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Nordic Scots Pine vs. Selected Competing Species and Non-Wood Substitute Materials in Mechanical Wood Products

Literature Survey

Mika Grekin

Wood Material Science Research Programme

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Abstract

In this study, Nordic Scots pine wood is benchmarked, based on literature, against selected competing tree species and non-wood substitute materials in selected end-use segments of mechanical wood products. In joinery, interior, and furniture products, the comparisons were made against Western red cedar, ponderosa pine, loblolly pine, and radiata pine, whereas in segment of structural products, lodgepole pine, Norway spruce, and Douglas-fir were included into the study. It should be noted that the material comparisons are valid for small clear wood specimens, not exactly for sawn timber. With respect to the substitute materials, the comparisons were made against a variety of materials in joinery products (case window frames), exterior cladding (siding), and structural products.

Based on the literature findings, the main strengths, the weaknesses that could be improved, and the weknesses that must be accepted were concluded for Nordic Scots pine wood as a raw material for joinery products, exterior claddings, and structural products and their end-uses. Compared to the competing tree species, Nordic Scots pine wood is quite superior in the strength and the stiffness properties essential for joinery, interior, and furniture products, as well as for structural products. The variation in several wood properties is the higher the southerly is the geographical origin; with this respect, Scots pine wood from the Nordic countries is more homogeneous compared to wood from the more southerly latitudes. In general, Nordic Scots pine wood is a suitable material for a wide selection of joinery, interior, and furniture products when it is processed and treated properly, and moderately high-quality wood material is selected. Also in structural uses Nordic Scots pine wood is well able to compete against other species, even if moderately large variations may be expected, especially in the strength and stiffness properties due to the geographical origin, knottiness properties, grain angle, and other background variables.

Compared to the competing non-wood substitute materials, the main problems of wood as a raw material for several end-uses are associated with the large variations in a variety of properties, as well as with the hygroscopicity and anisotropy of wood material. The main strengths of wood are based on good overall mechanical performance, operational safety and friendliness to the environment, and on the fact that wood is a well-known, traditional material.

Keywords

aesthetic properties, exterior claddings, furniture, joinery products, mechanical properties, morphological properties, physical properties, processing properties, structural products

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Other information

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Preface

The purpose of this literature survey is to benchmark Nordic Scots pine wood as a raw material for selected end-uses in joinery, interior and furniture products, as well as in structural products. The benchmarking is done against selected competing tree species and non-wood substitute materials, based on the information gained from the literature. As a result, the main strengths and weaknesses of Nordic Scots pine wood in the above mentioned end-use segments will be concluded.

This report is a product of the research consortium "Specific wood and timber properties, competitive ability and advanced conversion of Nordic Scots pine in mchanical wood processing (SPWT)" in the Wood Material Science and Engineering Research Programme (2003–2007). The initiative for compiling such a survey was taken by the Expert Group of the consortium, to position Nordic Scots pine with regard to the most important competing wood species and other materials, and to provide critical background information for the empirical studies to be performed within the consortium.

The study was financed by the Academy of Finland, the Finnish Ministry of Agriculture and Forestry, the Graduate School of Forest Sciences (GSForest) in the University of Joensuu, and the Finnish Forest Research Institute (Metla); all financers are gratefully acknowledged. I would like to express my gratitude to Professor Erkki Verkasalo from Metla and Associate Professor Anders Roos from the Swedish University of Agricultural Sciences (SLU) for providing expert assistance and suggestions for improving the contents of this publication.

Joensuu, November 2006

Mika Grekin

1 Introduction

Scots pine used to be the species for sawmilling with the largest volumes of lumber produced until the early 1990's in Finland. A slow but steady decrease could be seen in sawing of pine from the 1970's, compared to spruce. Meanwhile, Nordic Scots pine products lost their original position and market shares among the international markets. Increase in the supply of lumber from pine and other competing species, first from the subtropics (U.S. southern pines, radiata pine etc.) and later from the Baltic countries and Russia, as well as the ever-increasing competition of the materials replacing wood, such as MDF, aluminium, PVC and certain more advanced plastic products, steel etc. proved a severe obstacle for the success of Nordic pine products. Pine and spruce are also competitors within Nordic countries in some uses, such as lightweight structural members, structural billets, glued laminated timber etc. One can expect that this competitive situation becomes more prominent if pine industries plan to regain the market shares at the international level.

Due to the slow downhill of Nordic pine, for the value of softwood lumber export, spruce has already overtaken pine in Finland. In the future, the key growing area for pine should be in construction (structural use). This was defined as the main target segment for Nordic industries providing lumber and further products for both export and domestic markets. Joinery, interior and furniture products are important, as well, but, globally, they probably remain behind construction. Both in Finland and Sweden, there still are pine log resources available for a moderate expansion of sawmilling. However, the customer needs should be considered pro-actively not only in the product selection and marketing efforts but also in silvicultural management and wood procurement. Accordingly, the competitive properties of pine wood should be elaborated and implemented throughout the wood growing and supply chain.

The trend toward pan-European standardisation of industrial products mainly affects negatively the position of Nordic pine products at the current stage. The standards are eagerly set by the interest groups making the proposals according to the advantages of big softwood producing countries in Central Europe, resulting in evening the natural differences in wood. This results in defining only a few grades and setting the minimum criteria to lower levels, where the (typically Nordic) best grades cannot be specified nor exhibited as special value-added products. Accordingly, at least the big Nordic players in the market have to convince their key customers by their own marketing efforts. Here, proof of superior properties of Nordic pine wood for the particular market segments is needed.

The specific wood properties of Scots pine applicable for further processed end-use products, as well as their variation and the affecting factors are not well known or demonstrated. Basic research related to raw material properties for mechanical wood processing has in the last 25 years been rather scarce, especially regarding Nordic pine logs. Pine can also be expected to have larger variations in the material properties related to silvicultural and regional variations, especially compared with Norway spruce. The level and variations in the properties are most probably different compared to other competing species and non-wood materials in the market.

The aim of this study was to compare Nordic Scots pine with the most important competing softwood tree species, as well as with the most important substituting non-wood materials in selected groups of end-products in joinery, interior, and furniture products, and in structural products. The competing species and substitute materials were selected based on interviews of the Expert Group members and other professionals of the research consortium. The position of Nordic pine for the aforementioned end use segments is discussed based on the data from literature and other sources of information. First, a short description of the selected competing tree species is given, after which Nordic Scots pine is benchmarked against other species based on available qualitative and quantitative information on wood properties. Secondly, the basic characteristics of selected subsitute materials are given to be able to conclude the competitiveness of Nordic Scots pine wood against these substitutes. Finally, the main strengths and weaknesses of Nordic Scots pine wood in selected end use segments is concluded.

2 Nordic Scots pine vs. competing species

2.1 Description of the selected tree species

2.1.1 Scots pine - *Pinus sylvestris* L.

The growth range of the species is larger than that of any other pine. It occurs from Scotland to the Pacific Coast of Siberia, from Norway to Spain, and from Arctic Siberia to Mongolia (Fig. 1, Fig. 2). It is also reported to grow in the Mediterranean region, and is a naturalized species in localized areas in southeastern Canada and northeastern United States, from New England to Iowa. The tree tolerates city smoke rather well, and can thrive in various soils, from loams to sand.[153]

Because Scots pine is distributed over a wide geographical range, there is great variability in density, strength properties, and wood characteristics such as texture and number and size of knots.[153] Despite its huge range, it is remarkably uniform in its morphology with individual variation within populations much greater than between-population variation[154]. Over 140 subspecies, varieties, and forms have been described, but only the type var. *sylvestris*, var. *hamata* C. Steven, and var. *mongolica* Litvinov are now normally accepted[155], even these are barely distinguishable from each other.

Far northern trees, north of about 65°N, were formerly treated as var. *lapponica* Hartm. but are now thought to represent polyphyletic colonization and adaptations to harsh environments across a very broad front[154]. The variation is continuous and clinal, with no population definable[156], and the variety is no longer accepted[155, 156]. In this study, Scots pine wood from the Nordic countries (Finland, Sweden, Norway) is considered.

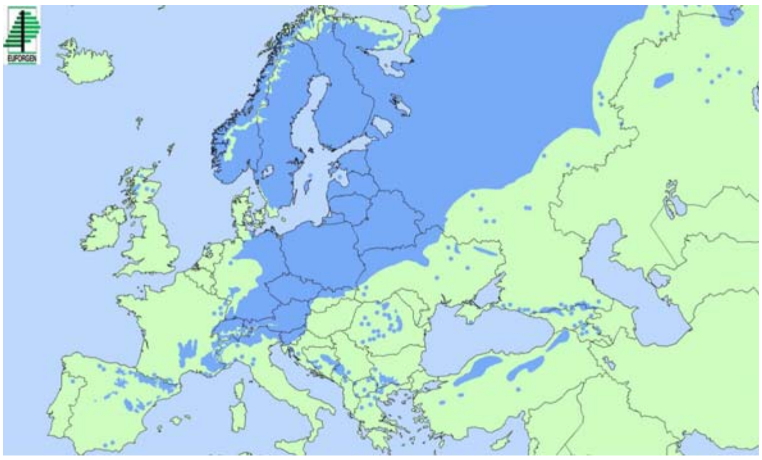

Figure 1. Natural distribution area of Scots pine in Europe[165].

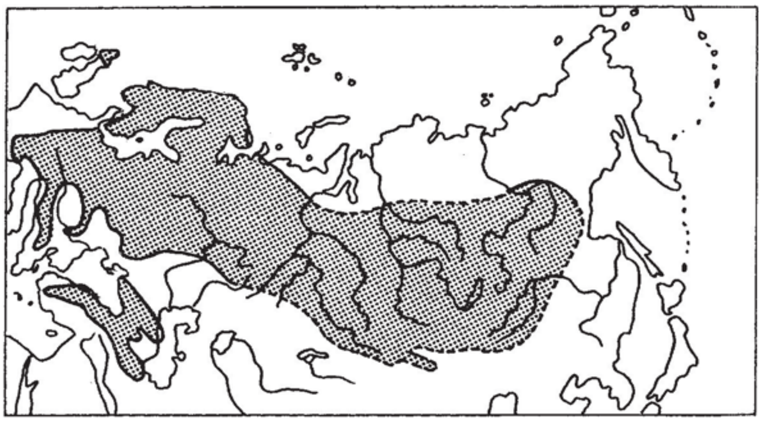

Figure 2. Global natural distribution area of Scots pine[166].

Scots pine is a tree to 25–40m tall and 50–120cm dbh[154], clearly smaller in the northern latitudes. Stem is straight and contorted only if lead shoot has damaged when young[154]. The typical end-uses of Scots pine lumber are in structural indoor and outdoor uses, joinery and interiors (roofs, walls, doors, parquets, windows), furniture, etc.[44]

2.1.2 Western red cedar - *Thuja plicata* D. Don

Western red cedar occurs in North America in Alberta, British Columbia, Alaska, California, Idaho, Montana, Oregon, and Washington (Fig. 3) at 0–1500m elevation[154]. It forms widespread forests with Western hemlock, and also with other conifers. It prefers moist, slightly acid soils.

Figure 3. Natural distribution area of Western red cedar[167]. Original map has been digitalised and reproduced by the U.S. Department of the Interior and the U.S. Geological Survey[169].

Western red redar is also cultivated from seedlings in nurseries as a source of timber in Britain and France.[153]

The tree is described as often large to very large (50m tall and 200cm dbh), producing a tapering trunk that is buttressed at the base. It produces a clear bole that is usually free from side branches for many feet up, which means the outer layers of the tree are knot free and clear. This feature is reported to make Western red cedar timber especially suitable for high-class joinery and woodwork.[153, 154]

Western red cedar wood is typically used for shingles, lumber, poles, posts, and piles. The lumber is used for exterior siding, decking, interior woodwork, sashes, doors etc.[40] In fact, western red cedar is a very popular timber and is considered to be one of the major lumber species in the United States and Canada[153]. It is said that western red cedar is highly suitable for ladder-poles because of its light weight, strength, straight grain, and freedom from knots. The wood is also known for its high rot resistance, and is a primary choice for shingles. It is also highly favored for siding, fenceposts, and other outdoor uses. The exceptionally light-weight wood is very strong. Its straight grain and moderate hardness are reported to combine to make it a very desirable material to work to very precise dimensions.[153]

2.1.3 Ponderosa pine - *Pinus ponderosa* Laws.

The most widely distributed and common pine in North America, ponderosa pine is found in Alberta and British Columbia in Canada, and in a variety of states in the United States and also in Mexico (Fig. 4). It grows mostly in the mountains, often in pure stands to form extensive forests,

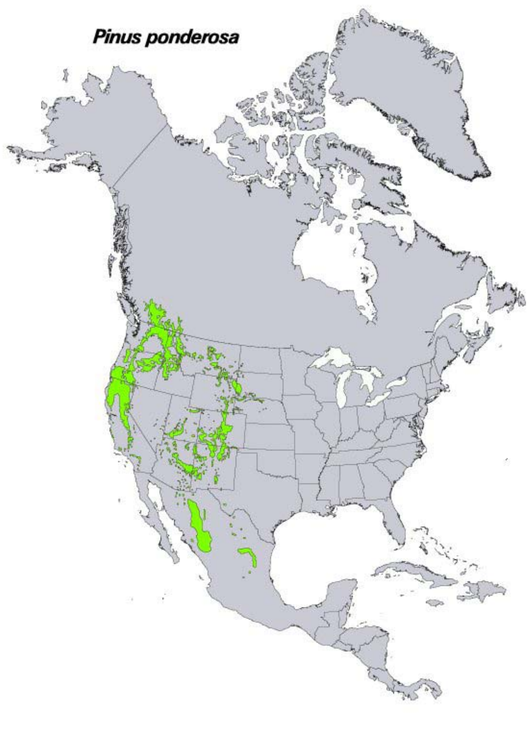

Figure 4. Natural distribution area of ponderosa pine[167]. Original map has been digitalised and reproduced by the U.S. Department of the Interior and the U.S. Geological Survey[169].

but may also be in mixed coniferous forests. Ponderosa pine grows from sea level in the northern parts of its range to an altitude of up 2700m in the south, with the best stand of trees occuring between 1200 and 2400m.[153]

Forestry studies indicate the existence of four distinct taxa termed 'races'[158, 159, 160] or 'ecotypes'[161]. These taxa are morphologically distinct[162, 163, 164] and would normally be treated as subspecies, but most have not been formally described at this rank. They have all been described at species rank in the past, as will be described in this study also. The following names, not all of which have been formally published, can be used for the taxa[154]:

— *P. ponderosa* subsp. *ponderosa*. The 'North Plateau' group includes populations formerly assigned to *P. washoensis* H. L. Mason & Stockwell, as well as those conventionally assigned to *P. ponderosa* subsp. *ponderosa* from British Columbia, western Montana, Idaho, and Washington, Oregon, California & Nevada east of the Cascades crest.
— *P. ponderosa* subsp. *benthiama* (not published). The 'Pacific' group includes populations from Sierra Nevada and west of the Cascade crest in California, Oregon and Washington.
— *P. ponderosa* subsp. *brachyptera* (not published). The 'South Rockies' group includes populations from Arizona and New Mexico. In the far south of those states, it is replaced by *P. arizonica* (q.v.).
— *P. ponderosa* subsp. *scopulorum* (Engelmann) E. Murray. The 'North Rockies' group, currently-described, is widely distributed to the east and north of the above-named taxa.

Ponderosa pine trees are up to 18–39m tall with 80–120cm dbh and the trunk is usually straight[154]. Wood is mainly used for lumber and to lesser extent for piles, poles, posts, veneer etc. The clear lumber is used for doors, blinds, moulding, paneling, interior woodwork etc. Low-grade lumber is used for boxes and crates. Intermediate- or low-grade lumber is used for sheating, subflooring, and roof boards. Knotty lumber is used for interior woodwork.[40]

2.1.4 Loblolly pine - *Pinus taeda* L.

Loblolly pine is native to fifteen southeastern states in the United States. Its range extends from southern New Jersey south to central Florida, west to eastern Texas, and north to the far southeastern region of Oklahama (Fig. 5). It grows on various soil types, from deep, poorly drained flood plains to well-drained slopes of rolling, hilly uplands, and it often forms pure stands, usually on abandoned farmlands. It grows from sea level to an elevation of 450 to 600m.[153] Originally most races of *Pinus taeda* were in the lowlands. Following disturbance of the natural vegetation after settlement by Europeans, the species spread to fine-textured, fallow, upland soils, where it now occurs intermixed with *P. echinata* and *P. virginiana*. In the southeast *P. taeda* is commonly used in plantation forestry, along with *P. elliottii* and *P. echinata*.[157]

Trees are to 46m tall with to 160cm dbh and the trunk is usually straight, without adventitious shoots. Commercially, loblolly pine is a valuable pulpwood and timber species.[157] The denser and higher strength wood is extensively used in the form of stringers in construction, and also for roof trusses, beams, posts, joists, and piles. Lumber of lower density is also used for building material, such as interior woodwork, sheating, and subflooring. Wood is usually treated with preservatives when used in exterior end uses.[40]

Figure 5. Natural distribution area of loblolly pine[167]. Original map has been digitalised and reproduced by the U.S. Department of the Interior and the U.S. Geological Survey[169].

2.1.5 Radiata pine - *Pinus radiata* D. Don

Although the natural range of radiata pine is extremely small, covering only three localities on the coast of central California in the fog belt that extends about 10km inland, its present expansion in the Southern Hemisphere through cultivation is quite substantial. The species is cultivated on a commercial scale in New Zealand, Australia, Chile, and South Africa. It has also been successfully cultivated in Spain, France, Argentina, Greece, and India, and a variety of radiata pine is also reported to grow in Guadeloupe Island and Mexico. The tree prefers to grow on slopes, in coarse soils, usually sandy loams, and is often found in pure stands or with Monterey cypress, Gowen cypress, and Coast live oak.[153]

Trees are 15–30m tall, 30–90cm in dbh, and contorted to straight. Radiata pine is the most common pine in the southern hemisphere, where no pines are native (except that *Pinus merkusii* barely crosses the Line in Sumatra).[154] Most of the commercially available timber of radiata pine is composed of fast grown plantation trees. These trees are reported to contain very high percentage of sapwood which makes them very easy to treat with preservatives. Radiata pine is steadily growing as a replacement for the more expensive ponderosa pine in the United States. Genetic improvements in Chile have resulted in radiata pine trees that are relatively free from knots and are also high in physical and mechanical properties.[153] The typical end-uses of radiata pine are for veneer, plywood, pulp, fiberboard, construction, boxes, and millwork[40].

Figure 6. Natural distribution area of lodgepole pine[167]. Original map has been digitalised and reproduced by the U.S. Department of the Interior and the U.S. Geological Survey[169].

2.1.6 Lodgepole pine - *Pinus contorta* var. *latifolia* Engelm.

The species is widely distributed (Fig. 6), and is the only conifer native to both Alaska and Mexico[153]. Three varieties of the species are published, but only var. *latifolia* is considered in this study. In fact, many researchers have concluded that these should be treated at the rank of subspecies instead of varieties[154]. Lodgepole pine or Rocky Mountain lodgepole pine (var. *latifolia*), which grows in the Rocky Mountains is tall and narrow. It is highly adaptable to forest fires, with cones that remain tightly closed on the tree for many years until a fire destroys the forest. Heat from fire causes the cones to open and expend their seeds to begin a new forest. Lodgepole pine has also been successfully cultivated in the United Kingdom, in Wales, northern Scotland, northwest England, and also throughout Ireland. The tree thrives on mostly well-drained soils, and is often found in pure stands. Inland varieties of the species are found at elevations of 450 to 900m in the north, and at 2100 to 3500m in the south. Lodgepole pine is capable of tolerating severe climatic and soil conditions. The species also grows in the interior of British Columbia and in western Alberta, as well as in adjacent areas in the southern Yukon and southwestern Northeast Territories in Canada.[153]

Trees are to 50m tall and 90cm dbh, and vary from straight to contorted[154]. Lodgepole pine wood is used for lumber, mine timbers, railroad crossties, and poles. It is also being increasingly used for framing, siding, millwork, flooring, and cabin logs.[40] On the other hand, moderately knotty wood sets some restrictions to possible end uses[44].

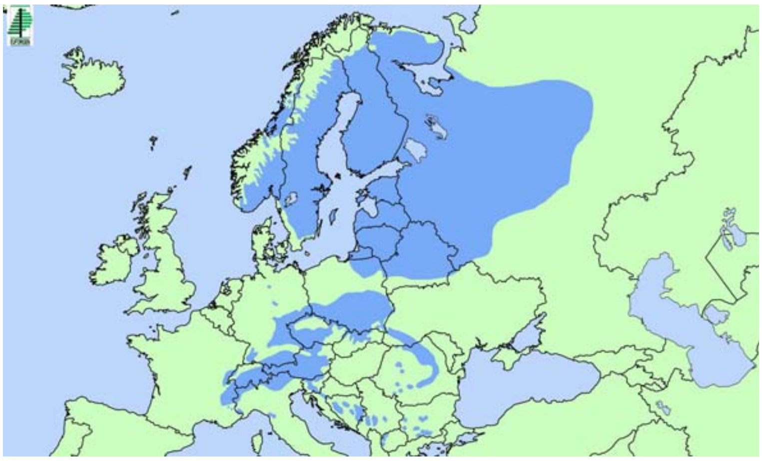

Figure 7. Natural distribution area of Norway spruce. Map is based on an earlier map published by H. Schmidt-Vogt in 1977 (Die Fichte, Verlag Paul Parey, Hamburg and Berlin, p.647)[168].

2.1.7 Norway spruce - *Picea abies* (L.) Karst

The species is widely distributed throughout continental Europe, except in Denmark and the Netherlands. Although Norway spruce is native to and occurs in the wild over most of northern and central Europe (Fig. 7), it is widely cultivated in the United Kingdom and southeastern Canada. It has also been successfully planted in the northeast, the Rocky Mountains, and the Pacific Coast regions in the United States. The tree usually grows in moist soils in humid, cool, temperate regions.[153]

The large tree usually has a straight trunk and grows to a height of about 30m, with a dbh of about 60cm[153, 157]. It is a timber tree of major economic importance throughout the cool temperate areas of Europe. Strength properties are reported to vary widely and are dependent upon origin. The wood is soft, and surfaces may dent easily. Wood is low in weight, and has medium density. Wood produced by spruce trees from central and eastern Europe possesses exceptional resonance qualities and is used for sound boards of pianos and bellies of violins and guitars.[153] The typical end-uses for Norway spruce wood are for structural end uses in indoor and out-door conditions, plywood, applied woodworking etc.[44]

2.1.8 Douglas-fir - *Pseudotsuga menziesii* Mirb.

The growth range of Douglas-fir includes Alberta, British Columbia, Arizona, California, Colorado, Idaho, Minnesota, Montana, New Mexico, Nevada, New York, Oregon, Texas, Utah, Washington, and Wyoming (Fig. 8). Coast Douglas-fir occurs in pure stands of vast forests on moist, well drained soils. Rocky Mountain Douglas-fir may occur in pure stands or mixed coniferous forests, and thrive mainly on rocky soils of mountain slopes. Douglas-fir has also been introduced to other regions in the world, including Great Britain, Ireland, France, Belgium, Germany, New Zealand, and Australia as a source of timber.[153]

Douglas-fir trees are to 90m tall and 440cm dbh. This is the largest member of the *Pinaceae* and larger by far than the other species in the genus. Supplies of Douglas-fir are adequate since the species grows rapidly, and its growth range extends over a wide area in North America. Remarkably knot-free, strong, and light, Douglas-fir is considered to be one of the best known softwood

Figure 8. Natural distribution area of Douglas-fir[167]. Original map has been digitalised and reproduced by the U.S. Department of the Interior and the U.S. Geological Survey[169].

timbers.[154] It is mostly used for building and construction purposes in the form of lumber, marine fendering, piles, and plywood. Small amounts of wood are used for flooring and furniture. Plywood has found applications in construction, furniture etc.[40]

2.2 Comparison of species for joinery, interior, and furniture products

In this study, the following tree species were assumed to be the most important ones competing with Nordic Scots pine in joinery, interior and furniture products (not in order of importance):
— Western red cedar
— Ponderosa pine
— Loblolly pine
— Radiata pine

In this chapter, comparisons of selected wood properties of Nordic Scots pine and above mentioned competing species are shown and discussed. The numerical data, gained from the literature, concerning each property and species of interest are shown in Appendix.

Considering the fibre properties, Scots pine wood differs quite clearly from the other species. The average tracheid length is smaller compared to any other competing species, as well as is tracheid diameter, whereas cell wall thickness may be smaller or larger depending on the species to be compared with. The volume percentage of tracheids does not differ between species (Table 1).

Table 1. Comparison of selected morphological properties between Nordic Scots pine and competing species in joinery, interior, and furniture products. + = average value is at least 5% bigger compared to that of Nordic Scots pine; – = average value is at least 5% smaller compared to that of Nordic Scots pine; 0 = average value does not differ from that of Nordic Scots pine; N/A = no information available. References are shown in brackets.

	***Thuja plicata* Western red cedar**	***Pinus ponderosa* Ponderosa pine**	***Pinus taeda* Loblolly pine**	***Pinus radiata* Radiata pine**
Fibres				
- Tracheid length [4, 5, 6, 28, 44, 45, 59, 75, 76, 77, 78, 93, 94, 101, 102, 152]	+	+	+	+
- Cell wall thickness [45, 59, 79, 80, 81, 93, 152]	0	N/A	+	–
- Tracheid diameter [45, 55, 59, 77, 78, 79, 80, 82, 83, 84, 93, 101, 102]	+	+	+	+
- Percentage (volume) [2, 59, 99, 100, 152]	0	0	N/A	0
Annual ring width [57, 59, 97, 104]	N/A	N/A	N/A	+

Table 2. Horizontal (from pith to bark) and vertical (from butt to top) variation in basic density of Nordic Scots pine and competing species in joinery, interior, and furniture products. N/A = no information available. References are shown in brackets.

	***Pinus sylvestris* Nordic Scots pine**	***Thuja plicata* Western red cedar**	***Pinus taeda* Loblolly pine**	***Pinus radiata* Radiata pine**
Density				
- Variation from pith to bark [1, 12, 13, 14, 50, 78, 105]	Density increases distinctly, the difference decreases with increasing height. In over-aged trees (over 80-100 yrs), the increase in density ends and density could even start decreasing.	Density decreases radially from the pith, rapidly during the first 5 years of growth, followed by a more gradual decrease until about the 20th year, and levels out thereafter.	Density increases sharply with radial distance from the pith until ring 5 to 10; it may increase slowly to about ring 30 (based on measurements on slash pine; observations probably apply to the other southern pines as well).	Density increases from pith outwards, and then remains more or less constant outside the 20th to 30th growth layers.
- Variation from butt to top [28, 29, 78]	Clear decrease in density from butt to top.	Density increases continuously from butt to top.	Density is nearly constant to breast height (probably maximum at breast height) and then decreases with height (based on measurements on slash pine; observations probably apply to the other southern pines as well).	N/A

In all species, a considerable horizontal variation in density can be found, with an exception of ponderosa pine where no data was available (Table 2). The density of western red cedar wood first decreases and finally levels out after about the 20th ring, whereas in other species the basic phenomenon is just inverse – density increases with increasing distance from the pith. Generally, density first undergoes a change radially from the pith outwards until a certain distance and levels out thereafter. Expressed as a number of annual rings from the pith, in Scots pine wood the density levels off at a greater distance compared to other species, but when the distance from the pith is expressed as millimetres instead of number of rings, the relationship is not so straightforward due to quite narrow rings of Scots pine. In vertical direction a similar relationship could be found between height position and density: in western red cedar density increases with increasing height,

Table 3. Comparison of selected physical properties between Nordic Scots pine and competing species in joinery, interior, and furniture products. For definition of symbols see Table 1. References are shown in brackets.

	Thuja plicata **Western red cedar**	***Pinus ponderosa*** **Ponderosa pine**	***Pinus taeda*** **Loblolly pine**	***Pinus radiata*** **Radiata pine**
Density				
- Density difference in horizontal direction [11, 12, 50, 59, 78, 91, 105]	– / 0	N/A	+	0 / +
- Density difference in vertical direction [11, 12, 21, 22, 23, 78, 91, 105]	–	N/A	+	N/A
- Basic ($\rho_{0,g}$) [12, 30, 32, 49, 51, 58, 59, 78, 88, 89, 90, 95, 97, 105, 152]	–	0	+	–
- Airdry ($\rho_{12\text{-}15}$) [40, 54, 57, 59, 73, 95, 104, 105]	–	–	+	0
- Dry-airdry ($\rho_{0,12\text{-}15}$) [33, 56, 152]	–	–	N/A	–
- Green (ρ_g) [58, 59, 105, 152]	–	N/A	N/A	+
Fibre saturation point at 20°C [34, 106]	–	N/A	N/A	N/A
Shrinkage from green to oven dry MC				
- Length (b_l) [35, 44, 52, 59, 95, 152]	–	N/A	N/A	–
- Radial (b_r) [40, 44, 52, 59, 72, 73, 92, 95, 107, 152]	–	0	+	–
- Tangential (b_t) [40, 44, 52, 72, 73, 92, 95, 107, 152]	–	–	–	–
- Volumetric (b_V) [37, 40, 52, 59, 73, 95, 107, 152]	–	–	0	–
- Volumetric per 1% change in MC (6-14%) [152]	–	N/A	N/A	–
Porosity [74, 152]	+	N/A	+	+

whereas the density of Scots pine and loblolly pine decreases with increasing height position. No data of vertical density variations were available for radiata pine.

The average basic density of the species varies from 330kg/m³ to 520kg/m³ in western red cedar and loblolly pine, respectively. Compared to Scots pine wood, the basic density is higher in loblolly pine and lower in western red cedar and radiata pine, and no differences occur between Scots pine and ponderosa pine. It should be remembered that the variation in basic density within each species is considerable due to within-tree location, geographical origin, growth conditions, etc. Even within individual trees of a given species the density variation is generally high, not to mention the variation between trees and stands. The density difference in horizontal direction (from pith to bark) within a tree ranges between 25kg/m³ and 210kg/m³ depending on the species, vertical position in the tree, etc. Also the density difference in vertical direction (from butt to top) varies much between species. The variations in other densities (airdry, dry-airdry, green) are also remarkably large within species, even though some differences between species can be found (Table 3).

The shrinkage of Scots pine wood is generally higher compared to the other species. The average radial shrinkage values range from 2.3% in western red cedar to 5.0% in loblolly pine, whereas

Table 4. Comparison of selected mechanical properties at 12% MC between Nordic Scots pine and competing species in joinery, interior, and furniture products. For definition of symbols see Table 1. References are shown in brackets.

	Thuja plicata **Western red cedar**	*Pinus ponderosa* **Ponderosa pine**	*Pinus taeda* **Loblolly pine**	*Pinus radiata* **Radiata pine**
Modulus of elasticity in bending, MOE (//) [21, 40, 53, 54, 57, 59, 66, 72, 73, 88, 103, 104, 107, 152]	–	–	0	–
Bending strength, MOR (//) [21, 40, 53, 54, 57, 59, 72, 73, 88, 95, 103, 104, 107, 152]	–	–	0	–
Compression strength (//) [21, 40, 53, 54, 59, 66, 72, 73, 88, 95, 103, 107, 152]	–	–	0	–
Compression strength (⊥) [40, 53, 66, 72, 73, 88, 95, 107]	–	–	–	–
Tensile strength (//) [40, 73, 95, 103, 152]	–	–	0	–
Tensile strength (⊥) [40, 53, 72, 88, 95, 107]	–	0	+	0
Shear strength (//) [40, 53, 54, 66, 72, 88, 95, 107, 152]	–	–	–	–
Shock resistance [43, 152]	–	N/A	+	+
Brinell hardness (⊥) [21, 40, 152]	0	N/A	+	–

tangential shrinkages get values from 4.9% to 7.8% in western red cedar and Scots pine, respectively. The average volumetric shrinkage is approximately equal between Scots pine and loblolly pine, whereas in other species the volumetric shrinkages are clearly lower. Porosity of Nordic Scots pine wood is remarkably lower compared to the other species of interest (Table 3).

Shear strength (||) and compression strength (⊥) is clearly the highest in Scots pine wood with the average values of 10.4MPa and 7.6MPa, respectively, whereas tensile strength (⊥) is highest in loblolly pine (approx. average 3.2MPa) and lowest in western red cedar (approx. average 1.5MPa). Scots pine is near to the highest-tensile-strength species with a value of approx. 2.9MPa. The Brinell hardness (⊥) of Scots pine wood is approx. 24MPa, which is in the middle of the range of hardness values of these five species. Average values of modulus of elasticity (MOE) in bending (||), bending strength (||), and compression strength (||) of Scots pine are approximately equal to the values of loblolly pine and higher than the values of the other species (Table 4).

A distinct and abrupt transition from earlywood to latewood is typical for all species under consideration. Moderately coarse or rough texture is a characteristic of Scots pine, western red cedar, and loblolly pine, whereas quite fine, even uniform texture is typical for ponderosa pine and radiata pine. All species are generally straight grained except loblolly pine, although the grain tends to tear around large knots. Sharp heartwood/sapwood boundary occurs in all species, and the colour of heartwood is usually brown with a hue of red or pink. The sapwood colour is typically nearly white or yellowish white to pale yellow or brown. Wood of western red cedar and ponderosa pine is reported to have bold variations in colour, and the darkening of heartwood colour in air contact and under UV radiation is a characteristic of Scots pine wood, especially. Almost all species have a characteristic resinous odour due to high pitch concentration, and the presence of pitch pockets is reported to be typical especially for Scots pine and loblolly pine. The heartwood section of these species is moderately to very resistant to decay due to high amounts of pitch, even if quite large variations may occur in amount of pitch in different parts of the trees. Also the genetic variations are reported to be large in some species (Table 5).

In all species, the workability of wood is good or very good, including rotary-cutting, veneer slicing, splitting and planing. Typically the sapwood of these species is moderately soft and tough, whereas hardness and fragility are characteristics of heartwood. Good stability in mechanical connecting can be achieved in all species except radiata pine, where wide earlywood regions may cause stability problems. All species are reported to be good or very good for kiln drying with the exception of radiata pine, which needs careful and slow kiln drying or high-temperature drying to achieve good drying results. Western red cedar and ponderosa pine tend to have low and quite even shrinkage during drying, whereas in Scots pine, loblolly pine and radiata pine the shrinkage is more severe. The severity of warp and twist and the susceptibility for checking during drying depend on the species and used drying formulas, and large differences could occur even within species. Risk for blue stain and susceptibility for discolouration during drying are reported to be drawbacks of Scots pine and loblolly pine wood, whereas the juvenile wood phenomenon may cause severe problems in drying of loblolly pine and radiata pine wood (Table 6).

Wood of these species bond satisfactorily (with good quality adhesives under well-controlled conditions) to very easily (with adhesives of a wide range of properties and under a wide range of bonding conditions), depending on the species. Extensive knottiness and high amounts of resins may cause problems in surface treatments (painting, waxing, varnishing). Scots pine, western red cedar, and radiata pine are the best species for surface treatments, and ponderosa pine and loblolly pine the worst. Still, the surface treatment ability depends highly on the finishes and techniques

Table 5. Selected aesthetic properties and other features of Nordic Scots pine and competing species in joinery, interior, and furniture products. References are shown in brackets.

	Pinus sylvestris **Nordic Scots pine**	*Thuja plicata* **Western red cedar**	*Pinus ponderosa* **Ponderosa pine**	*Pinus taeda* **Loblolly pine**	*Pinus radiata* **Radiata pine**
Rings [40, 44, 72, 110, 152]	Distinct growth rings, abrupt transition from earlywood to latewood; rather distinct earlywood / latewood boundary.	Distinct growth rings, abrupt transition from earlywood to latewood; rough and wavy, uneven ring width.	Sharp outlook, very strong earlywood / latewood boundary.	Broad bands of dense latewood; very wide rings, tone difference between earlywood / latewood.	Primarily wide and distinct, false rings may be common.
Texture [40, 44, 59, 72, 110, 152]	Generally straight grained and moderately coarse, often irregular and decorative texture; moderately abrupt transition from earlywood to latewood.	Generally straight grained and uniform but rather coarse / medium texture; moderately uneven grain, growth rings distinct; abrupt transition from earlywood to narrow latewood.	Generally straight grained, quite uniform in texture.	Broad bands of dense latewood; rough texture, not very straight grained.	Moderately even and fine texture and the grain is not interlocked; grain tends to tear around large knots.
Colour [40, 44, 152]	Sapwood is quite broad (5–7cm) and pale / reddish brown; heartwood reddish-brown, especially in the north; heartwood darkens fast in air contact; always sharp sapwood / heartwood boundary.	Sapwood (narrow, often not more than 2.5cm) nearly white, heartwood reddish or pinkish brown to dull brown or from medium to dark coffee-brown; heartwood unevenly coloured.	Sapwood is nearly white to pale yellow, heartwood is light reddish brown; very variable colour.	Sapwood (usually wide in second-growth stands; in old, slow growth trees, sapwood may be only 2 to 5cm) yellowish white and heartwood reddish brown; sharp sapwood / heartwood boundary.	Heartwood from plantation-grown trees is light brown to pinkish brown, distinct from the paler cream-colored sapwood; sharp sapwood / heartwood boundary.
Other features [40, 44, 72, 110, 152]	Characteristic resinous odour; lots of resin canals (large) and resins; moderately thin knots (dark).	Characteristic cedar odour; no resin canals, wood rays not visible.	Large knots, lots of pitch (odour).	Moderately high resin content, contains also pitch pockets; large genetic variations, long knot intervals, lots of pitch (both sapwood and heartwood); juvenile wood problems.	Very large genetic variations, very large knots (pruned), very long knot intervals, sapwood very prone to fungi, juvenile wood problems.

Table 6. Selected processing properties of Nordic Scots pine and competing species in joinery, interior, and furniture products. References are shown in brackets.

	Pinus sylvestris **Nordic Scots pine**	***Thuja plicata*** **Western red cedar**	***Pinus ponderosa*** **Ponderosa pine**	***Pinus taeda*** **Loblolly pine**	***Pinus radiata*** **Radiata pine**
Mechanical tooling / machining [40, 44, 59, 152]	Easy, including rotary-cutting, veneering and splitting; wood soft and tough; good stability in mechanical connecting; debarking and veneering is easy.	Easy, incl. rotary-cutting, veneering though often surface roughness; very easy to split; wood medium-hard and medium-fragile; good stability in mechanical connecting.	No problems in tooling; sapwood moderately soft and tough, heartwood hard and fragile; good stability in mechanical connecting.	No big problems in tooling; sapwood very soft and tough, heartwood very hard and fragile; good stability in mechanical connecting.	Moderately soft and tough wood; machines easily although the grain tends to tear around large knots; sharp tools needed; nails easily; easy planing for smooth surfaces; severe malformation, internal decay, and growth stresses are extremely rare; possible stability problems in mechanical connecting (wide earlywood sections).
Drying [40, 44, 59, 110, 152]	Dries rapidly; little tendency to warp, twist, and check; moderately high shrinkage; prone to blue stain (MC<25%, T 20–30°C).	Good for kiln drying; very good stability; very little warp or twist; minute shrinkage; resistance to cupping (1=most, 4=least): 1; conspicuousness of checking (1=least, 2=most): 1.	Good for kiln drying; moderately low shrinkage and little / very little tendency to warp, twist, and check; resistance to cupping (1=most, 4=least): 2; conspicuousness of checking (1=least, 2=most): 2.	Moderately high shrinkage but is dimensionally stable when properly dried; due to unequal shrinkage of early-wood/latewood, checks and raised grain may develop; high risk for blue stain; juvenile wood problems; resistance to cupping (1=most, 4=least): 2; conspicuousness of checking (1=least, 2=most): 2.	Careful and slow kiln drying or high-temperature drying needed; prone to splinter and check; moderate shrinkage; not unduly prone to deformations during drying; juvenile wood problems.
Gluing / bonding [40, 152]	Good unless too high resin content (heartwood); good stability.	Good; bond easily (bond very easily with adhesives of a wide range of properties and under a wide range of bonding conditions).	Good; bond well (bond well with a fairly wide range of adhesives under a moderately wide range of bonding conditions).	Good; bond satisfactorily (bond satisfactorily with good-quality adhesives under well-controlled bonding conditions).	Very good; glues easily; bond satisfactorily (bond satisfactorily with good-quality adhesives under well-controlled bonding conditions).

Table 6, continued. Selected processing properties of Nordic Scots pine and competing species in joinery, interior, and furniture products. References are shown in brackets.

	Pinus sylvestris **Nordic Scots pine**	***Thuja plicata*** **Western red cedar**	***Pinus ponderosa*** **Ponderosa pine**	***Pinus taeda*** **Loblolly pine**	***Pinus radiata*** **Radiata pine**
Surface treatments [40, 44, 110, 152]	Generally good, little difficult when high knottiness or lots of resins; lacquers, varnishes, paints, and waxes attach and stay easily; treatments are influenced by inner knots and extractives (resin acids and fatty acids).	Good; lacquers, varnishes and paints attach and stay easily; paint-holding characteristic (I=best, V=worst): oil-based paint I, Latex paint I.	Possible; lacquers, varnishes and paints attach and stay moderately easily; paint-holding characteristic (I=best, V=worst): oil-based paint III, Latex paint II.	Good; lacquers, varnishes and paints attach and stay easily; paint-holding characteristic (I=best, V=worst): oil-based paint IV, Latex paint III; accepts readily a wide variety of finishes designed for interior use; durable exterior finishes difficult to achieve; coatings tend to adhere poorly to broad bands of dense latewood; lumber may exude sufficient pitch to locally discolour finishes.	Very good; surface gumminess must be removed before painting and varnishing; lacquers and paints stay easily; takes paint and finishes well.
Other treatments / features [40, 44, 59, 152]	Sapwood impregnates easily, heartwood very difficult (durability class 3–4); resin leaks from heartwood when heated.	Penetration of the heartwood: very difficult (4/4, durability class 5); flame spread index 70; smoke developed index 213; wood may cause some biological reactions (bronchitasthma); green wood causes metal corrosion.	Penetration of the heartwood: least difficult (1/4); sapwood impregnates easily, heartwood not at all (durability class 3–4); flame spread index 105–230 (average 154).	Penetration of the heartwood: moderately difficult (2/4); impregnates easily; not durable (durability class 2–3).	Impregnates easily; not durable (durability class 2–3); sapwood treats readily with preservatives; heartwood is rated as durable above ground and is moderately resistant to preservative treatment; excellent treat ability with preservatives due to wide and permeable sapwood.

used. Sapwood can be easily impregnated, but the penetration of heartwood varies from very easy to very difficult in different species. Heartwood of western red cedar, radiata pine, and also to some extent Scots pine may be treated as durable material above ground conditions. Wood of western red cedar may cause some biological reactions (bronchitasthma, irritation), and also the occurrence of metal corrosion has been reported for the species (Table 6).

2.3 Comparison of species for structural products

In this study, the most important species competing with Nordic Scots pine were assumed to be in structural products (not in order of importance):
— Lodgepole pine
— Norway spruce
— Douglas-fir

In this chapter, comparisons of selected wood properties of Nordic Scots pine and above mentioned competing species are shown and discussed. The numerical data, gained from the literature, concerning each property and species of interest are shown in Appendix.

The length of Scots pine fibres is approximately equal to or smaller compared to the other species. Cell wall thickness is higher or equal to and tracheid diameter smaller in Scots pine than in other species, and the volume percentage of tracheids does not differ between species. Latewood percentage of Scots pine wood is higher compared to the other species (Table 7).

In lodgepole pine and Norway spruce the basic density first decreases from pith outwards, but after few rings it starts to increase with increasing distance from the pith (Table 8). The horizontal density variation of Douglas-fir is equal to that of Scots pine, since a considerable increase in density could be found with increasing distance from the pith. The average density difference in horizontal direction ranges between 25kg/m³ and 100kg/m³ depending on the species, vertical

Table 7. Comparison of selected morphological properties between Nordic Scots pine and competing species in structural products. For definition of symbols see Table 1. References are shown in brackets.

	Pinus contorta* var. *latifolia **Lodgepole pine**	***Picea abies*** **Norway spruce**	***Pseudotsuga menziesii*** **Douglas-fir**
Fibres			
- Tracheid length [4, 5, 6, 44, 59, 60, 61, 93, 94, 96, 101, 152]	0	0	+
- Cell wall thickness [36, 61, 93, 96, 152]	–	–	0
- Tracheid diameter [55, 60, 61, 93, 101]	+	+	+
- Percentage (volume) [2, 3, 99, 100, 152]	N/A	0	0
Annual ring width [57, 59, 60, 62, 97, 104]	–	+	+
Latewood percentage [61, 62, 97, 98]	–	–	N/A

Table 8. Horizontal (from pith to bark) and vertical (from butt to top) variation in basic density of Nordic Scots pine and competing species in structural products. N/A = no information available. References are shown in brackets.

	Pinus sylvestris **Nordic Scots pine**	***Pinus contorta* var. *latifolia*** **Lodgepole pine**	***Picea abies*** **Norway spruce**	***Pseudotsuga menziesii*** **Douglas-fir**
Density				
- Variation from pith to bark [1, 12, 13, 14, 16, 17, 18, 19, 20, 59, 67]	Density increases distinctly, the difference decreases with increasing height. In over-aged trees (over 80-100 yrs), the increase in density ends and density could even start decreasing.	At first, density decreases, but after few rings it increases distinctly with increasing distance from pith; high density in the 1st 5 rings, a pronounced dip in the 2nd 5-year period followed by a period of gradual rise to a more-or-less constant level, and finally a decrease beyond increment age of about 40.	At first, density decreases, but after few rings it starts to increase with increasing distance from pith.	An average density increase over the first 100 growth rings from the pith, and density thereafter remains more or less constant.
- Variation from butt to top [1, 24, 25, 26, 27, 63]	Clear decrease in density from butt to top.	Clear decrease from butt to approx. 70 % height, after that increasing; density diminishes curvilinearly from stump top to near the base of the live crown, above which it remains more-or-less constant.	Only minor changes in density, at first decreasing and later increasing; depends on silvicultural actions.	N/A

and radial position in the tree, etc. The density difference in vertical direction is the largest in Scots pine and the smallest in Norway spruce, where only minor changes occur in density with increasing vertical position in the stem. The basic relationship between height and density of all competing species except one (there was no data available for Douglas-fir) is different compared to that of Scots pine, since in these species the density first decreases with increasing height and later increases or remains more-or-less constant.

The average basic density of Scots pine is higher compared to Norway spruce, almost equal to compared to lodgepole pine, and smaller compared to Douglas-fir (Table 9). The variation of basic density within each species is considerable due to location and geographical origin, growth conditions, etc. Even within individual trees of a given species the density variation is generally high, not to mention the variation between trees and stands. In other density variables, the basic differences between species are similar to the differences in basic densities.

The radial shrinkage of Scots pine is approximately in the middle of the range of shrinkage values of the species, from 3.6% to 4.4% in Norway spruce and lodgepole pine, respectively, whereas

Table 9. Comparison of selected physical properties between Nordic Scots pine and competing species in structural products. For definition of symbols see Table 1. References are shown in brackets.

	Pinus contorta* var. *latifolia **Lodgepole pine**	***Picea abies*** **Norway spruce**	***Pseudotsuga menziesii*** **Douglas-fir**
Density			
- Density difference in horizontal direction [11, 12, 15, 59, 67]	0 / +	–	–
- Density difference in vertical direction [1, 11, 12, 21, 22, 23, 24, 25]	–	–	N/A
- Basic ($\rho_{0,g}$) [12, 30, 31, 32, 44, 49, 58, 59, 63, 66, 70, 95, 97, 152]	0	–	+
- Airdry ($\rho_{12\text{-}15}$) [54, 57, 59, 73, 95, 104]	–	–	0
- Dry-airdry ($\rho_{0,12\text{-}15}$) [33, 39, 56, 66, 70, 152]	–	–	0
- Green (ρ_g) [58, 59, 152]	N/A	0	–
Fibre saturation point at 20°C [34, 68, 69]	0	0	N/A
Shrinkage from green to oven dry MC			
- Length (b_l) [35, 39, 44, 59, 68, 95, 152]	–	+	–
- Radial (b_r) [40, 44, 59, 68, 72, 73, 95, 152]	+	–	+
- Tangential (b_t) [40, 44, 59, 68, 72, 73, 95, 152]	–	0	–
- Volumetric (b_V) [38, 39, 40, 59, 68, 73, 95, 152]	0	+	0
- Volumetric per 1% change in MC (6-14%) [152]	N/A	0	0
Porosity [152]	N/A	0	0

the tangential shrinkage is the highest (on average 7.8%) in Scots pine and Norway spruce and the smallest in Douglas-fir (7.1%). The average volumetric shrinkage is equal between Scots pine, lodgepole pine and Douglas-fir, and clearly higher for Norway spruce compared to other species. Neither the volumetric shrinkage per 1% change in moisture content (between 6 and 14% MC) nor porosity have any particular differences between species (Table 9).

Scots pine differs clearly from the other species in the mechanical properties (Table 10). The average modulus of elasticity (MOE, ||) in bending is 12.0GPa for Scots pine and 9.7, 11.9, and 13.0GPa for lodgepole pine, Norway spruce and Douglas-fir, respectively. The average values of bending strength (MOR, ||), compression strength (||), and compression strength (⊥) among all

Table 10. Comparison of selected mechanical properties at 12% MC between Nordic Scots pine and competing species in structural products. For definition of symbols see Table 1. References are shown in brackets.

	Pinus contorta var. *latifolia* Lodgepole pine	*Picea abies* Norway spruce	*Pseudotsuga menziesii* Douglas-fir
Modulus of elasticity in bending, MOE (‖) [21, 40, 54, 57, 59, 66, 70, 71, 72, 73, 95, 104, 152]	–	0	+
Bending strength, MOR (‖) [21, 40, 41, 42, 54, 57, 66, 70, 71, 72, 73, 95, 104, 152]	–	–	–
Compression strength (‖) [21, 40, 54, 66, 70, 71, 72, 73, 95, 152]	–	–	0
Compression strength (⊥) [40, 70, 71, 72, 73, 95]	–	–	–
Tensile strength (‖) [40, 66, 73, 95, 152]	N/A	–	+
Tensile strength (⊥) [40, 66, 70, 71, 72, 95]	–	–	–
Shear strength (‖) [40, 54, 70, 71, 72, 95, 152]	–	–	–
Shock resistance [43, 152]	N/A	–	–
Brinell hardness (⊥) [21, 40, 152]	–	–	+

species are the highest in Scots pine. Only the tensile strength (‖) and Brinell hardness (⊥) of Douglas-fir is higher compared to the values of Scots pine.

A distinct colour difference between heartwood and sapwood can be found in all species except Norway spruce. Heartwood of Scots pine and Douglas-fir is darker compared to the other species. Wood of all these species is generally straight grained and uniform to irregular textured. Gradual transition from earlywood to latewood is typical for Lodgepole pine and Norway spruce, whereas in Scots pine and Douglas-fir the transition from earlywood to latewood is more-or-less abrupt (Table 11).

Wood of all species is fairly easy to work, although dry knots may sometimes cause problems in processing of Norway spruce. Uneven growth rings and the density difference between earlywood and latewood may lead to some problems in sawing and machining of Douglas-fir. A good stability of mechanical connections can be achieved especially when using Scots pine and Norway spruce. Wood of these species is moderately good for kiln drying, despite the quite high shrinkage values. Scots pine and lodgepole pine wood can be dried very rapidly with only little deformation, whereas in Douglas-fir some surface checking may be occurring in flat-sawn timber, and the checking of

Table 11. Selected aesthetic properties and other features of Nordic Scots pine and competing species in structural products. References are shown in brackets.

	Pinus sylvestris **Nordic Scots pine**	*Pinus contorta* **var.** *latifolia* **Lodgepole pine**	*Picea abies* **Norway spruce**	*Pseudotsuga menziesii* **Douglas-fir**
Rings [40, 44, 59, 72, 152]	Distinct growth rings, abrupt transition from earlywood to latewood; rather distinct earlywood / latewood boundary.	Narrow / distinct growth rings; gradual transition from earlywood to latewood.	Gradual transition from earlywood to latewood; earlywood is usually wider than latewood.	Abrupt transition from earlywood to latewood; earlywood is usually wider than latewood; distinct growth rings, boundary between rings may be wavy; visually pronounced earlywood/latewood boundary.
Texture [40, 44, 59, 72, 109, 152]	Generally straight grained and moderately coarse, often irregular and decorative texture; moderately abrupt transition from earlywood to latewood.	Generally straight grained, not interlocked; uniform texture and straight and narrow grains.	Moderately straight grained and uniform texture.	Medium to medium-coarse; uneven grain, earlywood usually wider than latewood, with abrupt transition; usually straight grained and fine textured; strong and highly textured due to the pronounced earlywood / latewood contrast; coarse figure.
Colour [40, 44, 72, 152]	Sapwood is quite broad (5–7cm) and pale / reddish brown; heartwood reddish-brown, especially in the north; heartwood darkens fast in air contact; always sharp sapwood / heartwood boundary.	Sapwood (moderately narrow) yellow or nearly white, heartwood varies from light yellow to light yellow-brown.	Heartwood and sapwood pale yellowish-brown; colour is nearly uniform; heartwood might be slightly reddish in wet sites.	Heartwood reddish in young trees of moderate to rapid growth, narrow-ringed heartwood of old-growth trees may be yellowish brown; heartwood orange-brown to deep reddish brown or sometimes yellowish brown.
Other features [44, 72, 152]	Characteristic resinous odour; lots of resin canals (large) and resins; moderately thin knots (dark).	Slight resinous odour when green; moderately knotty wood.	Decay resistance is weak.	Characteristic resinous odour; colour, odour, ring width, strength and stiffness, and machinability differ due to geographical origin.

Table 12. Selected processing properties of Nordic Scots pine and competing species in structural products. References are shown in brackets.

	Pinus sylvestris **Nordic Scots pine**	***Pinus contorta* var. *latifolia*** **Lodgepole pine**	***Picea abies*** **Norway spruce**	***Pseudotsuga menziesii*** **Douglas-fir**
Mechanical tooling / machining [40, 44, 59, 109, 152]	Easy, including rotary-cutting, veneering and splitting; wood soft and tough; good stability in mechanical connecting; debarking and veneering is easy.	Fairly easy / easy to work (incl. planing); nails and screws easily; ranks high in ease of milling and machining – easily planed without defect.	Generally easy, incl. rotary-cutting, veneering and splitting; easily cleaved, moderately elastic material; hard knots that get removed may cause problems; wood moderately soft and tough, woolly surface when wide rings; easiness and moderately good stability in mechanical connecting.	Good (if narrow rings) to weak (if wide rings); otherwise easy, incl. rotary-cutting and veneering; shining planed surfaces; wood moderately hard and fragile; easy to work, especially debarking and facing; machining and finishing is quite difficult due to the earlywood / latewood density differences; uneven growth rings lead to some problems in sawing and machining, especially in rapidly grown stands.
Drying [40, 44, 59, 152]	Dries rapidly; little tendency to warp, twist, and check; moderately high shrinkage; prone to blue stain (MC<25%, T 20–30°C).	Moderately high shrinkage; little deformations during drying, dries rapidly; moderately low shrinkage.	Wood dries well, but might warp and check to some extent; good for kiln drying, but knots split easily; minute shrinkage; good stability; slightly prone to twist and split.	Moderately good for kiln drying, care needed for resin leaks; moderately high shrinkage; good stability; very little prone to split; surface checking is occurring in flat-sawn lumber, and the checking of intergrown knots may cause problems in drying; low incidence of spiral grain and compression wood around the pith allow lumber to better retain its shape on drying; moderately stable in response to changes in humidity; resistance to cupping (1=most, 4=least): 2; conspicuousness of checking (1=least, 2=most): 2.
Gluing / bonding [40, 44, 152]	Good unless too high resin content (heartwood); good stability.	Glues easily.	Very good.	Very good; bond well (bond well with a fairly wide range of adhesives under a moderately wide range of bonding conditions).

Table 12, continued. Selected processing properties of Nordic Scots pine and competing species in structural products. References are shown in brackets.

	Pinus sylvestris **Nordic Scots pine**	***Pinus contorta* var. *latifolia*** **Lodgepole pine**	*Picea abies* **Norway spruce**	*Pseudotsuga menziesii* **Douglas-fir**
Surface treatments [40, 44, 59, 109, 152]	Generally good, little difficult when high knottiness or lots of resins; lacquers, varnishes, paints, and waxes attach and stay easily; treatments are influenced by inner knots and extractives (resin acids and fatty acids).	Filling is not usually necessary (no large pores).	Good, care needed for resin leaks; lacquers, varnishes, paints and waxes attach and stay easily.	Generally good, care needed for resin leaks; oil and PE lacquers stay rather badly; machining and finishing is quite difficult due to the earlywood / latewood density differences; usually easy to polish; is renowned as a refractory species because of the difficulty of getting chemicals into both heartwood and the dry sapwood; paint-holding characteristic (I=best, V=worst): oil-based paint IV, Latex paint II.
Other treatments / features [40, 44, 59, 109, 152]	Sapwood impregnates easily, heartwood very difficult (durability class 3–4); resin leaks from heartwood when heated.	Penetration of the heartwood: difficult (3/4); sapwood is permeable and easily treated, while heartwood is impermeable; proportion of heartwood is usually relatively high; Incising – perforation of wood surfaces with blade or needle-shaped tools – might be necessary to get sufficient penetration into heartwood; flame spread index 93; smoke developed index 210.	Difficult to treat with preservatives; difficult to impregnate, not durable (durability class 2–3); rather resistant against weak acids and alkalis.	Sapwood impregnates (sometimes difficult), heartwood some durability (durability class 3–4); rather resistant against acids and alkalis; causes iron corrosion; penetration of the heartwood: moderately difficult (2/4) for coast; very difficult (4/4) for Rocky Mountain; sapwood and heartwood are considered to be untreatable with water-borne preservatives; sapwood is moderately treatable with oil-borne preservatives but the heartwood is refractory; flame spread index 70–100.

intergrown knots may also cause problems during drying. Risk for blue stain and susceptibility for discolouration during drying are reported to be drawbacks of Scots pine, although these can normally be controlled by the drying formulas used. In general, wood of all species can be bond quite easily with adhesives of a wide range of properties and under a wide range of bonding conditions (Table 12).

Surface treatment ability is generally good in all species, but some care is needed for resin leaks in Norway spruce and Douglas-fir. Still, all coatings are not suitable for all species. Douglas-fir is also renowned as a refractory species because of the difficulty of getting chemicals into both sapwood and heartwood; this leads to the fact that Douglas-fir wood can be considered to be untreatable or difficult to treat with preservatives. The same principles applies also to Norway spruce. Meanwhile, Scots pine and lodgepole pine sapwood is permeable and impregnates easily, while penetration of heartwood is more difficult. Norway spruce and Douglas-fir wood is reported to be rather resistant against weak acids and alkalis, whereas Douglas-fir wood can cause iron corrosion (Table 12).

2.4 Conclusions

Compared to other species of interest, the wood of Nordic Scots pine is quite transcendent in strength and stiffness properties. Only loblolly pine can challenge Scots pine in mechanical properties, especially in those that are important in joinery, interior, and furniture products. Based on the literature findings and considering the mechanical properties, the strongest competitor in structural end uses is Douglas-fir. It should be remembered that the variations in strength and stiffness values are remarkable within species, thus, the relations shown in the tables may not be correct in all circumstances of in-situ use. It should also be noted that the values used in the comparisons are representing the values of small clear wood specimens, which may differ from the values of sawn timber quite dramatically due to the background variables affecting these properties (morphological and physical properties etc.).

The fibre properties themselves do not play such a big role in mechanical wood processing or products, though in some applications they might have some influence on the suitability of material to certain processes or end-uses. To be mentioned, annual ring width is one of such properties, and it is almost impossible, or even irrelevant, to compare ring widths among different species due to great variations caused by geographical origin, growth conditions, etc. Still, the annual rings of Scots pine are quite narrow compared to most of the competing species, which is an advantage in such products where good stability is needed. Especially in wood from the extreme northern latitudes the average annual ring width may remain at a suprisingly low level.

The density variation patterns vary between species, but the basic phenomena is still present in all species: the density varies with varying horizontal and vertical position in the tree, and only the shape and course of these relationships may be different in different species. The great variation in density may cause some problems in some processes and end-uses, but these problems can usually be avoided, or at least reduced by using appropriate sawing patterns and processing schemes. With this respect, Scots pine wood from the northern latitudes is more homogeneous both in horizontal and vertical direction compared to wood with a more southerly origin. The average basic density of Scots pine is approximately in the middle of the basic density range of the selected species, which partly explains the excellence of Scots pine concerning mechanical properties. Still, there are some other properties, such as average annual ring width, that should explain the rest of the gap between Scots pine and other species.

Moderately high shrinkage of Scots pine may cause problems in drying of wood, but still it can be dried rapidly with only minor deformation and little checking, by using appropriate drying formulas. Again, the more northerly is the origin of wood the more homogeneous is it. Wood is generally straight grained and moderately soft and the knots are usually quite small, which makes Scots pine adequate for machining. Juvenile wood phenomenon may cause some difficulties also in Scots pine, but they are not so severe compared to some other species. Bonding is moderately easy unless too high resin content, as well as are the traditional surface treatments.

Scots pine wood is suitable for those end-uses where aesthetic properties are especially important, such as furniture and selected joinery products. Texture of Scots pine can be described as wavy, moderately irregular, and thus decorative. Presence of both heartwood and sapwood sections in panellings etc. may cause some imbalance due to quite large colour difference between heartwood and sapwood. In addition, knots and other defects cause also some disturbance to wooden surfaces, but this is the case also in other species than Scots pine. On the other hand, “optimal” amounts and location of features that mismatch in the surface may also increase the decorativeness of wood.

In general, Scots pine can be regarded as a healthy material that does not cause any health problems neither in a variety of end use conditions nor during manufacturing processes. Selected other species, such as Doulas-fir, may cause serious health problems, irritation, etc, and also some damage to other materials used with wood.

As a conclusion, Scots pine wood is very suitable material for a wide selection of joinery, interior, and furniture products when it is processed and treated properly, and moderately high-quality material is used. Also in the structural uses, Scots pine wood is well able to compete against other species, even if moderately large variations may be expected especially in the strength and stiffness properties due to the geographical origin, knottiness properties, grain angle, and other background variables affecting the strength and stiffness of wood.

3 Nordic Scots pine vs. non-wood substitute materials

3.1 Joinery products, case window frames

3.1.1 Introduction

Over centuries, but especially in the last decades, wood and wood-based products have had to face strong competition from non-wood substitute materials, such as plastics, concrete, steel, glass, or aluminium, as these materials appear to offer wider options to the customers[130]. Traditionally, window frames have been manufactured from solid wood, but the use of other materials has been increasing with time. Increasing amounts of aluminium, PVC, and steel windows have been produced in past decades, and timber windows have lost market share for these competitors. Also different kinds of combinations of materials, e.g., frames can be made of PVC and mountings and fittings from aluminium, and also selected composite materials have been used. In fact, the timber window industry is undergoing a renaissance due to dynamic initiatives to regain market share in the sector.

PVC-U is a general term for different modified, unplasticised, high impact resistant polyvinyl chlorides used, for instance, in window frame manufacturing. Material is especially intended for outdoor uses and is, therefore, to a large extent, light and weather stabilized. Window frames manufactured from PVC-U represent one of the largest markets for plastics in the European construction sector and one of the largest single markets for bulk polymers. On a European scale, PVC-U windows accounted for 37% of all the windows produced in 1998, whereas for instance in the UK this share had been doubled and PVC-U accounted for approximately 75% of the total windows produced[111].

Aluminium was the first of the new window framing materials. By now, aluminium has proved itself suitable as a metal for manufacture of windows, doors, and similar installations since it can be formed and fabricated in ways hitherto commercially impossible for both wood and steel[125]. Although the material has been in use for many decades the period of rapid growth began in the 1970's with the development of the UK double glazing market. In some degree, aluminium has suffered by the development of PVC-U. Different aluminium alloys and tempers are used depending on the end-use conditions, and some variation occurs also between manufacturers. In general, the series of aluminium alloys used for window frame manufacturing (*6xxx*) is characterized by modest additions of silicon and magnesium, and the alloys are usually strengthened by solution heat treatment and artificial ageing[112]. Steel window industry concentrates mainly in the commercial sector where the particular mechanical strengths of the products are utilised best[111].

New, even more sophisticated materials are coming also to the window frame markets, including glass fibre, different plastics (polystyrene, ABS plastics, cellular PVC), and different kinds of plastic and biological material composites[111, 148]. All of these materials have some positive and negative aspects, and their use is about to rise with time.

3.1.2 Aluminium

The chemical compositions of different aluminium alloys, and selected parts of the temper designation system for aluminium alloys are shown in Tables 13 and 14, respectively. In addition, a comparison of selected physical and mechanical properties of selected aluminium alloys used for instance in window frame manufacturing is shown in Table 15, whereas selected processing and servicing properties and general characteristics of these alloys are shown in Table 16.

Aluminium extrusions have a comparatively high coefficient of expansion. When designing, especially in building design, provision should be made for expansion and contraction caused by temperature changes. Thermal expansion is particularly important where aluminium extrusions

Table 13. Chemical composition (%) of selected aluminium alloys[113, 114, 115].

	Aluminium	*Silicon*	*Iron*	*Copper*	*Manganese*	*Magnesium*	*Chromium*	*Zinc*	*Titanium*		
Alloy	**Al**	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Other, each**	**Other, total**
6060	≤ 97.8	0.3–0.6	0.1–0.3	≤ 0.1	≤ 0.1	0.35–0.6	≤ 0.05	≤ 0.15	≤ 0.1	≤ 0.05	≤ 0.15
6061	95.8–98.6	0.4–0.8	≤ 0.7	0.15–0.4	≤ 0.15	0.8–1.2	0.04–0.35	≤ 0.25	≤ 0.15	≤ 0.05	≤ 0.15
6063	≤ 97.5	0.2–0.6	≤ 0.35	≤ 0.1	≤ 0.1	0.45–0.9	≤ 0.1	≤ 0.1	≤ 0.1	≤ 0.05	≤ 0.15

Table 14. Selected parts of the temper designation system for aluminium alloys[116].

Temper	Definition
T4	Solution heat-treated and naturally aged to a substantially stable condition
T5	Cooled from an elevated-temperature shaping process and artificially aged
T6	Solution heat-treated and artificially aged

Table 15. Physical and mechanical properties of selected aluminium alloys used for window frame manufacturing[113, 114, 115, 117, 118, 119, 120, 121, 122, 123, 124].

	EN AW-6060/T6	EN AW-6061/T6	EN AW-6063/T5	EN AW-6063/T6
Physical properties				
- Density, kg/m³	2700	2700	2700	2700
- Heat capacity, J/kg K	901 898	896 899	900 898	900 898
- Thermal conductivity (at 20°C), W/m K	200	167 166	200	200
Mechanical properties				
- Ultimate tensile strength, MPa	N/A	310 300	155–160 186 185	241 200–220 240
- Tensile yield strength, MPa	N/A	276 270 255	115–120 145 145	214 175–185 215
- Modulus of elasticity, GPa	69	68.9[2)] 68.3 70	68.9[2)]	68.9[2)] 69[2)]
- Ultimate bearing strength, MPa	N/A	607[3)]	N/A	434[3)]
- Bearing yield strength, MPa	N/A	386[3)]	N/A	276[3)]
- Fatigue strength, MPa	N/A	96.5[4)] 97	68.9[4)] 69	68.9[4)] 69
- Shear strength, MPa	N/A	207 205	117 115	152 150
- Brinell hardness (⊥), MPa	70	95[1)] 95	Approx. 60 60	73[1)] 73

Figures shown are typical values.
[1)] 500g load, 10mm ball.
[2)] Average of tension and compression. Compression modulus is about 2% greater than tensile modulus.
[3)] Edge distance / pin diameter=2.0.
[4)] 500,000,000 cycles completely reversed stress; RR Moore machine / specimen.

are used with other materials which have different expansion rates[125], such as window glass. Even though aluminium has a high natural resistance to the corrosive conditions, several characteristic modes of attack on aluminium may be distinguished, although the corrosion caused by environmental factors can be mainly prevented by appropriate care and maintenance actions. Heat losses of aluminium window frames caused by high thermal conductivity of aluminium can be limited by using thermal breaks which are made of a material with a lower thermal conductivity.

Table 16. Processing and servicing properties and general characteristics and uses of selected aluminium alloys used for window frame manufacturing[113, 114, 115, 117, 118, 119, 120, 121, 122, 123, 124].

	EN AW-6060/T6	EN AW-6061/T6	EN AW-6063/T5	EN AW-6063/T6
Processing and servicing properties				
- Workability (cold)***)	C: average	C: average	C: average	C: average
- Machinability***)	C: average	C: average	C: average	C: average
- Weldability****)	A: Generally weldable by all commercial procedures and methods.	A: Generally weldable by all commercial procedures and methods.	A: Generally weldable by all commercial procedures and methods.	A: Generally weldable by all commercial procedures and methods.
- Brazeability****)	A: Generally weldable by all commercial procedures and methods.	A: Generally weldable by all commercial procedures and methods.	A: Generally weldable by all commercial procedures and methods.	A: Generally weldable by all commercial procedures and methods.
- Resistance to corrosion: General*), Stress**), Compression, Shear	General A, Stress A: Can be used in industrial and seacoast atmospheres without protection.	General B, Stress A: Good corrosion resistance for high strength applications.	Compression A, Shear A: Can be used in industrial and seacoast atmospheres without protection.	Compression A, Shear A: Can be used in industrial and seacoast atmospheres without protection.
General characteristics and uses	Light structural & architectural extrusions such as glazing bars and window frames, general purpose extrusions. Good surface finish, anodises well. The most frequently used extrusion alloy.	Excellent joining characteristics, good acceptance of applied coatings. Combines relatively high strength, good workability, and high resistance to corrosion; widely available. Structural applications where corrosion resistance is needed, i.e. marine and transport use.	Light structural & architectural extrusions such as glazing bars and window frames, general purpose extrusions. Good surface finish, anodises well. The most frequently used extrusion alloy.	Light structural & architectural extrusions such as glazing bars and window frames, general purpose extrusions. Good surface finish, anodises well. The most frequently used extrusion alloy.

*) Ratings A through E are relative ratings in decreasing order of merit, based on exposures to sodium chloride solution by intermittent spraying or immersion. Alloys with A and B ratings can be used in industrial and seacoast atmospheres without protection. Alloys with C, D and E ratings generally should be protected at least on faying surfaces.

**) Stress-corrosion cracking ratings are based on service experience and laboratory tests of specimens exposed to the 3.5 % sodium chloride alternate immersion test.
- A = No known instance of failure in service or in laboratory tests.
- B = No known instance of failure in service; limited failures in laboratory tests of short transverse specimens.
- C = Service failures with sustained tension stress acting in short transverse direction relative to grain structure; limited failures in laboratory tests of long transverse specimens.
- D = Limited service failures with sustained longitudinal or long transverse specimens.

***) Ratings A through D for Workability (cold) and A through E for Machinability, are relative ratings in decreasing order of merit.

****) Ratings A through D for Weldability and Brazeability are relative ratings defined as follows:
- A = Generally weldable by all commercial procedures and methods.
- B = Weldable with special techniques or for specific applications that justify preliminary trails or testing to develop welding procedure and weld performance.
- C = Limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties.
- D = No commonly used welding methods have been developed.

3.1.3 Unplasticised polyvinyl chloride (PVC-U)

It is quite hard to compare literature findings about different PVC-U materials used in window frames, since almost every manufacturer is using different compounds with slightly different properties. In addition, data sheets of different compounds seem to be quite difficult to achieve. Selected physical and mechanical properties of one PVC-U compound commonly used for window

Table 17. Selected properties of one of the polyvinyl chloride compounds commonly used for window frame manufacturing[129].

	RAU-PVC 1406/1476
Physical properties	
- Density, kg/m³	1440 ± 20
- Heat capacity, J/kg K	Approx. 1050
- Thermal conductivity (at 20°C), W/m K	Approx. 0.21
Mechanical properties	
- Ultimate tensile strength, MPa	> 45
- Tensile yield strength, MPa	> 40
- Modulus of elasticity, GPa	> 2.5
- Impact strength, kJ/m², 0°C	No break
- Impact strength, kJ/m², -20°C	No break
- Impact strength, kJ/m², -40°C	No break
- Impact strength, notched, kJ/m², +23°C	> 25
- Impact strength, notched, kJ/m², 0°C	> 7
- Hardness (⊥), MPa	Approx. 95 *)
Processing and servicing properties	
- Colouring	All colours can be supplied, with the exception of transparent colours. For outdoor use, a wide range of practice-proven, extremely light-fast colours are available.
- Bonding	These can be bonded to themselves using conventional adhesives for use with unplasticised PVC. Bonding to other materials is possible in almost all cases.
- Weldability	These can be welded to themselves without difficulty.
- Chemical, weathering and ageing resistance	The special formulation designed for outdoor use gives 1406 excellent resistance to weathering and ageing. In addition to this, 1476 also meets the necessary requirements for countries with high levels of solar irradiation. Ketones, esters, chlorinated hydrocarbons, aromatic hydrocarbons, carbon disulphide and other solvents cause swelling or dissolution.
General characteristics and uses	These are unplasticised, modified polyvinyl chlorides, classed as high impact resistant to DIN 7748. These are distinguished by their excellent resistance to impact over a wide temperature range. The material is especially intended for outdoor use (construction industry: window construction, garden furniture; automotive and refrigeration industry) and is, therefore, to a large extent, light and weather stabilized. The performance is characteristic of a thermoplastic and is consequently dependent on temperature. Between -40 ... + 40 ° C the changes in mechanical values are small and can be disregarded.

*) Ball indentation hardness 30 sec, DIN 53456, ISO 2039-1

frame manufacturing is shown in Table 17. In general, PVC is one of the most versatile of the bulk polymers, and the impact modified rigid forms (PVC-U) are being used in window manufacturing purposes. The addition of impact modifiers is necessary to allow usage of PVC-U down to temperatures of -40°C, even when mechanical stresses are present. Different stabiliser systems allow a service life of over 40 years to be given to the PVC-U material component of windows[127].

PVC-U material is available in clear or coloured forms and it is durable, weatherproof, and flame resistant with good overall mechanical properties. Rigid PVC is a hard, rigid material: under a tensile load, once it has reached its high tensile strength, it flows in a plastic manner as the tensile stress is removed, until plastic fracture occurs. Excessive thermal expansion has been a problem with earlier windows, and although even more modern compounds have been developed, PVC still moves more than wood, metal, or glass. Movement is today unlikely to affect the window, but it is a reason to be careful about the joints between windows and exterior walls[128]. The material is easily welded and glued and certain formulations are physiologically safe[126].

In fact, PVC has encountered quite intensive hostility from environmental groups (usage of heavy metals as compounding agents etc.), and it has even been claimed to be dangerous for human and nature. Still, the basic scientific information shows that PVC-U material is safe to use when using appropriate compounds and working practises.

3.1.4 Steel

Steel windows are mostly used in the commercial sector where the particular mechanical strengths of the product are best utilised[111]. Window profiles from hot-rolled sections and cold-formed sections are used. The former are made from solid steel sections which have been hot-rolled from new billet into profiles or shapes to form frame assemblies and ventilation assemblies, and the latter are made by mechanically forming various profiles or shapes from low carbon cold-rolled steel, and are defined and categorized as commercial and industrial windows. For surface treatments, different kinds of finishes, galvanization etc. can be used[131]. In steel framed windows, thermal breaks are needed due to high thermal conductivity of the material. The problems with heat losses can be solved also by using steel in combination with other, heat insulating materials.

3.1.5 Comparison of wood and non-wood substitute materials in window frames

As a consequence of local building traditions and appreciations, the status of wood as a raw material for joinery products varies greatly between different parts of Europe. In the Nordic countries, the status of wood is strong, whereas in the other parts of Europe the status of wood is not so good. In joinery products the local traditions may play a great role, and also the tradition of using local tree species for specific products may be very strong. In the future, the main building trends affecting especially the use of joinery products will be[135]:

— Development and diversification of building materials;
— Importance of compatibility will be increased in projecting, new building solutions will be developed;
— Energy consumption and emissions will be reduced, new sources of energy will be introduced;
— In sales and marketing, the importance of environmental aspects will increase;
— Importance of issues concerning need for maintenance, healthiness, security, and modifiability will be emphasized;

— Demands set by end-users will be increased.

By far, the development of wooden building materials has been quite slow, and no changes are in sight in the near future. The threat for the development of wood products is the incoherent company structure in the area of wood product industries compared to the structure of plastics and metal industries. The use of standardised and modular building products will be increasing and the production volumes will also increase. This requires more stakes to R&D, which may debilitate the abilities of small-scaled wood frame window manufacturing companies to compete against other companies.[135]

As the energy consumption and other environmental issues become even more important in the future, the status of wood as a raw material should further brighten as a natural, heat insulating material. A major drawback with wood in window frames is the periodic need for maintenance actions during the life cycle of the product. On the other hand, the exclusiveness of wood products originating from the visual and aesthetic properties of wood should be an advantage when competing against plastics and other inorganic materials.[135]

In general, light weight, strength, and good machining ability are the main advantages of wood in window framing. The main weakness is the lack of long-term durability against weather, mould, and decay without proper treatments and finishes. In the future, the most important building trends, with respect to wood-based joinery products, will be associated to finger-jointing, utilization of laminated structures, and the possibilities to utilize heat treated wood.[135]

Based on the life cycle analyses of window frames made from aluminium, PVC, and wood, it can be concluded that for all impact categories the environmental burden of wooden windows is the lowest with a calculated lifetime of 30 years. Acidification potential of wooden windows amounts to only 40% to 47% of that of aluminium and PVC windows. Concerning the eutrophication potential and the photochemical ozone creation potential, the results for the wooden windows are around two-thirds of that for windows of other materials. Despite the highest global warming potential of wooden windows, caused by periodical needs for treatments with paint or other chemicals, the wooden window is the most favourable product when the entire life cycle is considered, while the PVC and aluminium windows are placed second and third, respectively.[130]

It is quite difficult to compare the exact properties of Scots pine wood with the before-mentioned competing materials in window frames, since each material has its own special characteristics which may not be as important for other materials in this use. In addition, it is hard to find any records where similar properties were reported for each material. Instead, comparisons can be performed by SWOT analyses, where the strengths, weaknesses, opportunities, and threats are reported separately for each material of interest (Tables 18–21). On the other hand, the applicability of selected materials for window frame manufacturing can be described as shown in Table 22.

3.2 Exterior cladding (siding)

3.2.1 Introduction

Cladding of a building is basically the external wall of the structure. It is used to protect internal environment of the building from the external environment. In cladding, the main non-wood substitute materials for sawn timber are assumed to be brick masonry (brickwork), concrete element

Table 18. SWOT analysis of timber windows[111].

Strengths	Weaknesses
- Well known and traditional material. - Low perceived cost (at first installation). - Stable and well established supply chain. - Easily modified on site. - Good thermal and sound insulation. - Easy for end-user to repair and maintain. - Doors have high consumer appeal and traditional base. - Appearance can be modified by consumer.	- Higher maintenance load for end-user if not treated correctly. - Expands and contracts due to the presence of moisture and can give interference problems. - Industry is under attack by alternative materials, is in general decline and activity is low.
Opportunities	**Threats**
- Private sector housing and extensions have always provided volume usage. - Improvements in surface coating techniques to reduce maintenance loads. - Use of composite materials / layer techniques to give lower cost, more efficient materials usage. - Surface coatings applied in factory to give factory finished products ready to install.	- Continued growth of alternative materials in new build sector. - Materials price increases for both types of raw material. - Sustainability issue and environmental action for tropical hardwoods. - Price decreases for alternative materials (at first installation).

Table 19. SWOT analysis of aluminium windows[111].

Strengths	Weaknesses
- Low maintenance load but not maintenance free. - High inherent corrosion resistance. - Lightweight products. - Fire resistance. - Good security results. - Recyclability of raw material. - High mechanical strength allows curtain walling and commercial applications without additional reinforcement.	- Raw material costs. - Low thermal insulation unless thermally broken or clad with additional materials. - On-site modification is difficult, difficult to work with once fabricated.
Opportunities	**Threats**
- Composite windows with good thermal properties and attractive finishes. - Curtain walling and large commercial structures in coloured products.	- PVC-U has mainly taken domestic market and commercial market is now being threatened by the development of PVC-U based curtain wall structures (for small developments only). - Revival of wooden windows (with improved surface coatings).

Table 20. SWOT analysis of PVC-U windows[111].

Strengths	Weaknesses
- Low maintenance load but not maintenance free. - Unaffected by moisture. - Good thermal insulation. - Lightweight. - Easy to machine and process. - Highly certified/accredited industry.	- Low mechanical strength. - High thermal expansion. - Over capacity of sector and fragmentation at all levels. - Decreasing gross margin at all levels. - Volatility of raw materials costs. - Structure of industry.
Opportunities	**Threats**
- Increased penetration of new build sector. - Rapid fitment methods. - Wide range of styles. - New finishes to provide colour options. - Small scale curtain walling applications.	- Retail replacement market slowing due to saturation and slow housing market. - Volatile raw material prices. - Fragmented market at all levels with emerging signs of consolidation. - Extreme price pressure at all levels of market. - Environmental pressure on the use of PVC-U as a material.

Table 21. SWOT analysis of steel windows[111].

Strengths	Weaknesses
- High mechanical strength. - Slim sight lines due to exceptional mechanical strength. - Excellent fire resistance in conventional tests.	- Low thermal insulation unless used in combination with other materials. - High maintenance load after initial coating. - Transport difficulties. - Small supplier base. - Difficult to make bespoke products. - On-site modification is difficult.
Opportunities	**Threats**
- High strength gives excellent security and mechanical response. - Door products using high mechanical strength to advantage i.e. composite doors. - Commercial work presents best opportunity. - Thermal assessments may prove surprising for new ranges of windows.	- Continued inroads by alternative materials. - Fashion moving away from steel as framing material.

Table 22. Applicability of wood, aluminium, and plastics for window frames[135].

End-use and product requirements	Wood	Aluminium	Plastics
- Strength	**0** Moderate strength, big variations cause problems	+ High strength (depending on the alloy composition)	**0** Moderate strength, small variation, fragile at low temperatures
- Appearance	+ Natural material	**0** Looks "cold"	– Usually looks "cheap"
- Environmental friendliness	+ Natural material, easy to demolish	**0** Easy to recycle	– Limited raw material source, difficult to recycle and demolish
- Dimensional stability (temp. & humidity)	– Changes in moisture content cause instability	– Thermal expansion should be taken into consideration in large structures	**0** Almost stable material
- Thermal insulation	+ Good thermal insulation	**0** High thermal conductivity, may be considered in structures	**0** Moderate thermal insulation
- Formability / machineability in manufacturing process	– Knots and other defects will be removed, raw material use efficiency varies	**0** Moderately easy to machine	+ Easy to machine with light tools
- Long-term durability / surface treatments	– Limited durability, demands maintenance in outdoor conditions	+ Good durability, almost no need to maintenance actions	**0** Long-term durability mainly good

surfaces, portland cement plaster (traditional stucco), and steel profiles especially in commercial and industrial applications. Especially in the U.S., wood-plastic composites and different kinds of plastics (extruded vinyl profiles etc.), and also cement-bonded wood composites (cement-based fibreboards etc.) play great role in this aspect, but these are included in this work only by applicable parts.

The U.S. exterior cladding market was estimated at 960 million square meters in 2002 and currently is comprised of 37% vinyl, 17% stucco, 17% wood, 11% brick, 10% wood plastic composites, and 8% other materials[150]. In 1999, timber products occupied almost 50% of the total weatherboarding market in the UK, but increasing use of cellular PVC-U weatherboarding in the private housing sector continues to impinge upon timber's share on the market. In 2002, the UK market for timber weatherboarding amounted to around £45 million per annum at factory gate prices.[151] In general, the status of wood as cladding material in Europe is strong in the Nordic countries, whereas in the other parts of Europe other cladding materials are mostly used. In Scotland, in the regions where timber cladding is used, the trend is towards durable woods such as western red cedar which need no painting, although painted, but generally untreated, Scandinavian redwood (Scots pine) and whitewood (Norway spruce) have been traditionally used[151].

3.2.2 Brickwork

Brick is the oldest of all artificial building materials. It is classified as face brick, common brick, and glazed brick. Face brick is used on the exterior of a wall and varies in colour, texture, and mechanical properties. Common brick consist of the kiln run of brick and is used principally as backup masonry behind whatever facing material is employed. It provides the necessary wall thickness and additional structural strength. Glazed brick is employed largely for interiors where beauty, ease of cleaning, and sanitation are primary considerations.[112]

Structural clay tiles are burned-clay masonry units having interior hollow spaces termed cells. Such tile is widely used because of its strength, light weight, and insulating and fire protection qualities. Its size varies with the intended use.[112]

Load-bearing tile is used in walls that support, in addition to their own weight, loads that frame into them, for example, floors and roof. Tiles manufactured for use as partition walls, for furring, and for fireproofing steel beams and columns are classed as non-load-bearing tile. Special units are manufactured for floor construction: some are used with reinforced concrete joists, and others with the steel beams in flat-arch and segmental-arch construction.[112]

Architectural terra-cotta is a burned-clay material used for decorative purposes. The shapes are moulded either by hand in plaster-of-paris moulds or by machine, using the stiff-mud process. Mortars, which are used to bond unit masonry, are similar in composition to concretes. Mortars, however, are normally made with sand as the sole aggregate, whereas concretes contain much larger aggregates and thus have greater strength.[112]

3.2.3 Concrete

General information concerning concrete is shown in chapter *3.3.3 Concrete*.

3.2.4 Glass

For centuries considered as a decorative, fragile material suitable for only glazing and art objects, today glass is produced in thousands of compositions and grades for a wide range of consumer and industrial applications. The basic ingredient of glass is silica (silicon dioxide), which is present in various amounts, ranging from about 50 to almost 100%. Other common ingredients are oxides of metals, such as lead, boron, aluminium, sodium, and potassium.[112]

Glass is an amorphous solid made by fusing silicon dioxide with a basic oxide. Its characteristic properties are its transparency, its hardness and rigidity at ordinary temperatures, its capacity for plastic working at elevated temperatures, and its resistance to weathering and to most chemicals except hydrofluoric acid.[112]

There are a number of general families of glasses, some of which have many of hundreds of variations in composition. The soda-lime family glasses (‘window glass’, commercial glass) are the glass for ordinary windows, bottles, and tumblers. The family is the oldest, lowest in cost, easiest to work, and most widely used. It accounts for about 90% of the glass used in the U.S. Soda-lime glasses have only fair to moderate corrosion resistance and are useful up to about 460°C, annealed, and up to 249°C, tempered.[112]

Plate glass is used for largest amounts for storefronts and office partitions. Plate glass is any glass that has been cast or rolled into a sheet, and then ground and polished. It generally contains slightly more calcium oxide and slightly less sodium oxide than window glass (Table 23), and small amounts of agents to give special properties may be added, such as agents to absorb ultraviolet or infrared rays, but inclusions that are considered impurities are kept to a minimum. Plate glass is now made on a large scale on continuous machines by pouring on a casting table at a temperature of about 1000°C, smoothing with a roller, annealing, setting rigidly on a grinding table, and grinding to a polished surface.[112]

During the past decades, different value-added glazing products, such as laminated, tempered, mirrored glass, and, above all, double-glazed insulating glass units, have became more and more popular in construction in developed countries.

3.2.5 Portland cement plaster, render, stucco

House construction technique involving the application of plaster to walls and ceilings is known as plastering, whereas exterior plasterwork is of a different composition and is generally known as stucco[140]. Stucco is a material usually made of portland cement, sand, and a small percentage of lime and applied in a plastic state to form a hard covering for exterior walls[141]. Traditionally, stucco has been applied to both internal and external masonry or timber wall construction as it

Table 23. Typical composition (%) of soda-lime glasses (window sheet and plate glass)[112].

Designation	*Silicon dioxide* **SiO_2**	*Sodium oxide* **Na_2O**	*Calcium oxide* **CaO**	*Magnesium oxide* **MgO**	*Aluminium oxide* **Al_2O_3**
Soda-lime (window sheet)	71–73	12–15	8–10	1.5–3.5	0.5–1.5
Soda-lime (plate glass)	71–73	12–14	10–12	1–4	0.5–1.5

requires a solid backing to give it strength. Modern techniques have enabled the use of stucco on timber frame walls. Although stucco is at first sight a very simple technique, its incorrect or inappropriate application can result in major problems causing the stucco to bulge, separate, crack or allow the entry of water causing timber frames to rot out[142].

When applied to masonry, the stucco can be applied directly onto the surface. As masonry walls tend to be fairly substantial and are not susceptible to significant movement, the applied stucco is unlikely to cause problems. On stout wooden structures, the surface needs to be covered in some form of damp proof membrane to prevent moisture passing from the stucco to the timber. Wooden laths are then fixed over the damp proof membrane to provide a key for the stucco. Providing that the wooden subsurface is stout and the laths are adequately secured, the stucco should last a long time. On wooden frame structures, a damp proof membrane is required and the horizontal laths can then be fixed to the frame. An alternative method is to use some form of metal mesh to provide the bonding key instead of the wooden laths. A problem with timber frame buildings is that the strength of the stucco siding is almost entirely dependent upon the stucco itself.[142]

A stucco system is said to have the following benefits[143]:
— Versatility of design and aesthetic appeal;
— Variety of finish styles and textures;
— Water resistance;
— Performance in a variety of climates, enduring of wet / dry and freeze / thaw cycles;
— Fire-resistive properties;
— Low maintenance and life-cycle cost;
— High abuse and impact resistance.

3.2.6 Wood-plastic composites

Wood-plastics composites (WPC) are quite a new group of materials that are raising interest in construction applications throughout the world[147]. Wood (fibre)-plastic composite can be defined as a product made using substantially conventional plastic processing equipment, where wood fibre serves as a reinforcing filler in a continuous plastic matrix. For construction applications, most wood fibre-plastic composites are made using extrusion equipment, whereby a piece of uniform cross section and any practical length can be produced.[148]

The most common types of WPCs are produced by mixing wood flour and plastics[147]. Most plastics are not stiff and creep-resistant enough for construction applications, and need further reinforcement to become viable products. Typical reinforcements for plastic are heavy and expensive materials, such as fibreglass and various minerals. Wood fibres can be used to provide the reinforcement, with little of the weight gain associated with mineral and glass fillers.[148]

The wood used in WPCs can be sawdust, planer shavings, short solid pieces, or conventional scrap from wood products, and the plastic can usually be from recycled materials, although in demanding applications new plastic materials are needed[147, 148]. WPCs are true composite materials and have properties of both raw materials. They have stiffness and strength between those for plastic or wood, but the density is generally higher than either. The properties of WPCs can be tailored to meet the product requirements by varying the type of wood or the type of plastic. Pigments, UV stabilisers, and fire retardants can all be added to the WPC material before extrusion to improve specific properties.[147]

In general, WPC's are said to have[147]:
— Good stiffness and impact resistance;
— Dimensional stability;
— Resistance to rot;
— Excellent thermal properties;
— Low moisture absorption.

WPCs for exterior construction applications are typically made to standard lumber profile cross-section dimensions. The products are not intended for primary structures. Instead, they are used as deck and dock surface boards, cladding, window frames, landscape timbers, industrial flooring, and the like.[147, 148] WPCs can be processed using conventional woodworking tools and have similar processing properties to wood or MDF. WPCs are only slowly gaining acceptance, e.g., in the UK, despite a commercial success in the U.S.[147] In fact, a sizable portion of the growth in the area of decking, fencing, roofing, and siding products is estimated to involve WPC materials based on low maintenance, decreased price differential with competing materials, and continuing research resulting in enhanced serviceability and performance[149].

3.2.7 Plastics

General information concerning plastics (rigid PVC) is shown in chapter *3.1.3 Unplasticised polyvinyl chloride (PVC-U)*.

3.2.8 Cement-bonded wood composites

Cement-bonded wood composites have been used in the fabrication of building materials for more than 70 years. The development and use of wood-cement composites attest to their attraction as building materials. Uses have focused primarily on the advantages of these composites: resistance to fire, acoustical properties, and thermal insulating properties. In addition to these aspects, wood-cement composites have a special attraction for use in warm, humid climates where termites and decay are a major concern. The cement binder provides a durable surface, as well as one that can be easily embossed and coloured for an attractive, low-maintenance finished product. Cement-bonded wood composites have been proven to be economically feasible as cladding materials. Research works have shown that these materials can be fabricated to resist cyclic moisture and temperature effects[145, 146], but still, more information on the strength, stiffness, toughness, connections, and reliability of wood-cement composites would be needed to extend their acceptance and use in the area of structural applications.[144]

Wood-cement composites are generally placed into two categories: 1) wood particle-cement composites, 2) wood fibre-reinforced cement products. Wood particle-cement composites have been in use as architectural, fire-resistant, and acoustic panels. Wood fibre-reinforced cement products were developed primarily as a substitute for asbestos-cement and are relatively new, developed and promoted mostly in the last 35 to 40 years.[144]

Wood particle-cement composites generally have densities in the range of 300 to 1300kg/m³, and their maximum bending strength is often limited to less than 10MPa. Interest in wood fiber-reinforced cement was sparked by the post-World War II shortage of asbestos fibres, which caused some private companies to consider cellulose fibre as a substitute for asbestos in fiber-reinforced cement. The controversy over health risks of asbestos led a number of companies in Australia, Europe, and Scandinavia to develop processes for fabricating fibre-reinforced cement boards using cellulose and other mineral fillers than asbestos. Today, cellulose fibre is used in a wide variety of fibre-reinforced cement products, which use only 5 to 15 percent cellulose fibre by weight, have densities ranging from 1100 to 1800kg/m³, and have bending strengths ranging up to 30MPa.[144]

3.2.9 Steel

General information concerning steels is shown in chapter *3.3.5 Steel*.

3.2.10 Comparison of wood and non-wood substitute materials in cladding

In the future, the main building trends affecting the use of exterior cladding materials will be[135]:
— Local decision making and national identity will be increasingly controlled and standardised by the bodies of the EU;
— The role of recycling will strengthen;
— Construction logistics will become more efficient, processes will be quickened and technically controlled;
— The role of environmental issues in sales and marketing of products will increase;
— Importance of issues concerning need for maintenance, healthiness, security, and modifiability will increase.

In the future, the national fire safety regulations and standards will probably be replaced by EU-wide standards and regulations. This will open new possibilities for using wood products in construction supposing that these standards are based on practises already in use in the Nordic countries. Thanks to easy recycling ability of wood products compared to other building materials, such as plastics and rock based materials, wood will become more eligible material as the role of recycling still strengthens in the future. As the construction logistics and processes will become even more efficient in the future, the building products and components should be easily and quickly installed. With this respect, to be able to maintain the competitiveness of wood on high level, the R&D efforts of wood products should be concentrated in developing different kinds of facade systems and solutions.[135]

As a consequence of local building traditions and appreciations, the status of timber as an exterior cladding material varies greatly in different parts of Europe. In the Nordic countries, the status of wood is strong, whereas in other parts of Europe other cladding materials are mostly used and the status of wood is quite poor. As in load-bearing structures, also in claddings the status of timber has been strong especially in residential construction and in other small buildings. The timber cladding materials have traditionally been treated and/or finished panels and boards produced from standard sawn timber.[135]

The cost-effectiveness is the main advantage of using wood in external claddings, whereas the main drawbacks are associated with the durability (low weather and, resultantly, mould and decay resistance without proper surface finishing) and the comparative high need for periodic maintenance compared to competing cladding materials. At the moment, different applications of heat treated wood are being developed to increase the long-term durability of wood products in exterior end-uses. The high market price of heat treated wood has limited the use of these products in Finland, but in countries with more severe maritime climates (Netherlands, U.K., etc.) wood products manufactured from heat treated wood are about to be proven to be competitive and cost effective. It can be assumed that during the following years the price of heat treated wood suitable for claddings will decrease and increasing volumes of heat treated wood products will be used. A precondition for such a trend is the developing of product chain to become more cost effective, meaning that the manufacturing processes of heat treated wood products should not differ significantly from the ones of traditional wood products.[135]

According to a study in Scotland, the benefits of external timber cladding could be as follows (in Scottish point of view)[151]:

— *Improved energy efficiency*. Timber framed, timber-clad houses can deliver real energy cost savings combined with good performance. When lightweight external cladding (e.g. timber) is used, heavy and bulky masonry walls can be eliminated from the outside of the building. Lightweight cladding, when combined with lightweight roof coverings and lightweight wall structures, can produce significant weight savings, allowing foundation depths and widths in a typical house to be reduced. Money saved can be used to increase the building's insulation so that, for no additional cost relative to masonry cladding, a more energy-efficient building envelope can be created.

— *Promotion of good design and siting*. Timber cladding complements current thinking on rural housing design. Timber cladding can reduce costs, introduce colour, and – because it is relatively easy to modify – is suited to the kind of long-life, loose-fit approach currently advocated through the "lifetime homes" approach to housing design.

— *Encouraging originality and innovation*. Timber cladding can have a bright and vibrant finish or, alternatively, a natural appearance which complements many other materials. It offers considerable design flexibility, and is easily adapted to both traditional and contemporary styles of building.

— *Overcoming the disadvantages of remoteness e.g. high building costs*. Timber cladding's light weight offers lower transport costs than masonry cladding and in not so weather-dependent to erect, both of which are considerable benefits in remote rural areas.

— *Stimulating the prudent use of natural resources*. Timber is a renewable and environmentally friendly raw material. Providing the felling operation has official approval, both UK and European timber is generally accepted as a low environmental impact raw material in terms of its production and compares favourably with non-renewable raw materials such as stone, metals, or plastics.

— *Supporting local economic development*. Customers will favour environmentally sound or locally sourced products providing their price and quality match existing alternatives. Although there may not always be a cost premium available, there is a potential market share advantage for those environmentally-sound or more locally-based suppliers able to capitalise on it. As the timber cladding market expands, local economic opportunities can grow.

— *Increasing the use of local raw materials*. Historically, the majority of timber cladding used in Scotland was imported and this continues to be so today. There is growing interest in buying locally manufactured products, thereby minimising energy consumed in transportation whilst contributing to the local economy and culture. European larch (*Larix decidua*) cladding is particularly popular and can be sourced in Scotland, as can European oak (*Quercus robur*, *Q. petraea*) and some other timbers.

Although timber frame is an enormously successful construction method in Scotland, with considerable performance advantages over traditional technologies, many owners of this type of house are unaware that a timber frame supports their roof or that the primary function of the outer blockwork is as a protective rainscreen cladding. As a result, house-buyers are often resistant to timber cladding since they perceive timber-clad and timber-framed homes to be somehow inferior to 'traditional' masonry-clad, timber-framed houses. Other concerns include misconceptions about increased fire risk, poor durability, and difficulties with insurance or mortgage companies. Maintenance is also a common concern and many people prefer to live in new-built houses which they do not expect to have to maintain.[151]

A comparison of the applicability of wood and selected substitute materials for external cladding is shown in Table 24.

Table 24. Applicability of wood, glass, plastering, plastics, and stone/brick masonry for external cladding[135].

End-use and product requirements	**Wood**	**Glass**	**Plastering**	**Plastics**	**Stone/brick masonry**
- Long-term durability	– Prone to decay, surface finishing need maintenance, good impact resistance, moderate UV resistance	+ Excellent weather resistance, weak impact resistance	**0** Moderate weather resistance, disintegration	**0** Moderate UV resistance, moderate impact resistance	+ Excellent durability
- Weight	+ Individual boards are lightweight and easy to handle	– Heavy material, large specimens	**0** Moderately heavy material, easy to handle	+ Light and easy to handle	**0** Heavy material
- Appearance	**0** Natural material	**0** Modern facade material	**0** Traditional material	– Artificial	**0** Natural material
- On-site machining	+ Easy to machine with hand tools	– Laborious to machine	**0** Adapts to construction	**0** Possible to machine on-site	– Time and special tools needed in machining
- Installation	+ Easy to install, but still time-consuming	**0** Easy to install, if appropriately prepared	**0** Heavy-duty equipment needed, strict requirements for conditions	+ Easy and quick to install	**0** Easy to install, if appropriately prepared
- Fire safety	– Inflammable material	+ Non-flammable material	+ Non-flammable material	– Inflammable material	+ Non-flammable material

3.3 Structural products

3.3.1 Introduction

Timber is a very commonly used raw material for framework construction especially in small-scaled (residential) construction in the Nordic countries, whereas in the other parts of Europe the use of wood is quite insignificant, except in the selected parts of the U.K., Germany, and the Alps region. The use of wood is usually controlled by historic aspects, such as building traditions and appreciations. Timber-frame construction has been commonly used especially in detached house construction (one-family houses, terrace houses), and the used wood material has traditionally been bulk timber. Within this segment the most important materials competing with wood are breeze-blocks (cinder blocks, blocks of lightweight aggregate concrete) and aerated concrete blocks (lightweight concrete, cellular c., pumecrete, low-density c.). In order to simplify the description of breeze-block and aerated concrete block construction only the selected products of the Leca and Siporex brands, respectively, will be reviewed in this paper.

In multi-storey buildings the possibilities to use wood as a frame material is limited by the set requirements for fire safety or strength properties. Accordingly, in block of flats construction, concrete (concreting and concrete elements) is the most used framework material, whereas in public and industrial construction concrete and steel based building systems are mostly used. The development work of engineered wood products (EWP) has opened new areas for wood as framework material, due to improved strength properties and precision of dimensions. In fact, the use of EWP has increased much more rapidly compared to bulk timber, and the EWP has gained market share from sawn timber during the last years. EWP (LVL, gluelam, and other glued products) can be used as framework materials also in multi-storey buildings, and some EWP-based pilot projects have already been executed in public construction for example in Finland (Metla, FinnForest).

3.3.2 Breeze-blocks and aerated concrete blocks

One of the commonly used trademarks of breeze-blocks is *Leca* (Table 25), which consist of small, lightweight, bloated particles of burnt clay. *Leca* blocks are used for construction of outer walls, inner-leaf walls, and partitions. The blocks are inorganic and impervious to dry-rot, wet-rot, and insect attack. It is simple to shape the blocks by using a carbide-toothed cutting saw, while small jobs can be carried out with a masonry hammer or axe. *Leca* is suitable for rendering and plastering by both manual and mechanical means. In addition to the blocks, *Leca* can be used as beams or bricks, fully insulated outer-wall components, basement and walls and foundations etc. Different kinds of *Leca* elements are also produced for block of flats construction purposes[133].

Like all other porous building materials, *Leca* will also release or absorb water until a state of equilibrium is attained with the moisture content of the ambient air. The fire resistance of blocks is good, while the fire-resistance period depends on the dimensions of the blocks.

The ingredients of *Siporex* are cement, fine sand, blast-furnace cinder, selected additives, and water. In casting phase the used inflating agent (aluminium powder) accomplishes a chemical reaction which generates hydrogen bubbles, and therefore causes the mixture to become porous[132]. The dry bulk density of *Siporex* ranges between 400 and 500kg/m³, and the other characteristics vary with varying density (Table 26).

Table 25. Selected physical and mechanical properties of *Leca* and *Lecaterm* blocks[133, 134].

	Leca block	Lecaterm block
Physical properties		
- Dimensions (w*h*l), mm	75–380*190*590	290–300*190*598
- Dry density, kg/m³	650	700
- Coefficient of expansion, 1/K	$6{\cdot}10^{-6}$	$6{\cdot}10^{-6}$
- Drying shrinkage in structure, ‰	≤ 0.6	≤ 0.6
Mechanical properties		
- Nominal bearing strength, MPa	3.0	4.0
- Modulus of elasticity, GPa	2.19	2.19
- Bending strength (i liggefugerne), MPa	0.20	0.20
- Bending strength (i studsfugerne), MPa	0.45	0.45

Table 26. Selected properties of aerated concrete (*Siporex*) material with different bulk densities[132].

	Siporex blocks (different densities)		
Physical properties			
- Dry density, kg/m³	400	450	500
- Maximum delivery density, kg/m³	560	630	700
- Drying shrinkage in structure, ‰	0.2	0.2	0.2
- Thermal conductivity, W/m K	0.09	0.11	0.12
- Heat capacity, J/kg K	Approx. 1050	Approx. 1050	Approx. 1050
- Coefficient of expansion, 1/K	$8{\cdot}10^{-6}$	$8{\cdot}10^{-6}$	$8{\cdot}10^{-6}$
Nominal stiffness and strengths			
- Modulus of elasticity, GPa *)	1.0	1.2	1.4
- Bearing strength, MPa	1.7	2.3	3.0
- Flexural strength, MPa	0.30	0.44	0.56
Design strengths (reinforced structures)			
- Bearing strength, MPa	1.26	1.70	2.22
- Flexural strength, MPa	0.22	0.33	0.43
Design strengths (unreinforced structures)			
- Bearing strength, MPa	0.85	1.15	1.50
- Flexural strength, MPa	0.15	0.22	0.29

*) in long-term stress conditions figures should be divided by 2.

Siporex is a hygroscopic material as the equilibrium moisture content of it depends on the ambient temperature and relative humidity. Acids and acidic salts and gases cause damage to *Siporex* surfaces, but the surfaces can be protected by different kinds of coatings. At first the moisture content of *Siporex* is quite high (usually during installation) which may cause problems when using it together with other porous, water-absorbent materials, such as wood[132].

3.3.3 Concrete

Concrete is a construction material composed of Portland cement and water combined with sand, gravel, crushed stone, or other inert material such as expanded slag or vermiculite. The cement and water form a paste that hardens by chemical reaction into a strong stone like mass. The concrete paste is plastic and easily moulded into any form or troweled to produce a smooth surface. The quality of the paste formed by the cement and water largely determines the character of the concrete.[112]

Proportioning of the ingredients of concrete is referred to as designing the mixture, and for most structural work the concrete is designed to give compressive strengths of 16 to 34MPa. Concrete may be produced as a dense mass that is practically artificial rock, and chemicals may be added to make it waterproof, or it can be made porous and highly permeable. Normally, the full hardening period of concrete is at least 7 days. The weight of concrete varies with the type and amount of rock and sand. Because ordinary concrete is much weaker in tension than in compression, it is usually reinforced or prestressed with a much stronger material, such as steel or fibre, to resist tension. Use of plain, or unreinforced, concrete is restricted to structures in which tensile stresses will be small, such as heavy foundations and unit-masonry walls. For reinforcement of other types of structures, steel bars or structural steel shapes may be incorporated in the concrete.[112] The flexural strength of plain concrete is also noticeably low.

3.3.4 Engineered wood products (EWP)

Engineered wood products (EWP) consist of wood veneers, strands, flakes, chips, or fibres bonded together by an adhesive. The reason for manufacturing EWP is to obtain more predictable and homogeneous wooden structures by chopping and evenly distributing the natural defects of wood throughout the product. This enables lighter and more graceful structures, longer spans, and smaller safety factors in design values. In general, EWP are partly competing against and partly complementary for traditional solid wood, metal, or concrete-made construction materials. Most of the currently produced EWP are either made of large logs, e.g., plywood, laminated veneer lumber (LVL), glued laminated beams, or their processing residues, e.g., medium density fibreboard (MDF) and particleboards. Some EWP, such as oriented strand board (OSB) and laminated strand lumber (LSL), can be made of small-diameter timber or even wood waste.[137]

3.3.5 Steel

Great variety of steels is being used for framework especially in industrial and commercial construction. Steel is the common name for a large family of iron alloys which are easily malleable after the molten stage[139]. According to the chemical compositions, standard steels can be classified into three major groups: carbon steels, alloy steels, and stainless steels. The typical properties of different types of steels at room temperature (25°C) are listed in Table 27.

In general, stainless steels are used in a wide range of applications requiring some degree of corrosion and/or heat resistance[112]. The exact properties of steels depend on the chemical element composition of the alloy. When machining steel structures quite heavy-duty tools are needed. Compared to other common building materials, the strength of steels is very high, as is also the surface hardness, volume density, thermal conductivity, and thermal expansion. Especially the strength properties are highly dependent on the ambient temperature, since the strength of steel dramatically decreases after a certain temperature has been reached. This phenomenon may cause problems with fire safety of steel structures.

Table 27. Typical properties of carbon, alloy, and stainless steels at room temperature (25°C)[138].

	Carbon Steels	Alloy Steels	Stainless Steels
Physical properties			
- Density (1000kg/m³)	7.85	7.85	7.75–8.1
- Elastic modulus (GPa)	190–210	190–210	190–210
- Poisson's ratio	0.27–0.3	0.27–0.3	0.27–0.3
- Thermal expansion (10^{-6}/K)	11–16.6	9.0–15	9.0–20.7
- Melting point (°C)			1371–1454
- Thermal conductivity (W/m -K)	24.3–65.2	26–48.6	11.2–36.7
- Specific heat (J/kg -K)	450–2081	452–1499	420–500
- Electrical resistivity (10^{-9}W -m)	130–1250	210–1251	75.7–1020
- Percent elongation (%)	10–32	4–31	12–40
Mechanical properties			
- Tensile strength (MPa)	276–1882	758–1882	515–827
- Yield strength (MPa)	186–758	366–1793	207–552
- Hardness (Brinell 3000kg)	86–388	149–627	137–595

The steel framing is said to have the following advantages[143]:
— Consistent quality;
— Greater strength;
— Simplified construction;
— Time savings;
— Design flexibility;
— Pest proof;
— Cold-formed steel is recyclable.

3.3.6 Comparison of wood and non-wood substitute materials in structural products

At the moment, wood in different forms (sawn timber and EWP) meets quite well the requirements set for the framework materials in construction. This will hold true also in the future. Especially in detached houses and terrace houses construction, wood, and especially sawn timber, has had and will have a firm status. The development of EWP has increased the utilisation of wood based materials in framework construction also in multi-storey buildings, where concrete and steel have traditionally been the most commonly used materials. In framework construction, the most important advantages of wood and wood based materials are light weight, machineability, modifiability, and good thermal insulation properties. The main drawbacks of sawn timber are simultaneously common properties for a natural/organic material: moderately large variation in the properties, decaying, dimensional instability caused by the variations in the moisture content, typically low precision of dimensions, and poor fire safety. On the other hand, solid wood could be considered as a material with good fire safety – in a fire the wood becomes quite slowly and evenly charred without any dramatic and rapid decrease in the mechanical properties. The above mentioned issues have been important driving forces for the development of the EWP, which are better with this respect compared to solid wood products.

In the future, the main building trends affecting especially the framework construction will be[135]:

— Local building traditions and methods of construction will be increasingly controlled and standardised by the bodies of the EU;
— Range of industrially produced building products/solutions widens and the amount of individualisticly built houses decreases;
— Construction logistics will become more efficient, processes will be quickened and technically controlled;
— Importance of compatibility will be increased in projecting, new building solutions will be developed;
— Energy consumption will be decreased and new energy sources will be introduced, emissions will be reduced;
— Importance of issues concerning need for maintenance, healthiness, security, and modifiability will increase.

In many construction-related brands, the EU-wide standardisation processes will go forward in the future. This will be a beneficial progress for big, international companies and strong associations. In the future, the main threats for using wooden products for construction will be the requirements set for fire safety, indoor air quality (natural volatile organic compound VOC emissions from wood), and the complicated structure of the standards for structural design and engineering (mainly EC5). In the industrialized building construction, the precision of dimensions of components, and the transportation ability of building elements will be emphasized, which will be an advantage for wood and steel based systems. On the other hand, the on-site use of wood (during the time of construction) may decrease, and the easiness of machining of wood will loose partly its importance as a consequence of widening the range of industrially produced building systems and solutions[135].

The present processes of construction are mainly based on the practices built up for concrete construction. The future trend of quickening the construction processes is an advantage for using wood and wood based materials, since no long setting times are needed in wood frame construction. At the moment, a great difficulty when using wood as frame material is the on-site protection of wooden members against weather during installation. The thermal insulation properties of wood are good compared to many competitors, which is a big advantage in the future, as the requirements for reducing energy consumption will be raised. The thickness of insulation layer is easy to change in wood framed buildings, and no thermal breaks are needed.[135] The need for maintenance needed to protect wood against decaying and weathering can be reduced by accurate surface treatment techniques and finishes, even though wooden structures always need some repairing or maintaining during their life cycle. As the aspect of healthy living and construction of healthy buildings arises, the status of wood as a natural material becomes even more firm.

According to a comparison made by Portland cement association in the U.S., the sale price of a house with concrete exterior walls was 3.5% higher compared to wood framed building. The total construction cost of concrete framed building was 7.2 to 8.4% higher compared to the wood framed construction.[136] These values should only be considered as trendsetting, since they are representative only for a particular construction project, but still provide an image of the relative building costs.

In Table 28, the applicability of wood and selected substitute materials is shown for framework construction. The applicability of breeze-blocks and aerated concrete blocks may mainly be related to applicability of concrete with some restrictions.

Table 28. Applicability of sawn timber, engineered wood products (EWP), concrete, and steel for framework construction[135].

End-use and product requirements	**Sawn timber**	**EWP**	**Concrete**	**Steel**
- Mechanical strength	**0** Good in clear wood, knots and other defects cause variation	+ Controlled strength and known variation	**0** Good compression strength, very low tensile strength	+ High strength, easy strength calculations
- Weight	+ Lightness is an advantage when building detached houses	+ Lightness is an advantage when building detached houses and sheds	+ / – Heaviness is an advantage in block-of-flats construction (sound insulation), drawback in detached houses	**0** Nominal weight of steel is quite high, but the structures could be designed to be light
- Long-term durability	– Prone to decay in moist conditions	– Prone to decay in moist conditions	**0** Disintegration, reinforcements may be affected by corrosion	**0** Corrosion
- Dimensional stability (temp. & humidity)	**0** Changes in moisture content cause instability	**0** Changes in moisture content cause instability, warping	+ No changes in dimensions	**0** Thermal expansion
- On-site machining	+ Easy to machine with hand tools	+ Easy to machine with hand tools	**0** Difficult to machine hardened concrete	– Machining requires heavy-duty tools
- Precision of dimensions	**0** Small variance in dimensions, form defects are usually causing problems	+ Precision of dimensions is good unless material is saturated	– Difficult to manufacture concrete members with accurate dimensions	+ Good precision of dimensions
- Thermal insulation	+ The change of the thickness of insulation is easy and inexpensive, no need for thermal breaks	+ The change of the thickness of insulation is easy and inexpensive, no need for thermal breaks	**0**	– Weak insulation unless thermally broken
- Fire safety	**0** Inflammable material, but no rapid decrease in strength	**0** Inflammable material, but no rapid decrease in strength	+ Non-flammable material, no changes in strength	**0** Non-flammable material, but in high temperatures the strength dramatically decreases

4 Conclusions

Compared to selected competing tree species and substitute materials, Nordic Scots pine wood has many fortes and flaws as a raw material. Based on the literature findings, the strengths and weaknesses of Nordic Scots pine wood in different end-uses could be concluded as follows:

Joinery products

Strengths that could be exploited
— Good thermal and sound insulation
— Low thermal expansion
— Moderately high mechanical strength and stiffness
— High density–strength/stiffness ratio
— Narrow rings and moderately low shrinkage; better stability compared to wood with more southerly origin
— Machining and surface treatments are easy
— Easily modified on site
— Environmentally friendly material, no health problems detected

Weaknesses that could be improved
— Large variation in a variety of properties; this could be controlled by a more accurate selection and allocation of raw-materials, as well as sorting and grading of primary wood products
— Problems with the durability against mould, decay, and weather; possible to use combined with other materials (composites)
— Problems with the durability against mould, decay, and weather; improved surface coating materials and techniques could reduce the need for maintenance actions

Weaknesses that must be accepted
— Anisotropy
— Large variation in a variety of properties (within-tree, between-tree, between-stand, between-region variation etc.)
— Hygroscopicity; form and dimension instability due to changes in moisture content
— Not durable in outdoor conditions against decay if not properly finished
— Demands maintenance in outdoor conditions
— Knots and other defects in wood

Exterior claddings

Strengths that could be exploited
— Lightweight material
— High density–strength/stiffness ratio
— Impact resistance
— Easy to machine and install
— Narrow rings and moderately low shrinkage; better stability compared to wood with more southerly origin
— Environmentally friendly material
— Finishing and surface treatments are easy
— Cost-effectiveness

Weaknesses that could be improved
— Low weather, mould, and decay resistance; this could be controlled by constructional design and improved surface coating materials and techniques
— Large variation in a variety of properties; this could be controlled by a more accurate selection and allocation of raw-materials, as well as sorting and grading of primary products
— Resin leaks
— Inflammability

Weaknesses that must be accepted
— Not durable against decay in outdoor conditions if not properly finished
— Demands maintenance in outdoor conditions against microbial attack and water
— Anisotropy
— Hygroscopicity; form and dimension instability due to changes in moisture content

Structural products

Strengths that could be exploited
— Good overall mechanical performance
— High density–strength/stiffness ratio
— Lightweight material
— Easy to machine
— Easily modified on-site
— Good stability in mechanical connections
— Good thermal insulation; no need to thermal breaks
— Fire safety; well predicted behaviour in the case of fire (charring), no unexpected drop in strength

Weaknesses that could be improved
— Mechanical performance can be improved by removing knots and other defects (finger-jointing etc.)
— Large variation in a variety of properties; this could be controlled by a more accurate selection and allocation of raw-materials, as well as sorting and grading of primary products
— Inflammable material; fire resistance could be improved by chemicals and surface treatments
— Poor impact sound insulation

Weaknesses that must be accepted
— Hygroscopicity; form and dimension instability due to changes in moisture content
— Not durable in outdoor conditions if not properly finished
— Demands maintenance in outdoor conditions
— Most strength properties decrease with increasing latitude

Compared to the substitute materials, the biggest problems of Nordic Scots pine wood are connected with the relatively large variation in the material properties. The variation could be better controlled by a more accurate selection and allocation of raw materials into different end-uses. Hygroscopicity and anisotropy are well known properties of wood materials that should be taken into account in designing and planning of wooden structures. Problems with the durability (mould, decay, and weather resistance etc.) could be reduced by constructional design and by using improved surface coating materials and techniques. What comes to the comparison between tree species, Nordic

Scots pine wood is well competitive with a relatively high mechanical strength and stiffness, and some lower variation of properties. In addition, compared to Scots pine wood from more southerly origin, the variation in the properties of pine wood from Finland and Sweden is clearly smaller.

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Appendix: Numerical data concerning wood properties of selected tree species

Data shown correspond to the average values, if not other stated. The references are shown in brackets. EW=earlywood, LW=latewood, JW=juvenile wood, MW=mature wood, HW=heartwood, SW=sapwood, R=range (min–average–max).

	Pinus sylvestris Scots pine	*Thuja plicata* Western red cedar	*Pinus ponderosa* Ponderosa pine	*Pinus taeda* Loblolly pine	*Pinus radiata* Radiata pine	*Pinus contorta* var. *latifolia* Lodgepole pine	*Picea abies* Norway spruce	*Pseudotsuga menziesii* Douglas-fir
Wood structure								
Fibers (tracheids)								
- Length, mm [4, 5, 6, 28, 44, 45, 59, 60, 61, 75, 76, 77, 78, 93, 94, 96, 101, 102, 152]	2.78 2.86 2.5–2.7 3.0 3.1 3.1	3.5 2.3 3.6–4.6–5.4 (R)	3.6	3.1 4.0 4.46 4.0 3.6	2.72 2.0–3.5 (EW) 2.5–4.0 (LW) 3.0 3.2–4.2–5.3 (R)	2.25–3.75 2.20 3.1	2.82 2.50 2.8–3.1 3.5 3.6 2.9 2.58 3.28	2.0–3.5 (JW) 4.0–4.5 (MW) 3.9) 2.5–4.5–5.6 (R)
- Cell wall thickness, µm [36, 45, 59, 61, 79, 80, 81, 93, 96, 152]	2.9–3.4–3.7 (EW R) 5.0–6.5–8.4 (LW R)	4.6–5.1–5.6 (R)		3.3–5.0 (EW) 7.2–12.3 (LW) 4-11	3.45 (EW) 3.0–4.0 (EW) 4.0–5.0 (LW) 1.8–2.5–2.9 (R)	5.07–5.50 (EW) 11.43–12.06 (LW) 2.07 (radial) 2.73 (tangential)	2.16 2.24 1.0–1.8–2.5 (EW R) 4.7–5.4–5.8 (LW R)	3–8 2.0–4.0 (EW) 4.0–8.0 (LW)
- Tracheid diameter (radial), µm [55, 59, 61, 78, 82, 83, 84, 93, 101, 102]	30.2 (EW) 20.8 (LW) 35 (dir. not known)	30–40 (dir. not known)	35–45 (dir. not known)	40–55 (EW) 22–33 (LW) 45 (dir not known)	30–40 (EW) 20–30 (LW) 44 (dir not known)	33.87 35–45 (dir. not known)	39.3 (EW) 13.1 (LW) 31 (dir. not known)	35–45 (dir. not known)
- Tracheid diameter (tangential), µm [45, 55, 60, 61, 77, 79, 80, 93]	25.3 (EW) 23.5 (LW)			45–54 (EW) 40–48 (LW)	38.35	27.0 33.31	32.7 (EW) 32.1 (LW)	35–45 (dir. not known)
- Volume percentage of tracheids [2, 3, 59, 99, 100, 152]	93.0 93.1 90.3–93.1–95.6 (R)	93.1	93.0		Over 90 88.6		94.0 94.3 95.3 94.5–95.3–96.5 (R)	92.4 92.5 93.0
Proportion of extractives, % [46, 47, 48, 59, 64, 65, 85, 86, 87, 108]		10.2		6.50 14.0 (EW) 12.9 (LW) 11.1 (SW EW) 11.0 (SW LW) 18.1 (HW EW) 21.2 (HW LW)	2.0 (SW) 2.5 1.6 (SW) 3.9–8.0 (HW) 1.5 (SW) 2–10 (HW)	2.87 2.03 (SW) 3.30 (HW)		5.9
Annual ring width, mm [57, 59, 60, 62, 97, 104]	1.65 (timber) 1.64 1.81				15–20	1.11 0.94–2.01	2.01 (timber) 2.33 1.76	3–6 (New Zealand) 1.5–3
Latewood percentage, % [61, 62, 97, 98]	23.9 25					14.77 22.0–44.7 12.59–15.31	21.7 15	
Maximum age, a [7, 8, 9, 10]	Over 810		860				800–1000 [*)]	890

Appendix, continued

Data shown correspond to the average values, if not other stated. The references are shown in brackets. EW=earlywood, LW=latewood, JW=juvenile wood, MW=mature wood, HW=heartwood, SW=sapwood, R=range (min–average–max).

	Pinus sylvestris Scots pine	*Thuja plicata* Western red cedar	*Pinus ponderosa* Ponderosa pine	*Pinus taeda* Loblolly pine	*Pinus radiata* Radiata pine	*Pinus contorta* var. *latifolia* Lodgepole pine	*Picea abies* Norway spruce	*Pseudotsuga menziesii* Douglas-fir
Physical properties								
Density								
- Density difference (kg/m³) in horizontal direction [11, 12, 15, 50, 59, 67, 78, 91, 105]	25–109 19–96	30–80 after drawing (difference increases with increasing height)		120–210 after drawing (based on meas. on slash pine; obs. probably apply to the other southern pines as well)	155 70 (first 10–15 rings from the pith); after that 10–100 100 (juvenile–mature)	Approx. 100	25	60 20–50 (New Zealand)
- Density difference (kg/m³) in vertical direction [1, 11, 12, 21, 22, 23, 24, 25, 78, 91, 105]	Over 100 93–101	40–50 after drawing		Approx. 200 after drawing (based on meas. on slash pine; obs. probably apply to the other southern pines as well)		Approx. 50	10–20	
- Basic ($\rho_{0,g}$), kg/m³ [12, 30, 31, 32, 44, 49, 51, 58, 59, 63, 66, 70, 78, 88, 89, 90, 95, 97, 105, 152]	381–418 417–427 410 308 (EW) 510 (LW) 401–438 (saw logs) 300–340 (EW) 670–920 (LW) 398 290–440–760 (R)	330–340 315–341 290–350–400 (R)	313 (EW) 578 (LW)	470 510 290 (EW) 630 (LW) 320 (EW) 670 (LW) 300 (EW) 850 (LW)	350 (EW) 550 (LW) 325–420 390–430 (saw logs) 420 400 (timber) 360–430	390 430 362 (EW) 632 (LW) 405–423 (SW) 412–459 (HW) 380–400 407–427 400	354–417 373–382 329 340 382.9 300–430–640 (R)	430 298 (EW) 687 (LW) under 200 (EW) over 800 (LW) 280–340 (EW) 740–840 (LW) 300–440–630 (R)
- Airdry ($\rho_{12\text{-}15}$), kg/m³ [40, 54, 57, 59, 73, 95, 104, 105]	482 504 (timber) 530 510 490 488.4	370 390 370–391	510 400	550 510	480 391–509	470	441 470 460 440 470.2	530 550 480 330
- Dry-airdry ($\rho_{0,12\text{-}15}$), kg/m³ [33, 39, 56, 66, 70, 152]	550 461 330–510–890 (R)	330–470–680 (R)	510 400		430–480–580 (R)	410 410	450 424 444 330–470–680 (R)	500 480 350–510–750 (R)
- Green (ρ_g), kg/m³ [58, 59, 105, 152]	890–992 (SW, saw logs) 539–552 (HW, saw logs) 750–820–850 (R)	528–544 700–800–850 (R)			1100 (SW) 600 (HW) 800–830–850 (R)		700–800–850 (R)	700–800 (New Zealand) 640–700

Appendix, continued

Data shown correspond to the average values, if not other stated. The references are shown in brackets. EW=earlywood, LW=latewood, JW=juvenile wood, MW=mature wood, HW=heartwood, SW=sapwood, R=range (min–average–max).

	Pinus sylvestris **Scots pine**	*Thuja plicata* **Western red cedar**	*Pinus ponderosa* **Ponderosa pine**	*Pinus taeda* **Loblolly pine**	*Pinus radiata* **Radiata pine**	*Pinus contorta* var. *latifolia* **Lodgepole pine**	*Picea abies* **Norway spruce**	*Pseudotsuga menziesii* **Douglas-fir**
Physical properties								
Fiber saturation point at 20°C, % [34, 68, 69, 106]	27.1–29.1	18–23				30.7 27.0 (HW)	29.3	
Shrinkage from green to ovendry MC, %								
- Length (b_l) [35, 39, 44, 52, 59, 68, 95, 152]	0.13–0.28 0.4 0.4 0.2–0.4	0.2			0.25 0.2 0.3	0.472 (Corewood; 6–7 mm from pith) 0.145 (Mature wood; 6–7 mm in from cambium)	0.3 0.3 0.57 0.61	0.1 0.3
- Radial (b_r) [40, 44, 52, 59, 68, 72, 73, 92, 95, 107, 152]	3.7 3.5 4.0 3.3–4.5	2.4 2.4 2.4 2.1 1.8–2.4	3.9	4.8 4.8 2.6 (EW) 8.3 (LW)	3.4 3.5 1.9–2.7	4.3 4.3 4.674	3.6 3.7 3.5–3.7	4.0 3.8–4.8 3.5 5.0
- Tangential (b_t) [40, 44, 52, 59, 68, 72, 73, 92, 95, 107, 152]	7.8 7.4 7.7 7.5–8.7	5.0 5.0 5.0 4.5 4.5–5.0	6.2 6.3	7.4 7.4 5.0 (EW) 7.1 (LW)	7.0 3.5–5.5	6.7 6.7 7.638	7.9 7.5 7.8 7.8–8.0	7.0 6.9–7.6 6.5 7.8
- Volumetric (b_V) [37, 38, 39, 40, 52, 59, 68, 73, 95, 107, 152]	12.0 12.4 11.2–12.4	Under 7 6.8 7.7 7.8 6.5–7.6	9.7 9.6	12.3	10.4 10.5 5.7–8.5	11.1 11.954	13.6 15.8 11.2 12.0 11.6–12.0	10.7–12.4 11.0 13.5 11.8
- Radial per 1% change in MC (6-14%) [40]		0.111	0.133	0.165		0.148		0.130–0.165
- Tangential per 1% change in MC (6-14%) [40]		0.234	0.216	0.259		0.234		0.241–0.267
- Volumetric per 1% change in MC (6-14%) [152]	0.37–0.43	0.22–0.25			0.19–0.28		0.39–0.40	0.38–0.42
Porosity, % [74, 152]	70	77		76	74		71	69

Appendix, continued

Data shown correspond to the average values, if not other stated. The references are shown in brackets. EW=earlywood, LW=latewood, JW=juvenile wood, MW=mature wood, HW=heartwood, SW=sapwood, R=range (min–average–max).

	Pinus sylvestris **Scots pine**	***Thuja plicata*** **Western red cedar**	***Pinus ponderosa*** **Ponderosa pine**	***Pinus taeda*** **Loblolly pine**	***Pinus radiata*** **Radiata pine**	***Pinus contorta* var. *latifolia*** **Lodgepole pine**	***Picea abies*** **Norway spruce**	***Pseudotsuga menziesii*** **Douglas-fir**
Mechanical properties (12% MC)								
MOE - Modulus of elasticity in bending (‖); GPa [21, 40, 53, 54, 57, 59, 66, 70, 71, 72, 73, 88, 95, 103, 104, 107, 152]	12.7 10.6 12.0 11.9 6.9–12.0–20.1 (R)	7.7 8.2 7.4 8.3 7.4–8.3	8.9 9.5 8.7	12.3 12.1 12.4 12.1	10.2 9.1 5.9-9.9 7.3–12.9 8.5–13.6	9.2 10.9 10.9 8.2–8.5 9.2	13.7 11.0 9.1 12.9 7.3–11.0–21.4 (R)	13.4 10.3–13.4 12.7 13.7 11.2–13.5
MOR - Modulus of rupture in bending (‖), MPa [21, 40, 41, 42, 53, 54, 57, 59, 66, 70, 71, 72, 73, 88, 95, 103, 104, 107, 152]	85.8 96 51.4 (timber) 87.0 98 85.6 41–80–105 (R)	51.7 54.0 53.1 48.0 53.8 48–55	65.0 73.0 63.4	88.0 86.9 98.9	80.7 75.9 67.6–100.3 62–92 60–91	65.0 76.0 75.8 72.3–75.7 64.8	85.7 58.9 94.0 75.0 60 82.3 49–78–136 (R)	85.0 82.0–90.0 84.1 72.0 83 68–89
Compression strength (‖), MPa [21, 40, 53, 54, 59, 66, 70, 71, 72, 73, 88, 95, 103, 107, 152]	47.5 48.0 47.0 54 35–55–94 (R)	31.4 29.6 34.6 21.0 43 33.9 29–35	36.7 42.3 36.3 36	49.2 47.8 49 44.5	41.9 40.7 28.4–43.5 28–50 36–65	37.0 43.2 43.2 31.6–33.4 37.0	45.2 43.0 30 33–50–79 (R)	49.9 43.0–51.2 51.2 43.0 51 43–68
Compression strength (⊥) (stress at proportional limit), MPa [40, 53, 66, 70, 71, 72, 73, 88, 95, 107]	7.7 7.5	3.2 3.4 4.2 3.6 3.4	4.0 5.2 5.1	5.4 5.8 6.8	5.9	4.2 3.6 3.7 6.8 5.1	5.8 4.1	5.1–5.5 6.0 5.3
Tensile strength (‖), MPa [40, 66, 73, 95, 103, 152]	104.0 102 35–104–196 (R)	51.4 50.0 ca. 50	64.4	90.4 107.1	72–86		90.0 84 21–90–245 (R)	121.6 105.0 130
Tensile strength (⊥), MPa [40, 53, 66, 70, 71, 72, 88, 95, 107]	2.9	1.5 1.5 1.5	2.9 2.8	3.2 3.2	2.34–3.31	3.8 (max. strength) 2.6–2.9 (max.) 2.0	1.5	2.3–2.7 2.3 2.3
Shear strength (‖), MPa [40, 53, 54, 66, 70, 71, 72, 88, 95, 107, 152]	11.0 9.8 6.1–10.0–14.6 (R)	6.8 5.9 5.6 5.5–7.5	7.8 7.0 8.0	9.6 9.6 9.4	11.0 9.7–11.7 6.8–7.6	8.5 8.5 6.7–7.1 6.1	5.3 4.0–6.7–12.1 (R)	7.8–10.4 8.0 7.8–10.2
Shock resistance (a), kJ/m² [43, 152]	49.7 15–40–130 (R)	24–34		63.7	ca. 94		43.5 10–46–110 (R)	42.2 38–60
Brinell hardness (⊥), MPa [21, 40, 152]	24.4 13–19–24 (R)	Ca. 25		31.0	ca. 13	21.0	20.9 ca. 12 (R)	32.0 ca. 50