1 Wood Durability and Lifetime of Wooden Products

Wooden products (furniture, flooring, doors, etc.) and constructions (log cabins, bridges, ceilings, trusses, etc.) produced from various species of wood and types of wooden composites are in practice exposed to different environments, where they can be subjected to more forms of degradation (see Chapters 2 and 3).

With the aim to suppress the degradation processes in the wood, and also in glues, paints and other materials used for wooden products and constructions, it is desirable to use suitable forms of their structural, chemical and modifying protection so that their lifetime can be suitably increased (see Chapters 4, 5 and 6).

The service life of wooden products and constructions can be increased by their regular maintenance. However, when degradation processes in wood and/or in additional materials occur and cause damage, appropriate restoration methods should be used (see Chapter 7).

1.1 Basic information about wood structure and its properties

The structure of wood and wooden composites (Figures 1.1 and 1.2) and their exposure in conditions suitable for the action of abiotic factors and/or the activity of biological pests (Figure 1.3) are the basic prerequisites for potential damage of wooden products and constructions.

Wood is a biopolymer, created by a genetically encoded system of photosynthetic and subsequent biochemical reactions in the cambial initials of trees (Figure 1.1). Trees consist of approximately 70–93 vol.% of wood, with the rest being bast, bark and needles or leaves. Wood is the internal, lignified part of the stem, branches and roots. The characteristics of wood include: (1) anisotropy, typical in three anatomical directions – longitudinal, radial and tangential;

Wood Deterioration, Protection and Maintenance, First Edition. Ladislav Reinprecht.

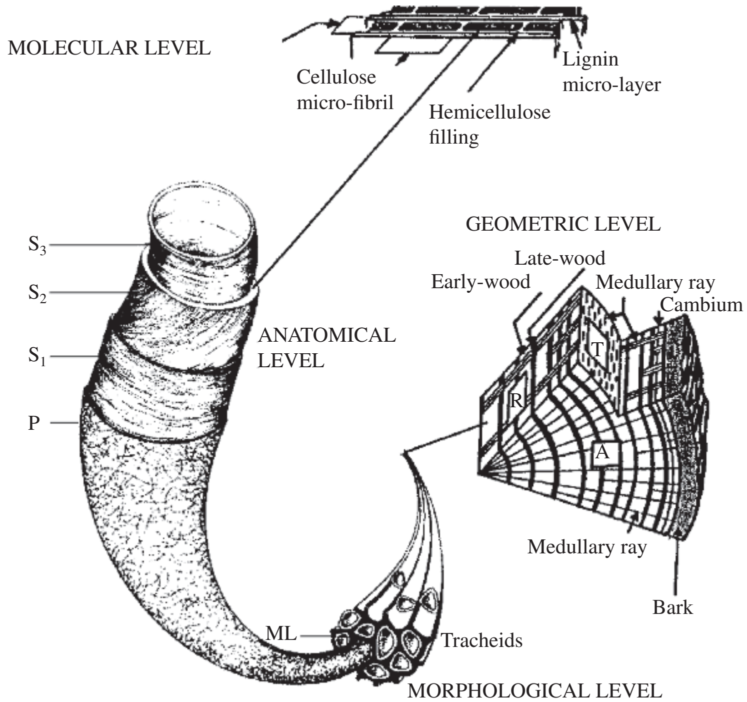


Figure 1.1 Structural levels of wood (modified from Eriksson et al. (1990) and Reinprecht (2008))

Source: Eriksson, K-E., Blanchette, R. A. and Ander, P. (1990) Microbial and enzymatic degradation of wood and wood components. Springer Verlag – Berlin Heidelberg, 407 p. Reproduced by permission of Springer

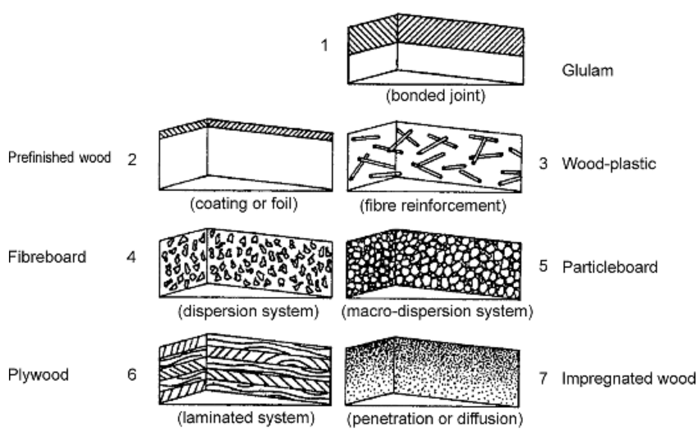


Figure 1.2 The basic types of wooden composites: (1) glulam (glued joints); (2) prefinished wood (coatings or foils); (3) wood–plastic (fibre reinforcement); (4) fibreboard (dispersion systems); (5) particleboard (macro-dispersion systems); (6) plywood (laminated systems); (7) impregnated wood (penetrations or diffusions). (Note: composite is a multicomponent system of materials consisting of at least two macroscopically distinguishable phases, of which at least one is solid)

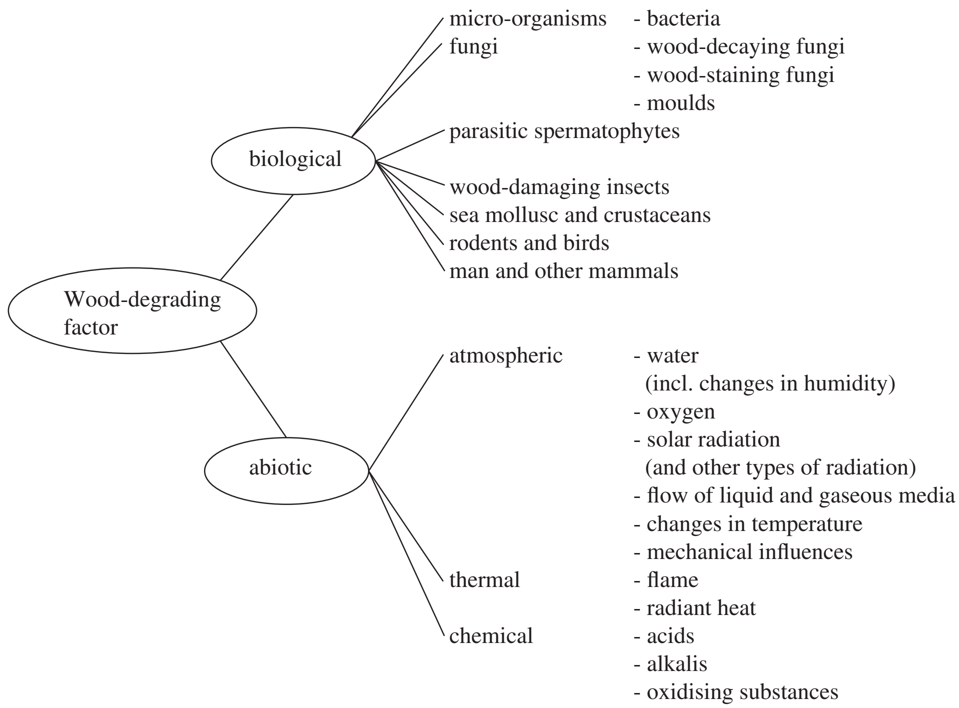


Figure 1.3 Biological and abiotic wood-degrading factors

Source: R., L. (2013) *Wood Protection*, Handbook, TU Zvolen, Slovakia, 134 p. Reproduced by permission of TU Zvolen

(2) inhomogeneity, influenced by the sapwood and heartwood, the early wood and late wood, and so on; (3) specificity, given by the wood species; and (4) variability, given by the growth conditions of the tree of a given wood species.

Wood is a traditional material, used for producing wooden buildings, furniture, work and sport tools, as well as art works. It is currently an irreplaceable raw material for the production of bio-based composites with the targeted combination of wood particles in various stages of disintegration and pretreatment with a complementary system of adhesives, waxes and other additives (Figure 1.2).

1.1.1 Wood structure

The *structure of wood* (Figure 1.1, Boxes 1.1, 1.2, 1.3 and 1.4) and *wooden composites* (Figure 1.2) is defined at four levels:

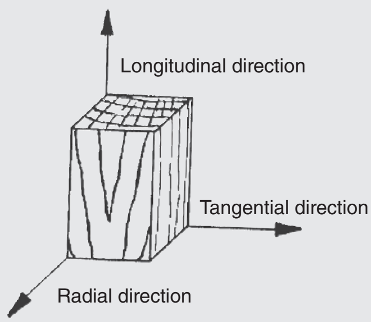
- primary (i.e. molecular/chemical structure);
- secondary (i.e. anatomical/submicroscopic structure);
- tertiary (i.e. morphological/microscopic structure);
- quaternary (i.e. geometric/macroscopic structure).

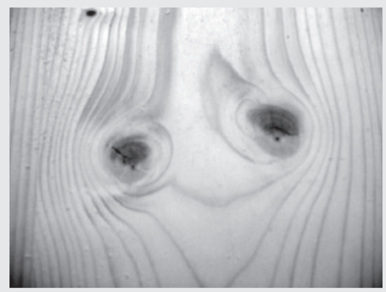
Box 1.1 A basic preview of the geometric structure of wood

The geometric structure of wood

Defines

The external appearance – shape, volume, colour, the ratio of tangential, radial and facial areas, the proportion of sapwood, heartwood and/or mature wood, the proportion of early and late wood in annual rings, the roughness and overall quality of the surfaces, and so on.





Knots

The macroscopic inhomogeneities – knots, compression or tension wood, juvenile wood, false heart, resin chanals, and so on, together with their type, frequency and state of health (e.g. damage by rot).

Depends on

- the morphological structural level (i.e. the proportional and spatial distribution of various types of cell elements in the wood);
- the growth defects and anomalies in the wood;
- the mechanical and other loads/treatments of the wood.

Source: R., L. (2008) *Ochrana Dreva* (*Wood Protection*), Handbook, TU Zvolen, Slovakia, 453 p. Reproduced by permission of TU Zvolen.

Box 1.2 A basic preview of the morphological structure of wood

The morphological structure of wood

Defines

The individual cells – type, shape, dimensions, slenderness factor, orientation to the pith (longitudinal, radial), thickness of the cell wall, thinning in the cell wall (type, frequency, location), and so on.

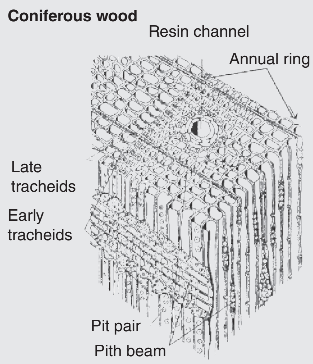
The grouping of cells – proportion and location of parenchymatic, libriform, vessel, tracheid and other cell-types in the wood tissues.

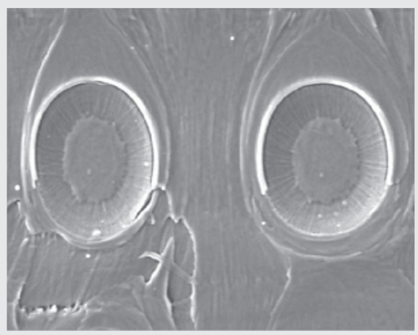
Depends on

The wood species (Fengel & Wegener, 2003; Wagenführ, 2007; Wiedenhoeft, 2010; Wiemann, 2010):

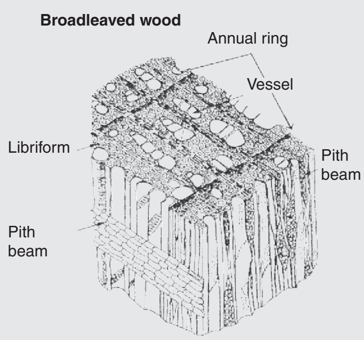
- *Wood of coniferous species* has a simple and fairly regular morphological structure. Approximately 90–95% of wood volume is formed of early and late tracheids. Tracheids have a conductive and strengthening function. They are 2–5 mm long (late are approximately 10% longer) and 0.015–0.045 mm wide. Their cell walls, with a thickness of 0.002–0.008 mm, contain a fairly high number of pit pairs, usually 60–100 in early tracheids and 5–25 in late tracheids. Pit-pairs with a diameter of 0.008–0.03 mm are mainly at the end of tracheids on their radial walls. Opened pit-pairs provide interconnection between tracheids, which is used in the transport of liquids into the wood at its chemical protection and modification. Parenchymatic, thin-walled cells form stock tissue with living protoplasm. They are located in radially oriented pith beams and in longitudinally oriented parenchymatic fibres and resin channels. Resin chanals are lacking in some coniferous species (i.e. they are not present in fir or yew wood).
- *Wood of broadleaved species* has a more complicated morphological structure compared with coniferous wood. Libriform fibres, present in a volume of 36–76%, have a strengthening function. They are relatively short, from 0.3 to 2.2 mm, with a width from 0.005 to 0.03 mm. They have a weak connection with other types of cells due to the small number of simple pit or half-pit thinned areas. Vessels, present in a volume of 20–40%, have a conductive function. Their conductive function is important for the transport of nutrients during a tree's growth, as well as for transport of preservatives and modifying substances into wood.

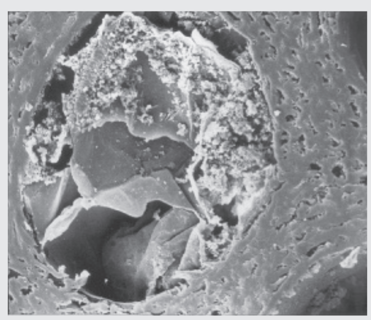
In ring-porous species (ash, elm, hickory, oak), large vessels in early wood have a diameter from 0.2 to 0.5 mm, whilst small vessels in late wood are from 0.016 to 0.1 mm. The length of vascular systems are usually up to 0.1 m, but in some wood species this can even be several metres (e.g. as long as 7 m in oak). They are created from a long, vertical line of vessels connected via openings – simple, reticular or ranking perforations. Cell walls of vessels have circular and spiral thickenings. The conductive function of vessels decreases under the influence of tyloses (i.e. when blocked by outgrowth from the surrounding paratracheal parenchyma). Parenchymatic cells, present in a volume of 2–15%, mainly have a storage function. Longitudinal, paratracheal parenchymata (single-sided, group, vasicentric, etc.) group around the vessels and vessel tracheids and connect to them via single-sided pit pairs. Longitudinal, apotracheal parenchymata do not come into contact with the vessels. In radially oriented pith beams, several parenchymatic cells are combined with a rectangular shape, horizontal or vertical, either in morphological unity (homogeneous beam) or in morphological diversity (heterogenic beam).





Closed pit pairs in tracheids





Vessel blocked by tyloses

Source: R., L. (2008) *Ochrana Dreva* (*Wood Protection*), Handbook, TU Zvolen, Slovakia, 453 p. Reproduced by permission of TU Zvolen.

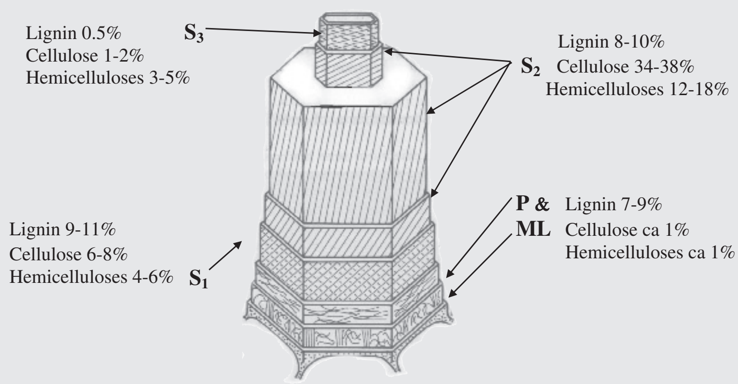
Box 1.3 A basic preview of the anatomical structure of wood

The anatomical structure of wood

Defines

The structure of the cell walls of wood's cells:

- layering (i.e. the individual layers ML, P, S_1, S_2, S_3 – see Figure 1.1);
- proportion and localization of the structural polymers (cellulose, hemicelluloses and lignin) and extractives in the individual layers of the cell wall.



Depends on

The wood species and the type of cell (Fengel & Wegener, 2003; Wiedenhoeft, 2010):

- Elementary fibrils, formed usually of 40 macromolecules of cellulose, are the basic elements of the cells' walls with a cross-section of ca 3.4 nm × 3.8 nm. Microfibrils consist of 20–60 elementary fibrils. Macrofibrils consist of cellulose microfibrils as well as of hemicellulose fillings and lignin microlayers.
- Microfibrils and macrofibrils form substantial lamellae that are the structural base for individual layers of a cell wall (i.e. the ML, P, S_1, S_2 and S_3):
  - ML → middle lamella, mainly formed of lignin granules;
  - P → primary wall, with a thickness of 0.06–0.09 μm, formed of a high proportion of lignin and cellulose fibrils orientated randomly into a multilayered network;

– S → secondary wall, with a thickness of 1–6 μm, formed of three separate layers, S_1, S_2 and S_3; these layers differ in thickness, orientation of fibrils and the proportion and structure of lignin and polysaccharides; for example, in the tracheids of conifers the ratio of layers $S_1/S_2/S_3$ is around 12/78/10.

Affects

The permeability of the wood:

- Cell walls of wood are able to transmit gases and polar liquids. This is due to their microporous structure with vacant pores of size 1–80 nm, as well as due to hydroxyl (—OH), carbonyl (C═O) and other polar groups of lignin and polysaccharides. Macromolecules of polysaccharides in the cell walls repel each other in the presence of polar liquid molecules (e.g. water), which also continuously increase the porosity of the cell wall to a maximum size of ~80 nm. Therefore, its permeability for diffusion and capillary transports continually increases.
- Micropores in the cell walls of wood – gaps in elementary fibrils (~1 nm), capillaries in microfibrils (~10 nm), capillaries in macrofibrils (<80 nm), pores in a pit membrane (<150 nm).

The mechanical properties of the wood:

- For example, cell walls with a greater proportion of the S_2 layer, and also therefore cellulose, provide wood with a greater tensile strength along the fibres.

Source: R., L. (2008) *Ochrana Dreva* (*Wood Protection*), Handbook, TU Zvolen, Slovakia, 453 p. Reproduced by permission of TU Zvolen.

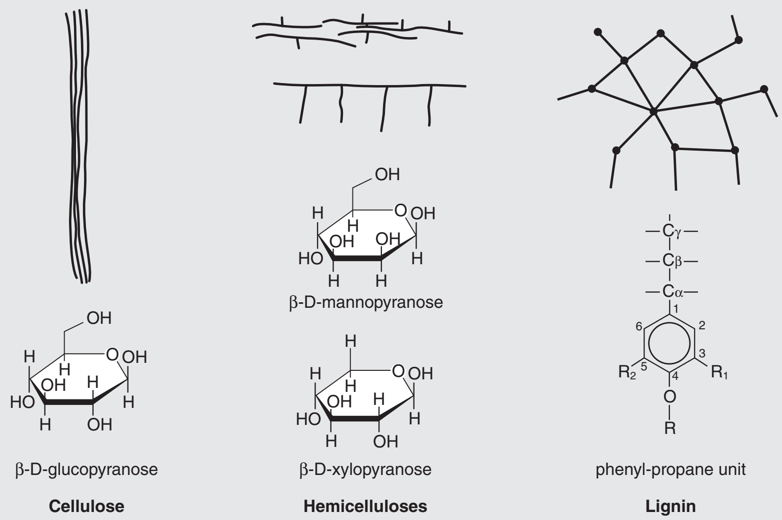
Box 1.4 A basic preview of the molecular structure of wood

The molecular structure of wood

Defines

The types and chemical structure of wood components – cellulose, hemicelluloses and lignin located in the cell walls, and extractives (accompanying substances) located in the cell walls or also in the lumens.

The physical–chemical status of wood components – the degree of polymerization, conformation and configuration structures (spatial grouping into globules, rods, helixes), the supramolecular status (crystalline, amorphous), the physical status (glassy, plastic, viscoelastic), the ability to form intramolecular bonds (hydrogen bonds, van der Waals interactions).



Depends on

The wood species, the type of cell, and the specifics of its composition (Eriksson et al., 1990; Fengel & Wegener 2003):

- Cellulose is a linear polymer consisting of 1,4-β-D-glucopyranose units. These are either arranged into crystalline units (elementary fibrils) or are in an amorphous state.
- Hemicelluloses form branched macromolecular systems of mannanes (in coniferous wood), xylanes (in broadleaved wood) and other polysaccharides.
- Lignin in coniferous woods is a guaiacyl-type based on coniferyl phenyl-propane units (i.e. 15% $-OCH_3$ groups/C_9). Lignin in broadleaved woods is a mixture of guaiacyl-type and syringyl-type, at which lignin of syringyl-type is based on synapyl phenyl-propane units (i.e. 20–21% $-OCH_3$ groups/C_9).
- Terpenes are accompanying biologically effective substances in the wood of more durable coniferous species. Tannins, flavonoids and some other substances play this role in the wood of more durable broadleaved species.

Affects

The durability of the wood:

- hemicelluloses are the overall most unstable component of the wood, mainly against high temperatures and hydrolysis in the presence of acids in the environment or enzymes produced by wood-decaying fungi;

- lignin is not stable when facing oxidation induced by ultraviolet (UV) radiation in exterior, or by peroxidases and other enzymes of white-rot fungi;
- accompanying substances affect the resistance of wood to biological damage; various woods contain different amounts of (1) easily biodegradable substances (e.g. starch, pectin, glycosides and lipids) and (2) substances biologically effective against wood-decaying fungi, moulds or wood-boring insects (e.g. tannins, flavonoids, stilbenes, terpenes and resin acids).

The preservation and modification of the wood:

- diffusion and fixation processes of preservatives and modifying substances in wood depend not only upon their physical and chemical properties but also upon the molecular structure of the cell walls in the wood;
- modification of the molecular structure of wood (acetylation, etherification, etc.) can increase resistance to biological pests, and the dimensional stability and strength properties can be improved.

Source: R., L. (2008) *Ochrana Dreva* (*Wood Protection*), Handbook, TU Zvolen, Slovakia, 453 p. Reproduced by permission of TU Zvolen.

The structure of wood significantly determines its natural durability, defined as its resistance to abiotic and biological damages (see Chapters 2 and 3). In this view, the structure of wood also affects the conditions for storing of cut logs and produced timber, the methods and technologies for the structural, chemical and modifying protection of wooden products (see Chapters 4, 5 and 6), as well as the methods and technologies for their maintenance and restoration (see Chapter 7).

1.1.2 Wood properties

The properties of wood (Box 1.5) usually worsen due to its damage (see Chapters 2 and 3). The restoration of damaged wood returns its original properties – strength, dimensional stability, aesthetics, and so on (see Chapter 7).

Box 1.5 A basic preview of the properties of wood

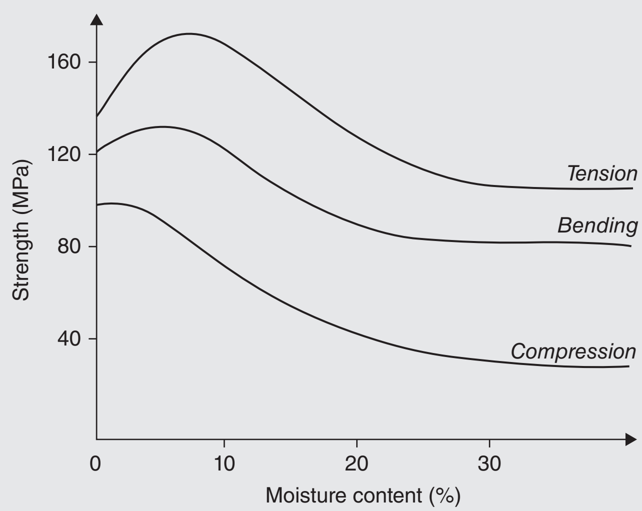
See also Sections 2.4 and 3.6.

Density

The wood of broadleaved species commonly used in Europe for products and constructions (Table 1.3: beech, birch, black locust, elm, hornbeam, linden, maple, oak, poplar, etc., 440–800 kg/m^3) is usually more dense than the wood of commonly used coniferous species (Table 1.3: cedar, Douglas fir, fir, larch, pine, spruce, 370–530 kg/m^3). The density of wood is decreased after being damaged by fire, fungal rot or insect galleries. However, the opposite trend (i.e. an increase of density) is not uncommon in subfossil wood or wood attacked by alkalis.

Strength properties

Wood has a relatively high strength in relation to its density when compared with other materials used in construction. The strength properties of wood (compression, tension, bending, hardness, etc.) depend upon its density and structure, which assist us in selecting a suitable type of wood for a particular use. Depolymerization of polysaccharides in decayed or otherwise damaged wood decreases its strength, mainly in its wet state, where the support strengthening effect of hydrogen bonds and van der Waals interactions already do not apply.



Moisture properties

The humidity of wood adapts to climatic conditions of its exposure. During long-term exposure to air with a relative humidity of 95–99%, wood greatly humidifies and its equilibrium moisture content settles around 28–30%; that is, the fibre saturation point (FSP). The wood also easily receives liquid water via capillary forces, and its maximum moisture depends upon its porosity/density; for example, beech with a density of 600 kg/m^3 has a maximum moisture of ~120%, whereas for spruce with density of 400 kg/m^3 it is as much as ~200%.

The swelling and shrinkage of wood are processes connected with receiving of bound water until it reaches the FSP (wood swells) and vice versa with its drying when water is released (wood shrinkages). The dimensions of wood change as well as when its moisture changes from FSP to 0%; for example, for common wood species the maximum shrinkages are in a longitudinal direction $\alpha_L = 0.15–0.65\%$, a radial direction $\alpha_R = 2.5–6.7\%$ and in a tangential direction $\alpha_T = 8.3–14.7\%$.

The moisture properties of wood also affect its strength, durability and use; that is, (1) strength of wood usually decreases with increased moisture within the range from 0% to the FSP; (2) resistance of wood to biological damage is usually lower at higher moistures; and (3) frequent and marked changes in the moisture content of wood lead to shape deformation and the creation of cracks.

Thermal properties

Wood has relatively good thermal insulation properties. However, it does not resist temperatures over 150 °C for a long time and may ignite. Despite the fact that it is flammable, during fires it is often more stable in terms of shape and strength than metals or plastics are.

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1.2 Types and principles of wood degradation

Wood is more or less susceptible to various forms of degradation (Figure 1.3, Table 1.1; and see Chapters 2 and 3). In wood degradation, the dominant role is played by its molecular structure (Box 1.4). However, its higher structural levels – anatomical (Box 1.3), morphological (Box 1.2), and geometric (Box 1.1) – also have significant roles. Wood can already be damaged during its growth in trees, subsequently at harvesting, during storage and transport of logs and timbers, and also after processing on products and constructions.

Changes in structural levels of wood are caused by abiotic agents or energies and biological pests. Subsequently, its strength, hygroscopic, thermal, aesthetic and other properties are also changed, and usually impaired. The intensity and scope of the structural and property changes of wood depend upon the type and mechanism of the degradation process. In the case of some degradation types (e.g. due to weathering or moulds), just surface damage of wood occurs. In contrast, in the case of fire, fungal decay or feeding by wood-damaging insects, wood is degraded to a greater depth, often in full.

Damage that begins at the molecular structure of wood is the most important for changes in its properties (Table 1.1). All degradation effects in the

Table 1.1 Types of wood degradation related to the deterioration of its polymers (polysaccharides and lignin) or without their deterioration

Type of wood degradation	Wood-degrading factor
With destruction of wood polymers	
Photo-oxidations (mainly in lignin, 0.05–2.5 mm from surface)	UV radiation
Thermo-oxidations, dehydrations (mainly in hemicelluloses)	Thermal effects • temperature of air above ~150 °C • fire (flame)
Hydrolytic reactions, lignin plasticizing	Hydrothermal effects • temperature of water/steam above ~70 °C
Various reactions – hydrolytic, dehydration, oxidation, etc., cellulose de-crystallization	Aggressive chemicals • emissions (e.g. SO_2, NO_x) • acids and alkalis • inorganic fungicides • fire retardants
Biochemical reactions catalysed by enzymes and low molecular weight agents of fungi and bacteria	Wood-decaying fungi • white rot • brown rot • soft rot Bacteria
Mechanical decompositions and then biochemical reactions in digestive tract	Wood-damaging insects Marine organisms
Without destruction of wood polymers	
Mechanical cracks	Humidity and thermal gradients
Mechanical holes, nibbling marks	Some insects, birds and mammals
Colour changes	Wood-staining fungi and moulds
Degradation of bordered pits in tracheids	Bacteria and moulds

Source: R., L. (2013) *Wood Protection*, Handbook, TU Zvolen, Slovakia, 134 p. Reproduced by permission of TU Zvolen.

molecular structure of wood – in its polymers, caused by atmospheric factors, high temperatures, aggressive chemicals and fungal decay – are reflected also at its anatomical and morphological structural levels (e.g. with regard to damage of cell walls and entire tissues), and usually also at its geometric level (e.g. more intensive degradation of sapwood or early wood), and of course in its properties as well.

Damage that begins only at the upper structural levels of wood is usually less important for changes in its properties. For example, small changes in the density and strength of wood can occur as a result of microscopic and macroscopic cracks created by moisture stresses due to badly regulated drying, although without great changes in its hygroscopicity and colour.

1.3 Natural durability of wood

Wood has several implicit advantages in comparison with other materials (e.g. stone, clay, brick, concrete, metals, plastics):

- it is a permanently renewable material source (e.g. it has low impact on the environment and low energetic demands for processing in total);
- it is easily workable;
- it has high strength in relation to density;
- it has low thermal conductivity;
- aesthetically pleasing qualities in products.

In contrast, *wood also has negative properties, reflected by its lower natural durability*:

- weathering
- flammability
- biodegradability.

The *natural durability of wood* is its inherent resistance to various abiotic factors and biological pests (see Chapters 2 and 3). The natural durability of a defined wood species (and also of a defined type of wooden composite) may be only supposed – it may not be exactly defined. The cause is the complementary effects of many variables. The most significant of these are:

- Differences in the structure of the individual wood species; that is, there is a specific dependence on the age of the wood and the presence of juvenile wood, and also on the climatic, soil and other conditions of tree growth (Table 1.2).
- The environment around the wooden product. That is, there is usually a difference between interior and exterior environments, as well as in various exterior climatic zones; there is also an influence of the structural protection of wood used (prEN 16818). For example, weather factors acting on the exterior are more aggressive in a direct contact with the ground or above ground without shelter (Brischke & Rapp, 2008); a northerly orientation is usually more suitable for the activity of wood-damaging fungi, while abiotic degradation of wood surfaces due to UV radiation and temperature changes is stronger in a southerly orientation.

The *natural durability of individual wood species* is known from practice; however, it is permanently studied also on the basis of both laboratory and field tests. Several studies on the natural durability of various wood species were elaborated by, for example, Rapp et al. (2000), Van Acker et al. (2003) and Van Acker and Stevens (2003). The natural durability of woods is now based on practical knowledge and experiments assembled in the form of (1) the percentage ratio

Table 1.2 Natural durability of wood predetermined by its structure

Structural level of wood	Wood durability
Molecular	
• Accompanying substances:	
Tannins (e.g. black locust, chestnut, oak)	higher resistance to fungi and insects
Resins (e.g. Douglas fir, larch, pine)	higher resistance to fungi and insects lower resistance against ignition
Inorganic substances (e.g. containing Na, K, Ca, Mg, P, S) comprised mainly in the wood of fast-growing species (e.g. poplar, alder)	lower resistance against fungi
• Crystalline cellulose	higher resistance against fungi
• Lignin	higher resistance against combustion lower resistance against UV radiation
Anatomical	
• Both polysaccharides and lignin in cell walls	impeded transfer of enzymes of fungi and bacteria in cell walls
Morphological	
• Parenchyma cells	easily attacked by bacteria and fungi (since they comprise nutrients)
• Vessels	easily permeable for fungi hyphae (also for liquids and gases)
• Libriform fibres	easily attacked by some decay-causing fungi (compared with vessels)
• Opened pits in cell walls	easier transfer of enzymes in wood easier changes of wood moisture
Geometric	
• More frontal surfaces	worse durability
• More sap-wood	worse durability
• More early wood	usually worse durability
• Rougher surface	usually worse durability

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durability, with regard to a well-known wood species (e.g. to oak heartwood), or (2) durability classes (e.g. by EN 350-2), which rank woods on the basis of their resistance to activity of selected biological pests (Table 1.3).

The natural durability of individual wood species is influenced also by the pest's interest about the wood, or by the ability of a specific chemical compound to be attacked in the wood. For example, some species of wood-damaging insects attack only wood of conifers and only in interiors – typically, the house longhorn beetle (*Hylotrupes bajulus*). Woods having tannins or similar extractives (e.g. oak) become black in colour near to a contact with iron nails or screws, but others woods (e.g. beech) are resistant to such colour changes.

Table 1.3 Classes of natural durability of selected wood species in their contact with ground – against rot (modified from EN 350-2)

Durability class	Commercial name	Scientific name	B or C[a]	Density (kg/m^3)	Occurrence
1					
Very durable	Greenheart	*Ocotea rodiaei*	B	1030	South America
	Jarrah	*Eucalyptus marginata*	B	830	Australia
	Mansonia	*Mansonia altissima*	B	620	West Africa
	Okan	*Cylicodiscus gabunensis*	B	920	West Africa
	Padouk	*Pterocarpus soyauxii*	B	740	West Africa
	Teak	*Tectona grandis*	B	680	Asia
	Walaba	*Eperua falcata*	B	900	South America
1–2					
	Black locust	*Robinia pseudoacacia*	B	740	Europe
	Kapur	*Dryobalanops aromatica*	B	700	South-East Asia
2					
Durable	Bubinga	*Guibourtia demeusii*	B	830	West Africa
	Chestnut	*Castanea sativa*	B	590	Europe
	Oak	*Quercus robur (Q. petraea)*	B	710	Europe
	White cedar	*Thuja plicata*	C	370	North America
3					
Medium durable	Douglas fir	*Pseudotsuga menziesii*	C	530	North America
	Turkey oak	*Quercus cerris*	B	770	Europe
	Walnut	*Juglans regia*	B	670	Europe
3–4					
	Larch	*Larix decidua*	C	600	Europe
	Pine	*Pinus sylvestris*	C	520	Europe
4					
Less durable	Elm	*Ulmus* sp.	B	650	Europe
	Fir	*Abies alba*	C	460	Europe
	Spruce	*Picea abies*	C	460	Europe
5					
Non-durable	Ash	*Fraxinus excelsior*	B	700	Europe
	Beech	*Fagus sylvatica*	B	710	Europe

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Table 1.3 (*Continued*)

Durability class	Commercial name	Scientific name	B or C[a]	Density (kg/m³)	Occurrence
	Birch	*Betula pubescens*	B	660	Europe
	Hornbeam	*Carpinus betulus*	B	800	Europe
	Lime tree	*Tilia cordata*	B	540	Europe
	Maple	*Acer pseudo-platanus*	B	640	Europe
	Poplar	*Populus* sp.	B	440	Europe

Durability classes 1 to 5 are relative; that is, usable only for mutual comparison of durability of the individual types of wood.
Durability classes are applicable only to heartwood.
Sapwood of all broadleaved and coniferous species is classified in class 5 (non-durable), unless other data are available.
[a] B: broadleaved; C: coniferous.

From the point of view of the natural durability of wood against pests, it can be generally stated that this does not depend upon the wood density. For example, the mature or heart parts of beech, hornbeam and other woods having a high density but no biologically active agents (tannins, stilbenes, terpenes, etc.) belong to the less durable species like alder, lime tree and poplar woods that have substantially lower densities.

A *decrease in the high natural durability (resistance to pests)* of several exotic wood species (Kazemi, 2003; Yamamoto et al., 2004; Nzokou et al., 2005) or some European woods (e.g. black locust and oak) can occur during their exposure when mainly in a permanently moist environment. Tannins and also other low molecular weight substances, which significantly increase the resistance of woods to biological pests, may be gradually washed out or evaporated from the wood, and thus suffer from a decreased natural durability against fungi or other pests over time. Similar experiences are known for archaeological or subfossil oaks that have lain under a wet ground for several thousand years (Horský & Reinprecht, 1986).

1.4 Methods of wood protection for improvement its durability

Wood protection is defined as the set of measures for securing its quality and increasing its natural durability. Protection of wood is carried out from growing interventions by foresters, through suitable tree harvesting, logs and sawn timbers transportation and storage, compliance with technological principles of production and protection of wooden products up to their use in practice.

Protection of wood can be performed by applying various methods throughout the various stages:

- protection of growing trees (i.e. in the forest) against physiological pests and other factors, which is provided for by foresters (i.e. forest and tree protection);
- protection of harvested wood (i.e. on round-wood yards) and during first-stage processing to sawn timber, veneers, chips and other intermediate products (i.e. the physical – totally wet conditions or quick drying) and possibly also short-term chemical wood protection;
- protection of new wooden products (i.e. use of suitable structural designs and selection of suitable chemical, modifying and other processing) – all these methods of preventive and supplementary wood protection are based on physical, structural, chemical and/or modification technologies (Table 1.4; and see Chapters 4, 5 and 6);
- protection of older wooden products – that is, maintenance of wood, or conservation and reconstruction of markedly degraded wood, typically of historical artefacts and constructions (see Chapter 7).

In general, the objective of wood protection is to create such conditions in its structure and surrounding environment that are unfavourable for the damaging effect of abiotic factors and biological pests. The natural durability of wood can be improved using several methods (Table 1.4). However, it holds true that improvement of the natural durability of wood should be specifically reasonable for every type of wooden product; that is, it is not expedient to unreasonably improve the service life of a wooden product using such technology that evidently burdens the environment and the protected wood becomes harmful to the health of people and animals.

1.5 Service life prediction of wooden products

Wooden products and constructions wear in time both physically (i.e. due to the impact of defects caused by various wood-degrading factors) and morally (i.e. due to the changed demands of humans regarding their functionality, aesthetic aspects, etc.).

The service life means the period of time after installation during which a building or its parts meets or exceeds the performance requirements (ISO 15686). Similarly, the service life of log cabins, trusses, ceilings, windows, doors, furniture and other products made of wood is defined by the time for which they should meet the function, technical and aesthetic requirements under the supposed conditions of application. Their service life can be defined also as the time after which they get to a so-called terminal condition (i.e. they become unusable). The service life is a variable value since it is determined from supposed exposure conditions that are not always fully implemented

Table 1.4 Principles of preventive protection of wooden products in order to increase their durability

Principle of wood protection		Technology of wood protection	Utilization in practice
Natural durability		Application of:	
		(a) more durable wood species and wooden composites; that is, using durable woods with tannins, terpenoids, and so on (e.g. heartwood of teak, black locust, oak, larch) and durable wood species in plywood, oriented strand board, and so on	+++
		(b) durable glues and other agents in wooden composites	+
		Gene engineering applied for cultivation of trees	N
Exposures		Permanently dry conditions (biological pests are inactive); that is, timber drying-up and correct structural protection of wooden products and constructions	+++
		Permanently wet conditions with minimal amount of oxygen (biological pests are inactive, expect for anaerobic bacteria and marine organisms); that is, logs sprayed with water, stored in water pools or wet ground	++
		Atmosphere unsuitable for biological pests; that is, placement of wood into inert gases (nitrogen, argon)	+
		Barriers created on wood surfaces; that is, regulation of air and moisture transport to wood and out from wood	+
Preservatives	Biocides	Toxic biocides against pests; that is, bactericides, fungicides and insecticides (e.g. creosote, boric acid, quaternary ammonium compounds, triazoles, pyrethroids)	+++
		Nontoxic biocides against pests (e.g. growth regulators of insects)	++
		Vegetable extracts; that is, substances with toxic effect against some pests and also with hydrophobic effect	+
		Pheromones, attractants, repellents; that is, regulators of behaviour of insects and other pests during their life	+

(*continued*)

Table 1.4 (*Continued*)

Principle of wood protection		Technology of wood protection	Utilization in practice
	Others	Fire retardants	+++
		Resins and oils with hydrophobic effect	++
		Film-forming paints against weathering (e.g. polymers with UV-stabilizers, water repellents, and other additives)	+++
Modification		Thermal treatment (at ~160–220 °C)	++
		Chemical treatment (e.g. acetylation, furfurylation)	+
		Mineralization (e.g. silicates)	(+)
		Enzymatic treatment	N
		Bio-control (i.e. antagonistic organisms – bacteria, moulds, etc.) against wood-decaying fungi or/and wood-damaging insects	(+)

Source: R., L. (2013) *Wood Protection*, Handbook, TU Zvolen, Slovakia, 134 p. Reproduced by permission of TU Zvolen.
+++: significant application; ++: medium application; +: little (limited, specialized) application; (+): rare application; N: application in practice maybe in future.

(Van Acker et al., 2014). Moisture content of wood is frequently used as an input variable to modelling conditions and the resulting risk of decay, and then also of the service life prediction of wooden products (Brischke & Thelandersson, 2014).

1.5.1 Lifetime of wooden products

The lifetime of materials and structures is defined as the:

- *physical useful lifetime* – reflecting the real technical condition;
- *ethical lifetime* – relating mainly to aesthetic aspects and the satisfaction of functional demands of the present user (e.g. stylishness, spatialization and/or higher demands for thermal and acoustic insulation);
- *economical lifetime* – considering the time within which the costs of maintenance, operation and depreciation are still economical with regard to usability.

The *useful lifetime* is not usually the same for the entire wooden product or wooden structure; it means for all the wooden elements in a log cabin, truss, and so on (see Chapters 4 and 7). For example, in log cabins, the most suitable humidity conditions for action of biological pests are created in the lowest beams, which are more often in contact with rain or capillary water. Shortening of the physical lifetime of products/structures can be caused mainly due to the following effects:

- failures in a project (i.e. errors in static, material composition, structural protection, etc.);
- failures in execution (i.e. technological errors);
- failures during usage (i.e. increased aggressiveness of environment, increased mechanical load, poor or insufficient maintenance);
- unforeseeable events (i.e. fire, storm, etc.);
- amendments in standards and regulations (i.e. innovations in static standards, new safety regulations, etc.).

The useful lifetime, or service life, of wooden buildings or bridges is usually from 40 to 200 years, trusses from 60 to 400 years, windows from 30 to 70 years, untreated sleepers from 3 to 5 years, sleepers preserved with creosote from 25 to 50 years, and so on. In Eurocode, the suggested minimum design service life of a building's elements varies from 10 to 100 years. However, the age of well-maintained wooden historical buildings and their components is often greater; for example, there are log-cabin-churches more than 200 years old (Reinprecht, 2004; Viitanen, 2013), and there are windows greater than 100 years old (Menzies, 2013). Hansson et al. (2012), on the basis of selected climatic data (i.e. the average outdoor temperatures and average daily precipitations from 28 European field trials), proposed decay risk models that should be helpful for service life prediction of wooden constructions in above-ground exposures. Kirker and Winandy (2014) concisely summarized biotic and abiotic factors that impact service life of wood and wood-based materials above ground.

1.5.2 Service life prediction of wooden products by factor method

The *service life prediction or planning* of wooden constructions and wooden products can be performed by the factor method (ISO 15686).

The factor method is used to obtain an estimated service life of a component or a design object by modifying a reference service life by considering the differences between the object-specific and the reference in-use conditions under which the reference service life is valid:

$$\mathrm{ESL_{WP}} = f(A, B, C, D, E, F, G) = \mathrm{RSL_{WP}} \times (A \times B \times C \times D \times E \times F \times G) \tag{1.1}$$

where $\mathrm{ESL_{WP}}$ (years) is the estimated (predicted) service life of the wooden product, $\mathrm{RSL_{WP}}$ (years) is the reference service life of the wooden product (i.e. its lifetime under standard production and application conditions) and A–G are nondimensional factors, the values of which are usually in the range 0.8–1.2 but which in some situations (e.g. an error in design or, in contrast, a perfect maintenance) can also cover a greater range (e.g. 0.5–3). A is a measure of the quality of the components (i.e. of the wood and also of any complementary materials – see Chapters 5 and 6); *B* is a measure of the design (i.e. of the product/structure in its entirety, and its details – see Chapter 4); *C* is a measure of the technology level of works carried out (see Chapters 4, 5 and 6); *D* is a measure of the internal environment (i.e. in joints and other details); *E* is a measure of the external environment (i.e. around the product/structure); *F* is a measure of the user conditions (e.g. unexpected changes in loading, storm); and *G* is a measure of the maintenance level (see Chapter 7).

However, in practice the computation of ESL_{WP} by the factor method is sometimes connected with a certain subjectivity and sometimes also with less professionalism (Viitanen, 2005, 2013):

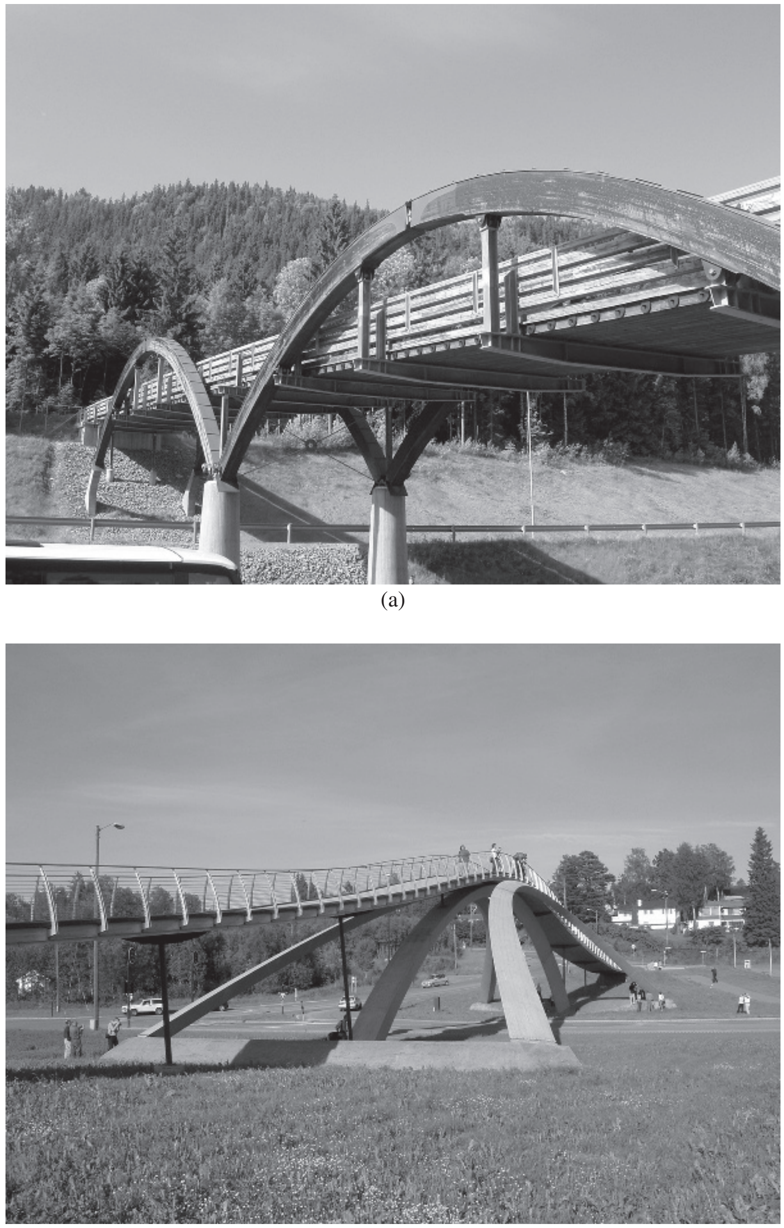
- it is not a really scientific method;
- need for intensive preparatory work – for example, many-year observations in terrain and/or model experiments, with the aim to reliably define all specific effects influencing the individual factors *A* to *G*;
- there can be a subjective overestimation of the importance of a certain factor and the underestimation of another;
- there can be ambiguities in the mutual interactions of the individual factors *A* to *G*.

An example of the application of the factor method, with the subjective highlighting of the importance of using chemical protection, regular maintenance with needed repairs and reconstruction works is the calculation of the ESL of wooden bridges (Figure 1.4, Table 1.5). The service life of a correctly designed, materially and technologically executed and maintained wooden bridge is usually from 40 to 200 years, sometimes even more, which is in accordance with the results in Table 1.5. However, there are also cases where, when selecting less durable types of wood species and not implementing a suitable protection method (e.g. badly structurally designing details) and when neglecting maintenance, the service life of a wooden bridge can be significantly reduced, sometimes not even reaching 5–10 years.

Similarly, it is possible to calculate the lifetime of wooden ceilings, trusses, pergolas, children's playgrounds, shingle roofs or claddings, windows and other wooden structures and products. However, it is necessary to always bear in mind that the reliability of the calculation depends upon the selected RSL_{WP} to a notable extent and at the same time also upon the selection of specific nondimensional factors *A* to *G* in relation to a particular project, and its implementation into practice.

1.5.3 Life cycle assessment of wooden products

Life cycle assessment (LCA) is a technique for assessing the environmental aspects and potential impacts associated with a product and has been used by



(a) (b)

Figure 1.4 Estimated service life (ESL_{WP}) of wooden uncovered bridges is ∼40–50 years when using suitable design for rainfall drain and at the same time also chemical protection of wood elements, either with creosote (a) or with inorganic biocide fixable in wood (b); examples are from Norway (Reinprecht, 2008)

Source: R., L. (2008) *Ochrana Dreva* (*Wood Protection*), Handbook, TU Zvolen, Slovakia, 453 p. Reproduced by permission of TU Zvolen

Table 1.5 Calculation of estimated service life (ESL) of wooden bridges (Reinprecht, 2005)

Wooden bridge without a roof – good lifetime	
Glued lamellae prepared from Norway spruce (*Picea abies*), which according to EN 350-2 is less durable wood species against wood-decaying fungi (class 4) and is also prone to degradation by wood-damaging insects (class SH). The individual lamellae are first treated with stable and highly efficient biocide (fungicide and insecticide) against pests using vacuum-pressure technology, and then bonded with stable water-resistant adhesive. The glued lamellae are also treated with a water-repellent paint. Finally, biocide cartridges are inserted to the end (frontal) sections of glued lamellae.	$A = 3$
The bridge is not roofed. However, the details are structurally correctly designed, with possible drain of rainwater.	$B = 0.5$
Proper input humidity of wood when producing glued lamellae (moisture content of wood $w = 15\,\%$).	$C = 1$
Microclimate in details of bridge is sometimes (e.g. after rains) suitable for fungal rot.	$D = 0.6$
The bridge is exposed to rainfall, alternation of rainy and sunny weather, thermal differences between day and night, and so on. This all enables the swelling and shrinkage of wood, and gradually creation of cracks. Environment for activity of fungi and insects is also suitable.	$E = 0.6$
The bridge is not exposed to more significant mechanical stresses, emissions, and so on.	$F = 1$
Regular inspection with diagnosis of damage (every third year), and suitable maintenance (exchange of biocide cartridges, new paints, etc.) and improvement interventions (replacement or reinforcement of damaged elements by prostheses, etc.) carried out.	$G = 2$
$ESL_{WP} = RSL_{WP} \times (A \times B \times C \times D \times E \times F \times G) = 40 \times (3 \times 0.5 \times 1 \times 0.6 \times 0.6 \times 1 \times 2) \approx 43.2$ years	
Wooden bridge with a roof – very good lifetime	
Solid larch (*Larix decidua*) heartwood, which according to EN 350-2 is from moderately durable to less durable against wood-decaying fungi (class 3–4) and durable against wood-damaging insects (only sapwood is susceptible to attack – class S). The individual wooden elements of bridge (note: elements dimensionally greater than lamellae and thus harder to impregnate) treated with stable biocide (fungicide and insecticide) against wood pests using a long-term dipping technology. Finally, all surfaces of wood elements painted with a water-repellent coating.	$A = 2.25$
The bridge is both roofed and structurally correctly designed.	$B = 1$
Proper input humidity of wood for the production of bridge elements ($w = 18\,\%$).	$C = 1$

Table 1.5 (*Continued*)

Wooden bridge with a roof – very good lifetime	
Microclimate in construction details is rarely suitable for fungal rot.	$D = 0.8$
The bridge is not exposed to direct water precipitations.	$E = 1$
The bridge is not exposed to more significant mechanical stresses, emissions, and so on.	$F = 1$
Regular inspection with diagnosis of damage (every third year), and the execution of both suitable maintenance and improvement interventions.	$G = 2$
$ESL_{WP} = RSL_{WP} \times (A \times B \times C \times D \times E \times F \times G) = 40 \times (2.25 \times 1 \times 1 \times 0.8 \times 1 \times 1 \times 2) \approx 144$ years	

Source: R., L. (2005) Investigation of wooden constructions – the basis for their renovation. In: *Restoration and Reconstruction of Constructions*, 27th Conference WTA, pp. 23–30. Brno, Czech Republic. (In Slovak.)

industry in many situations; for example, to help reduce overall environmental burdens across the whole life cycle of goods and services, to improve the competitiveness of a company's products or to communicate with governmental bodies. It can also be used in decision-making, as a tool to improve material composition and design of the product, the selection of optimal technologies, and so on. The benefit of LCA is that it provides a single tool that is able to provide insights into the upstream and downstream trade-offs associated with environmental pressures, human health and the consumption of resources (Ferreira et al., 2015).

The *LCA of wooden products and constructions* is usually better for comparing with those made from steel, aluminium, concrete or other materials (Brischke & Rapp, 2010). For example, the Bolin and Smith (2011) state that the individual factors of LCA are evidently better for borate-treated lumber structural framing in comparison with galvanized steel framing: (1) there are 3.7 times less fossil fuel use and 38 times less water use; (2) there are 1.8 times lower greenhouse gases, 3.5 times lower acid rain, 2.8 times lower smog and 3.3 times lower emissions; and (3) they are candidates for energy recovery as a renewable fuel source. Similarly, in a comparison of wooden and plastic PVC windows, in a mild exposure scenario the service life of plastic windows should be beyond 35 years and wooden windows 60–65 years, at which time the recycling of wooden windows is easier (Menzies, 2013).

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