Chapter 2
Building Materials and Sustainability

Abstract This chapter introduces wood and wood-based composites used in timber architecture (Sect. 2.1). Slovenian production, export, and import, as well as trade flows of primary wood products are presented and discussed. The primary wood-based products used in Slovenian timber architecture, together with current development in the field are described in Sect. 2.2. The chapter concludes with environmental impacts of primary wood products, including carbon storage mechanism and introduction of Environmental Product Declarations (EPDs) in Sect. 2.3.

2.1 Wood-Based Building Materials

Wood is a commonly used construction material in many parts of the world because of its reasonable cost, ease of working, attractive appearance, and adequate life if protected from moisture and insects. The various species of wood have a number of physical characteristics that enable performance of wood needed in building construction. However, wood properties vary among species, between trees of the same species, and between pieces from the same tree. This leads to variability in the performance of wood, which is one of its inherent deficiencies as a material [10]. Therefore, a broad range of wood-based composites have been developed in the past. Wood composites are a family of materials, which contain wood either in whole or fiber form as the basic constituent [5]. A binding adhesive of either natural or synthetic origin interconnects the wood or fiber elements. Composites are normally thought of as two-phase systems, i.e., particles interconnected by a binder; wood composites, however, are multiphase systems including moisture, voids, and additives. Furthermore, Berglund and Rowell [4] defined a composite as two or more elements held together by a matrix. By this definition, what we call "solid wood" is also a composite. Solid wood is a three-dimensional composite composed of cellulose and hemicelluloses (with smaller amounts of inorganics and extractives), held together by a lignin matrix.

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The advantages of developing wood composites are (1) to use smaller trees, (2) to use waste wood from other processing, (3) to remove defects, (4) to create more uniform components, (5) to develop composites that are stronger than the original solid wood, and (6) to be able to make composites of different shapes.

Wood-based composites have long been used as both decorative and structural components in the human environment. These materials extract the best properties of wood (and eliminate or minimize the defects) and combine them with other materials (adhesives, plastics, etc.) to create a wide variety of new products that meet market demands. In Europe, the most commonly produced wood-based panels are particleboard and Medium Density Fiberboard (MDF). However, Oriented Strand Board (OSB), traditional plywood, insulation board, and hardboard are also important products. Other more recent products include Laminated Veneer Lumber (LVL), light MDF (LDF), High-Density Fiberboard (HDF), and Cross-Laminated Timber (CLT). In the past years, technological innovations have advanced the field of wood-based panels. Most notably, hot pressing and the consequent viability of thermosetting resins have improved composites produced from particles and strands (particleboard, OSB), fibers (as MDF, HDF), and veneers (plywood, LVL).

Sawn softwood timber is most commonly used directly in structural applications or as a component of engineered products (e.g., glulams). Planed (also called surfaced or dressed) timber has been machined to have a smooth, uniform surface and ensures proper sizing. Air-dried timber has been dried without mechanical aid, while kiln-dried timber has been dried with mechanical aid, often using cogenerated electricity or natural gas as an energy source to provide heat and maintain regular air flow.

Conventional wood composites fall into five main categories based on the physical configuration of the wood: plywood, oriented strand board, particleboard, hardboard, and fiber board [43]. The performance of composites can be tailored to the end-use application of a product by optimally arranging the physical configuration of the wood components, adjusting the density, varying the resin type and amount, and incorporating additives to increase water or fire resistance or to resist specific environmental conditions.

Below, the description of various primary wood-based products is summarized and simplified from Suchsland [40].

Glued laminated timbers (Glulam) are structural composite beams used to support large loads in building construction. Sawn timber, selected for stress-related mechanical properties, are glued and arranged in layers (with the high-grade timber in the outer layers, and low-grade timber in the inner layers) with the grain direction parallel to the length of the timber. The size of the resulting glued laminated timbers may vary greatly, allowing the beams to be used as needed for a specific application. Glued laminated timbers for indoor use may use adhesives that are less resistant to the effects of the outdoor environment (e.g., relative humidity and temperature), while glued laminated timbers for outdoor use must use adhesives that are more resistant to changes in the outdoor environment.

Oriented Strand Board (OSB) is a structural panel product most often used for roof, wall, and floor sheathing in construction. The product is usually made of three or more layers with strands in each layer oriented in alternating directions (i.e., parallel to the length of the panel, or perpendicular to it). Water-resistant adhesives are used for OSB. The strands in the outer layer are oriented with the grain direction parallel to the length of the panel. The strands used are typically about three times longer than they are wide.

Plywood is made from thin layers of wood, which has been peeled from a log on a rotary lathe. These thin veneers are then combined into three or more (usually an odd number) of layers in alternating grain directions. The outer layers are aligned with the grain direction parallel to the length of the panel. Plywood for indoor applications may use an adhesive that is less water resistant than plywood for outdoor use. In indoor applications plywood is often used in furniture. Plywood for outdoor applications must use a water-resistant adhesive. Sheathing is the most common use of plywood in exterior applications.

Beginning around 2000, Cross-Laminated Timber (CLT), a new type of wood-based panel, began development, and soon after went into commercial production. CLT is an engineered wood panel typically consisting of three, five, or seven layers of dimension lumber oriented at right angles to one another and then glued to form structural panels with exceptional strength, dimensional stability, and rigidity.

Wood composites produced in large quantities that are not used in wood construction are particleboard and medium density fiberboard (MDF). They are most commonly used for indoor, nonstructural applications such as in furniture. Particleboard is constructed by reducing wood product manufacturing residues (e.g., planer shavings, sawdust) and recycled wood products to small particles. Particle sizes often vary across the thickness of the board, with smaller particles in the outer layers, and larger particles in the core layer. MDF is made by breaking wood (most often residues from other manufacturing processes) down to small fibers, then mixing the fibers with resin and wax to form mats that are compressed with pressure and heat. MDF density varies between 600 and 800 kg m^{-3}.

2.1.1 Slovenian Primary Wood Products

The woodworking industry in Slovenia has always been important. Cabinet, furniture, millwork, and custom woodworking manufacturers tap the local skills heritage. Slovenia produces a full product range from mechanical and chemical processing in addition to energy production. The mechanical branch comprises milling, plywood and particleboard manufacturing, and fabrication of furniture and timber components for the construction industry. Pulp and paper, cardboard, and packaging materials are produced by the chemical branch. The production of biofuel from biomass uses waste and residues from forestry and related industries.

Key products of the Slovenian wood-processing industry are pre-fabricated wooden houses, builders' joinery and carpentry of wood, plywood, veneered panels and similar laminated wood; fiberboard of wood or other ligneous materials; decorative veneer sheets and veneer sheets for plywood and sawnwood; particleboard

Table 2.1 European and Slovenian wood-based panel (WBP), sawnwood, glulam, and wood pellets production for 2012 [17]

Product	Slovenia QTY (m^3)	Europe QTY (m^3)
Hardboard	0	4,408,653
MDF	130,000	11,852,683
Particleboard	90,000	45,243,727
Plywood	67,000[a]	3,204,944[a]
OSB	0	3,917,153[a]
Total WBP	277,000	68,627,160
Sawn hardwood	80,000	13,533,427
Sawn softwood	580,000	126,751,739
Total sawnwood	660,000	140,285,166
Glulam[b]	/	4,800,000
Wood pellets[c]	83,000	9,262,990

[a] These numbers are from FAOStat, which combines plywood and OSB into one category. It was estimated that OSB was 55 % of the total, and traditional plywood was the remaining 45 %
[b] Glulam estimate derived from graph 12.3.1 in the report for 2010: http://www.unece.org/fileadmin/DAM/timber/docs/tc-sessions/tc-65/md/presentations/19Dory.pdf
[c] Wood pellet quantity estimated gathered from the report (2010 value): http://www.bioenergytrade.org/downloads/t40-global-wood-pellet-market-study_final.pdf (executive summary, Fig. 1.5, p. 8)

and similar boards of wood or other ligneous materials; packaging materials of wood; furniture of dinning rooms and kitchens; wooden furniture for kitchens, living quarters, and public institutions; wood marquetry and inlaid wood; wooden frames for paintings etc.; and casks, barrels, vats, tubs etc.

In Table 2.1, the European and Slovenian wood-based panel (excluding insulation boards), sawnwood, glulam, and wood pellets productions for 2012 are shown. The Slovenian production of the listed primary wood products accounts for less than 1 % of European production.

The production of wood-based panels has recently experienced a dramatic, worldwide growth period. Europe and China each control more than 30 % of the worldwide capacity for wood-based panel production [2]. In Eastern Europe, new production is increasing, particularly in the Commonwealth of Independent States (CIS) and Turkey. In Western Europe, Germany is the main wood-based panel producer (25 %), followed by France and Poland (10 % each), then Italy and Spain (8 % each). Turkey has dramatically increased production and is now approaching Germany's capacity. Russia surpassed German production in 2011, but Germany may have latent capacity remaining from production constricted during the economic downturn [17]. The total European production was approximately 71 million m^3 in 2012, an increase of 14 % from 2002 (62 million m^3), but a decrease of 14 % from peak production in 2007 (81 million m^3) [17]. As of 2010, Austrian group owners Kaindl (Krono Group) and Eggers control 40 % of European wood-based panel production (28 and 12 % each, respectively). The top four producers (Sonae and Pfleiderer, in addition to Kaindl and Eggers) control more than 50 % of European wood-based panel production, while the top 10 producers control more than 75 % of total production [1].

Since 2000, when the CLT panels were developed, CLT production has increased and more companies continue to enter the market. Austria is by far the largest producer with approximately 65 % of European production in 2011/2012, while Germany contributed approximately 27 % in the same period [38]. CLT production is expected to continue to increase as companies continue to add production capacity and these panels provide new opportunities to use wood in very tall buildings, even in seismic zones. Austria continues to see investment in facilities, even from companies headquartered outside the region. All of the top 5 producers are located in Austria and increased capacity from 2010 to 2011/2012 [38].

The production of primary wood products in Slovenia from 2006 to 2012 is shown in Table 2.2. Production values include the production of products that may immediately be consumed in the production of another product. It includes production from all sources within the country including public, private, and informal sources. It excludes the production of veneer sheets that are used for plywood production. It is reported in cubic meters of solid volume in the case of roundwood, sawnwood, and wood-based panels. In Table 2.2, as well as in Tables 2.3, 2.4, 2.5, and 2.6, the capital letter "C" stands for Coniferous (softwood), which includes all woods derived from trees classified botanically as *Gymnospermae*, e.g. *Abies spp., Araucaria spp., Cedrus spp., Chamaecyparis spp., Cupressus spp., Larix spp., Picea spp., Pinus spp., Thuja spp., Tsuga spp.,* etc. Furthermore, capital letter "NC" means Non-Coniferous (hardwoods), which includes all woods derived from trees classified botanically as *Angiospermae*, e.g., *Acer spp., Dipterocarpus spp., Entandrophragma spp., Eucalyptus spp., Fagus spp., Populus spp., Quercus spp., Shorea spp., Swietonia spp., Tectona spp.,* etc.

In the Tables 2.2, 2.3, and 2.4 data given include the following:

- "other industrial roundwood"—industrial roundwood other than sawlogs, veneer logs, and/or pulpwood. It includes roundwood that will be used for poles, piling, posts, fencing, pitprops, tanning, distillation, and match blocks, etc. It is reported in cubic meters of solid volume under the bark (i.e., excluding bark).
- "sawlogs and veneer logs"—roundwood that will be sawn lengthwise (or chipped) for the manufacture of sawnwood or railway sleepers (ties) or used for the production of veneer (mainly by peeling or slicing). It includes roundwood (whether or not it is roughly squared) that will be used for these purposes; shingle bolts and stave bolts; match billets and other special types of roundwood (e.g. burls and roots, etc.) used for veneer production. It is reported in cubic meters solid volume under the bark (i.e., excluding bark).
- "sawnwood"—wood that has been produced from both domestic and imported roundwood, either by sawing lengthwise or by a profile-chipping process and that exceeds 6 mm in thickness. It includes planks, beams, joists, boards, rafters, scantlings, laths, boxboards, and "lumber," etc., in the following forms: unplaned,

Table 2.2 Production (in m^3) of primary wood products in Slovenia in the years from 2006 to 2012 [17]

Product	2006	2007	2008	2009	2010	2011	2012
Chips and particles	86,000	122,000	150,000	118,437	82,000	82,000	105,000
Hardboard	110,000	110,000	0	0	0	0	0
Insulating board	0	0	15,057	1,679	0	0	0
MDF	128,000	79,000	177,000	150,000	110,000	120,000	130,000
Other Indust Roundwd (C)	22,190	26,829	26,202	44,178	52,492	63,060	41,294
Other Indust Roundwd (NC)	16,426	14,590	33,936	19,113	20,970	26,846	21,917
Particle board	136,000	211,000	147,218	117,489	130,000	130,000	90,000
Plywood	81,000	171,000	70,000	103,222	100,000	81,000	67,000
Sawlogs + veneer logs (C)	1,422,090	1,412,932	1,385,903	1,213,078	1,179,884	1,297,112	1,389,607
Sawlogs + veneer logs (NC)	289,970	285,767	299,759	301,252	272,205	284,436	251,681
Sawnwood (C)	446,000	464,000	367,000	449,000	625,000	610,000	580,000
Sawnwood (NC)	134,000	146,000	108,000	76,000	135,000	93,000	80,000
Veneer sheets	68,000	45,000	65,000	37,000	20,000	30,000	25,000

C Coniferous, *NC* Non-coniferous

Table 2.3 Import (in m^3) of primary wood products to Slovenia in the years from 2006 to 2012 [17]

Product	2006	2007	2008	2009	2010	2011	2012
Chips and particles	56,331	32,710	46,132	124,644	170,454	194,269	198,792
Hardboard	25,429	21,834	19,758	15,066	13,423	11,216	9,575
Ind Rwd Wir (C)	189,006	73,554	48,359	58,679	59,244	103,776	119,279
Ind Rwd Wir (NC) other	167,759	115,263	108,838	102,050	132,714	140,552	84,007
Ind Rwd Wir (NC) Tropica	5,258	5,910	3,084	2,723	1,556	1,301	1,206
Insulating board	7,218	10,650	4,064	3,711	3,752	4,802	4,141
MDF	57,103	65,526	39,081	30,457	36,666	37,093	37,006
Particle board	215,099	178,786	179,556	152,712	163,610	152,177	143,532
Plywood	30,632	35,239	22,796	18,036	22,898	22,250	21,228
Sawnwood (C)	55,866	808,525	810,823	940,648	873,639	726,957	922,066
Sawnwood (NC)	167,134	173,655	128,073	72,519	85,451	94,061	85,496
Veneer sheets	14,493	6,435	13,969	9,550	9,657	9,100	8,514

C Coniferous, *NC* Non-coniferous

planed, end-jointed, etc. It excludes sleepers, wooden flooring, moulding (sawnwood continuously shaped along any of its edges or faces, like tongued, grooved, rebated, V-jointed, beaded, moulded, rounded or the like), and sawnwood produced by resawing previously sawn pieces. It is reported in cubic meters solid volume.

- "plywood"—veneer plywood (plywood manufactured by bonding together more than two veneer sheets, where the grain of alternate veneer sheets is crossed, generally at right angles); core plywood or blockboard (plywood with a solid core (i.e. the central layer, generally thicker than the other plies) that consists of narrow boards, blocks or strips of wood placed side by side, which may or may not be glued together); cellular board (plywood with a core of cellular construction); and composite plywood (plywood with the core or certain layers made of material other than solid wood or veneers). It excludes laminated construction materials (e.g., glulam), where the grain of the veneer sheets generally runs in the same direction. It is reported in cubic meters solid volume.
- "chips and particles"—wood that has been reduced to small pieces and is suitable for pulping, for particle board and/or fibreboard production, for use as a fuel, or for other purposes. It excludes wood chips made directly in the forest from roundwood. It is reported in cubic meters solid volume excluding bark.
- "particleboard"—category is an aggregate category. It includes oriented strandboard (OSB), waferboard, and flaxboard. It excludes wood wool and other particle boards bonded together with inorganic binders. It is reported in cubic meters solid volume.

Table 2.4 Export (in m^3) of primary wood products from Slovenia in the years from 2006 to 2012 [17]

Product	2006	2007	2008	2009	2010	2011	2012
Chips and particles	142,204	154,677	196,144	177,533	153,229	200,955	281,238
Hardboard	46,511	12,110	9,252	7,725	4,916	3,679	6,087
Ind Rwd Wir (C)	275,978	308,565	274,149	306,085	337,480	512,887	669,902
Ind Rwd Wir (NC) Other	106,770	195,997	201,375	200,779	228,137	295,400	358,392
Ind Rwd Wir (NC) Tropica	0	1,183	0	0	0	0	0
Insulating board	1,865	8,740	19,421	1,004	157	218	367
MDF	31,495	144,015	94,012	94,202	114,048	114,880	104,079
Particle board	97,067	129,070	125,277	92,167	104,107	96,485	71,807
Plywood	87,345	90,330	93,029	78,081	73,293	67,712	52,193
Sawnwood (C)	334,611	833,429	944,170	1,002,819	1,021,413	910,967	1,079,148
Sawnwood (NC)	97,534	97,227	93,562	66,554	70,019	72,086	67,133
Veneer sheets	27,442	24,205	29,317	19,974	18,312	21,326	17,904

C Coniferous, *NC* Non-coniferous

Table 2.5 Slovenian trade flows (in m^3) of primary wood products (>10,000 m^3) with Austria from 2005 to 2011 [17]

	Roundwood (C)		Roundwood (NC)		Sawnwood (C)		Sawnwood (NC)		Particleboard	
Year	Import	Export	Import	Export	Import	Export	Import	Export	Import	Export
2005	40,436	144,937	/	89,744	24,303	26,888	/	/	17,949	/
2006	30,924	255,168	/	/	44,858	27,922	/	/	88,656	/
2007	/	329,095	/	19,377	41,502	15,549	360,835	/	55,912	/
2008	25,628	317,993	/	15,443	340,000	/	/	/	56,859	/
2009	31,209	381,273	/	31,234	489,000	12,437	/	/	48,332	/
2010	40,993	530,561	/	38,174	585,000	11,690	/	/	45,585	/
2011	77,824	963,316	/	37,089	689,000	13,000	/	/	43,196	/

C Coniferous, *NC* Non-coniferous

Table 2.6 Slovenian trade flows (in m^3) of primary wood products (>10,000 m^3) with Italy from 2005 to 2011 [17]

	Roundwood (C)	Roundwood (NC)	Sawnwood (C)		Sawnwood (NC)	Particleboard		Plywood	
Year	Export	Export	Import	Export	Export	Import	Export	Import	Export
2005	61,120	43,733	/	124,835	73,387	13,200	/	/	10,756
2006	95,058	119,939	/	102,419	74,087	42,168	32,673	/	22,172
2007	110,424	176,221	/	23,229	52,242	20,870	24,351	/	15,529
2008	70,043	180,437	/	/	51,007	17,898	14,690	/	17,229
2009	40,542	166,365	/	/	34,916	12,856	/	/	13,810
2010	46,498	184,598	/	/	37,527	23,341	/	/	11,857
2011	79,866	248,741	/	16,000	39,692	13,332	/	/	11,357

C Coniferous *NC* Non-coniferous

- "hardboard"—wet-process fiberboard of a density exceeding 0.8 g/cm^3. It excludes similar products made from pieces of wood, wood flour, or other lignocellulosic material where additional binders are required to make the panel; and panels made of gypsum or other mineral material. It is reported in cubic meters solid volume.
- "MDF"—dry-process fibreboard. When density exceeds 0.8 g/cm3, it may also be referred to as "high-density fibreboard" (HDF). It is reported in cubic meters solid volume.

The production of primary wood products in Slovenia shown in Table 2.2 has not significantly changed in the past 7 years. However, the economic crisis in 2008 resulted in significant production downsizing. However, production started to increase again in 2010. Despite this mild recovery, production of particleboard and veneer sheets decreased considerably. Significant decreases in production can also be identified in hardwood sawnwood. Hardboard production ended in 2008 and has not recovered.

In Table 2.3 imports of primary wood products from 2005 to 2012 are shown. Data for imports include products imported for domestic consumption or processing shipped into a country. It includes imports for re-export. It excludes "intransit" shipments. The import of softwood sawnwood increased considerably. The most significant jump in imports occurred in 2007, from 55,866 m^3 to 808,525 m^3. The reasons could be related to Slovenia's adoption of the Euro in place of the tolar. Chips and particle imports have also increased in the past 6 years, which corresponds to the increased use of wood for bioenergy. Due to the downsizing of furniture production in Slovenia particleboards imports have decreased in recent years.

In Table 2.4 exports of primary wood products are shown. Data for exports include products of domestic origin or manufacture shipped out of the country. It includes re-exports and "in-transit" shipments. The export of primary wood products increased significantly in recent years, especially the export of softwood roundwood and softwood sawnwood. The biggest change in exports happened for all primary wood products in 2007. The reason is most likely the entry of Slovenia into the Eurozone.

The most important trade partner for Slovenian primary wood products is Austria. In Table 2.5 the trade flows between Slovenia and Austria from 2005 to 2011 that are above 10,000 m^3 are shown. The export of softwood roundwood to Austria has been rising sharply. Over the seven-year period these exports increased by more than 8,00,000 m^3. During the same period softwood sawnwood imports have increased by more than 6,00,000 m^3. Although speculative, the numbers seem to indicate that Slovenia is exporting the roundwood and importing back the sawnwood. The Slovenian primary wood processing industry is aware of this and is constantly warning the politicians and general public about it. However, before the primary wood processing plants in Slovenia need to be modernized in order to be compatible with the neighboring countries.

Besides Austria, Italy, Croatia, and Hungary are also important Slovenian trade partners. In Table 2.6 the trade flows of primary wood products above 10,000 m^3 with Italy are presented for the years from 2005 to 2011. In 2011 79,866 m^3 of softwood roundwood, 248,741 m^3 of hardwood roundwood, and 39,692 m^3 of hardwood sawnwood were exported to Italy [17]. The main difference in Slovenian trade flows between Austria and Italy are that plywood export to Italy exceeds 10,000 m^3, while the trade flows with Austria are bellow 10,000 m^3.

The majority of trades with Austria and Italy are exports, while trades with Croatia and Hungary are mostly imports, especially of softwood and hardwood roundwood. However, the quantities are significantly lower. For example, in 2011 13,265 m^3 of softwood roundwood and 1,10,000 m^3 of hardwood roundwood were imported from Croatia. The quantities of trades with Hungary are even lower. In 2011 13,559 m^3 of softwood roundwood and 18,000 m^3 of hardwood roundwood was imported from Hungary [17].

The list of other countries, with which Slovenia has trades of primary wood products, is changing every year. In 2011, in addition to trade with neighboring countries, trading exceeded 10,000 m^3 with Algeria, Bosnia and Herzegovina, Czech Republic, Libya, Morocco, Saudi Arabia, Slovakia, and Tunisia [17].

2.2 Wood Products in Slovenian Timber Architecture

The dominating methods of timber construction in Slovenia, which are explained in Chap. 3, include panel construction, wood frame construction, and solid wood construction. Primary wood products used in these methods range from solid wood to various wood-based composites.

Globally due to technical, economic, and social reasons, solid wood usage is shrinking and numerous wood fiber-based derivative materials such as wood composites, wood fiber–plastic, and other lightweight materials are becoming increasingly used. Buehlmann and Schuler [6] positioned selected wood products on a product life cycle based on their global market share. In the development phase are lightweight panels, recycled and reusable wood products and straw boards. In the expansion phase are wood fiber-plastic composites, LVL, parallel laminated timbers, and I-joists. In the fast growing phase are OSB, MDF, and multi-plywood panels. Solid wood panels, glulam beams, and spanplatte are positioned in the saturation phase. Plywood is at the border with between the saturation and declining phase. Products that are in the declining phase are bloc panels, masonite panels, and solid wood. Also in Slovenia, the global trends can be seen.

In solid wood construction, glulam, CLT, LVL, and laminated strand lumber (LSL) are used for walls, floors, and roofs. In wood-frame construction wooden wall sections are assembled from studs and crossbars of various dimensions. For the exterior and interior faces various panel systems are used. Besides drywall panels and gypsum board, also particleboard, wood–cement panels, wood fiberboard, OSB, and plywood are used. Although the production of CLT panels and their use in timber construction is increasing, solid wood use has been losing its historical dominance and has been replaced by engineered wood composites. According to Buehlmann and Schuler [6], this is due to the fact that solid wood is no longer available in sufficient quantities to meet global demand and due to the properties of substitute products, which offer better quality at competitive prices.

In Slovenia, as in other parts of the world, softwoods are primary used in the construction sector. For the last 40 years, the European timber industry concentrated its investments and technological developments on processing softwoods, whereas forestry-developed silviculture strategies that led to enhancing the share of hardwood species. Consequently, the growing stock of hardwood forests is increasing (almost 50 % of European forests, in some southern countries up to about 85 %) and will be significantly amplified within the next tree generation (100–150 years). In contrast, hardwood species are hardly used for wood constructions. Due to different physical and chemical properties, an immediate substitution of softwood by hardwood into existing processing technologies and final products is impossible. Therefore, research and development activities will be important drivers of the future development of wood construction, where hardwoods will be used to a higher extent.

To utilize the full range of possibilities provided by building design codes, new structural grade hardwood lumber must be delivered to the market. Many widely available hardwood species have clearly denser, stiffer, and stronger wood than the current structural softwood lumber species. However, there is limited information on their load carrying capacity as structural components and limited data on the behavior of structural adhesives and mechanical connections for hardwood species. Besides construction purposes, hardwood is an interesting resource for the production of furniture and insulation materials. Moreover, combined approaches—hardwood as construction and insulation materials—promise the highest level of hardwood timber use. Additionally, new construction materials and products development have to take into account environmental performance. New developments must follow the requirements given in the CEN/TC 350 [7] standards, especially EN 15804 [14] for construction product Environmental Product Declarations (EPDs) and EN 15978 [13] for assessment of environmental performance.

Research and development dealing with utilizing hardwoods as construction material can also be found in Slovenia. For example, in March 2014 the Wood-Wisdom-net + project “European hardwoods for the building sector” (EU hardwoods), coordinated by Holzforschung Austria and includes Slovenian partners, started. The EU hardwoods project aims to develop hardwood glulam and CLT.

2.3 Environmental Impacts of Primary Wood Products

As sustainability becomes a greater concern, the environmental impact of construction and furnishing materials should be included in planning by considering the life cycle and embodied energy of the materials used. Therefore, Life Cycle

Assessment (LCA) should be used to reveal the environmental and energy performances of the used materials throughout their whole life cycle. The common LCA methodology is defined in ISO 14040 [23] and ISO 14044 [24]. Since the 1980s, when LCA analysis was first developed, numerous methodologies to classify, characterize, and normalize environmental effects have been developed. The most common (e.g., CML 2 (2000), IPCC Greenhouse gas emissions, Ecopoints 97 and Eco-indicator 99) are focused on the following indicators: acidification, eutrophication, thinning the ozone layer, various types of ecotoxicity, air contaminants, resource usage, and greenhouse gas emissions. Furthermore, these processes continue to be improved to provide greater consistency and enhanced communication (as in ISO/TS 14067 [26]). LCA is performed for various stages of a product's life span. The LCA methodology involves four steps (ISO 14040, 2006). First, the goal and scope definition step spells out the purpose of the study and its breadth and depth. The second step, Life Cycle Inventory (LCI), quantifies the environmental inputs and outputs associated with a product over its entire life cycle or during the time frame, which is being considered. Inventory flows include inputs of water, energy, and raw materials, and releases to air, land, and water. Third, impact assessment (LCIA), characterizes these inventory flows in relation to a set of environmental impacts as identified in LCI. Finally, the interpretation step combines environmental impact in accordance with the goals of the study.

A product life cycle starts with procuring the raw material, and follows the product through primary processing, secondary processing or manufacturing, packaging, shipping and handling, installation, in-use energy consumption, maintenance, and end-of-life scenarios. LCA analyses products over specific periods of a products life cycle, for example, cradle-to-gate refers to life cycle assessment from raw material stage to the point directly before the product is shipped. Similarly, cradle-to-grave involves LCA of all stages of the product or the material, starting from raw material procurement to its end-of-life. For wood products, the life cycle generally starts with extraction of raw resources from the natural environment or recovery of materials from a previous use. The raw resources are then manufactured into useable products. The finished products are shipped to a site, consuming energy in the process. During the service life of the product, it may consume energy based on its use (e.g., energy used to maintain the product). Over time, renovations or retrofitting may be performed on the products, which may require additional materials and energy. Finally, the product is removed/demolished and its materials disposed of either as construction waste or recycled for reuse. Each of these steps consumes energy and materials and produces waste. The purpose of LCA is to quantify how a product or system affects the environment during each phase of its life. Examples of parameters that may be quantified include: energy consumption, resource use, greenhouse gas production, solid waste generation, and pollution generation.

With regard to greenhouse gas emissions, wood is a better alternative than other materials. Werner and Richter [42] reviewed the results of approximately 20 years of international research on the environmental impact of the life cycle of wood products used in the building sector compared to functionally equivalent products from other materials. The study concluded that fossil fuel consumption, potential contributions to the greenhouse effect, and quantities of solid waste tend to be minor for wood products compared to competing products; impregnated wood products tend to be more critical than comparative products with respect to toxicological effects and/or photo-generated smog depending on the type of preservative; although composite wood products such as particleboard or fiberboard make use of a larger share of the wood of a tree compared to products out of solid wood, there is a high consumption of fossil energy associated with the production of fibers and particles/chips as well as with the production of glues, resins, etc. Furthermore, wood causes less emissions of SO_2 and generates less waste compared to the alternative materials [31]. However, treated wood, adhesively bonded wood and coated wood might have toxicological impacts on human health and ecosystems. Richter [33] provided a comparison of environmental assessment data of different wood adhesives. Little LCA data has been published so far for resins based on renewable resources or components (e.g. tannins, lignins, proteins). A study of the use of a lignin-based phenolic adhesive in combination with a laccase initiating system has found a significant environmental impact associated with the enzyme production [18].

Incineration of wood products at end of life provides various environmental benefits. The use of woody biomass as feedstock for biofuels production avoids the food versus fuel debate, which makes it more attractive from the environmental perspective [41]. However, Rivela et al. [34, 35] applied a multicriterial approach in order to define the most adequate use of wood wastes. The study concluded that based on the environmental, economical, and social considerations the use of forest residues in particleboard manufacture is more sustainable than their use as fuel. Cascading through several life cycles prior to incineration is a better option.

In a sensitivity analysis of an LCA of MDF manufacture, it was found that the final transport of product and the electricity generation profile had a significant influence on the results [36]. A study of medium density particleboard production in the Brazilian context showed that the use of heavy fuel in the manufacturing process (including forestry operations) was the hotspot in all impact categories except ecotoxicity [39]. Benetto et al. [3] conducted an LCA of OSB production with emphasis on evaluating the environmental impact associated with a new wood drying process that had reduced VOC emissions. The study concluded that the environmental gains resulting from the new drying process were largely negated by changes required in the adhesive formulation. This shows the need to consider the whole process when considering the environmental impact of production and not focusing on making improvements in one part of the production. Combination of an OSB production plant with a biorefinery for the production of acetic acid and methanol has been studied from an LCA perspective recently [11]. Significant reductions in human toxicity potential and freshwater ecotoxicity potential were recorded for the combined plant compared to a conventional OSB production process. Furthermore, it has been shown that increasing amounts of recycled wood can reduce the environmental footprint associated with particleboard production [37].

A renewable origin does not necessarily mean ‘environmentally friendly’ or sustainable use [29]. Hall and Scrase [19] provided a literature review concerning greenhouse gas and energy balances of bioenergy. The results of LCA study might differ due to the type and management of raw materials, conversion technologies, end-use technologies, system boundaries, and reference energy systems with which the bioenergy chain is compared. A comprehensive sustainability assessment of biofuels is urgently needed to assess economic, social, and environmental impacts of biofuels production and consumption [20]. Lindholm et al. [29] modeled and calculated the environmental performance from an LCA prospective of different procurement chains of forest energy in Sweden. One of the conclusions of the study was that uncertainties and use of specific local factors for indirect effects (like land-use change and nitrogen-based soil emissions) might give rise to wide ranges of final results. Cherubini and Strømman [8] performed a review of the recent bio-energy LCA literature concluding that most LCAs found a significant net reduction in greenhouse gas emissions and fossil energy consumption when bioenergy replaces fossil energy. Cherubini et al. [9] explained that determination of energy balance and greenhouse gas emissions from bioenergy reporting that the initial use of biomass for products, followed by use for energy (‘cascading’), can further enhance greenhouse gas savings given what will be increasingly scarce resources of biomass.

The number of LCA studies of wood-based composites is relatively limited, geographically distributed, uses a variety of databases, and impacts assessment protocols. Kutnar and Hill [28] used a cradle-to-gate analysis to present the carbon footprint of 14 different primary wood products. The largest source of emissions for all sawn timber products is removing the timber from the forest, while for kiln dried sawn timber the drying process follows closely behind. For fiber composites (MDF and HDF) the extra energy required to convert the raw material into fibers, in addition to the energy required to apply pressure and heat to the products is responsible for the bulk of the emissions from these products. The adhesives used in particleboard, plywood, and OSB are responsible for the largest fraction of emissions from these products. This is especially significant considering the low total volume they represent in the final products. Glulam emissions derive mostly from the harvest and initial production of the softwood, but also from the extra energy required to apply pressure and set the adhesives used. Altering the system boundaries would yield different results. Furthermore, results would have been modified if the carbon footprint calculation accounted for carbon sequestration of wood, the use of recycled wood products, and other similar issues pertinent to LCA. Furthermore, the results would have been different if a full life cycle of products, cradle to grave or cradle to cradle, would be considered. Hill and Norton [21] discussed the environmental impact of the wood modification process in relation to life extension of the material. A comparison among different wood modification treatments was made. By determination of carbon neutrality they determine at which point the benefits of life extension compensate for the increased environmental impact associated with the modification. The effect of increased

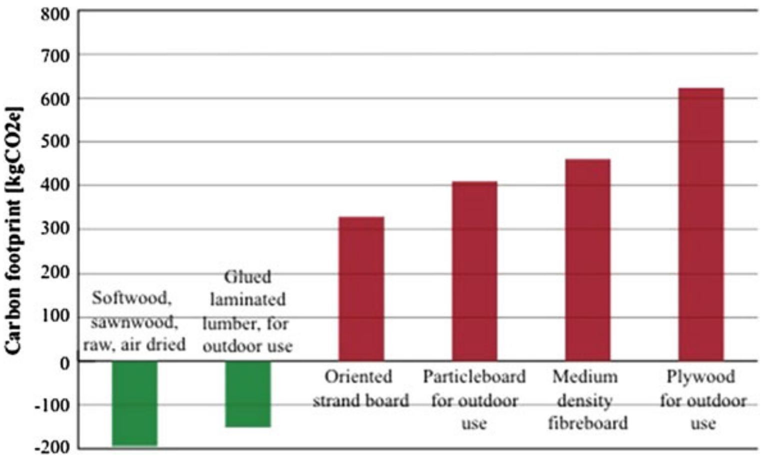

Fig. 2.1 Carbon footprint of 1 m^3 of selected primary wood products from Ecoinvent 3.0 [12]

maintenance intervals with the modified woods could be a powerful argument in favor of the use of modified wood products with increased maintenance intervals.

In Fig. 2.1 carbon footprints of selected primary wood products are presented, calculated with IPCC 2007 GWP 100a V1.02 method, which was developed by the Intergovernmental Panel on Climate Change [22]. The method contains the climate change factors of IPCC with a timeframe of 100 years.

The products with the lowest carbon footprints are air-dried sawn timber and glued laminated timber. This is unsurprising, because these products are processed less than wood-based composites. The glued laminated timber has higher carbon footprint due to adhesives, but is still negative. Wood has a negative footprint because of the carbon dioxide fixed by the original living tree. The emissions associated with harvesting, transporting, and processing sawnwood products are small compared to the total amount of carbon stored in the wood. This means that even when energy use for harvesting, transport, and processing are taken into account, sawnwood still has a negative footprint. Wood-based composite production requires additional energy inputs to process raw materials, manufacturing byproducts, and recycled wood into the desired form, as well as adhesives and other additives to form the composite matrices, which considerably increases the carbon footprint of these wood products. The highest carbon footprint among the compared products has plywood for outdoor use, followed by MDF and particleboard. Among compared wood-based composites, oriented strand board has the lowest carbon footprint.

Results of LCA analysis can be significantly affected by the used allocation method [27]. Kutnar and Hill [28] discussed the influence of allocation on the results of environmental impacts. EN 15804 [14] states that allocation shall be based on physical properties (e.g., mass, volume) when the difference in revenue between co-products is low (of 1 % or less). In all other cases, allocation shall be based on economic values. Furthermore, in EN 16485 [15], allocation recommendations follow EN 15804, but different examples for the wood processing chain are given. According to EN 16485, allocations shall respect the main purpose of the process studied and the purpose of the plant should be taken into account as well. Market prices from official statistics should be used for determination of revenues for assortments for which no company specific prices are available. However, a discussion arises as impacts from allocation procedures differ between panels and sawmill industries. Concerning the different raw materials, processes and co/by-products, a clear rule to harmonize the allocation procedures across all wood industry sectors should be determined in the future.

2.3.1 Carbon Storage in Wood and Wood Products

Trees capture atmospheric carbon dioxide via photosynthesis and a proportion of this sequestered carbon is stored in the above-ground woody biomass. The net benefit of this ability to store atmospheric carbon depends on the length of time before the material is subsequently oxidized and the carbon released back into the atmosphere. In all situations where carbon flows and stocks are considered, it is essential that a distinction is made between biogenic and fossil carbon sources [28]. Even with biogenic carbon it is also important to differentiate between carbon that is held in long-term storage (such as old-growth forest) and that derived from newer managed, or plantation forests.

Although the storage of biogenic carbon clearly has benefits, it is necessary to consider an appropriate framework for reporting this. There has been some attempt to deal with the evaluation of biogenic carbon storage in long-life products in national standards. In the UK this issue was dealt with in Publically Available Specification (PAS) 2050 (2011). Additionally, methodologies for evaluating the atmospheric carbon stored in products are given in the International Reference Life Cycle Data (ILCD) Handbook, published by the European Commission Joint Research Centre (Institute for Environment and Sustainability). In both, a 100-year assessment period is considered, following IPCC guidelines. It is recommended that fossil and biogenic carbon releases (as CO_2 and CH_4) should be differentiated. Two methods for calculating the weighted average of the effect of carbon storage in a product are given, although for a product with a life less than 2 years, no carbon storage benefit can be assigned. This can only be applied to the storage of biogenic carbon, which is assigned a negative CO_2 value. However, this cannot be applied if the biogenic carbon is derived from old growth or native forests, where land use change has occurred.

The methodologies for reporting sequestered carbon in timber products in EN 16485 are similar to those given in [30], in that different calculations are used for carbon stored in a product between 2 and 25 years than carbon stored in a product for 26–100 years. There is also a draft standard FprEN 16449 [16], which gives guidance on calculating the amount of sequestered carbon in timber.

2.3.2 Environmental Product Declarations, EPDs

In March 2011, the Construction Products Regulation (305/2011) was introduced, replacing the Construction Products Directive (89/106/EEC). The Construction Products Regulation states that where a European standard exists, then this has to be used. In addition, it states that "For the assessment of the sustainable use of resources and of the impact of construction works on environment Environmental Product Declarations should be used when available." The Construction Products Regulation has come into full force as of July 2013.

With the objective to develop a framework that allows for comparability of environmental performance between products, ISO 14025 [25] was introduced. This describes the procedures required to produce Type III environmental products declaration (EPD). This is based on the principle of developing product category rules (PCR), which specify how the information from an LCA is to be used to produce the EPD. A PCR will typically specify what the functional unit is to be for the product. Within the framework of ISO 14025, it is only necessary for the production phase (cradle to gate) of the lifecycle to be included in the EPD. It is also possible to include other lifecycle stages, such as the in-service stage and the end of life stage, but this is not compulsory. ISO 14025 also gives guidance on the process of managing an EPD program. This requires program operators to set up a scheme for the publication of a PCR under the guidance of general program instructions. Until recently, PCRs have tended to be developed in an ad hoc manner by different program operators, although there has been activity to harmonize the different rules. The situation now is one where European Standards are being introduced, which lay down the PCRs. For the construction sector the core PCR is EN 15804. The standard that applies to sawn timber is the draft standard EN 16485. The draft standard allows for the reporting of sequestered carbon in timber products under the following conditions "Consideration of the biogenic carbon-neutrality of wood is valid for wood from countries that have decided to account for [Article] 3.4 of the Kyoto Protocol or which are operating under established sustainable forest management or certification schemes."

EPDs have been used for construction products since the first environmental assessment schemes were developed in the 1990s and an ISO standard for EPDs, ISO 14425 [25] sets out standards they should meet.

The EPDs of several wood products used in timber architecture can be found. To be able to compare the EPDs of different products, EPDs must have the same PCR. This ensures that scope, methodology, data quality, and indicators are the same. PCR for construction products have been developed in the UK, France, the Netherlands, Scandinavia, Germany, the USA, and Australia. All construction EPD programs should comply with ISO 14040 and ISO 14044, as well as ISO 14025. However, these standards still leave many aspects of the PCR and format up to the individual EPD program, resulting in different PCRs. Some of the differences between the different EPD programs can cause considerable variation in results for the same product due to differences in the underlying assumptions, boundaries, and scope. In Europe, EPDs are published by a program operator such as BRE Global, EPD Norge, or IBU (Institut Bauen und Umwelt e.V.) using ISO 14025-compliant PCRs. In Slovenia, the Slovenian National Building and Civil Engineering Institute developed an EPD program in 2013. However, to our best of knowledge there was no EPD issued for wood products as of 1 July 2014.

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