RESEARCH REPORT

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100 years' service life of wood in service class 1 and 2 - dry and moderately humid condition.

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Summary

The **service life of buildings and structures** is an important part of the life cycle planning. The **performance** of wood and wood-based materials with a given level is quantified as the level of ability to withstand load, exposure or deterioration over time in specified service conditions. EN 1995-1-1 defines a set of three service classes which are relevant to a designer. In this work the focus is in the service class 1 (dry) and 2 (moderately humid conditions). Performance requirement means the **minimum acceptable level of a property of a product**, which can be defined as **a limit state**. This defines the limit between acceptable performance and non-acceptable performance. **Durability** is defined "The ability of a product to maintain its required performance over a given time, under the influence of foreseeable actions, subject to **normal maintenance**". No significant differences on durability between massive wood and wood based engineering products (plywood, LVL, CLT) have been found, and the same service life category can be used.

Service life is the period of time after installation during which a building or its parts meets or exceeds the performance requirements. For the structures in service class 1 (dry) and 2 (attics, outdoor structures protected from weather), most important performance requirement is to prevent water penetration in the construction. Humidity and moisture control is a key action to prevent moisture excess and damage caused by water, microbes or other organisms. **Reference service life** (RSL) is the expected service life of a building, material or component situated in well-defined set of conditions. **Design or expected service life** is an evaluated service life calculated on the base of RSL and several different factors. Obviously most advanced service life evaluations are shown in the ISO 15686 series: the RSL or standard service life multiplied by a variety of factors based on a more careful consideration of the quality of materials, actual design, construction, use condition, maintenance and climate exposure of a specific building, building material, element, component or equipment.

Using a factor method to **evaluate the service life of wooden material in service class 1 and 2 situation**, the most important factors are design, execution and maintenance. If the values of these factors are high and moisture exposure does not exceed the tolerances, there is no obstacle to get service life above 100 years using 50 years reference service life in service classes 1 and 2. The eventual climatic load has to be taken into account as follows: when the service life of wooden loadbearing structure will be higher than 50 years, the natural loading is evaluated to be 10 % higher than that for 50 years' service life and 20 % higher when the expected service life is above 100 years.

To achieve 100 years' service life, the following facts should be taken care of: use dry and CE marked wood material, correct glue type and glue class for engineering components, good detailing and design, good execution and protection against weathering, take into account the effect of natural loading, proper maintenance and manual of maintenance for the users, guarantee proper condition for materials in building during the service life.

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Tiivistelmä

Rakenteiden ja rakennusten kestoikä on tärkeä osa elinkaarisuunnittelua. Puun ja puutuotteiden **toimivuus** ja sen taso arvioidaan sen mukaan, miten ne kestävät kuormia, rasitusta ja vioittumista ajan suhteen sekä määritellyissä käyttöoloissa. Standardissa EN 1995-1 (Eurocode) on annettu kolme käyttöluokkaa, jotka ovat tärkeitä suunnittelijan arvioidessa rakenteissa käytettävien puuosien lujuutta ja pitkäaikaiskestävyyttä. Tässä työssä keskitytään käyttöluokkaan 1 (kuivat) ja 2 (kohtuulliset kosteusolot). Toimivuusvaatimukset tarkoittavat **pienintä hyväksyttävää tuotteen ominaisuutta eli rajatilaa** (hyväksyttävyystasoa). **Pitkäaikaiskestävyys** tarkoittaa tuotteen kykyä ylläpitää tarvittavaa toimivuustasoa ajan suhteen etukäteen arvioiduissa oloissa, normaalien huoltotoimenpiteiden puitteissa. Puumateriaalin ja vaatimusten mukaan valmistettujen puukomponenttien (vaneri, LVL, CLT) pitkäaikaiskestävyydessä ei ole havaittu merkittäviä eroja ja niitä tarkastellaan kuten massiivipuut.
Kestoikä on vastaavasti se aika, jolloin rakenne pystyy ylläpitämään vähintään vaadittua toimivuustasoa rakennuksen tai rakennusosan asennuksen jälkeen. Säältä suojatun rakenteen kannalta tärkein toimivuusvaatimus on puun ja rakenteen pysyminen riittävän kuivana. Rakenteen kosteuden hallinta on tärkein periaate suojattaessa rakenteita kosteuden kertymistä sekä veden, mikrobien, sienten ja muiden organismien aiheuttamia vikoja ja vaurioita vastaan.
Vertailukestoikä on rakennuksen, materiaalin tai komponentin odotettavissa oleva kestoikä etukäteen määritetyissä oloissa. **Suunniteltu tai odotettu kestoikä** on arvioitu kestoikä, joka perustuu vertailukestoikään ja siihen liitettyjen eri tekijöiden funktioon. Kehittynein kestoikäarviointimenetelmä lienee standardisarjassa ISO 15686 esitetty menetelmä, jossa määritellyn materiaalin, rakenteen tai rakenneosan vertailukestoikään lisätään kertoimina materiaalin laatu, suunnittelu, rakenteet, käyttöolot, ilmasto-olot sekä huolto. **Kestoikäanalyysien mukaan säältä suojatun puurakenteen kestoiän** kannalta tärkeimmät tekijät ovat hyvä suunnittelu, rakentaminen ja huolto. Jos nämä ovat onnistuneet ja puurakenteen kosteus on sallituissa rajoissa, puurakenteiden kestoikä voidaan hyvin lisätä 50 vuodesta 100 vuoteen tai ylikin käyttöluokissa 1 ja 2. Laajennettaessa kestoikätavoitetta 50 vuodesta 100 vuoteen suunnitellun käyttöiän ollessa yli 50 vuotta kuormien ominaisarvoja korotetaan 10 prosentilla ja suunnitellun käyttöiän ollessa yli 100 vuotta kuormien ominaisarvoja korotetaan 20 prosentilla.
Yli 100 vuoden toiminnallinen kestävyys käyttöluokissa 1 ja 2 saavutetaan: käytä kuivaa CE merkittyä puumateriaalia, oikea liimatyyppi (vanerit, kertopuu, liimapuu, CLT tuotteet), kosteusteknisesti toimivat suunnitteluratkaisut ja detaljit – vältetään rakennevirheet ja hoidetaan suojaus säätä vastaan, noudatetaan hyvää rakennustapaa, huomioidaan luonnonkuormien muutokset suunnittelussa, huolto-ohjeet käyttäjille ja huollon oikea-aikainen toteutus, varmistetaan oikeat materiaalin vaatimat olosuhteet koko rakennuksen käyttöajan.

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Contents

1. Introduction

The service life of structures is an important part of the life cycle planning of buildings and structures. It has also an essential effect on the carbon footprint of the building, since this determines the length of the use phase of the building or a building part.

Material performance based models to estimate the service life of building materials and structures has been used for the service class 1 or 2 conditions (dry or moderately humidity conditions). There is more research done for the service class 3 and 4 conditions, where the exposure conditions are much harder. Potential factor method is shown in the ISO 15686 series on service life evaluation. The best way to estimate the service life of timber structures is based on existing experience, which can then be used as a tool to aplly the factor method in practice.

2. Scope

The scope of this research was to define and evaluate the service life, performance and durability of wood material in structures under dry or moderate humidity conditions (service classes 1 and 2). The focus was especially in performance of the wood material and wood based products in the wood structure dry or protected from weather and water exposure (Figure 1).

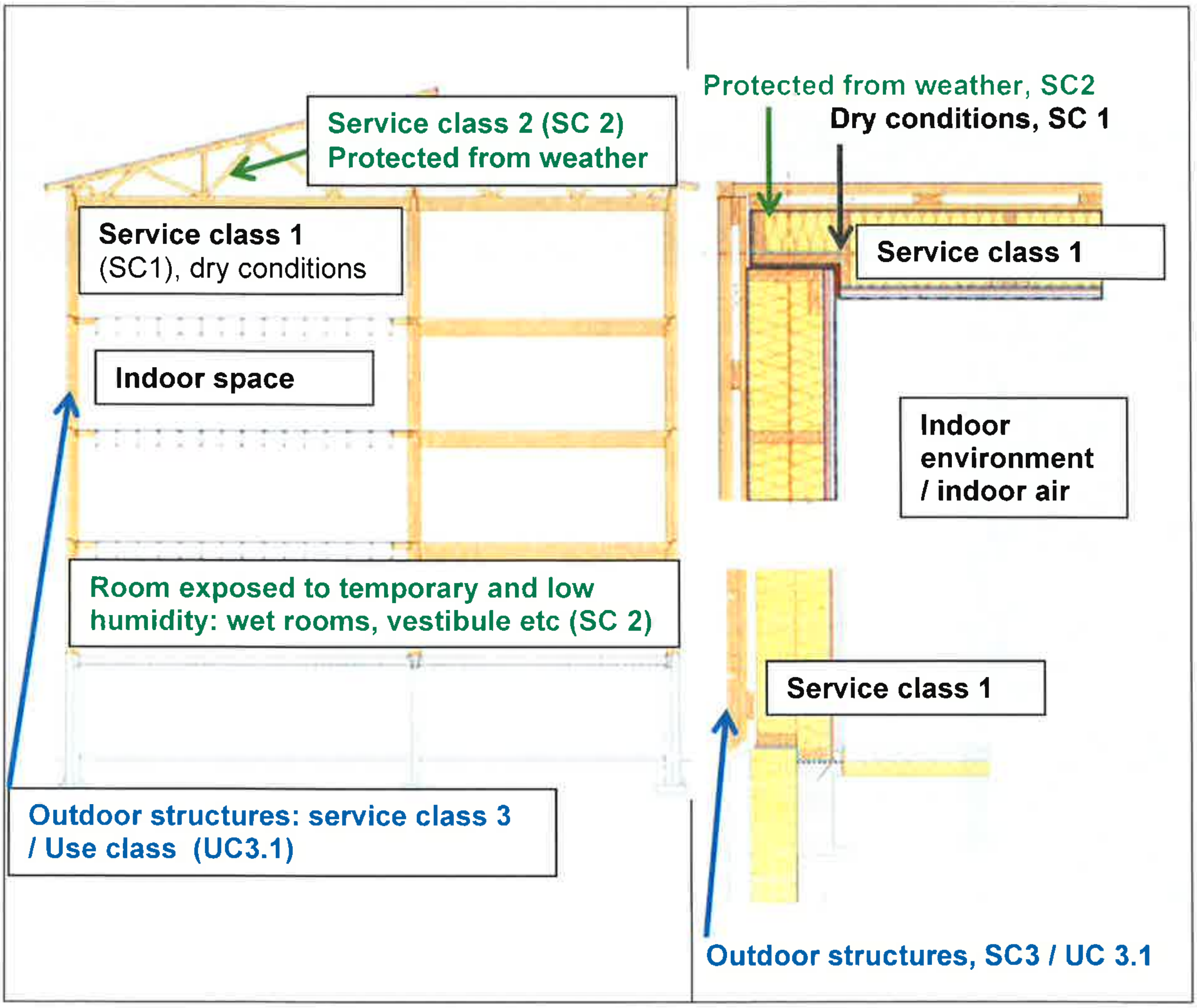


***Figure 1**. The scope of the evaluation: the performance and durability of wood material in structures of service class 1 (dry) or 2 (moderately humidity conditions).*

In this report, the performance, durability and service life of wood material in structures in service class 1 and 2 conditions will be monitored and evaluated. This means that no water damage or moisture risks will be included, or these have been taken care of using protection against moisture exposure and drying capacity of the structure. This report is based on a literature review, previous knowledge and standardization.

3. Definitions

3.1 Service class and use class

The performance of wood and wood-based materials with a given level is quantified as the level of ability to withstand load, exposure or deterioration over time in specified use conditions. EN 1995-1-1 defines a set of three service classes which are relevant to a designer when assigning strength values and calculating deformations for timber elements to be used in a construction. These service classes are determined by the wood moisture content corresponding to the humidity and temperature which are expected to prevail in service.

EN 335-1 defines five use classes on occurrence of the potential attack of biological agents: fungi (discolouring, decay), insects and termites. In the service class 1 / or use class 1 condition, there should not be any deterioration processes caused by long lasting humidity or water exposure (Table 1).

Table 1*.Definitions and conditions of service classes and use classes.*

Service class according to EN 1995-1-1	Humidity conditions in a service class	Corresponding use class according to the EN 335 standard
Service class 1	Moisture content in materials corresponding to +20 °C and RH of air exceeding 65 % for a few weeks per year. MC of softwood will not exceed 12 %.	Use class 1. Indoor, dry.
Service class 2	Moisture content in materials corresponding to +20 °C and RH of air exceeding 85 % for a few weeks per year. MC of softwood will not exceed 20 %.	Use class 1. Use class 2 if the component is in a situation where it could be subjected to occasional wetting caused by e.g. condensation.
Service class 3	Climatic conditions leading to higher moisture contents than in service class 2.	Use class 2 *Use class 3 or higher if used externally. Use class 3 contains subclasses 3.1 (claddings) and 3.2 (decking exposed to weathering).*

3.2 Performance

Humidity and moisture control in the building envelope are the key elements to prevent excess of moisture and damage caused by water, microbes, fungi or other organisms, which are the bio-deterioration risks for wood material.

Important parts of the performance are the requirements and limit states. **Performance requirement** means the **minimum acceptable level of a critical property**, which can be defined as **a limit state**. This defines the limit between acceptable performance and non-acceptable performance. An example of a limit state is the onset of mould growth in the building envelope, in attic or indoor side of the outdoor storage building which can be regarded as non-acceptable since it may create aesthetic problems and uncomfortableness to users of a building. This is comparable to a serviceability limit state for structures. **In dry conditions**, this will not be a limiting factor for the wood performance, except for the outer part of exterior walls.

For **service class 2 conditions**, wood material will be exposed to occasional, temporary humidity conditions exceeding RH of 85 % for few weeks per year. This means, that there is option for mould growth on untreated wood. The humidity conditions of service class 2 are also affected on the ambient outdoor humidity conditions. In the climatic conditions of Scandinavia, North Europe and continental climate area, this may have smaller effect than that in Southern Europe and Atlantic coast area (Viitanen et al 2011).

Another example of a limit state is an attack by decay fungi, which will reduce the capacity of a load bearing structure. In this case the limit state can be formulated in the same way as for mechanically loaded structures considering that the capacity of the structure is reduced with time. The effect of decay may be considered as a mass loss of wood caused by the decay fungi, since the mass loss strongly correlates with the loss in strength (Wilcox 1978, Metsä-Kortelainen and Viitanen 2010). The effect of decay fungi is connected to water damage situation and is not considered as an intended use condition of service class 1 and 2 in climate conditions of North and Continental Europe.

Permeability to water is one of the key factors affecting the performance of a wooden component, as it conditions the possibilities of form stability, discoloration and fungal decay. For structural components, the water vapor or humidity is the main acting exposure for wood. In the structure of service class 1 (dry condition) or service class 2 (moderately humid condition), the water permeability or natural decay resistance will have a minor role, except that the particular structural part exposed to potential high humidity exposure. These will be the lower beam on the foundation, the outer part of the external wall or the structural part of the storage building having only gladding as a protective structure against weathering and exposure to outdoor air.

In a storage building exposed to outdoor humidity, most often the wood materials are protected by coating (varnish, paints or other coatings). The similar situation is for log houses, where the same wood component will form the outer and the indoor part of the envelope. Most often the log houses have wide eaves which protect well the upper part of the outer walls. In the cases of storage and log houses, the outer wall can be defined partly as service class 2 or service class 3 (wood in outdoor, above ground) or use class 3, subclass 3.1 (limited wetting conditions). In Nordic Countries, the wood material used in these components is often spruce, which is known for the low water permeability. Coated spruce gladding has found to perform well in the Nordic climate conditions. The performance of the gladding and façade has an important role for the protection of structural elements both in service class 1 and 2 condition. The performance of wood in exterior conditions (service class 3 or use class 3, subclass 3.1) shall be separately evaluated.

3.3 Durability

Durability is defined "The ability of a product to maintain its required performance over a given time, under the influence of foreseeable actions, subject to **normal maintenance**". Normal maintenance means repair accidental damage, fast drying of water leakage, repainting of the surface. For structural components in service class 1 condition, dry protected from weather, there should be no moisture or biological exposure situations. For wood material, this means no limits for the durability or service life. According to the standard EN 335, the use class 1 condition show no fungal exposure, but insect and termite attack can be expected in some climatic areas. In service class 2, the moisture conditions may be higher and ambient humidity will be short time above RH 85 %. In this circumstance, growth of mould fungi is possible but no decay will develop in North European climate.

According to the table 1, the service class 2 include partly use classes 1 and 2. In the standard EN 335, the moisture or humidity exposure conditions are not explained, and the focus is more on the wood discolouring and decay organisms. For use class 2, the main organisms attacking wood are most often discolouring fungi and insects. In more humid climate conditions, also decay fungi may exist in the use class 2, but mainly in the use class 3. The use class 3 is divided two parts: use class 3.1 (protected from wetting) and use class 3.2 (exposed to wetting).

The durability relates to many different factors affecting the performance of the building material during the life time of the building and the durability can be evaluated using different limit state levels. The limit states include the strength properties, aesthetic condition, surface quality, etc. For structural part of the building, the strength properties are the most important factors. In use class 1 and 2 condition, the wood is be protected from moisture, UV light, high temperature and decay fungi which can effect on the strength properties of wood.

3.4 Strength properties

Wood moisture content, density, grain direction, knots, high temperature (above 80 - 100 °C) and eventual faults and damage can have impact on strength properties of wood (Siimes and Liiri 1952, Toratti and Ranta-Maunus 2002, Naylor et al 2012, Metsä-Kortelainen & Viitanen 2010, Wilcox 1978). Aging of the wood in dry conditions will not have any significant effect on strength properties of wood. VTT has studied the conditions of old wooden piles and according to the results, the compression strength of sound wood (not decayed) in old piles is around the same level as that of new or fresh wood, even the moisture content of wood has been high during long periods (Juvankoski &Viitanen 1989). Same type of results have also being obtained from practical findings from existing old buildings in dry conditions (service class 1).

If no decay exists wood will show very stable strength properties in dry conditions, but fast wetting-drying cycles have affect on the cracking and form stability of wood. In service class 2 condition short period of high humidity will be expected, when there is a bit higher risk of water condensation on the wood surface and also higher risk of the cracking of uncoated wood surface. The water activity, however, will stay for long time so low that no risk of decay exists (no direct or long exposure to water).

Strength properties are connected with limit state, design stress, load capacity and load duration. The limit state design means adequate resistance to certain limit states: the ultimate limit state and the serviceability limit state. Ultimate limit state refers to the maximum load capacity and serviceability limit state to the normal use of the construction. The strength properties of materials are defined at RH 65 % for 5 min loading. Design stress should be less than the design strength. K_{mod} is a factor which shifts the design strength, characteristic value of strength and partial safety factor of the material. K_{def} is the factor taking into account the effect of duration of load and moisture content (service class). In different service class situations, the following values of k_{mod} and k_{def} should be used.

***Table 2**. Values of k_{mod} and k_{def} in service classes 1 – 3 (EN 1995-1) for massive wood and plywood. K_{def} values are different for massive wood and plywood for permanent loading. Long term – short term values are given here only for plywood (in italics).*

Load duration class	k_{mod} in service classes			k_{def} in service classes		
	1	2	3	1	2	3
Permanent	**0.60**	**0.60**	**0.50**	**0.6** / *0.8*	**0.8** / *1.0*	**2.0** / *2.5*
Long-term	**0.70**	**0.70**	**0.55**	*0.50*	*0.60*	*1.80*
Medium-term	**0.80**	**0.80**	**0.65**	*0.25*	*0.30*	*0.90*
Short-term	**0.90**	**0.90**	**0.70**	*0.00*	*0.00*	*0.40*
Instantaneous	**1.10**	**1.10**	**0.90**	-	-	-

In service class 1 climatic factor should not affect but it should be taken into account when evaluating the design service life. In service class 2, the climatic factor is shown as elevated ambient relative humidity. This is presented in the chapter 4. Some additives e.g. fire resistance chemicals (e.g. phosphoric compounds) may affect the durability and service life of wood based products including massive wood, especially induced by elevated temperature. These reactions are results from acid-catalyzed dehydration or thermal-induced acid degradation (Nurmi et al 2010). Also long-term high temperature (> 80 - 90 °C) will decrease the strength of wood material.

3.5 Service life classification

3.5.1 Wood material and timber

Service life is a concept dealing with many factors affecting the performance, durability and service life of buildings and buildings components. **Service life means the period of time after installation during which a building or its parts meet or exceed the performance requirements** (ISO 15686). Most advanced service life evaluations are shown in the ISO 15686 series (Table 3). Also in Eurocode, the suggested minimum design service life for components vary from 10 to 100 years (Table 4). In EOTA, there is a bit different service life given for buildings (Table 5). In Canada, the design service lives vary between 10 – over 100 years (Table 6).

The basic number of the years for wood and for other building materials (e.g. concrete) for frames and for gladding will vary. Different numbers of years can be expressed depending on the structures and building components. Wood structures are adaptable and allow for design flexibility to meet the changing needs. Wood buildings can last even centuries if they have been designed properly with local climate impacts and exposure in mind. Furthermore, when wood products are part of a well-planned regular maintenance program, they will last well beyond their planned service life. When it is time to refurbish, wood products can be re-used and recycled.

***Table 3**. Suggested minimum design lives for buildings and components (ISO 15686-1).*

Design life of building	Components			Building services
	Inaccessible or structural	Replacement is expensive or difficult *	Major replaceable	
Unlimited	Unlimited	100	40	25
150	150	100	40	25
100	100	100	40	25
60	60	60	40	25
25	25	25	25	25
15	15	15	15	15
10	10	10	10	10

- *Note 1*: Easy to replace components may have design lives of 3 or 6 years
- *Note 2*: An unlimited design life should very rarely be used, as it significantly reduces design options, including below ground drainage.

***Table 4.** Indicative design working life (EN 1990,Eurocode)*

Design working life category	Indicative design working life (years)	Examples
1	10	Temporary structures (*)
2	10 to 25	Replaceable structural parts e.g. gantry girders, bearings
3	15 to 30	Agricultural and similar structures
4	50	Building structures and other common structures
5	100	Monumental building structures, bridges and other civil engineering structures

(*) Structures or parts of structures that can be dismantled with an option of being re-used should not be considered as temporary

***Table 5**. Assumed service life of works and construction products (EOTA 1999).*

Assumed life of works (years)		Working life of construction products		
Category	**Years**	**Category**		
		Repairable or easily replaceable	**Repairable or replaceable with some more efforts**	**Lifelong** [2]
Short	10	10 [1]	10	10
Medium	25	10 [1]	25	25
Normal	50	10 [1]	25	50
Long	100	10 [1]	25	100

[1]In exceptional and justified cases, e.g. for certain products of repair, a working life of 3 to 6 years may be envisaged (when agreed by EOTA, TB or CEN respectively.

[2]When not repairable or replaceable "easily" or "with some more efforts"

The CIB / RILEM technical committee (CIB W080 / RILEM TC 175-SLM) on methods of service life prediction of building materials and components was created in September 1996. The Factor method is one that has been promoted in the AIJ (Japanese) Guide for Service Life Planning of Buildings as well as in the subsequent ISO standard 15686-1 on Service Life Planning (CIB 2004).

In Japan, work has been carried out for decades on how to deal with methods to predict the durability and service life of materials and buildings both in the planning and the management phase of a building. The outcome of national activities has been published in a Principal Guide (1989) that was published in a short version in English in 1993 [AIJ 1993]. This Principal Guide is intended to show the fundamental concept of durability within each stage of the life cycle of buildings, such as planning, design, contract, construction, utilization, maintenance and modernisation and demolition.

Canada has also been active for service life evaluation (Table 6). According to CSA 478-95, the requirements for durability may vary from building to building and from one component to another. These requirements are related to intended use, to cost, and to frequency, difficulty and extent of maintenance, replacement and repair.

Requirements for durability are expressed in terms of **design service life** or **expected service life**. The design service life of the building provides one basis for the determination of the design service life of the building components. The **reference service life** will be used as a basic for the factor analysis of service life.

The COST E37 TFPC and TGSLP of WG21 have been considering how the ISO expressed factor method (ISO 15686 series) can be applied to wood products and timber in construction. The ISO factor method includes several general factors in order to evaluate the service life of building components for different performance requirement levels (ISO 15686-1, 2006).

***Table 6**. Categories of design service life for buildings in Canada (CSA 1995)*

Category	Design service life for building	Examples
Temporary	Up to 10 years	non-permanent construction buildings, sales offices, bunkhouses, temporary exhibition buildings
Short life	10 to 24 years	temporary classrooms
Medium life	25 to 49 years	most industrial buildings most parking structures
Long life	50 to 99 years	most residential, commercial, and office buildings health and educational buildings parking structures below buildings designed for long life category
Permanent	Minimum period 100 years	monumental buildings (e.g. national museums, art galleries, archives heritage buildings

A survey of buildings demolished between 2000 and 2003 in the Minneapolis/St. Paul area demonstrated that the durability or service life was not the main reason for the demolition. The developers demolish most buildings well before the end of the useful life of their structural framing. Wood buildings in the study had the longest life spans, 63 % the demolished wood buildings were older than 50 years at demolition and the majority were older than 75 years. The conclusion was that the expected service life of structural parts of the buildings would be more than 100 years (Woodworks.org 2011).

The service life of wooden commodities is often connected to use class and protection needs of the building components or wood protection. In these analyses and codes the service life evaluation are most often subjected to use class 3 or even use class 4 condition, where structures are more or less exposed to water and bio-deterioration.

Building elements shall with only **normal maintenance** continue to satisfy the performance of this code for accepted service life:

- For the structure, including building elements such as floors and walls which provide structural stability; the life of the building being **not less than 50 years**.
- For services to which access is difficult, and for hidden fixings of the external envelope and attached structures of a building: the life of the building being not less than 50 years.
- For other fixings of the building envelope and attached structures, the lining supports and other building elements having moderate ease of access but which are difficult to replace: **15 years**. For linings, renewable protective clothing, fittings and other building elements to which there is ready access: 5 years

3.5.2 Glued materials and products

Glued timber products have been commonly used since the beginning of 1900s. Glulam constructions made for almost 100 years ago with phenolic based adhesives are still performing well. Plywood has been manufactured even longer. LVL and OSB are, in principle, manufactured similar way as plywood.

According to research results and experience, glued timber products will have around the same service life expectations than solid wood in dry and moderately humid conditions. Major durability problems with glulam and plywood have rather been affiliated with degradation of the timber material itself than with the glue bond quality. This is because a prerequisite for an adhesive to be approved for constructional purposes is that it is – and will remain - stronger than wood material.

Adhesives and glue bond quality are subject for intensive approval and control testing. There are standardised approval test methods for all main types of adhesives for load-bearing timber constructions; EN 301/302-series deals with phenolic and aminoplastic adhesives, EN 15425 with polyurethane adhesives, EN 12436 with casein adhesives, and EN 15416-series with others than phenolic and aminoplastic adhesives. The approval of an adhesive normally comprises the use in service class 2 (adhesive of type 1). The test programmes are a mix of short and long term loading tests in different climatic conditions, tests of effects of wood shrinkage, tests of chemical effects of the adhesive to the timber material and accelerated aging tests. Also manufacturing provisions are tested like maximum assembly time, minimum pressure and pressing time, and curing conditions. For new types of adhesives, some of the tests may take 3 years to be performed. The adhesive must not be used in load-bearing constructions before it has passed the relevant tests.

An ideal adhesive would be chemically stable against temperature changes, water and other common chemicals, and bonded via irreversible crosslinking reaction. It also should have a rate of expansion and contraction similar to solid wood. Phenolic resins fulfil these conditions and have therefore formerly been the most often used adhesives for glued constructions. For plywood and LVL, the most often used adhesive still is the phenol-formaldehyde adhesive (PF).

Another frequently used adhesive that is resistant to water and has a rate of expansion and contraction similar to solid wood is melamine-urea-formaldehyde adhesive (MUF) that is the most often used adhesive type for glulam.

In plywood manufacturing urea-formaldehyde adhesive (UF) is also used. This adhesive is suitable for use in dry (service class 1) or moderately humid (service class 2) conditions. Some polyurethane adhesives (PU) have been approved for glulam manufacturing, while the use of phenol-resorcinol-formaldehyde adhesive (PRF) is decreased because of the adverse health effects of formaldehyde.

Main concern for degradation of glued constructions is damage caused by ageing. For different adhesives, different ageing mechanisms are relevant. High moisture content and elevated temperature will speed up the ageing procedure and the mechanisms will change when the conditions are changed excessively. In accelerated tests, conditions are chosen so that the ageing mechanism corresponds to the one in intended use conditions, but the velocity of the ageing procedure is much more rapid. Thus, in a reasonable period of time, it is possible to predict whether the adhesive is suitable to be used for construction purposes or not.

Glue bond quality – and thus the durability of the glued product – is substantially affected by numerous factors like moisture content of the timber materials to be glued together, temperature of the timber, cleanness of the surfaces, roughness of the surfaces, mixing ratio of the adhesive and hardener, age of the (mixed) adhesive etc. These are followed during the manufacturing control of the products that is made in accordance with relevant product standards. In addition, most product standards provide for some accelerated ageing testing to be made. These may be of same type as used in approval testing of adhesives. A specific test for glulam is delamination test, where specimens are exposed for water pressure during several hours, oven dried and inspected for any signs of delamination of the glue lines. For plywood, glue bond quality tests comprise inspection of the broken surfaces of aged specimens, where the amount of failure in wood is recorded.

These test methods are challenging and if the product will pass the test conditions it will show a good performance in use. According to a survey of damage cases, deficiencies with adhesive or bonding have not been found to be the causes for damage or collapse of load bearing structures (Kortesmaa 1984).

New adhesives are developed especially in the group of isocyanate-based adhesives (IBAs), called e.g. aqueous polymeric isocyanate adhesives (API), emulsion-polymer-isocyanate adhesives (EPI), polymeric methylene diphenyl diisocyanate (pMDI). Also older adhesive types are continuously improved; the composition of the adhesives can be altered within the same group to suit different environmental conditions and different manufacturing methods.

Isocyanate-based adhesives (IBAs) have been known and used for over 60 years since their discovery by Bayer in the late 1930s. The isocyanate chemical group is extremely reactive and can form a chemical bond with any chemical group that contains an active hydrogen atom. Isocyanates are very soluble in many solvents, due to their low molecular weight, and they can easily wet and penetrate into porous structures to form strong mechanical interlocks (Van Langenberg et al 2010). Scoville (2001) concluded that the pMDI adhesive was more resistant to degradation than the PF adhesive when the fracture energy of the adhesive was used as a measure of durability.

When a service life of 100 years is required in service classes 1 and 2, Plywood and LVL made with phenol-formaldehyde adhesive (PF) and glulam or multiple laminated LVL made with phenolic or aminoplastic adehesives (PRF or MUF), all these adhesive types are approved according to standards EN 301/EN 302 to be used in service class 2, will fulfil the requirements on basis of experience and test results. Products where polyurethane adhesives (PU), approved according to standard EN 15425, have been used, do not have such a long history of use, but there are no indications that their service life would not be of the same order as for the other approved adhesives.

3.6 The Construction Products Regulation

The Construction Products Regulations is a basis for performance based building regulations in European countries. Requirements for durability and service life of construction products are implemented into national building regulations in Europe.

For the selection of a particular material or product to serve a particular purpose in a building, there are a number of factors that need to be considered. The seven “essential requirements” contained in the Construction Products Regulation (CPR) defines which properties must be ensured for all construction works during an “economically reasonable working life”:

- Mechanical resistance and stability
- Safety in case of fire
- Hygiene, health and the environment
- Safety in use
- Protection against noise
- Energy economy and heat retention
- Sustainability

4. Determination of the service life

4.1 Determination of the reference service life

Reference service life (RSL) is the **expected service life of a component or an assemblage situated in well-defined set of conditions** (ISO 15686). The reference service life will be used as a basic start for the service life evaluation. In order to determine an appropriate estimated or expected service life (ESL), the RSL needs to be modified by taking into account the differences between the object-specific in-use conditions and the reference in-use conditions.

The Factor method described in the ISO Standard provides a systematic way of carrying out a modification. Any possible alternative method of determining the ESL from the RSL should also be based on similar information on in-use conditions. The guidance for reference service life is structured into discussions regarding:

- provision of RSL data utilizing existing general data
- selection of RSL data or general data ;
- formatting of general data into RSL data records .

Manufacturers of building and construction products are usually in possession of considerable knowledge concerning the service life and durability of their products. However, such information is only occasionally made public, typically in product declarations, other documents, company websites and/or databases.

Reference Service life data is the information that includes the reference service life and any qualitative or quantitative data describing the validity of the reference service life. Reference in-use condition is the condition under which the RSL data are valid (ISO 15686-8). Usage condition is the **factor category** of **in-use conditions** that considers the influence on performance due to the use of a building/constructed asset or any human activity adjacent to a building/constructed asset.

The discussion on provision of RSL data is intended for the various providers of data, such as (Figure 2):

- manufacturers of building and construction products;
- test laboratories
- national assessment bodies and technical approval organizations;
- database holders; and
- other data providers.

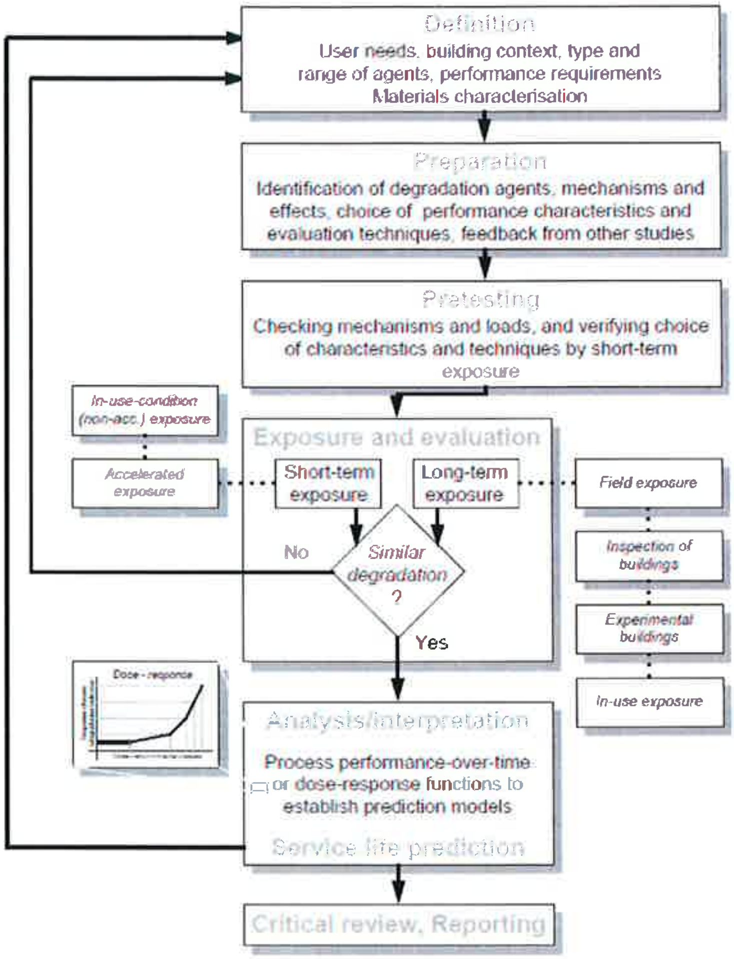


***Figure 2**. Systematic methodology for service life prediction of building components (ISO 15686-2).*

The reference service life can also be stated **as standard service life** when evaluate the potential deterioration state. The time until a deteriorated stage is reached when the whole building or its parts, elements, components or equipment have degraded under any one of specified conditions, under the circumstances of "normal" design, construction, use maintenance and climate exposure. The standard service life has to be predicted on the basis of experience.

RSL data should at least contain general description of the material or component and data on service life, in an indicated outdoor (or indoor) environment, and should preferably encompass all relevant information concerning the generation of the service life data. The following types of data are of particular importance:

- in-use conditions structured according to all corresponding factor categories;
- critical properties;
- performance requirements.

This set of data should form part of a RSL data record (Figure 3)

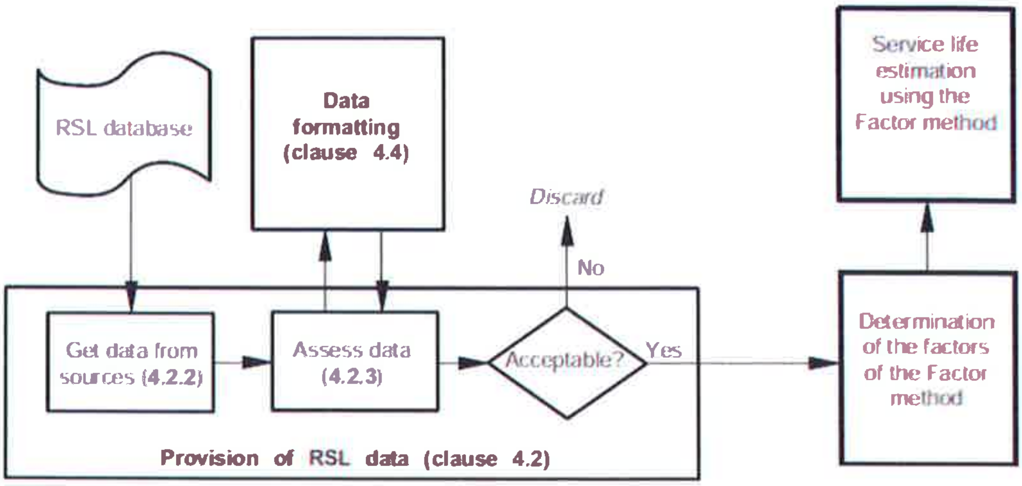


Figure 3*. The process of selecting RSL data (ISO 15686-8).*

Data sources will be the users and manufacturers information on the service life of structural components in use class 1 situation. In Finland, there are several wooden buildings, where the service life of wood is more than 100 years: e.g. the old wooden buildings in Turku, Naantali, Rauma, Porvoo, Tammisaari, Loviisa, Oulu etc (Table 7). In old Rauma, there were already several buildings in the town plan from 1756, and the age of many buildings is more than 250 years. Today in old Rauma there are c.a. 600 old wooden buildings (http//www.rauma.fi).

In Sweden, there are even more old wooden buildings (service life more than 100 years) and still in use. Wooden churches are typical old wooden buildings (table 6). Oldest wooden buildings in Finland are several hundred years old. The highest risk for the service life of wooden buildings is fire, e.g. old church of Tyrvää in Finland was built in 1510, and old wood interior was built in 1780. The wooden roof and interior part was destroyed by a fire set on in 1997, after which the church was again rebuilt.

Table 7*. Examples of old wooden buildings or wood structures in Finland.*

Building or structure	Place	Year of construction	Age (years
Buildings in Puuvallila	Helsinki	1910 - >	103
Hvitträsk, Suurtupa	Kirkkonummi	1901 - 1903	110
Church of Juua	Juva	1850 - 1851	162
Old church of Helsinki	Helsinki	1825 - 1826	187
The Petäjävesi old church	Petäjävesi	1763 – 1765	248
The old Rauma buildings	Rauma	before 1756	>250
Church of Karuna	Seurasaari museum	1685 - 1685	328

For façade and gladding (use class 3.1), the exposure conditions are higher than that in use class 1 and 2, but even for gladding, we have found service life above 100 years (Viitanen et al 2010). The most important factor for long service life is the structural protection of wood from water and wetting. Especially the design of details is important. For Europe, the Nordic climate is the most suitable for wood material, where temperature and humidity is lower than that e.g. in Atlantic climate area.

4.2 Estimation of the service life

4.2.1 Many factor involved

Estimated service life (ESL) / Design service life: the standard service life multiplied by a variety of factors based on a more careful consideration of the quality of materials, actual design, construction, use condition, maintenance and climate exposure of a specific building, part of the building, element, component or equipment. **ESLC** and **RSLC** are used for the evaluation of a building component.

ESL = RSL x A x B x C x D x E x F x G.

The method uses modifying factors for each of the following for service class 1:

A. quality of components (quality marked material, no coatings needed)
B. design level (according to rules of building codes, normal or high level of planning, protection by design, good detailing)
C. work execution level (quality of workmanship, rules of building codes)
D. indoor environment (temperature and RH, according to rules of building codes)
E. outdoor environment (Service class 1 and 2: no exposure to weathering or water)
F. in-use conditions (wear, mechanical impacts, natural loads)
G. maintenance level (inspections and repair shall be performed in time when needed)

Reference service life (RSL) for several structures is 50 years, but for structures in service classes 1 and 2 it may or should be higher. This is still an open question and RSL depends also on the whole service life estimation methods: which factors are included and which coefficient value is used. The reference service life of 100 years may be in future realistic task for the estimation process of wood structure in service class 1 (dry conditions), but also for service class 2 conditions, especially in North European climate and continental climate area.

Engineering design method based on equation of factorial method is very similar but the distribution of the factors also is taken care of:

$$\mathbf{PSLCD = RSLC \cdot \mathit{f}A \cdot \mathit{f}B \cdot \mathit{f}C \cdot \mathit{f}D \cdot \mathit{f}E \cdot \mathit{f}F \cdot \mathit{f}G}$$

PSLCD: is the predicted service life distribution of the component based on the reference service life of component **RSLC**. The factorial indices are same as shown in the service life estimation process.

4.2.2 Numerical factor estimate (ISO 15686-10)

Allocating values to the factors A to G involve considerable uncertainty (ISO 15686 -10).This uncertainty should be taken into account by treating the estimates as stochastic values. Each estimate should therefore be expressed as three values:

l = lower limit. E.g. the 5 % percentile

h = upper limit, e.g. the 95 % percentile

m = the most expected value

These triple estimates for each factor A to G can be represented by β-distribution. The statistical expected value f and the standard deviation σ should be calculated for each factor from the following equations:

$$f = \frac{l + 4 * m + h}{6}$$

$$\sigma = \frac{h - l}{6}$$

The quality of the ESLC (Estimated Service Life of Component) can be improved by performing a recursive Deplhi -process (using a small group of skilled people instead of leaving the estimating process to single person). Once the triple estimates or each factor (and sub-factors) are done, the most uncertain estimate should be revised, in order to see if the uncertainty could be reduced, i.e. by gathering more information. This should be repeated until the uncertainty could is considered acceptable or until nothing more can be done (with available recourses) to reduce it. Finally, the product of triple estimates should be calculated by carrying out the Monte Carlo simulation.

4.2.3 Linguistic factor estimates (ISO 15686-10)

An alternative estimate of ESLC may be more appropriate, rather than relying on a product of uncertain and insufficient factors. Instead each factor (or sub-factor) could be given a linguistic value ("worse", "as reference", "better" etc.) depending on its assumed contribution to the ESLC. The list of factors A to G (with sufficient sub-division) could be used as a memo only, for ensuring that all aspects relevant to the ESLC are assessed. In the end, after going through the list of factors, the ESLC should be given as a triple estimate based on the total impression of the linguistic values. In the following calculation for service life in service class 1 and 2 are evaluated using the linguistic factor estimates

4.2.4 Service class 1

There is very few data on the service life of wood in the use class 1 structure. This may be caused by the fact, that the research has been focused on the more critical structures like facades, gladding, decking and terraces, where the weathering, moisture exposure and damage risks are higher.

A number of specific factors affecting the moisture safety of wooden buildings have been identified. In order to build moisture-safe wooden building with an appropriate service life or even higher than reference service life 50 years, at minimum following factors have to be considered (Toratti & Arfvidsson 2013):

1. Well-ventilated air gap behind the façade. It has been evaluated, that wooden cladding will be perform better than that of brick façade (Lahdensivu et al 2012).

2. Protection for mould growth in the external wall. This is especially important for the inner part of the wall or constructions connected to indoor air.

3. Influence of driving rain and site location. It's especially important to protect the wall behind the cladding for the impact of water penetration.

4. Dry out possibilities of water from leakages and initial moisture from the building phase. Moisture in the walls should always have possibility to dry out. Use of protection against weather during building phase is an important part for dry building. In Sweden, the weather protection is used during the whole building process, and some cases, only dry materials are used.

5. Interior vapour barrier of the wall. This is an important part to prevent the moisture transport from indoor air to the structure, but it's also important for prevent the eventual air leakages from the envelope to indoor air.

Using ISO 15686 factor method it is important to define the most fitted factors and their values. If the factor will not change the expected design service life (as reference), the factor has value 1. If the factor is expected to have negative impact, the value is lower than 1 and if positive, the value is higher than 1.

Classification of each factor for service class 1 has been evaluated and shown in Table 8. The evaluation of factors are based partly on the previous research on Use class 3.1 (coated cladding) from Thelandersson et al. (2011) and Viitanen et al. (2011). Design and work execution factors are based on the calculation method of Lund University and VTT. Outdoor environment is based on the service class 1 selection (good or excellent protection from weather). If needed, climate factor can be included as shown in the report Viitanen et al 2011. The climate factor, however, is not an active factor for service class 1 situation.

***Table 8**. Potential values of factors A – G for service life evaluation for service class 1 of wood construction (dry conditions).*

Factor	Name	Poor	Fair	Normal	Good	Excellent
A	quality of components	0.95	0.98	1	1,02	1.05
B	design	0.6	0.8	1	1.3	1.8
C	work execution	0.6	0.8	1	1.3	1.8
D	indoor environment ([1]		0.98	1	1.02	
E	outdoor environment ([2]			1	1.5	1.8
F	in-use conditions	0.9	0.95	1	1.05	1.1
G	maintenance level	0.8	0.9	1	1.3	1.5

([1] service class 1 in dry condition (low impact of indoor environment)

([2] service class 1 in dry condition, protected from the weather (no impact of outdoor and selection will be good or excellent)

To obtain long service life, the design and execution are the most important. This means, that the whole planning process including details will be performed well (level should be good 1.3 or excellent 1.8) to avoid moisture excess in the building process and during the use of the building. The numbers of design and execution are taken from the previous work of Thelandersson etal. (2011) and Viitanen etal (2011). Good execution means that the whole building process will be performed well using the plans, and protected against wetting and weathering during the building process.

The whole building process will guarantee proper condition for material in building during the service life (ventilation, protection, drying of accidental water damage). The role of the wood material itself has a minor part in the whole process. The components should be manufactured in dry and controlled conditions, transported as protected to building site and assembled as dry in the building.

The importance of each factor is evaluated using the mathematic calculation or evaluation based on the expertise. Important part of the evaluation is the definition of reference service life (RSL). Most often the RSL is evaluated to be 50 years for cladding and façade in service class 3. For structures in service class 1, the reference service life could be higher, but more research work should be included.

If the RSL is 50 years, to obtain over 100 years' service life good quality of design and work execution are needed to protect the structure from effect of outdoor climate. This means the use of weather protection during the execution and building process. If good or excellent design is used, the service life above 100 years can be achieved. If also good or excellent execution is used, the expected service life will be longer than 200 years. Service life above 100 or 200 years has also been detected in the real buildings (see Table 7).

Below two different evaluations for service class 1 are shown. Service class 1 selection will give value 1.8 for factor E (dry conditions). Good design and execution are needed, this

Wood material and structure in dry conditions, protected from weather (service class 1)

RSL	= 50	years	RSL	= 50	years
A	= 1.0	(normal quality of wood)	A	= 1.0	(normal quality of wood)
B	= 1.0	(normal quality of design)	B	= 1.3	(good quality of design)
C	= 1.0	(normal work execution)	C	= 1.3	(good work execution)
D	= 1.0	(normal indoor environment)	D	= 1.0	(normal indoor environment)
E	= 1.8	(service class 1)	E	= 1.8	(service class 1)
F	= 1.0	(normal use condition)	F	= 1.0	(normal use condition)
G	= 1.0	(normal maintenance)	G	= 1.0	(normal maintenance)
ESL	= 90.0	years	ESL	= 152	years

If RSLC would be 100 years, the factor analysis can give even higher results if the same factors and values are used.

In Germany, the expected service life for roof structures and for structures in use class 1 is over 100 years. In the German standard, there is also use class 0, which means that there should not be any risk of insect attack. In the use class 1, a low potential of insect attack may exist (DIN 68 800). In France the definition of use class 1 is: no exposure to exterior climate and > 20 cm from soil. This is classified as lasting class L1 and expected service life is > 100 years. In UK, the minimum service life period of the long life buildings is 120 years. They are e.g. civic and high quality buildings.

4.2.5 Service class 2

In service class 2 condition the expected humidity level will be higher than that in the service class 1. This will affect also on the service life evaluation. Most often the wood material will be pine and spruce, but often some thin surface treatment will be used. The structural components are often similar, but exposure to humidity may be higher and longer. Normally use condition there will be no risk of decay, but surface discolouring may exists, especially in building construction exposed to outdoor air, e.g. storage buildings, roofs and attics. Classification of each factor for service class 2 has been evaluated and shown in Table 9.

Table 9*. Potential values of factors A – G for service life evaluation for service class 2 of wood construction (low humid conditions).*

Factor	Name	Poor	Fair	Normal	Good	Excellent
A	quality of components ([1]	0.90	0.95	1	1,1	1.2
B	design	0.6	0.8	1	1.3	1.8
C	work execution	0.6	0.8	1	1.3	1.8
D	indoor environment ([2]		0.9	1		
E	outdoor environment ([3]	0.8	0.9	1	1.2	1.5
F	in-use conditions	0.9	0.95	1	1.05	1.1
G	maintenance level	0.8	0.9	1	1.3	1.5

([1] surface treatment (coatings and protection against water and mould fungi included)

([2] service class 2, no impact of indoor environment or impact is negative (no heating)

([3] service class 2, protected from the weather (low impact of outdoor climate) depending on the macro- and meso-climate of the environment. Excellent means very mild outdoor climate of North Europe or low impact of the climate to the structure in SC 2. 1 is equal for continental European Climate area (Helsinki) and 0.8 and 0.9 for high impact of climate.

In the following calculation model, two different cases are calculated and shown below.

Service class 2, temporary and low humidity conditions. Example roof beam in attic, wood material in outdoor storage without heating in North European Climate area.

Beam in cold attic		Outer wall of a storage building without heating	
RSL	= 50 years	RSL	= 50 years
A1	= 1.0 (normal quality wood material)	A1	= 1.0 (normal quality wood material)
A2	= 1.0 (no surface protection)	A2	= 1.1 (use of protective coating)
B	= 1.3 (good quality of design)	B	= 1.3 (good quality of design)
C	= 1.3 (good work execution)	C	= 1,3 (good work execution)
D	= 1.0 (service class 2)	D	= 0.9 (service class 2, no heating)
E	= 1.2 (protected from weather)	E	= 1.0 (outdoor climate in South Finland)
F	= 1.0 (normal use condition)	F	= 1.0 (normal use condition)
G	= 1.0 (normal maintenance)	G	= 1.3 (maintenance taken care in time)
ESL	= 101 years	ESL	= 99 years

In service class 2, service life over 100 years can be achieved, but it is more difficult and demanding to get over 100 years' service life. It is more likely to get service life between 60 and 90 years, but using good design and execution, the service life above 100 years' can be achieved. Very critical is the needed performance level: for structural strength there will be no risk for durability if the critical moisture level will be not achieved caused by moisture damage of decay. Discolouration of the wood surface can be often caused by mould and blue-stain fungi. Surface protection against moisture and mould growth are needed to avoid surface discolouration of wood and wood based products

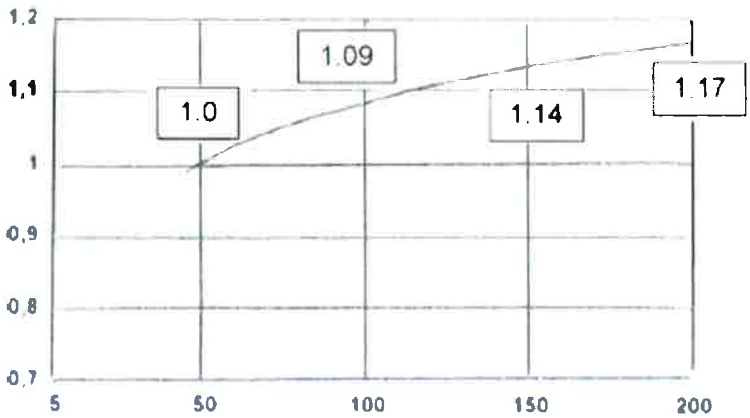
The service life evaluations shown above are connected to the North European climate conditions, in Atlantic costal or Southern European climate the expected service life may be shorter for service class 2 conditions due to higher humidity and temperature of outdoor air, which should be taken care in the factor E.

The service life of wooden commodities is often connected to use class and protection needs of the building components or wood protection. In these analyses and codes the service life evaluation are most often subjected to use class 3 or even use class 4 condition, where structures are more or less exposed to water and bio-deterioration.

Most advanced service life evaluations are shown in the ISO 15686 series (see Table 3). In Eurocode, the suggested minimum design service life for components vary from 10 to 100 years. In Canada, the design service lives vary between 10 – over 100 years (Table 4).

4.3 Effect of variable loads

When the service life of wooden loadbearing structure will be higher than 50 years, the eventual loading caused by climatic factors (wind, snow, rain, ice) has to be taken care. For buildings which service life is expected to be longer than 50 years, eigenvalues shown in the figure 8 have been calculated by Weck (2013, Figure 4). For buildings which service life is expected to be longer than 50 years, following eigenvalues could be used: for 50 years 1, for 100 years 1.09 for 150 years 1,04 and for 200 years 1.17. In the new building code (RakMK, part B1, draft 2014), the design service life and loading will be taken care as following: when the design service life is above 50 years, the characteristic values of loading shall be10 % higher, and for above service life of 100 years, the characteristic values of loading shall be 20 % higher than that for 50 years design life.



Design service life (years)

***Figure 4**. Interdependence of the eigenvalue of climatic load and design service life in relation of the eigenvalue of the design service life of 50 years. Climatic loads are snow, wind, ice and variation of the temperature of outer air. The load of climate is based on the Gumbel-distribution with variation factor of 0.26 (Weck, 2013, Tikanoja 2013).The values less than 50 years are removed from the graph.*

The durability and service life of wood constructions in service class 1 conditions is also depending on the function of cladding and other protective structure. In WoodExter project, service life of gladding in several different countries was surveyed (Suttie et al 2011). The estimated mean service life of all claddings is 63 years and the mean age of the claddings during the survey was 29 years.

It has been shown that for claddings a 50 year service life is achievable with the correct materials and coatings and with a proper design and detailing. Even longer (more than 100 years) service lives may be achieved for cladding. This of course requires maintenance of the surfaces as indicated by the recommendations given by the coating/paint producer or material producer. Nordic continental climates seem to be more advantageous in this respect (Viitanen et al 2011).

Comparing the results of cladding in service class 3 or use class 3, subclass 3.1 conditions, the service life of wood structure in service life 1 condition can be expected to be above 100 years, when the moisture damage will be avoided and drying after eventual moisture exposure has been taken care in accepted time schedule. Fasteners, nails, joints and junctions have to be performed according to the rules and building codes. Special attention should be arrested to design of joints, drying capacity, deformation of the materials.

5. End of service life and critical limit states

5.1 End of the service life

All design methods require clear definitions of the end of the service life. They are often connected to critical limit states. This is however not a universal and easily defined value. In general terms it is **the point in time, when the foreseen function is no longer fulfilled** (CIB 2004). Properties of a building part can be split up into several sub-properties, e.g.

- **Safety:** The integrity of the building part is maintained at the standard level of safety,
- **Function:** The required function is fulfilled, (i.e. deflections are still within limits, a window can easily be opened and closed, etc.),
- **Appearance:** The expected appearance is given (i.e. the surface of the building part is of acceptable appearance, the glazing of windows has not deteriorated or turned opaque, etc.).

Building maintenance is an important factor to guarantee the fulfilment of the needed quality. During the service life of a building, several maintenance and repair work will be included in order to obtain the needed or wanted performance level and limit states, depending on the service conditions (Figure 5). In service class 1 and 2, no exposure to weather and water should be expected when there is lower need for maintenance and repair than that in service class 3 (exposure to weather).

In service class 2 condition, however, the ambient humidity will be shorter periods above RH 85 % and occasional growth of mould and discoloration fungi may be expected. Also quality of wood material, especially the surface properties will have an impact on the mould growth on wood surface. Additional surface treatment using coatings will add the resistance of the wood surface against moisture impact and mould growth.

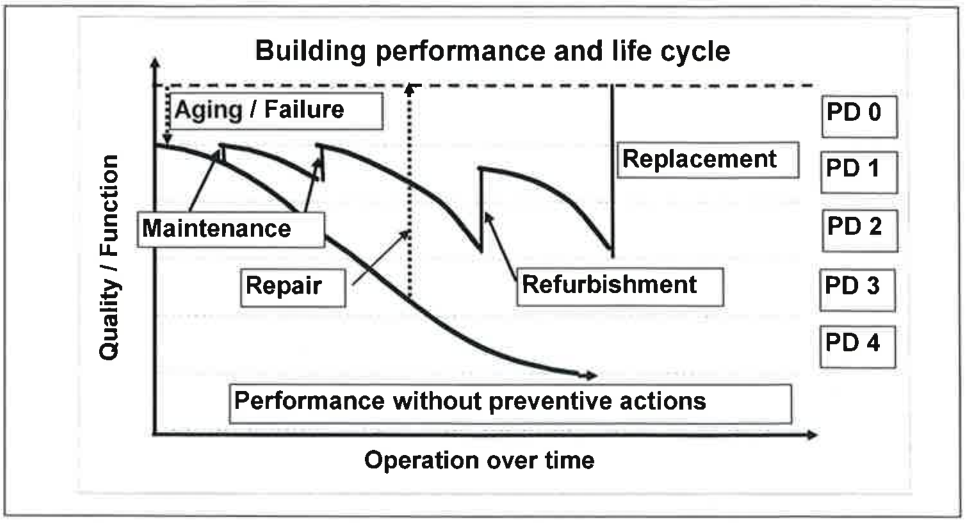


***Figure 5**. Building performance, performance degree (PD) during the life time of a building for high exposure conditions. Maintenance, repair, refurbishment and replacement may be needed during the service life of building depending on the exposure factors and aging of the building components. Performance degrees: PD 0 = performance fine, no symptoms of problems, PD 1 = normal performance, light symptoms, PD 2 = lowered performance, medium symptoms, PD 3 = not accepted performance, strong symptoms, PD 4 = no performance left, totally unacceptable, collapse and malfunction (based on ISO 15686 – 7).*

5.2 Reuse of the wood material after the end of life in a building.

The reuse of wooden building materials has mainly been for energy supply (Sathre 2007). Several different targets are presented by Mantau (2012, Pass 2012). In the future, reuse of wood building material should be targeted for building or material use. This means, that the quality of reused wood material has been approved for the targeted use. If the wood material has been used in dry conditions, no mould or decay should be expected and the wood quality should be acceptable for the reuse. This should be inspected before the use, and in the present situation, there is no organisation to take care of this. In Germany, the old wood material is reused for manufacturing of particle boards.

The strength properties of wood material are the most important for building use. The strength grading of old wood material become important in future, but in the present situation, there is no method for this purpose.

5.3 Quality of building process and critical conditions

5.3.1 General

The primary objective to protect wood from moisture loads is to keep water out of the building envelope and to balance the moisture content within the building itself. Moisture control by means of accepted design and construction details is practical method of protect wooden building against faults and damage. Details of construction have most important role to avoid moisture exposure and accumulation into the structures (Lahdensivu et al 2012, Toratti & Arfidsson 2013). There are several old buildings having well functioning structure and long service life. Excellent examples of well functioning structural protection of wood are stave churches in Norway built in 1500 – 1600. The indoor structures of churches are well protected from the weather using protective roofs and eaves and covered decking around the indoor structure.

For the use class 1 situation, the structure should be protected from exposure to high humidity conditions (humidity of ambient air of the structure should only exceeding RH 65 % for a few weeks per year) and only eventual short high humidity exposure should be expected. For the use class 2 situation, the structure should be protected from exposure to high humidity conditions (RH of air exceeding 85 % for a few weeks per year) and from exposure to weathering.

For quality assurance in building execution several crucial tasks should be considered (Toratti 2011, Toratti & Arfvidsson 2013): 1) project description, 2) initial risk assessment, 3) structural design, 4) risk analysis and external supervision of design, 5) moisture control plan, 6) assembly planning, 7) maintenance manual of the building.

Materials that are located in the outer section of the wall or in the service class 2 are occasionally exposed to conditions that might cause mould growth in the structure. Adding a mould-resistant insulation board on the outside of the insulation layer next of the air gap improves the situation (Toratti & Arfvidsson 2013).

5.3.2 Critical conditions

Humidity and moisture control in a building envelope are key actions to prevent moisture excess and damage caused by water, microbes, fungi or other organisms, which are the bio-deterioration risks for wood material. Water, solar radiation and temperature extremes are the main environmental factors that affect the performance of materials. Water is responsible for the swelling and bio-deterioration of organic materials and the corrosion of metals. It is also involved in the freeze-thaw deterioration of porous materials like concrete and the swelling of soils. Solar radiation attacks the chemical composition of organic materials like plastics, PVC, paints, caulk compounds and others. Changes in the ambient temperature cause many materials to expand and contract like metals and concrete. Materials become more rigid in cold temperature and some may shatter unexpectedly when the temperature falls below their glass transition temperature.

The first step to evaluate the exposure conditions for moisture exposure is the macroclimate conditions. The driving rains, moisture, temperature and also the solar radiation are the most important factors for the exterior structure and components in use class 3 and 4 conditions. For use class 1 conditions, there should not be any moisture exposure. However, some accidental humidity and water exposure should be taken care of.

For the performance of building materials, the microclimate condition of the material is the most important factor (Figures 6 and 7). Microclimatic means the climate conditions close the materials and structure, and it is a result of several simultaneous factors: macroclimate (rainfall, temperature, humidity, air pressure conditions etc.) and meso-climate (location of the building, structural details and the materials used). The micro-climate conditions are the basic level for building physical and microbial activity evaluations.

The effect of eventual humidity and water exposure can be evaluated using e.g. different bio-deterioration models. E.g. the mould and decay models can be incorporated with climatic and building physic models to evaluate the effect of different exposure conditions on the durability and service life of wooden products. **Period of wetness** of the substrate and the actual moisture and temperature condition is the determining factor for the development of mould and decay in timber. Long period, high moisture levels may start biological growth on timber surfaces, first mould or stain fungi and finally decay (Viitanen 1996).

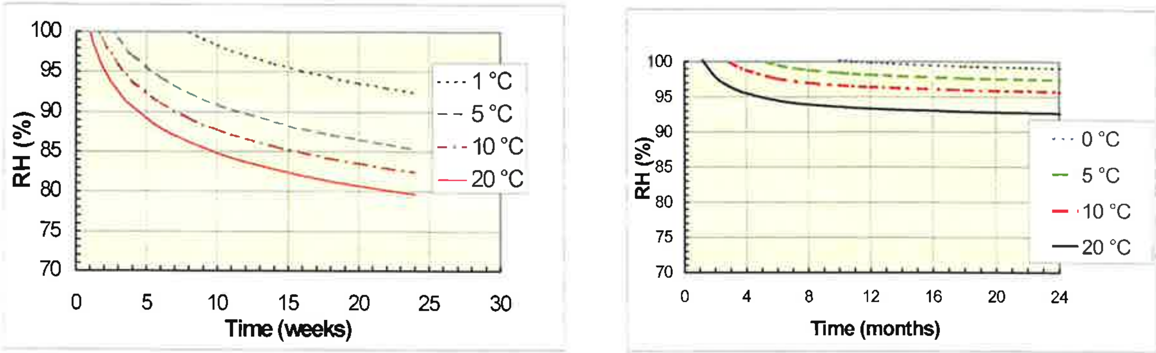


Figure 6. *RH and temperature isoplets as a function of time for start of mould growth (left) and early stage of decay development (right) in pine sapwood (Viitanen 1996, 1997a, b)*

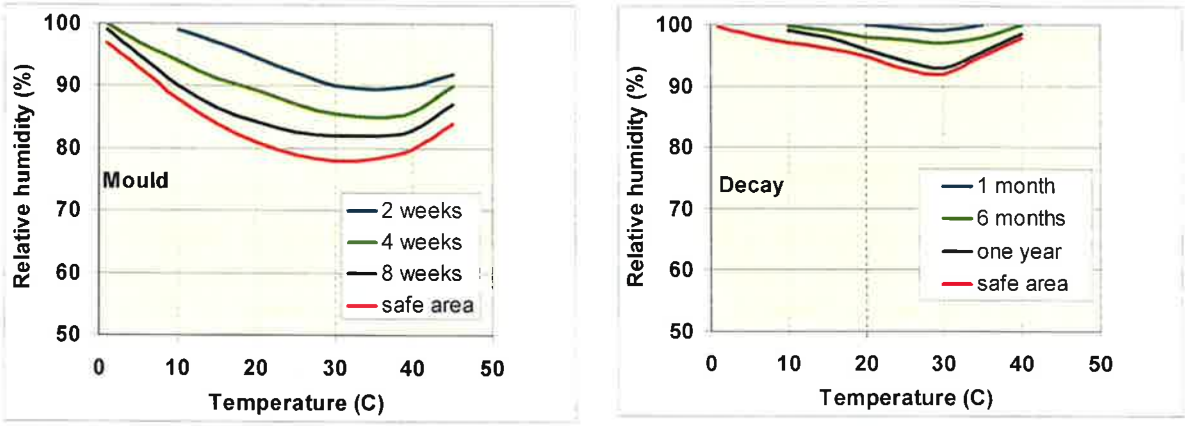


Figure 7*. Isoplets of ambient relative humidity, temperature and exposure time of microclimate for development of mould growth (left) and decay development (right) in untreated pine sapwood. Wood moisture content is more critical for decay development than ambient relative humidity of the microclimate. Wood moisture content is around 30 % at RH of 99 % and around 25 % at RH of 95 %.*

For start of the growth of decay fungi and decay development, the ambient critical humidity level of microclimate should be above RH 95 – 100 % and moisture content of pine sapwood above 25 – 30 % (Viitanen 1996). The humidity and moisture limits were based on large laboratory work on pine and spruce sapwood. According to experience, the decay will develop when moisture content of wood excess the fibre saturation point (RH above 99.9 % or wood moisture content 30 %. Morris *et al.* (2006) have modelled decay development in wooden sheathing and found the critical ambient humidity condition for decay development is around RH 98 - 99 %, depending on the temperature and exposure time.

The models on bio-deterioration and mould growth can be used as a tool for building physic performance and service life evaluation. Models can been incorporated in a hygrothermal calculation tool like Wufi and Ojanen and Salonvaara (2000) have used the "VTT mould growth model" implemented in another building physic simulation model TCCC2D for evaluate the risk of mould growth in different humidity exposure conditions in building envelope.

5.3.3 Effect of climate

The climatic conditions in different part of Europe vary. For evaluation the climatic exposure conditions, the empirical wood decay model developed in the WoodExter project was used for the ERA-40 data for air temperature, humidity and precipitation at 6 hour intervals for evaluation of use class 3.2 (Viitanen et al. 2011). ERA-40 is a massive data archive produced by the European Centre of Medium-Range Weather Forecasts (ECMWF). The re-analysis involved a comprehensive use of a wide range of observation systems including, of course, the basic synoptic surface weather measurements. The ERA-40 domain covers all of Europe and has a grid spacing of approximately 270 km).

The decay index mapping for Europe with respect to macro-climate was developed. In a first step different climatic exposure areas or zones could be identified: Northern European (north and south), Continental, Atlantic (north, middle and south), Mediterranean zone (wet and dry). The classification will give relative values for decay risks of outdoor structure in different parts of Europe (Figure 8). The exposure of horizontal exterior surfaces to solar radiation of Europe was simulated using the average solar radiation values (GW/m^{2}s) during a 30 year period. The solar radiation is lowest in North Europe even though the days during summer time are longer. The highest solar radiation was found in Southern Europe.

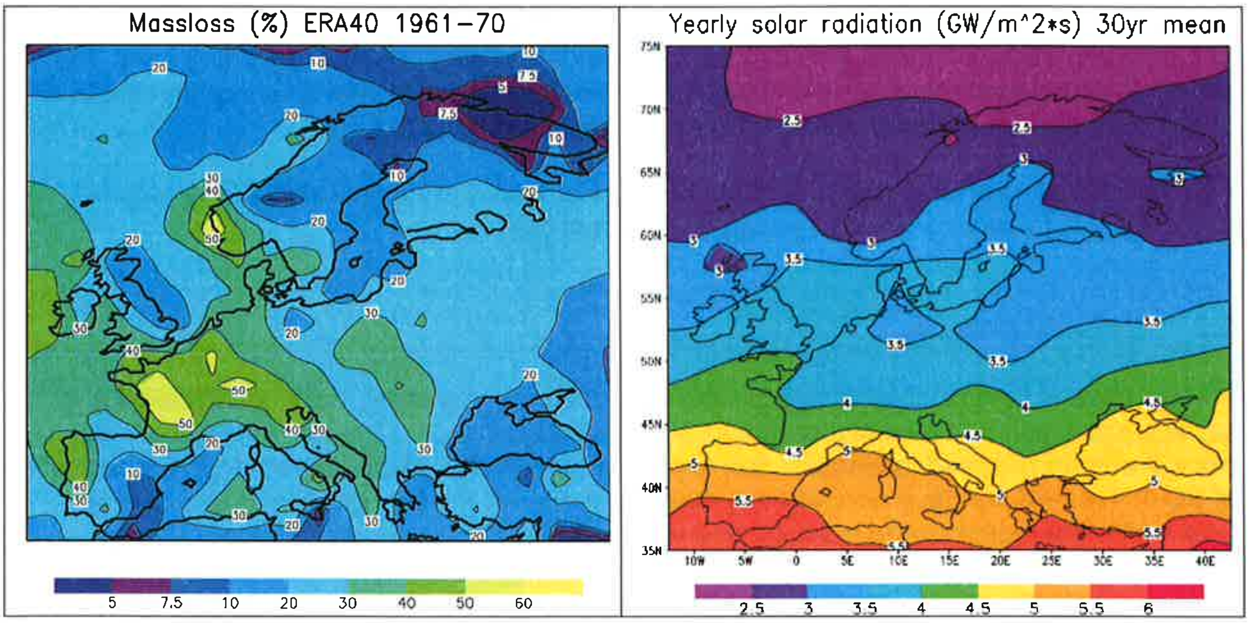


Figure 8. Effect of climate for the exterior construction of service class 3 / use class 3.2. Left: Modelled expected mass loss (in %) of small pieces of pine wood that were exposed to rain for 10 years in Europe. Right: Simulated solar radiation in Europe.

In north Europe, the climatic conditions are clearly more suitable for use of wood in outdoor part of the construction than that in Southwest part of Europe, especially around the Atlantic coast.

6. What should be taken care to obtain 100 years' service life of wooden buildings and structures in service class 1 and 2

6.1 Service class 1

To obtain 100 years' service life, several aspects should be taken care (ISO 15686). For durability and service life of wood structure in service class 1, most important factors are the design and work execution. Wood material quality and outdoor conditions have lower impact for durability in service class 1 than that in service class 2 and 3. The wood material should be dry and CE-marked. Glued material has been found to have the same performance level than that of timber in dry structures. Correct glue type and glue class should be used for engineering wood components.

Using elements and prefabricated elements under protective weather shield, the execution of structure can be performed fast and safety without risk of wetting or moisture exposure.

For successful building the compatibility of components, joints and connections between elements and HPAC (heating, plumbing, air-conditioning) are very important. Clear and easily executed solutions for these connections help builders to obtain the needed quality of building.

For safe use of water, the wet rooms, pipes and drains should be assembled in care, and the joints of pipes and wood elements should be well designed and executed. New techniques for tight and safe moisture barrier and durable leading-through solutions have been developed.

During the use of building, service and reparation of faults and malfunction is important. After accidental water damage, structures should be dried fast and efficiently. During the planning of a building, ability of moisture to be dried out from the structure should be taken care. The effect of natural loading should be taken care of to obtain the 100 years' service life. Manual of the maintenance for the building is very important for the users.

The structures in service class 2 and 3 should perform as a protective shield for structures and materials in service class 1 to keep the material dry.

6.2 Service class 2.

For structure in service class 2, design and execution are important, but wood material and surface protection has a bit higher role in SC 2 than that in SC 1. The structures in service class 2 are not exposed to weather, but exposure to humidity will be higher in SC 2 than that of SC 1. This will not have normally any significant role for the strength properties, but can give a bit higher exposure to cracking and mould growth on the surface of wood. Using surface treatment with agents against humidity and water penetration, the condition of the surface will remain more acceptable for the users. Acceptable performance level is often varied depending on the user needs, and surface discolouring give not often any sign of malfunction of the structure. For indoor environment, however, discolouring of surface by fungi is not allowed.

Using elements and prefabricated elements under protective weather shield, the execution of structure in SC 2 can be performed fast and safety without risk of wetting or moisture exposure. Details are very important to avoid water and moisture accumulation during the use of building.

The structures in SC 2 are short time exposed to outdoor air when the humidity will be high for short periods. Outdoor climate has a more important role for the performance of materials in SC 2. In humid climate conditions, the role of protective action of gladding and facades is important to avoid moisture and water penetration in wood of service class 1 and 2.

As structures in service class 1, also service is important and water damage situations should be repaired in time. Manual of the maintenance for the components s very important for the users.

7. Conclusions

For the service class 1 and 2 situation, the structures are protected from exposure to weathering, when only eventual short and low humidity exposure should be expected. The service class 1 means that the humidity of ambient air of the structure should only exceed RH 65 % for a few weeks per year. For service class 2, the short periods (weeks) of humidity higher than 85 % may be expected. For quality assurance in construction, several crucial tasks should been take care of: 1) project description, 2) initial risk assessment, 3) structural design, 4) risk analysis and external supervision of design, 5) moisture control plan, 6) assembly planning, 7) manual of the maintenance for the building. If these factors are well managed, there are no limitations to get service life of 100 years or more in the service life 1 (dry) conditions. For service class 2, the service life of 100 years is more demanding and the focus should be especially on the design, exposure conditions and maintenance.

Obviously most advanced service life evaluations are shown in the ISO 15686 series: the RSL or standard service life multiplied by a variety of factors based on a more careful consideration of the quality of materials, actual design, construction, use condition, maintenance and climate exposure of a specific building, building material, element, component or equipment. Using a factor method to evaluate the service life of insulated wooden building envelope (service class 1), the most important factors are design and execution. If the values of these factors are high and moisture exposure is not exceeding the tolerances, there is no obstacle to get service life above 100 years using 50 years reference service life in the service class 1 condition.

When the service life of wooden loadbearing structure will be higher than 50 years, the eventual loading caused by wind, snow an ice has to be taken care of as following: when the service life of wooden loadbearing structure will be higher than 50 years, the natural loading is evaluated to be 10 % higher than that for 50 years' service life and 20 % higher when the expected service life is above 100 years. This evaluation is suitable for the North Europe, where the climatic conditions are more suitable for the use of wood material than these in South and Southwest Europe.

In the service class 2 the expected humidity conditions can be higher than that in the service class 1, when some mould growth on untreated wood may be expected. The wood material and products against mould growth can be protected using different types of coatings.

When a service life of 100 years is required in service class 1 and 2, Plywood and LVL made with phenol-formaldehyde adhesive (PF) and glulam or multiple laminated LVL made with phenolic or aminoplastic adhesives (PRF or MUF), all these adhesive types will fulfil the requirements on basis of experience and test results when approved according to standards EN 301/EN 302. Products where polyurethane adhesives (PU), approved according to standard EN 15425, have been used, do not have such a long history of use, but there are no indications that their service life would not be of the same order as for the other approved adhesives.

To achieve 100 years' service life, following facts should be taken care of:

- use dry and CE marked wood material,
- correct glue type and glue class should be used for engineering components
- good detailing and design to avoid malfunction of the structure and protection of the structure from weathering
- good execution and protection against weathering during building process
- take care of the effect of natural loading for the higher service life
- proper maintenance during the use and manual of maintenance for the users
- guarantee proper condition for material in building during the service life (ventilation, protection, drying of accidental water damage).

8. Summary

The **service life of buildings and structures** is an important part of the life cycle planning. The **performance** of wood and wood-based materials with a given level is quantified as the level of ability to withstand load, exposure or deterioration over time in specified service conditions. EN 1995-1-1 defines a set of three service classes which are relevant to a designer when assigning strength and durability for timber elements to be used in a construction. In this work the focus is in the service class 1 (dry) and 2 (moderately humid conditions).

Performance requirement means the **minimum acceptable level of a property of a product**, which can be defined as **a limit state**. This defines the limit between acceptable performance and non-acceptable performance. **Durability** is defined "The ability of a product to maintain its required performance over a given time, under the influence of foreseeable actions, subject to **normal maintenance**". No significant differences on durability between massive wood and wood based engineering products (plywood, LVL, CLT) have been found, and the same service life category can be used for timber and engineering wood based products.

Service life is the period of time after installation during which a building or its parts meets or exceeds the performance requirements. For the structures in service class 1 (dry) and 2 (attics, outdoor structures protected from weather), most important performance requirement is to prevent water penetration in the construction. Humidity and moisture control is a key action to prevent moisture excess and damage caused by water, microbes or other organisms**. Reference service life** (RSL) is the expected service life of a building, material or component situated in well-defined set of conditions.

Design or expected service life is an evaluated service life calculated on the base of RSL and several different factors. Obviously most advanced service life evaluations are shown in the ISO 15686 series: the RSL or standard service life multiplied by a variety of factors based on a more careful consideration of the quality of materials, actual design, construction, use condition, maintenance and climate exposure of a specific building, building material, element, component or equipment.

Using a factor method to **evaluate the service life of wooden material in service class 1 and 2 situation**, the most important factors are design, execution and maintenance. If the values of these factors are high and moisture exposure is not exceeded the tolerances, there is no obstacle to get service life above 100 years using 50 years reference service life in service classes 1 and 2. The eventual climatic loading has to be taken care as following: when the service life of wooden loadbearing structure will be higher than 50 years, the natural loading is evaluated to be 10 % higher than that for 50 years' service life and 20 % higher when the expected service life is above 100 years.

To achieve 100 years' service life, following facts should be taken care:

- use dry and CE marked wood material,
- correct glue type and glue class should be used for engineering components
- good detailing and design to avoid malfunction of the structure and protection of the structure from weathering
- good execution and protection against weathering during building process
- take care the effect of natural loading for the longer service life
- proper maintenance during the use and manual of maintenance for the users
- guarantee proper condition for material in building during the service life (ventilation, protection, drying of accidental water damage).

9. Tiivistelmä

Rakenteiden ja rakennusten kestoikä on tärkeä osa elinkaarisuunnittelua. Puun ja puutuotteiden **toimivuus** ja sen taso arvioidaan sen mukaan, miten ne kestävät kuormia, rasitusta ja vioittumista ajan suhteen sekä määritellyissä käyttöoloissa. Standardissa EN 1995-1 (Eurocode) on annettu kolme käyttöluokkaa, jotka ovat tärkeitä suunnittelijan arvioidessa rakenteissa käytettävien puuosien lujuutta ja pitkäaikaiskestävyyttä. Tässä työssä keskitytään käyttöluokkaan 1 (kuivat) ja 2 (kohtuulliset kosteusolot).

Toimivuusvaatimukset tarkoittavat **pienintä hyväksyttävää tuotteen ominaisuutta eli rajatilaa** (hyväksyttävyystasoa). **Pitkäaikaiskestävyys** tarkoittaa tuotteen kykyä ylläpitää tarvittavaa toimivuustasoa ajan suhteen etukäteen arvioiduissa oloissa, normaalien huoltotoimenpiteiden puitteissa. Puumateriaalin ja vaatimusten mukaan valmistettujen puukomponenttien (vaneri, LVL, CLT) pitkäaikaiskestävyydessä ei ole havaittu merkittäviä eroja, jolloin niiden ja massiivipuurakenteiden osalta voidaan tarkastella kestoikää samoista lähtökohdista.

Kestoikä on vastaavasti se aika, jolloin rakenne pystyy ylläpitämään vähintään vaadittua toimivuustasoa rakennuksen tai rakennusosan asennuksen jälkeen. Säältä suojatun rakenteen kannalta tärkein toimivuusvaatimus on puun ja rakenteen pysyminen riittävän kuivana. Rakenteen kosteuden hallinta on tärkein periaate suojattaessa rakenteita kosteuden kertymistä sekä veden, mikrobien, sienten ja muiden organismien aiheuttamia vikoja ja vaurioita vastaan.

Vertailukestoikä on rakennuksen, materiaalin tai komponentin odotettavissa oleva kestoikä etukäteen määritetyissä oloissa. **Suunniteltu tai odotettu kestoikä** on arvioitu kestoikä. joka perustuu vertailukestoikään ja siihen liitettyjen eri tekijöiden funktioon. Kehittynein kestoikäarviointimenetelmä lienee standardisarjassa ISO 15686 esitetty menetelmä, jossa määritellyn materiaalin, rakenteen tai rakenneosan vertailukestoikään lisätään kertoimina materiaalin laatu, suunnittelu, rakenteet, käyttöolot, ilmasto-olot sekä huolto.

Kestoikäanalyysien mukaan säältä suojatun puurakenteen kestoiän kannalta tärkeimmät tekijät ovat hyvä suunnittelu, rakentaminen ja huolto. Jos nämä ovat onnistuneet ja puurakenteen kosteus on sallituissa rajoissa, puurakenteiden kestoikä voidaan hyvin lisätä 50 vuodesta 100 vuoteen tai ylikin käyttöluokissa 1 ja 2. Laajennettaessa kestoikätavoitetta 50 vuodesta 100 vuoteen, on otettava erikseen huomioon mahdollisista luonnonkuormista johtuva lisäkuormat seuraavasti: suunnitellun käyttöiän ollessa yli 50 vuotta kuormien ominaisarvoja korotetaan 10 prosentilla ja suunnitellun käyttöiän ollessa yli 100 vuotta kuormien ominaisarvoja korotetaan 20 prosentilla.

Näin saavutetaan yli 100 vuoden toiminnallinen kestävyys käyttöluokissa 1 ja 2

- Käytä kuivaa CE merkittyä puumateriaalia
- Oikea liimatyyppi: vanerit, kertopuu, liimapuu, CLT tuotteet
- Kosteusteknisesti toimivat suunnitteluratkaisut ja detaljit – vältetään rakennevirheet ja hoidetaan suojaus säätä vastaan
- Hyvä rakennustapa: materiaalit ja komponentit valmiiksi kuivissa oloissa - suojataan rakennukset säältä rakennusvaiheessa – kuiva rakentaminen koko prosessin läpi
- Otetaan luonnonkuormien muutokset huomioon suunnittelussa
- Huolto-ohjeet käyttäjille ja huollon oikea-aikainen toteutus
- Varmistetaan oikeat materiaalin vaatimat olosuhteet koko rakennuksen käyttöajan: ilmanvaihto, suojaus kosteudelta, yllättävien kosteusongelmien kuivaus tehokkaasti ja ajallaan.

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