end{cases} \tag{4.17}$$

An other outcome of these tests was that there seemed to be no correlation between $k_{climate}$ and the local mean annual temperature.

Paint parameter k_p

For unpainted wood the value of k_p is 1.0. For timber elements that are painted the value depends on the durability class of the wood:

$$k_p = \begin{cases} 3.5, & \text{for durability class 1.} \\ 2.0, & \text{for durability class 2.} \\ 1.8, & \text{for durability class 3.} \\ 1.4, & \text{for durability class 4.} \\ 1.3, & \text{for sapwood.} \end{cases} \tag{4.18}$$

Thickness parameter k_t

The thickness parameter accounts for the effect of drying in the transverse direction to the timber grain. When a part of a timber element is not in contact with another element it tends to dry rapidly when it is thin enough. For surfaces in contact with other elements the value of k_t is 1.0

$$k_p = \begin{cases} 1, & \text{for } t \geq 20mm. \\ 0.5, & \text{for } t \leq 10mm. \\ 0.05t, & \text{otherwise.} \end{cases} \tag{4.19}$$

Width parameter k_w

Bigger width of the element means more restrains on the wood surface during drying and can thus lead to larger and deeper checks on the surface that can subsequently lead to faster decay. For surfaces in contact with other elements the value of k_w is 1.0

$$k_w = \begin{cases} 1, & \text{for } w \leq 50mm. \\ 2, & \text{for } w \geq 200mm. \\ 1 + \dfrac{w-50}{150}, & \text{otherwise.} \end{cases} \tag{4.20}$$

Connector parameter k_n

Parameter that accounts for the effect of a connector on the decaying surface. The interface/gap between the connector and its hole would act as a path of moisture entry to enhance the decay progress.

$$k_n = \begin{cases} 2.0, & \text{if a connector is present.} \\ 1.0, & \text{if a connector is not present.} \end{cases} \tag{4.21}$$

Geometry parameter k_g

The geometry factor k_g is a multiplication of the two sub-factors k_{g1}, the contact factor, and k_{g2}, the position factor. These two factors take into account the detailing of the element or connection, and its orientation. These factors were at first based on estimations of experts and were later modified based on construction field data. They are considered as critical factors in the prediction of the decay rate.

Contact factor k_{g1}:
The value of the contact factor k_{g1} depends on whether the assessed surface is in contact with other structural elements or not. Three options are possible: a non-contact surface, a flat contact surface and an embedded contact surface. Figure 4.6 shows these three options with their corresponding k_{g1} values.

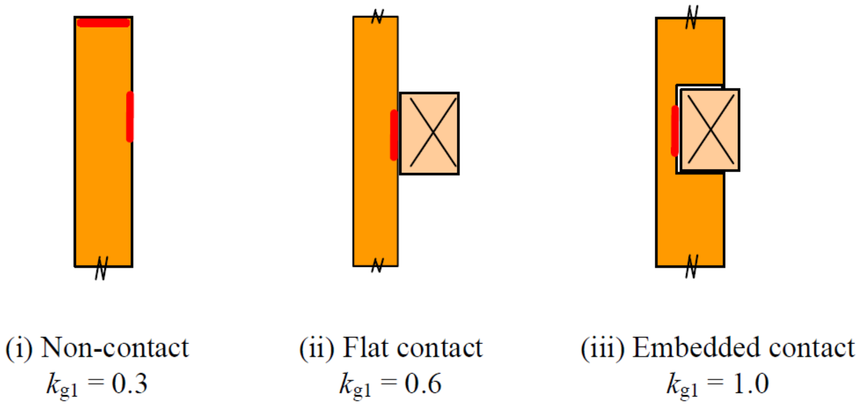


Figure 4.6: Illustrations of non-contact, flat contact and embedded contact surfaces [3].

Position factor k_{g2} for non-contact surfaces:
For non-contact surfaces, the position factor k_{g2} takes into account the orientation of the member and the surface, and the sheltering effect. The orientation effect is taken into account because of the mechanical degradation caused by the sun.

(a) For vertical members
For vertical members the position factor k_{g2} depends on the orientation of the surface that is being assessed. The following six options are possible: (see also figure 4.7)

- Top (flat) $k_{g2} = 6.0$
- Top (sloped) $k_{g2} = 5.0$
- facing north $k_{g2} = 2.0$
- facing south $k_{g2} = 1.5$
- facing east $k_{g2} = 1.5$
- facing west $k_{g2} = 2.0$

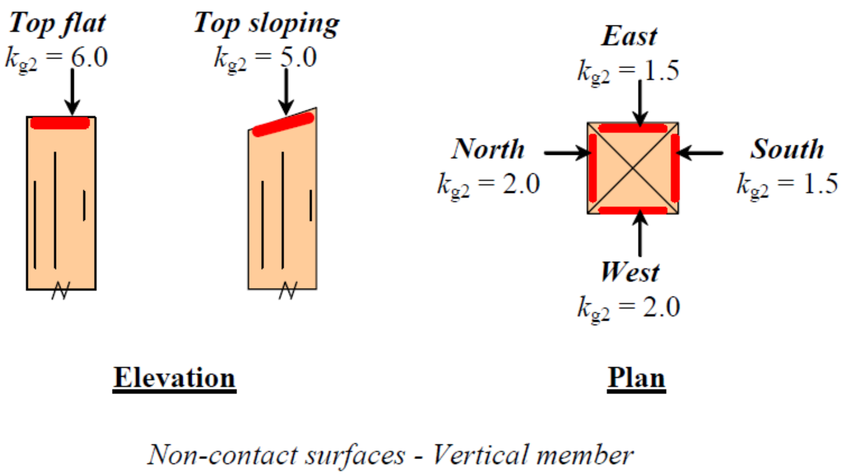


Figure 4.7: The different orientations for factor k_{g2} for vertical members [3].

(b) For horizontal members

For horizontal members the position factor k_{g2} also depends on the orientation of the surface that is being assessed. In this case the following options are possible:

- Horizontal surface
  - Top of member $k_{g2} = 3.0$
  - Bottom of member $k_{g2} = 1.5$
- Vertical side surface (side grain)
  - Sheltered (by decking) $k_{g2} = 1.0$
  - Exposed to north $k_{g2} = 2.0$
  - Exposed to south $k_{g2} = 1.5$
  - Exposed to east $k_{g2} = 1.5$
  - Exposed to west $k_{g2} = 2.0$
- Vertical end surface (end grain)
  - Sheltered (by decking) $k_{g2} = 2.0$
  - Exposed to north $k_{g2} = 4.0$
  - Exposed to south $k_{g2} = 3.0$
  - Exposed to east $k_{g2} = 3.0$
  - Exposed to west $k_{g2} = 4.0$

Position factor k_{g2} for contact surfaces:

The position factor k_{g2} for contact surfaces, both flat and embedded contacts, takes into account the type of material in contact, the presence of a gap, and the gap size and location. The factor k_{g2} is a multiplication of the factors k_{g21}, k_{g22} and k_{g23}.

$$k_{g2} = k_{g21} k_{g22} k_{g23} \tag{4.22}$$

The factor k_{g21} takes into account the material with which the timber element is in contact with:

$$k_{g21} = \begin{cases} 1.0, & \text{when in contact with wood.} \\ 0.7, & \text{when in contact with steel.} \\ 1.0, & \text{when in contact with concrete.} \end{cases} \tag{4.23}$$

The factor k_{g22} takes into account the orientation of the assessed surface.

$$k_{g22} = \begin{cases} 2.0, & \text{for a horizontal surface facing upwards.} \\ 1.0, & \text{otherwise.} \end{cases} \tag{4.24}$$

The factor k_{g23} takes into account the presence of a gap together with its size and location. There are three options: (see also figure 4.8)

(a) A continuous member in contact with a continuous member.

$$k_{g23} = 1.0$$

(b) A continuous member in contact with a butted member.

$$k_{g23} = 1.2$$

(c) A butted member.

$$k_{g23} = \begin{cases} 2.0, & \text{when gap size is} \leq 1.0mm. \\ 1.3, & \text{when gap size is} \geq 2.5mm. \\ \frac{3.7}{1.5} - \frac{0.7}{1.5} * gapsize, & \text{otherwise.} \end{cases} \tag{4.25}$$

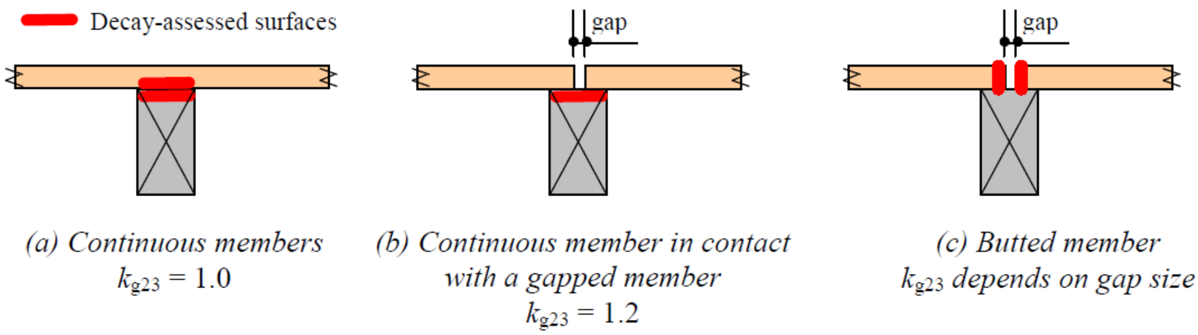


Figure 4.8: Illustrations showing the different options for factor k_{g23} [3].

Effect of sealing layers

In the proposal for the Australian standard AS1720.5, an extra parameter was added taking into account the effect of a sealing layer, used as shown in figure 4.9. The effect of such a sealing layer is accounted for by adding an extra time lag to the time lag t_{lag} determined from equation 4.9. The extra time lag is shown in table 4.5. Three different sealing materials are considered for this. The sealing layer has no effect on the decay rate r.

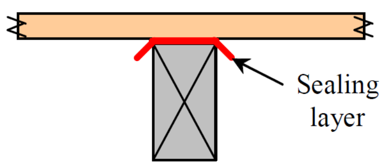


Figure 4.9: Sealing layer placed below the deck [14].

Table 4.5: Extra time lag due to sealing layer [14].

Sealing layer material	**Extra lag (years)**
Copper naphthenate paste	5
Malthoid DPC	10
Plastic aluminium DPC	10

4.3. Mechanical performance modelling

Mechanical performance modelling has been used by van de Kuilen and Gard to estimate the service life of timber structures. Their method is based on the reliability function shown in equation 4.26 [18].

$$Z = R - S \tag{4.26}$$

Where R is the resistance and S the load. The method states that both the resistance and the load are time dependent. The assumption is that in time the resistance decreases, due to the load level and degredation processes, and the load increases, due to for instance increasing snow or wind loads. Equation 4.26 then can be written as follows.

$$Z(t) = R(t) - S(t) \tag{4.27}$$

The distribution of Z(t) over time is shown in figure 4.10.

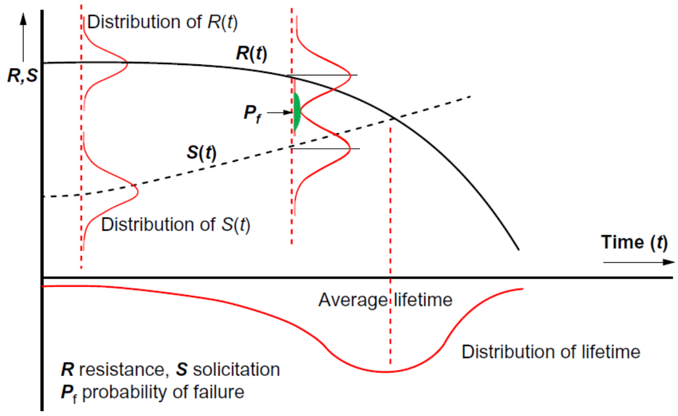


Figure 4.10: Lifetime distribution of structures [18]

van de Kuilen and Gard (2017)

The method is applied by van de Kuilen and Gard to determine the service life of an outdoor glulam beam. Visual inspection of the beam showed that it suffered from funghi decay and delamination cracks. A linear exponential damage acumulation model is used to calculate the degradation due to the load effect, and an assumed constant decay rate is used to calculate the deteriation due to biological decay. One of the results is shown in figure 4.11.

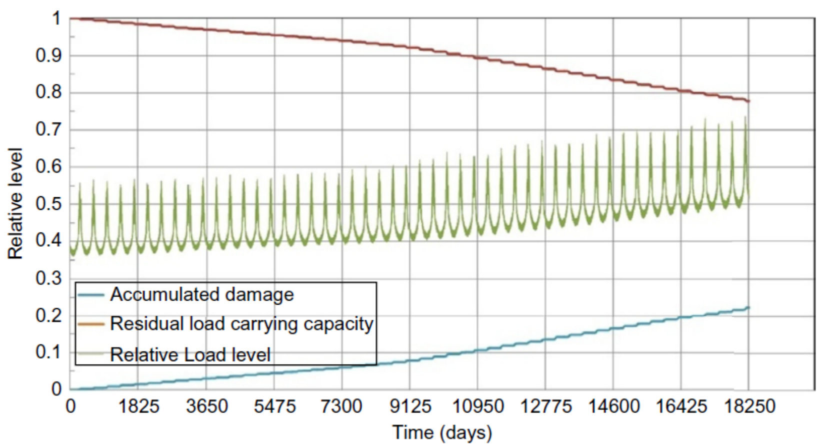


Figure 4.11: Service life calculation for 50 years, load case 2 (dead load + live load + snow load) and biological deterioration 0.5 mm/year with a delay time of 5 years. [18]

4.4. Markov Chain

In their article *Deterioration Prediction of Timber Bridge Elements Using the Markov Chain*, Ranjith et al. give the following description of what a Markov process is:
"A Markov process describes a system that can be in one of several (numbered) states, and can pass from one state to another at each time step according to fixed probabilities. If a Markov system is in state i, there is a fixed probability, p_{ij}, of it going into state j at the next time step, and p_{ij} is called a transition probability."
An example of a Markov process with a typical transition matrix is shown in figure 4.12

Condition state	State 1	State 2	State 3	State 4	Sum
1	0.4	0.3	0.2	0.1	1
2	0	0.5	0.3	0.2	1
3	0	0	0.7	0.3	1
4	0	0	0	1	1

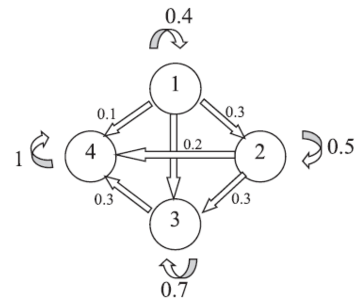


Figure 4.12: Example of a markov process with corresponding transition matrix for a four-stage condition stage [17]

The Markov Chain model can be used in combination with bridge condition data that includes ratings of individual components such as the deck, the main girders and the corbels. The Roads Corporation of Victoria, Australia, for instance uses four condition classes for the rating of timber bridge elements ranging from C1 (good condition) to C4 (bad condition) [17]. Another example is the rating system that the USA's Federal Highway Administration (FHWA) uses for all of their bridges (not just timber) and which exists of nine condition classes going from class 9 (excellent condition) to class 0 (failed condition) [3].

Research using the Markov Chain

Ranjith et al. 2013 [17]

Ranjith et al. use a stochastic Markov chain model to predict the future condition of timber bridge elements. For this they make use of condition data obtained from the Australian Roads Corporation of Victoria which they used to develop the transition probabilities. A typical set of data for a certain timber bridge is shown in figure 4.6. A timber bridge is divided into eight main elements and the condition of each of these elements can be divided into four condition classes. These condition classes go from C1 (good condition with no decay) to C4 (Heavy rot, decay, splitting or crushing). The percentages in the table in figure 4.6 show what percentage of an element is in a certain condition class.

Table 4.6: Typical data set for a certain timber bridge [17].

Element	Inspection period	Structural identification number	Year of inspection	$\%C_1$	$\%C_2$	$\%C_3$	$\%C_4$
Deck	2	SN4867	1998	60	40	0	0
			2000	20	60	20	0
Pile	3	SN6997	1999	80	20	0	0
			2002	50	50	0	0
Abutment	4	SN6996	1997	90	5	5	0
			2001	70	0	30	0
Curbs	3	SN3776	1996	100	0	0	0
			1999	75	0	25	0
Railing	2	SN5878	1997	0	0	0	100
			2001	0	0	0	100
Cross	3	SN5772	1999	50	50	0	0
beam			2002	50	50	0	0
Girder	2	SN8970	1998	90	0	10	0
			2000	0	0	100	0
Corbels	4	SN8791	2002	95	5	0	0
			2006	55	26	19	0

4.5. Swedish dose-response method

This service life estimation method had been developed within the Swedish DuraTB - Durable Timber Bridges - project. The goal of this project was "to contribute to the development of sustainable timber bridges by making guidelines for moisture design and developing new and improved bridge concepts and details in terms of durability and maintenance aspects" [16].

The method deals with timber in outdoor above ground applications, which is timber in use class 3 according to EN 335 (2013), and consideres fungal decay as deterioration mechanism. It is based on the assumption that the service life of a wooden structure with respect to fungal decay is based on the following two main factors:

- **The climatic exposure**: i.e. geographical location, local climate, degree of protection against rain, distance to ground, detailing with respect to moisture trapping and maintenance measures.
- **The material resistance**: different wood species with different kinds of preservation (or without preservation) display different resistance against decay.

The exposure is primarily affected by the design and construction of the bridge and is independent of which wood specie is used, while the resistance is primarily a function of the choice of material.

Service life

The climatic exposure and material resistance are measured as a dose of which the unit is time (in days). The method can be used to evaluate the durability of individual elements of timber bridges. It states that a selected design solution is acceptable when the cumulative exposure during the intended service life time is smaller than the material resistance.

Exposure ≤ Resistance

Mathematically this is shown in equation 4.28.

$$D_{Ed} * SL = D_{Ek,c}\gamma_d \ * SL \leq \ D_{Rd} \tag{4.28}$$

In which:

D_{Ek}	:	is the characteristic **annual** exposure dose,
SL	:	is the intended service life of the element,
D_{Rd}	:	is the design value of the resistance dose,
γ_d	:	is a factor that depends on the severity class.

In the final report of the DuraTB project, Durable timber bridges - Final report and guidelines [16], procedures are set out on how to determine the characteristic annual exposure dose D_{Ek}, the design resistance dose D_{Rd} and the severity factor γ_d. When these are all known, the estimated service life can be determined as follows:

$$\text{Estimated service life } = \frac{D_{Rd}}{D_{Ek} * \gamma_d} \text{ (in years)} \tag{4.29}$$

Limit state

In the research the severity of decay is rated following the decay rating from EN 252 which consists of five decay rankings: 0 (no decay), 1 (slight attack), 2 (moderate attack), 3 (severe attack) and 4 (failure). The design resistance dose, discussed in more detail later on, is based on the point in time at which the wood reaches decay ranking 1 (slight attack), which in the research is also defined as the onset of decay.

Limit state = onset of fungal decay (slight attack)

Dose response functions

In order to obtain data for the development of timber durability models, field trials with Scots pine sapwood (*Pinus sylvestris* L.) and Douglas fir heartwood (*Pseudotsuga menziesii* Franco) were conducted at 24 test sites in Europe [6]. The specimens were monitored in terms of moisture content, temperature and progress of fungal decay. The decay rating was done following EN 252 which uses the following five rankings: 0 (no decay), 1 (slight attack), 2 (moderate attack), 3 (severe attack) and 4 (failure).

The tests resulted in so called dose-response functions that are able to show the relationship between the mean decay rating and the cumulative dose at a certain moment in time, see figure 4.13. The annual dose D is a function of two components: a component D_u which depends on the moisture content m_u of the wood, and a component D_T that depends on the temperature T of the wood. This can be mathematically written as follows:

$$D = f(D_T(T), D_u(u)) \tag{4.30}$$

For n days the cumulative dose is given by:

$$D(n) = \sum_1^n D_i = \sum_1^n f(D_T(T_i), D_u(u_i)) \tag{4.31}$$

Where T_i is the average temperature and u_i the average moisture content of the wood on day i.

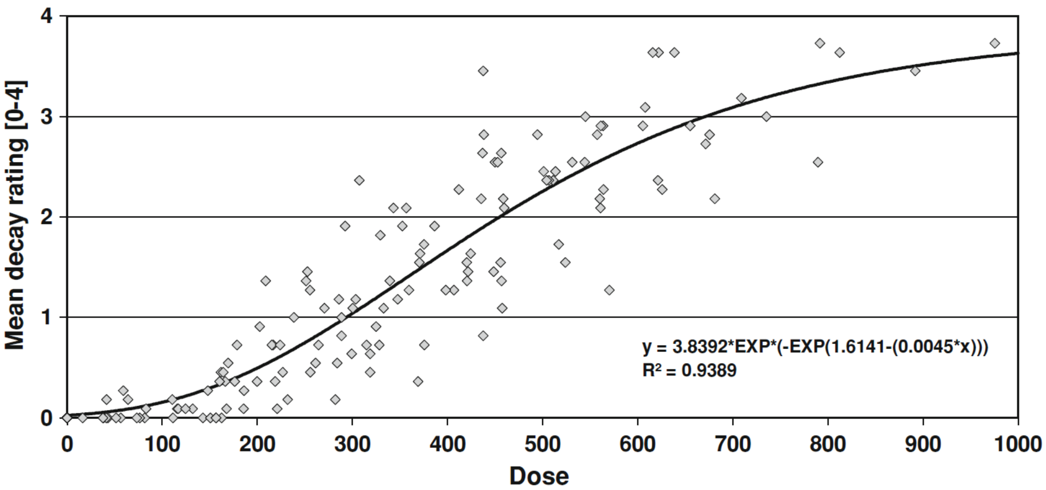


Figure 4.13: Example of a dose response function. This graph shows the relationship between the dose and the decay rating according to EN 252 for Scots pine sapwood test specimens located at 26 different field test sites. Each dot represents the mean decay rating at one exposure site at a certain time of exposure; black line: Gompertz smoothing function [1]

Annual exposure dose

The annual characteristic exposure dose D_{Ek} is determined as follows:

$$D_{Ek} = D_{E0} * k_{E1} * k_{E2} * k_{E3} * k_{E4} * c_a \tag{4.32}$$

In which:

D_{E0}	is the annual reference exposure dose depending on the geographical location. The reference exposure dose is determined for a horizontal timber element exposed to outdoor conditions such as rain, relative humidity and temperature, see figure 4.14.
k_{E1}	is a factor accounting for the effect of local climate conditions and driving rain.
k_{E2}	is a factor accounting for the effect of sheltering.
k_{E3}	is a factor accounting for the distance to the ground .
k_{E4}	is a factor accounting for the effect of durable detail design.
c_a	= 1.4, is a calibration factor estimated on the basis of reality checks, safety considerations and expert estimates.

How these factors are determined is described in the final report of the DuraTB study [16] and in a background document written by Isaksson et al. [7].

Annual reference exposure dose D_{E0}

Based on field tests, the annual reference exposure dose has been determined for the reference object shown in figure 4.14. This reference object consists of a horizontally exposed Norway spruce board with no moisture traps. The annual reference exposure dose depends on the climate conditions of the region the bridge is located at. It is a function of the relative humidity, rainfall and temperature of the location. In the DuraTB project multiple ways of determining the exposure dose have been discussed. In the final report the exposure dose has been estimated with the help of the following simplified logistic dose model (SLM) described by Isaksson et al [6]:

$$D = D_u(u) * D_T(T) \tag{4.33}$$

$$D_u(u) = \begin{cases} (u/30)^2 & \text{when } u \leq 30\%. \\ 1 & \text{when } u > 30\%. \end{cases} \tag{4.34}$$

$$D_T(T) = \begin{cases} 0 & \text{when } T < 0°C. \\ (T/30) & \text{when } 0°C \leq T \leq 30°C. \\ 1 & \text{when } T > 30°C. \end{cases} \tag{4.35}$$

In which:

D	is the exposure dose in days.
D_u	is the component of the dose that takes into account the wood moisture content
D_T	is the component of the dose that takes into account the wood temperature
u	is the moisture content of the wood in %.
T	is the temperature of the wood in ° C.

The wood moisture content and wood temperature are determined using climate data in the form of relative humidity, rainfall and temperature. For the estimation of the moisture content of the wood, a numerical model was developed within the DuraTB program [15] that uses the relative humidity and rainfall as input. The temperature of the wood is assumed to be the same as the air temperature.

Figure 4.14: Reference element for climate exposure – horizontally exposed spruce board without moisture traps [16]

The annual reference exposure dose was calculated for a large number of locations throughout Europe. The result was is shown in the form of a contour plot shown in figure 4.15 with the corresponding values listed in table 4.7.

Table 4.7: Annual exposure dose D_{E0} values for the zones displayed in figure 4.15. Valid for the reference object shown in Figure 4.14.

Zone	Annual exposure dose D_{E0} (days)		
	Mean	Range	Color code
a	66	63-69	
b	60	57-63	
c	55	52-57	
d	49	46-52	
e	43	40-46	
f	37	34-40	
g	32	29-34	
h	26	23-29	
i	20	17-23	
k	15	12-17	
m	9	6-12	

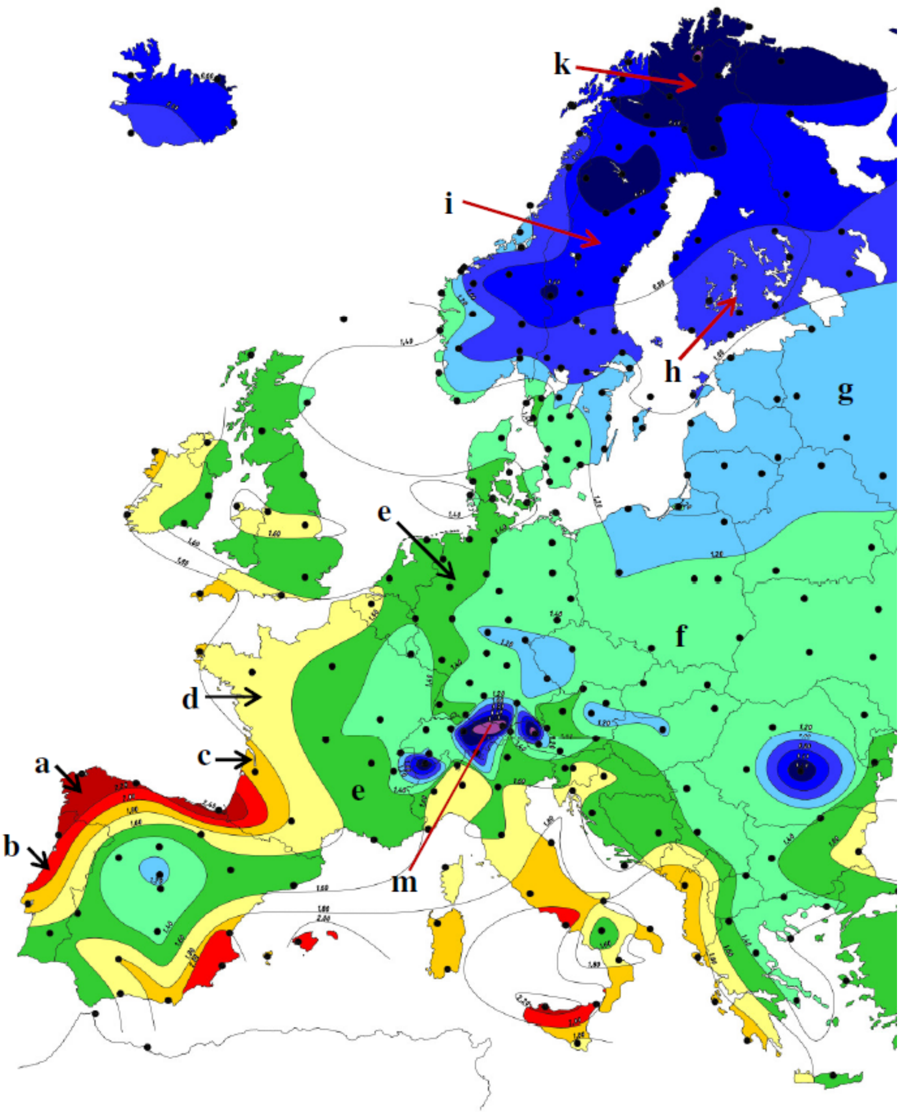


Figure 4.15: European climate zones [16].

Local climate factor k_{E1}

This factor takes into account the expected amount of driving rain and any protection that the surrounding provides against this phenomena. Protection against driving rain can for instance come from adjacent buildings. The values are shown in table 4.8. These values are based on expert opinions, not on experiments. For horizontal rain-exposed surfaces the value should always be taken as 1.0.

Table 4.8: Values for local climate factor k_{E1} [16]. For horizontal surfaces the k_{E1} should always be taken as 1.0.

Degree of exposure	**Protective effects are present**	**Driving rain expected at the site**	k_{E1}
Light	yes	no	0.8
Medium	yes	yes	0.9
Medium	no	no	0.9
Severe	no	yes	1.0

Degree of sheltering and distance to the ground (k_{E2} and k_{E3})

The effect of sheltering against above a timber element is described by the factor k_{E2}. It is determined by the ratio e/d, see figure 4.16.

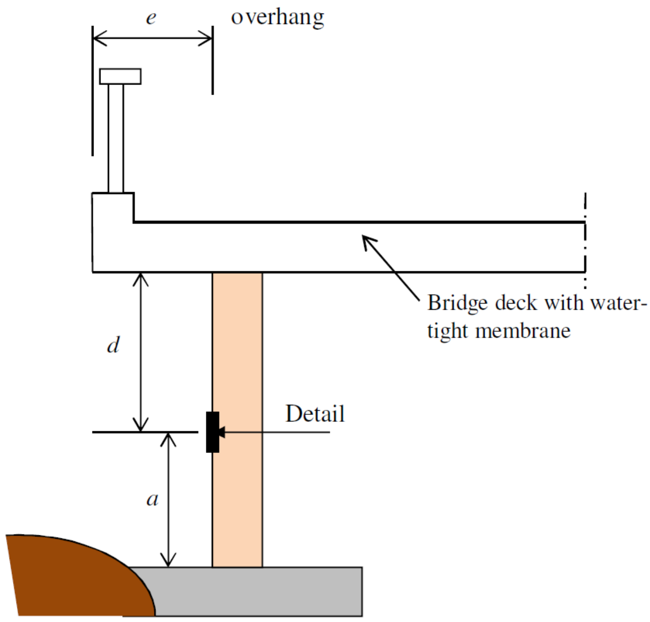


Figure 4.16: Definitions the parameters used for the determination of factors k_{E2} and k_{E3} [16].

When sheltering is provided the exposure dose is reduced by factor k_{E2} which can be calculated according to:

$$k_{E2} = \begin{cases} 1 - 0.2\dfrac{e}{d} & \text{if } 0 < \dfrac{e}{d} \leq 1 \\ 0.8 & \text{if } \dfrac{e}{d} > 1 \end{cases} \tag{4.36}$$

When elements are placed closer than 400 mm from the ground, an increase of exposure is considered. When the distance is smaller than 100 mm, the element is not considered since durability effects are very uncertain due being almost in ground-contact. The factor k_{E3} is calculated as follows:

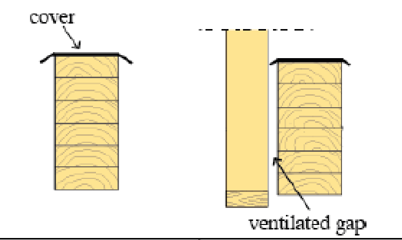
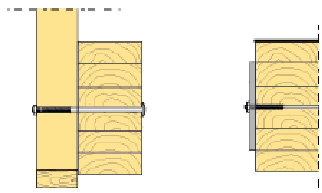
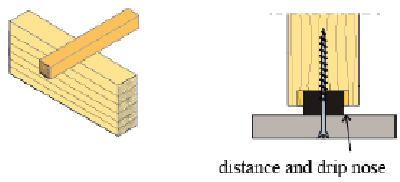
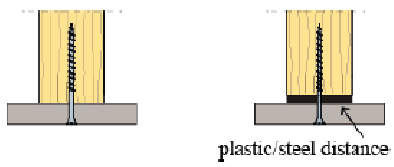
$$k_{E3} = \begin{cases} \dfrac{700 - a}{300} & \text{if } 100 < a \leq 400 \text{ mm} \\ 1.0 & \text{if } a > 400 \text{ mm} \end{cases} \tag{4.37}$$

Effect of detail design (k_{E4})

The effect of detail design was evaluated based on field tests carried out in the DURA-TB project, where a number of bridge details were exposed outdoors while the moisture content was measured continuously. A ranking was made containing five classes ranging from excellent to poor detail design. This ranking is shown in table 4.9.

Details that differ from the examples shown in table 4.9 need to be assessed by the degree of moisture exposure and related to one of the five classes shown in the table. Important in this assessment is the degree of rain exposure and the possibility of fast drying in order to avoid moisture traps. Also the opportunity for soil and dirt getting trapped in the joints need to be considered.

Table 4.9: Ranking of details with respect to exposure and corresponding values for factor k_{E4} [16].

Class	Description	Example	k_{E4}
Excellent	Design characterized by excellent ventilation (air gap > 10 mm) and no standing water. For example: a vertical surface without connecting members or with sufficient gap between members[1]		0,8
Good	Design characterized by excellent ventilation but standing water after rain events. For example: horizontal surface without connecting member.		1,0
Medium	Design characterized by poor ventilation but limited exposure to water. For example, vertical contact areas without sufficient air gap.		1,25
Fair	Design characterized by poor ventilation and high exposure to water **or** end-grain with good ventilation and limited exposure to water.[1] For example: horizontal contact areas and end-grain with sufficient air gap.		1,5
Poor	Design characterized by exposed end-grain with no ventilation and very high exposure to water. For example: end-grain contact area without air gap.		2

Material resistance dose

The material resistance dose D_{Rd} is determined as follows:

$$D_{Rd} = D_{crit} * k_{wa} * k_{inh} \tag{4.38}$$

In which:

- D_{crit} is the critical reference dose corresponding to the onset of decay, which is rating 1 (slight attack) according to EN 252 (2015). D_{crit} was evaluated for Scots pine sapwood and douglas fir heartwood and is estimated at 325 days [1].
- k_{wa} is a factor accounting for the wetting ability of the tested material, relative to the reference Norway spruce.
- k_{inh} is a factor accounting for the inherent protective properties of the tested material against decay, relative to the reference Norway spruce.

Within the DuraTB project the values of k_{wa} and k_{inh} for a number of timber species were determined by tests [12]. The resulting values of the material resistance dose D_{Rd} are shown in table 4.10.

Table 4.10: Material resistance D_{Rd} for a number of wood species, calculated with equation 4.38. The values of k_{wa} and k_{inh} were determined by tests [16]

Wood species	Botanical name	D_{Rd} (in days)	Relative D_{Rd}^2
Hardwoods			
Norway maple	Acer platanoides	344	1.06
Aspen	Populus tremula	373	1.15
Birch	Betula pendula	284	0.87
English oak	Quercus robur	1670	5.14
Beech	Fagus sylvatica	313	0.96
Teak	Tectona grandis	3027	9.32
Black locust	Robinia pseudoacacia	2298	7.07
Softwoods			
Norway spruce	Picea abies	325	1.00
Southern Yellow Pine (SYP)	Pinus spp.	727	2.24
Scots pine heart	Pinus sylvestris	856	2.63
Scots pine sap	Pinus sylvestris	304	0.93
Western Red Cedar (WRC)	Thuja plicata	1049	3.23
Juniper	Juniperus communis	1909	5.87
Siberian larch	Larix sibirica	1136	3.50
European larch	Larix decidua	1914	5.89
Douglas fir	Pseudotsuga menziesii	1716	5.28
Modified materials			
Oil-heat treated Spruce	Picea abies	2691	8.28
Oil-haet treated Ash	Fraxinus excelsior	3314	10.20
Thermally modified Scots pine	Pinus sylvestris	2850	8.77
Acetylated SYP (acetyl content: 19 %)[1]	Pinus spp.	3305	10.17
Acetylated Radiata pine (acetyl content: 20 %)[1]	Pinus radiata	3119	9.60
Furfurylated SYP (WPG:50 %)[1]	Pinus spp.	3049	9.38
Furfurylated Scots pine (WPG: 40 %)[1]	Pinus sylvestris	4886	15.03

[1] Weight percent gain of furfurylated wood and acetyl content of acetylated wood according to manufacturer's data.
[2] Relative to Norway spruce.

Calibration factor c_a

The value for the calibration factor c_a was set on 1.4, based on a number of reality checks.

Severity class γ_d

The durability severity class can be seen as a safety factor which takes into account the consequences of a lifespan shorter than estimated. The values of γ_d are shown in table 4.11.

Table 4.11: Different severity classes and corresponding values for γ_d [16].

Severity class	γ_d
1. Low (e.g. where it is accepted and easy to replace a limited number of components if decay should be initiated within expected service life)	0.6
2. Medium (e.g. when the expected economical and practical consequences are significant)	0.8
3. High (risk for human injuries or loss of lives)	1.0

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[1] Brischke C., Rapp A.O. (2008). *Dose-response relationship between wood moisture content, wood temperature and fungal decay determined for 23 European field test sites.*, Wood Sci. Technol., 42:507-518.

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5

Model examination

5.1. Introduction

In this chapter conclusions will be drawn about the five in chapter 4 described service life models. These conclusions will be based on the information found in the literature study described in chapters 2, 3 and 4, and they will be based on model characteristics such as: the required input, the usability, the reliability and the output. Table 5.1 gives a short overview of the five models.

Factor methods vs. mathematical methods

The models are grouped into one out of two types of methods: factor methods and mathematical methods. Factor methods usually make use of a reference situation for which the service life is known. For any other situation the service life can then be estimated by multiplying the reference service life with a number of factors of which the values depend on this new situation.
Mathematical methods use more complex calculations to determine the estimated service life.

Usability

An estimation of the service life is something that should be integrated into the design process of any structure, since most design considerations will have an influence on the service life. For timber bridges this is especially important, see chapters 2 and 3 in which the importance of good 'durable' design choices for timber bridges is described.

The usability of a model describes with what ease the model can be used and for which design stage and for what purpose the model is best suited. A designer who is in the early stages of designing a bridge will for instance ask for a different type of model than an engineer who has to say something about the remaining service life of an existing bridge which has already been exposed to some minor (or major) biological damage.

Input and output

The differences in usability described above also reflect on the necessary input and the required output. For the same example used earlier, the designer would want to know what the influence of his or her design choices is on the service life. Therefore his (or her) available input consists of these design choices such as the wood specie, the type of connection and/or any protective measures. As output he (or she) will want an estimation of the service life in years and the influence of the design choices on this service life. Since designing is an iterative process during which multiple design options are being assessed, the designer will need for a model that is relatively quick and easy in use so that these different options can be compared without having to make long and difficult calculations at every iteration step.

The engineer who has to assess an existing bridge and has to give an estimation of the remaining service life will have different input available and will also ask for different output. The input will consist of again the bridge design (which is now no longer variable), the current state of the bridge (amount of biological damage) and, if available, the state of the bridge at earlier points in time, documented in inspection reports.

The required output will likely be a plot as shown in figures 4.10 and 4.11 showing the decrease in strength of the critical points of the main structural elements.

Table 5.1: Overview of service life estimation methods discussed in chapter 4.

Method	**Type of method**	**Procedure**	**result**
Japanese factor method	Factor method	Reference service life is multiplied by several factors based on e.g. climate, timber specie and design.	An estimated service life for the entire bridge.
Australian TimberLife method	Factor method	For a timber surface, a decay rate and a time lag are determined by multiplying several factors based on e.g. climate, timber specie and design.	A decay rate over time plus a time lag, which can be used to obtain the development of the decay depth over time of a timber surface.
Swedish DuraTB Dose-Response method	Factor method	An annual exposure dose is determined by multiplying a reference exposure dose with several factors based on the climate and design. The material resistance dose is determined by multiplying a reference resistance by factors based on the material properties. The service life is estimated by dividing the material resistance dose by the annual exposure dose.	An estimated service life for the assessed timber bridge element.
Mechanical performance modelling	Mathematical model	The mechanical resistance R of a structure or element is taken as a function of time. The decrease in strength of the wood due to biological deterioration is taken into account by using a decay rate in combination with a time lag.	A function, or plot, of the decreasing mechanical resistance R over time. When combined with a load S (which could be increasing in time) the point in time can be found where S(t)>R(t) and the structure or element fails.
Markov Chain	Mathematical model	Based on data from inspections with a regular interval (e.g. every one or two years) in which bridge elements are ranked on a certain scale (e.g. from 0 (no decay) to 4 (failure)) transition matrices can be made. Such a matrix gives the probability that within the inspection interval an element goes from one scale into the next (e.g. from 0 (no decay) to 1 (light decay)).	An on transition matrices based prediction of the deterioration progress of a timber element over time.

5.2. Factor methods

The three models that are classified as factor methods are being assessed with the use of the NEN-ISO 15686 series, the Dutch publication of the international standard ISO 15686 "Buildings and constructed assets — Service life planning". This series discusses service life estimation as a part of the larger process of service life planning. The parts of the series that are involved in service life estimation are shown in figure 5.1.

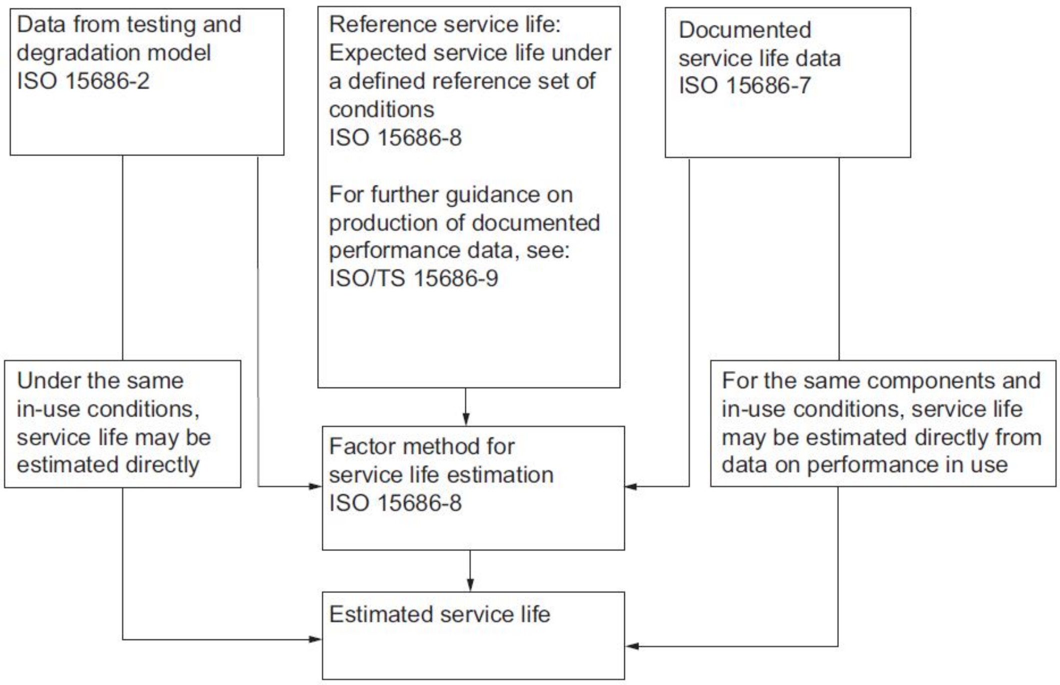

Figure 5.1: Overview of the approaches to service life estimation as described in the NEN-ISO 15686 series. [2].

In an ideal scenario, the service life of a component is predicted by knowing the intended conditions (such as the microclimate), the performance of the component under these conditions, and the construction and maintenance routine. However this data is often not completely available and thus other sources need to be used as a basis of the service life prediction. These sources can for example come from testing (ISO 15686-2), from documented service life data (ISO 15686-7) or from a reference situation (ISO 1568608).

To be used for a specific building, the data from these various sources needs to be adjusted to suit the particular design conditions. This adjustment may be carried out by using a factor method. ISO 15686-8 focusses specifically on the use of factor methods for service life estimation.

In the following subsections, the three earlier discussed factor methods will be reviewed on the basis of the NEN-ISO 15686 series. Table 5.2 gives an overview of the three models that follow the factor method approach. The table shortly describes the limit states that the models use, the reference situation and the different factors that are taken into account.

Remarks

Factors of influence

From chapters

Table 5.2: Overview of the factors used by the models following the factor method.

	Japanese factor method	**Australian TimberLife method**	**Swedish DuraTB method**
Use for	Complete bridge	Bridge element or detail	Bridge element or detail
Limit states	Replacement of the entire bridge	1. Onset of decay, corresponding to a decay depth of 2mm. 2. Element replacement, corresponding to a decay depth of 10mm.	Replacement, corresponding to a decay rating of 1 according to EN 252 (2015)
Reference situation	Cedar timber girder bridge without preservative treatment in an average Japanese climate without any structural or executional protective measures and without any maintenance done.	The method is based on three large scale field tests performed in Australia. These tests used multiple test object configurations and multiple timber species.	Norway spruce board without moisture traps exposed to weather conditions Large scale testing
Climate	Factor E1: environmental climate, based only on the mean temperature of the region. Factor E2: accounts for the moistness of the local conditions.	Climate parameter $k_{climate}$: depends only on the total annual duration of rainfall (in days per year).	D_{E0}: reference annual exposure dose, takes into account both the temperature and the moisture content of the wood. Factor k_{E1}: accounting for local climate and driving rain
Timber specie	Factor P1: accounting for the natural durability of the timber specie used Factor P2: accounting for the permeability of the timber Factor P3: depending on the type of preservative treatment used. The three factors are combined as $P = P1 + P2 * P3$	Parameter K_{wood}: depends on the durability class the timber specie is in.	Factor k_{wa}: accounting for the wetting ability of the tested material, relative to the reference Norway spruce. Factor k_{inh}: accounting for the inherent protective properties of the tested material against decay, relative to the reference Norway spruce.
Design: Structural style	Factor S1: presence of roof yes or no. Factor S2: location of deck: above or below structural members. Factor S3: main structural type. Factor S4: type of deck.	-	-

Design: Detailing	Factor D: takes into account whether durable design measures have been implemented or not. It considers only two options: either yes, durable details have been used, or no, durable design has not been used.	Thickness parameter k_t: Takes into account the thickness of the timber element. The assumption is that thinner elements tend to dry faster. Width parameter k_w: a bigger width can potentially cause larger and deeper checks. Connector parameter k_n: presence of a connector can act as a moisture entrance. Contact factor k_{g1}: depends on whether the assessed surface is in contact with other structural members or not. This factor is multiplied with a position factor k_{g2} which takes into account the orientation of the surface and, in case of contact, the detailing of the connection. The effect of a sealing layer below the deck is accounted for by an extra time lag.	Factor k_{E2}: takes into account the effect of sheltering. Factor k_{E3}: takes into account the distance to the ground. Factor k_{E4}: takes into account the design of the detail. Details are ranked in one out of five classes rating the detail from excellent to poor with respect to moisture exposure.
Paint	-	Paint parameter k_p: when no paint applied $k_p = 1$. When paint is applied, the value of k_p is higher than 1, which means faster decay, and depends on the durability class of the timber specie it is applied on.	
Execution	Factor C: • Yes, extra measures against decay have been considered during construction. • No, standard execution.	-	
Maintenance	Factor, M, takes into account the maintenance done.	-	

Limit states
In normal structural design the two main limit states are the ultimate limit state (ULS) and the Serviceability limit state (SLS), where the ULS can be considered to account for the safety while the SLS accounts for the usability and the comfort of a structure.

For durability design these same two limit states can be used. However biological decay phenomena such as fungi affect not only the mechanical properties but also the aesthetic value of timber elements. Consequently the service life of timber elements does not necessarily has to only go hand in hand with the exceeding of the SLS or ULS. The unpleasant look of rotten or stained timber can be a reason for bridge owners to replace elements that, from a structural point of view, are still in good condition.

Aesthetic value is however something that is not easily measured and the accepted amount of visual decay will vary widely between clients. Some clients will attach highly to the visual appearance of their timber structure and will not allow for any sign of biological decay, which can thus lead to the replacement of timber elements long before they reach their structural limit state. On the other side there might be clients who do not care at all about the visual decay and who will replace the timber elements only when the biological decay has developed to the point where the structure is no longer safe.

The two limit states used in the three different factor methods are:

1. **Onset of decay**:
2. **Replacement**:

However the three factor methods mention different meanings of these limit states. The Japanese method only uses the second limit state, replacement, but they do not link it to a certain amount of biological deterioration. In the Australian method both limit states are used. Onset of decay is linked to a decay depth of 2 mm while replacement corresponds to a decay depth of 10 mm. The Swedish method states that the moment when onset of decay occurs is also the moment to replace the timber element. Onset of decay in this method corresponds to a decay rating of 1 (slight attack) on the 0 to 4 decay scale from EN 252 (2015).

Reference sources

As stated earlier, factor methods usually rely on a certain reference situation for which, due to testing or experience, the service life is known.

Japanese factor method

The Japanese method is based on the following reference situation:

- Bridge type : Girder bridge
- Timber specie : Cedar (no preservative treatment)
- Deck : Cedar timber deck
- Climate : Average Japanese climate (annual mean temperature of 15.5°C)
- Roof : No roof
- Detailing : No durable detailing
- Execution : Standard execution
- Maintenance : No maintenance during the service life

These reference bridge characteristics were chosen because from experience it was known that these kind of bridges are usually replaced after 15 years. Therefore the reference service life was set to 15 years.

Australian TimberLife method

The Australian model was developed based on the results of three different large scale field tests performed in Australia.

The first of these field tests consists of a series of L-joint tests initiated in 1987 and performed over a period of 20 years. The test objects were mortice and tenon L-joints as shown in figure 5.2. The tests were performed at 10 different test sites scattered over the east coast of Australia. Multiple wood species were tested. Nine reference species were tested at all 10 sites and 33 more species were installed at one specific site only. For each species, 24 painted and 24 unpainted replicates were installed at each site.

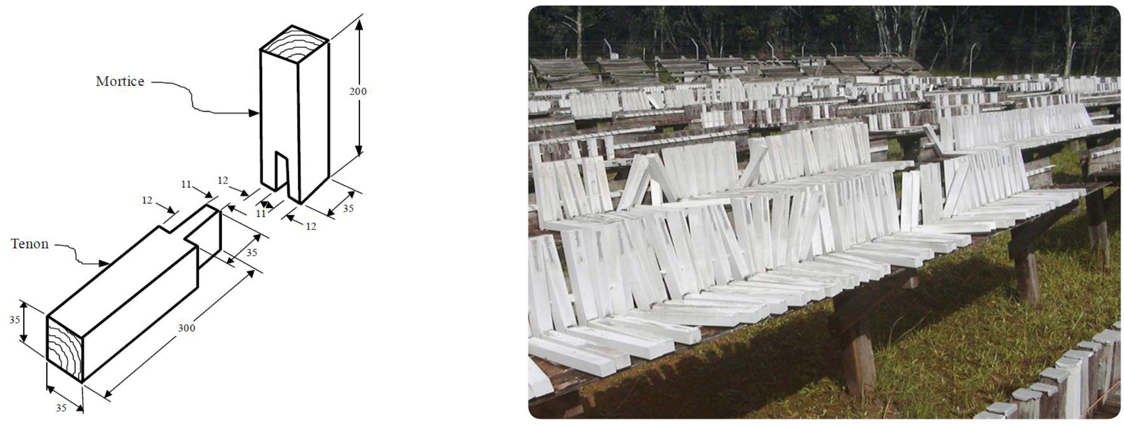

Figure 5.2: Dimensions of the L-joint test objects (left) and photo of one of the test sites (right) [3].

Swedish DuraTB method

Climate parameters

Japanese factor method

In the Japanese research the climate factor is only influenced by the mean annual temperature of the region in which the bridge is located, see table 6.1.

Table 5.3: Determination of the climate factor E1 in the Japanese research [4] [8].

E1:	1.2	1.1	1.0	0.9	0.8
$R_T = T_L/T_A$	$R_T \leq 0.74$	$0.74 < R_T \leq 1.0$	$1.00 < R_T \leq 1.16$	$1.16 < R_T \leq 1.25$	$1.25 < R_T$
T_L = annual mean temperature at bridge location T_A = National (Japanese) annual mean temperature ($15.5°C$)					

Australian TimberLife method

In the Australian research, the values of the climate parameter $k_{climate}$ were calculated as a function of the time of rainfall per year as shown in equation 6.1 [3].

$$k_{climate} = 0.15 t_{rain}^{0.5} \tag{5.1}$$

With t_{rain} in days/year.

DuraTB dose response method

In this method the regional climate is taken into account by the reference annual exposure dose D_{E0}. Based on European climate data this exposure dose was calculated for the whole of Europe, see figure 4.16 and table 4.6.

The exposure dose is calculated using formulas 4.33 - 4.35. To use these formulas first the moisture content and temperature of the wood need to be linked to the global climate data such as rainfall, relative humidity and temperature. In order to determine the moisture content of the wood several so called exposure models were tested and compared to measured data obtained from experiments. Two of these climate models are shown in figure 6.4. The blue line represents the numerical exposure model which in the end was used to calculate the moisture content, the grey line represents a simple empirical model and the dotted line represents the measured moisture content.

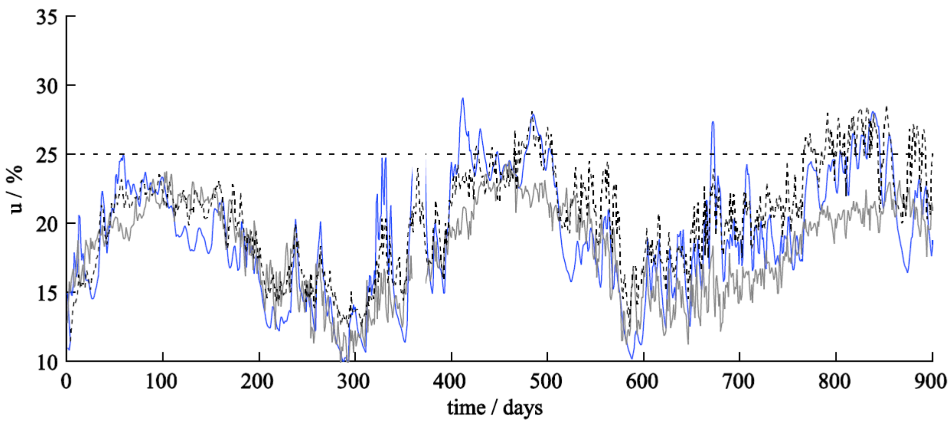

Figure 5.3: Measured average moisture content (dotted) in a Norway spruce board plotted together with the calculated moisture content from the empirical model (grey) and the numerical model (blue) [?].

Wood parameters

An often used timber specie in Dutch timber bridges is the tropical hardwood Azobé (sometimes called Ekki or Bongossi).

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6
Model modification

Climate parameters

The three models are all based on the climate conditions of the region in which they were developed. In order to see whether the models are also applicable in the Netherlands, the climate data used in the models is compared with weather data of the Netherlands, obtained from the Dutch Meteorological Institute (KNMI) [2].

Weather data

Weather data is obtained from the KNMI in the form of the daily average relative humidity and temperature, and the daily total rainfall over a period of ten years from the first day of 2009 to the last day of 2018 for 29 locations in the Netherlands, see figure 6.2. An example of the obtained weather data is shown in figure 6.1.

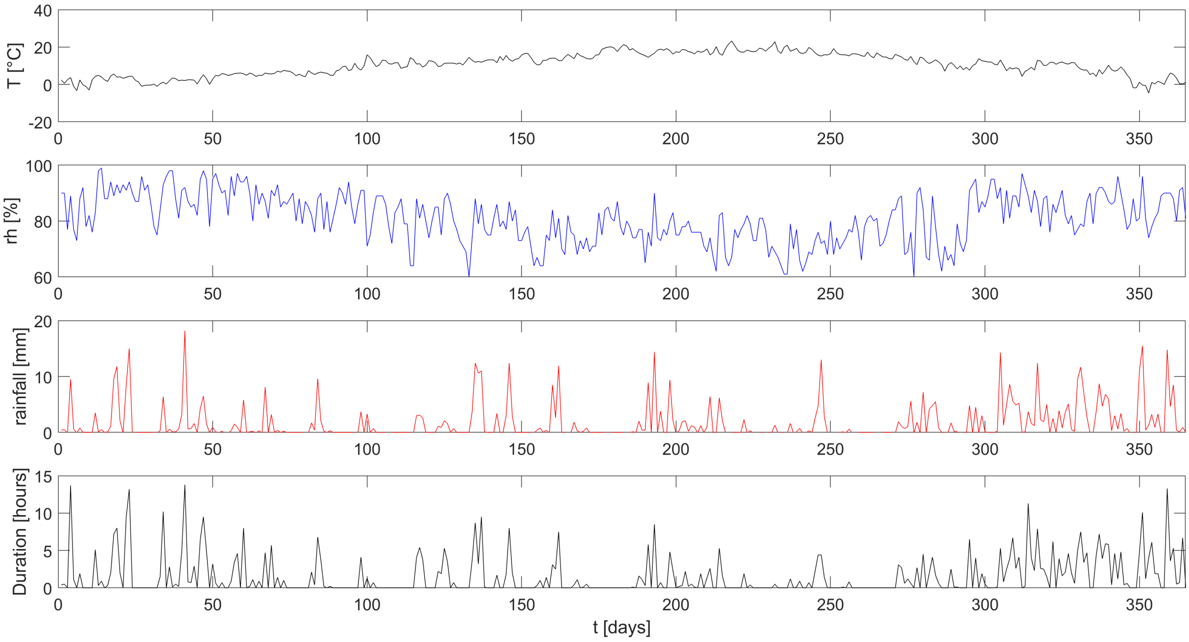

Figure 6.1: Weather data measured at weather station De Kooy (Netherlands) in the year 2009.

Figure 6.2: Locations of the weather stations from which weather data is obtained.

Japanese factor method

In the Japanese research the climate factor is only influenced by the mean annual temperature of the region in which the bridge is located, see table 6.1. From the obtained weather data it is found that the average yearly temperature for the period of 2009 to 2018 is 10.5°C, which is the average value over all the 29 locations. So according to table 6.1: $R_T = 10.5/15.5 = 0.68$, which corresponds to **an E1 value of 1.2.**

Table 6.1: Determination of the climate factor E1 in the Japanese research [4] [8].

E1:	1.2	1.1	1.0	0.9	0.8
$R_T = T_L/T_A$	$R_T \leq 0.74$	$0.74 < R_T \leq 1.0$	$1.00 < R_T \leq 1.16$	$1.16 < R_T \leq 1.25$	$1.25 < R_T$
T_L = annual mean temperature at bridge location T_A = National (Japanese) annual mean temperature (15.5°C)					

Australian TimberLife method

In the Australian research, the values of the climate parameter $k_{climate}$ were calculated as a function of the time of rainfall per year as shown in equation 6.1 [3].

$$k_{climate} = 0.15 t_{rain}^{0.5} \tag{6.1}$$

With t_{rain} in days/year.

From the weather data obtained from the KNMI, the total yearly rainfall duration has been determined for the 29 weather stations. The yearly rain time for the ten year period between 2009 and 2018 is plotted in figure 6.3 for all the 29 weather stations. The average value of all the stations in the ten year period is equal to:

$$t_{rain} = 26.3 \text{ days/year}$$

Which corresponds to a climate parameter value of:

$$k_{climate} = 0.15 * 26.3^{0.5} = \mathbf{0.77}$$

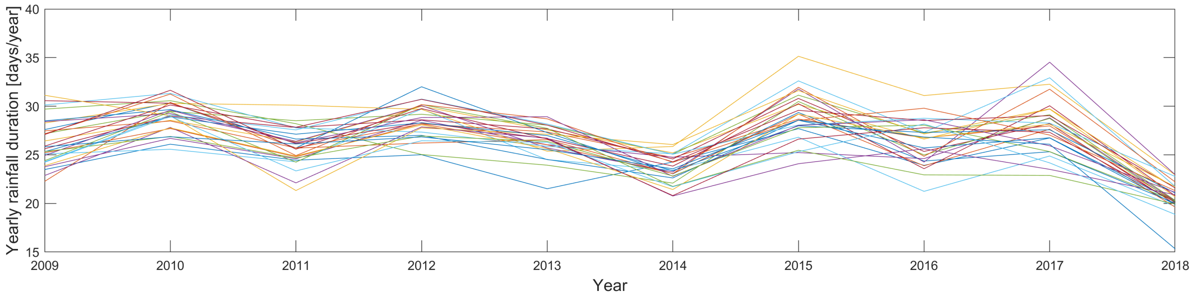

Figure 6.3: Plot of the annual total rain duration for 29 weather stations in the period from 2009 till 2018.

DuraTB dose response method

In this method the regional climate is taken into account by the reference annual exposure dose D_{E0}. Based on European climate data this exposure dose was calculated for the whole of Europe, see figure 4.16 and table 4.6. For the Netherlands the annual exposure dose is set on 43 days. In this section this value is verified using the climate data obtained from the KNMI.

The exposure dose is calculated using formulas 4.33 - 4.35. To use these formulas first the moisture content and temperature of the wood need to be linked to the global climate data such as rainfall, relative humidity and temperature. In order to determine the moisture content of the wood several so called exposure models were tested and compared to measured data obtained from experiments. Two of these climate models are shown in figure 6.4. The blue line represents the numerical exposure model which in the end was used to calculate the moisture content, the grey line represents a simple empirical model and the dotted line represents the measured moisture content.

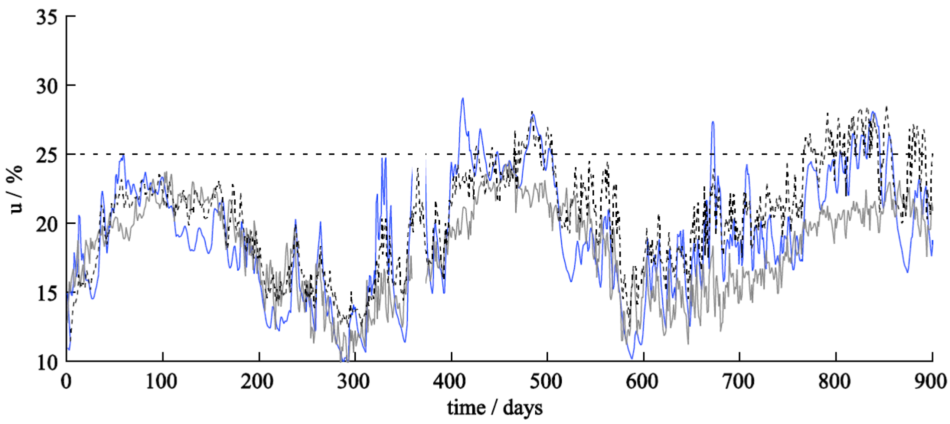

Figure 6.4: Measured average moisture content (dotted) in a Norway spruce board plotted together with the calculated moisture content from the empirical model (grey) and the numerical model (blue) [**?**].

For simplicity the simple empirical exposure model is used to verify the annual exposure dose for the Dutch climate. This model uses the following formula to calculate the wood moisture content:

$$u(\Phi, T) = 10.17 + 0.122\Phi - 0.275T \tag{6.2}$$

In which:

u	:	is the moisture content of the wood in %.
Φ	:	is the relative humidity in %.
T	:	is the temperature in °C.

Rain is only implicitly considered by setting the relative humidity to 100% during a rain event.

Figure 6.5 shows the result of combining the Dutch weather data with equations 5.2 and 4.33 - 4.35. The result shown is the average annual exposure dose for the ten year period from 2009 till 2018, plotted for the 29 data locations and interpolated for the whole Netherlands.

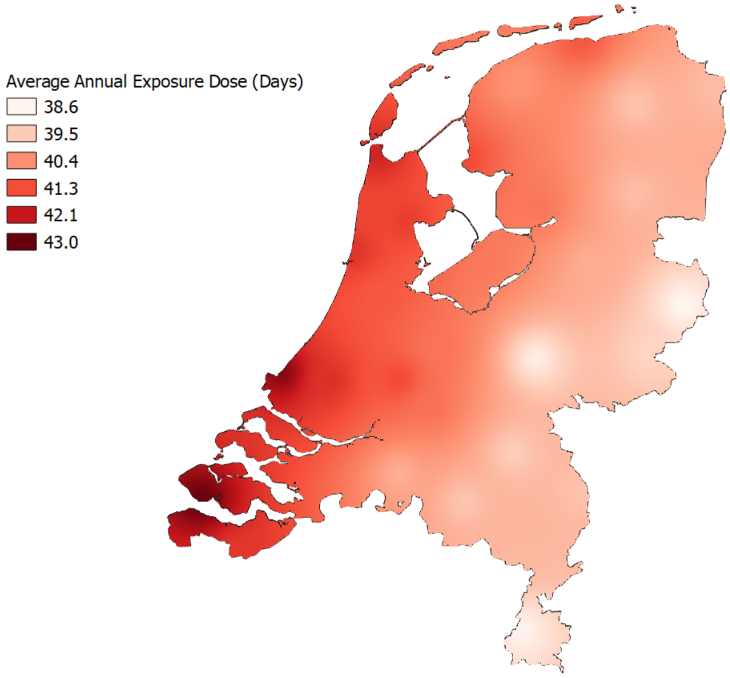

Figure 6.5: Average annual exposure dose for the Netherlands. Calculated using the empirical exposure model of equation 5.2.

In the DuraTB project the Netherlands is located in climate zone E, see figure 4.15, which corresponds to a annual exposure dose of 43 days. Based on figure 6.5 it can be concluded that this value indeed corresponds to the Dutch climate.

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III

Part III: Reality checks

7
Approach

8

Reality checks - Bridges in Amsterdam

9
Reality checks - Findings

IV

Part IV: Service Life Planning

10
Service life planning

10.1. Service life planning

From 'NEN-ISO 15686-1 Buildings and constructed assets - Service life planning':
The key principle of service life planning is to demonstrate that the service life of a proposed structure will exceed the design life. The following general principles should guide the process:

- The service life plan should provide sufficient evidence to give reasonable assurance that the estimated service life of a new structure on a specific site, operated as specified in the design brief and with appropiate maintenance and replacement, will be at least as long as the design life.
- The service life of a structure is determined using available knowledge about the service life of each component that is to be used in the building. Service life planning is a process of estimation and/or prediction of future events, and therefore complete accuracy can not be expected.
- If the estimated service life of any component is less than the design life of the building, a decision should be made as to how the essential functions are to be maintained adequately (e.g. by replacement or other maintenance).
- Service life planning should include projections of the needs for, and timing of, maintenance and replacement activities over the life cycle of the building. The projections will be based on data which should be assessed for robustness and reliability, and records of the data sources should be kept.

Service life planning facilitates the making of decisions regarding value engineering, cost planning, maintenance planning and replacement cycles.

Service life planning should consider the following:

1. The likely performance of the components of the building within the building life cycle in the expected external environment and conditions of occupancy and use.
2. The life-cycle cost and environmental impact of the building over its life cycle.
3. Operating and maintenance costs.
4. The need for repairs, replacements, dismantling, removal, re-use and disposal, and the costs of each;
5. The construction of the whole building, installation of components and the maintenance and replacement of short-life components.

Service life planning in the design process

Service life planning should be integrated into the building design process, since most design decisions will affect the service life. Service life needs to be considered from the earliest stages of design, when the client brief is being developed. As the design develops in more detail, the service life will need to be estimated in more detail and compared with the required design life identified in the client's brief, to ensure that the predicted service life is adequate.

Service life planning usually requires iterations of the design process to identify the preferred way of meeting the performance and maintenance requirements at an acceptable cost.

Service life planning requires access to relevant performance data on components at appropriate stages of the design process. The generation and provision of this data are the subject of other parts of ISO 15686, as shown in Figure 1.

The final stage of service life planning is the communication of results to parties who will occupy and maintain the building so that they are aware of assumptions made about the in-use environment and the maintenance needed to achieve the estimated service lives of the building's components.

10.2. Life cycle costs

LCC methodology is specified in ISO 15686-5.

11

Total Costs of Ownership

Conclusion

Conclusion…