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# Chapter 21

## Engineered Wood Products (EWP)—Resource Efficiency and Environmental Performance



Maximilian Pramreiter, Johannes Konnerth, and Paul Mayencourt

**Abstract** Today, the construction sector has access to a vast array of resources, ranging from non-renewable materials like steel and concrete to natural materials like stone and timber. These materials are either used alone or in combination as part of composites. Driven by the need to reduce the environmental impact of the built environment, Engineered Wood Products (EWPs) like Glued Laminated Timber (GLT) or Cross Laminated Timber (CLT) have gained increasing interest in the construction sector in recent years. This chapter explores the resource efficiency and environmental performance of these EWPs, by examining established literature on production processes, material yields, and life cycle assessments. The chapter highlights the role of different wood species, processing methods, and mechanical as well as environmental performances. It also discusses circularity and potential areas for future research to enhance the overall sustainability of the wood value chain. This comparative approach aims to support material selection decisions and foster more responsible use of forest resources in the built environment.

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## 21.1 Introduction

### 21.1.1 *Is There Enough Wood for Construction?*

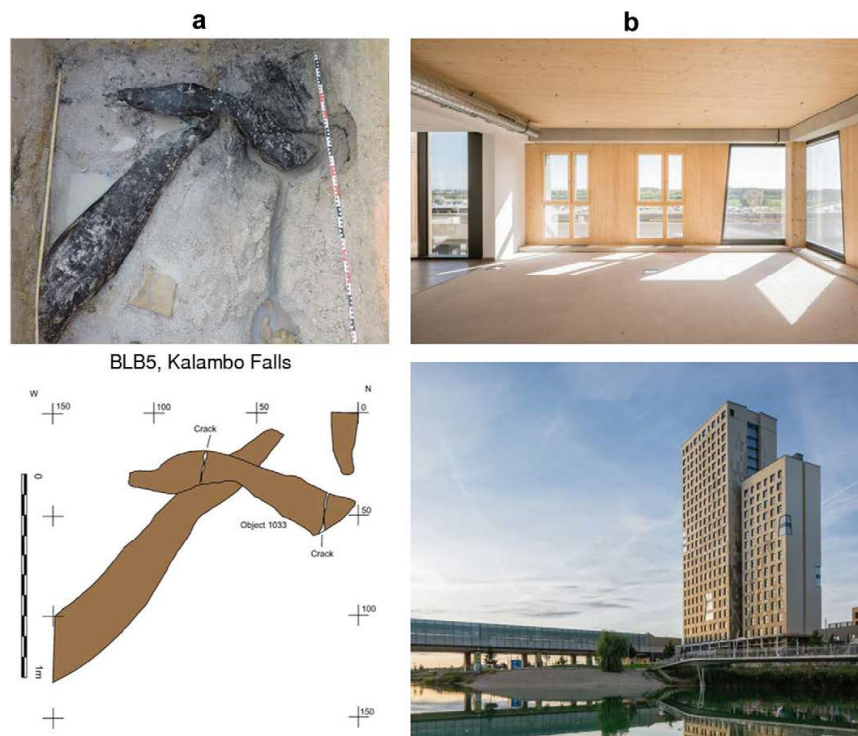
The built environment fulfils a multitude of functions in our modern society. While in the Stone Age it primarily served as a shelter and mankind spent most of its time in nature, today we spend a large part of our day in or around man-made structures. Similarly, the materials we use to create these environments have significantly changed and expanded throughout the course of history. Today, the construction sector has access to a vast array of resources, ranging from non-renewable materials like steel and concrete to natural materials like stones and timber. These materials are either used alone or in combination in the form of composites and are either load-bearing or non-load bearing. One of these natural materials, wood, is currently experiencing a renaissance in construction.

This renaissance is fuelled by the need to create a sustainable living space for our society while at the same time tackling climate change [1, 2]. Wood as building material offers not only the capability to build high rise and large volume structures but it also sequesters carbon while being used as material. It is therefore no surprise that a race for the tallest wooden skyscraper has ensued in recent years, with height records sometimes being broken only by one metre to the previous champion (e.g. the Ascent Tower in the USA at 87 m, followed by the Mjøstårnet Building in Norway at 85 m, the HoHo Tower in Austria at 84 m as seen in Fig. 21.1b and the Sara Kulturhus Centre in Sweden at 75 m). It will not stop here, future projects like the “Rocket & Tigerli” in Switzerland (100 m, targeted completion in 2027) or the “C6” in Australia (planned with 183 m) in Australia are already in the pipeline. Considering humans’ past, it is not the first time that wood is considered to be an excellent building material. Recent discoveries by Barham et al. [3] assume that wood was used as structural material already 476,000 years ago (see Fig. 21.1a).

However, compared to this distant past, the current material need for construction is on a totally different level [4] and when society talks about (partially) substituting steel and concrete with wood, the following question arises: “Is there enough wood for construction and how should we build with wood to preserve our forests?”

### 21.1.2 *The Global Wood Value Chain*

In an attempt to answer this question, it is necessary to take a look at the globally available woody biomass from forests, the current areas of use and the potential demand for building products in the future.



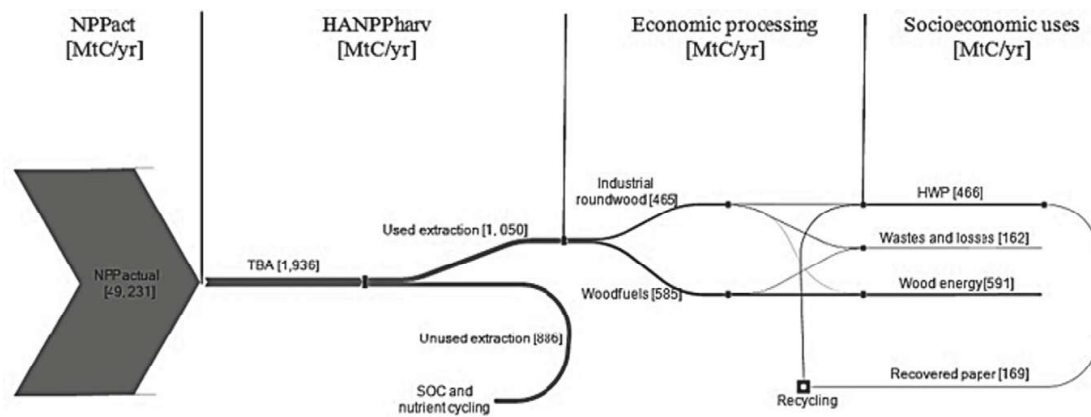
**Fig. 21.1** Wood as oldest building material and current shooting star in architecture and design. **a** Earliest evidence of structural use of wood in archaeological records, dating back at least 476,000 years (adopted with permission from [3], copyright Prof. Larry Barham)). **b** HoHo in Vienna, high-rise flagship project using mass timber, completed in 2021 (with permission from KiTO photography <https://www.kito.at/>, copyright by Michael Baumgartner/KiTO)

### 21.1.2.1 Current Material Flows and Areas of Use

According to Bais et al. [5] roughly 158 megatons of carbon [MtC] of the annually extracted woody biomass (1936 MtC) end up in wood-based products (part of HWP in Fig. 21.2). This represents roughly 13% of the annually socioeconomically used biomass of the world's forests (1219 MtC, "Used extraction" plus "Recovered paper"), with the remaining 87% divided between wood energy use (48%), paper and paperboards (22%), losses (8%), wood waste (6%) and poles as well as posts among other niche products (3%).

Based on these current wood carbon flows (see Fig. 21.2), a significant utilisation potential for wood in construction can be identified, as almost 56% of the annually used forest biomass (1050 MtC) is used as fuel wood. A portion of these resources could be used for construction products with higher added value and longer carbon sequestration periods, while remaining available for further material use after re-use or recycling [8]. The material can then still be used as fuel at the end of its use cycles. However, it should be noted that there are considerable regional differences. For example, looking at the findings of Mantau [9] for wood flows in Europe (EU 27), only 36% of the annually used forest biomass is directly put into fuel wood.

In addition, there are still available reserves in our forests that could be sustainably harvested for the production of building materials. According to Bais et al. [5]



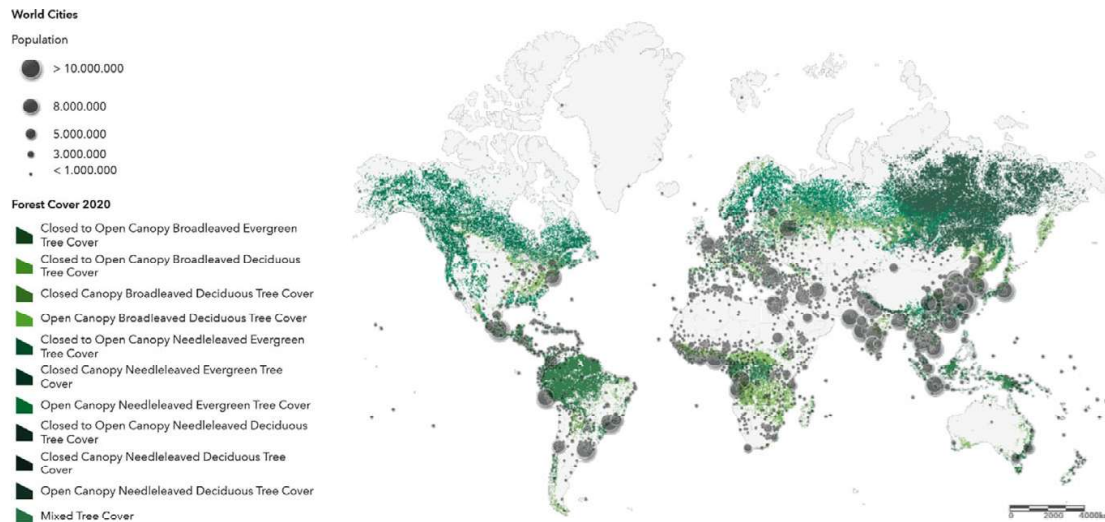
**Fig. 21.2** Global wood carbon flows [MtC/yr] from net primary production (NPP<sub>actual</sub>) to final consumption in 2010 (adopted with permission from [5], copyright by Anna Liza Bais). TBA (total biomass appropriation), HANPPharv (human appropriated net primary production), SOC (soil organic carbon) and HWP (harvested wood products). To estimate [m<sup>3</sup>/yr] divide numbers by 0.5 (carbon to wood ratio [6]) and then by density of assumed wood species mix (e.g. 0.650 t/m<sup>3</sup> average density according to [7])

roughly 30% of the annual net primary production (currently 4% of 49,200 MtC/yr, globally) could be harvested without impairing the health of the forests. However, regional differences must also be considered here, as parts of the world have already exceeded this threshold [5]. However, in the European Union (EU 27) for example, only 75.7% of the annually available forest biomass is utilised [9]. A similar potential was recently reported by the European Commission [10]. In addition, the availability and accessibility of forest area for wood supply is also essential to mobilize these potential reserves in the future [11, 12]. Considering accessibility, it is worth mentioning that countries with large cities not necessarily also have access to vast amounts of forest resources (see Fig. 21.3). Therefore, the utilisation of wood might not be the best solution everywhere on the planet yet, due to increasing transport distances and potential exploitation of foreign forest resources without proper regulations and adequate forest management practices.

To sum up the supply side for wood in construction it can be said, that there is still potential for raw materials from the world's forests and not mentioned so far, forest plantations. However, sustainable forest management practices and accurate resource monitoring will be an absolute necessity in order to prevent overuse in the future [15].

### 21.1.2.2 Potential Demand for Construction

Taking a look on the demand side, projecting future growth for wood in construction is even more complex than the available forest resources. The various methods of collecting data on the current consumption and flows of building materials are already a much-researched topic [16]. However, future shares of different materials and their demand are often not even considered at this stage. Furthermore, it is also difficult



**Fig. 21.3** The world's largest cities and global forest cover in 2020. (Created with ArcGIS online, copyright by ESRI [13, 14])

to provide a global perspective, as regional customs, policies and regulations play an important role when it comes to the demand side of the construction sector [17–21]. Nevertheless, a possible approach estimating future demand for wood in construction was recently provided by Churkina et al. [1]. They investigated different transition scenarios (“business as usual”, “10% timber”, “50% timber” and “90% timber”) to provide a sustainable living space for the additional 2.3 billion urban residences until 2050 by incrementally substituting a steel- and concrete-based construction method with a timber-based building system. According to their findings, the additional wood demand could range from 20 MtC/yr in the “10% timber” scenario up to 1360 MtC/yr in the “90% timber” scenario, which would outstrip the current total roundwood supply reported by the FAO [22, 23]. This wide range of potential demand shows the high uncertainties linked to the different visions for the future of the construction sector and underlines the unpredictability that the forest-based industries have to deal with. Especially considering the wide range of EWPs and possible building systems they are used for. However, besides a singular focus on mass timber construction as assumed by Churkina et al. [1], a wide range of possibly more resource-efficient systems or combinations of them could be employed to create the future living space. For example, timber frame construction stands out in particular as a possible complementary construction method with potentially lower raw material consumption compared to systems based only on mass timber.

Paired with the push to also transition the energy sector to a more sustainable mix of energy sources it becomes clear that in order to prepare for this future market conditions the resource efficiency and environmental performance of processes and products needs to be part of the discussion. This will help provide the necessary baseline in order to support policymakers with the sustainably distribution of the available forest-based raw materials.

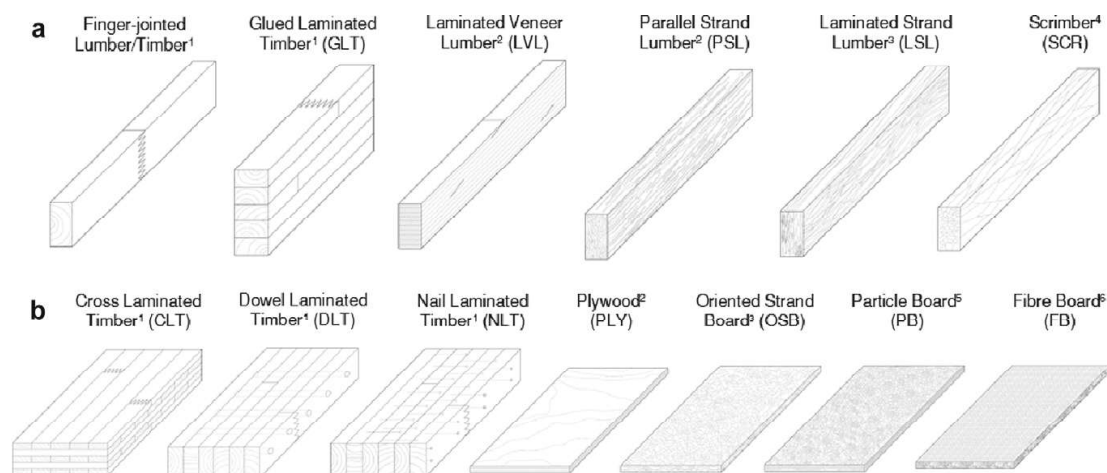


### 21.1.3 Scope of This Chapter

This chapter aims to present currently available Engineered Wood Products (EWPs) for structural applications (see Fig. 21.4) and summarizes the current state of the art in regard to their resource efficiencies as well as production processes (Sect. 21.2). The overview is complemented by a concise discussion of their mechanical (Sect. 21.3) and environmental (Sect. 21.4) performance.

These aspects of EWPs have recently been reviewed in depth by Pramreiter et al. [24]. This publication serves as the foundation for this chapter and is supplemented by a more detailed look into the by-products, sometimes referred to as residues or scrap, during the production processes. Furthermore, six additional EWPs are added to the comparison. It should be mentioned that a detailed description of the different products and production steps has been published multiple times up to this day and can be found most recently in Niemz et al. [25] and also in Dunky et al. [26], Ansell [27], Walker [28], Wagenführ [29], Williamson [30] and the Forest Products Laboratory [31]. These references serve as a baseline for the depicted production steps in Sect. 21.2.

It should be noted here that the chapter aims to present the products without the goal of promoting one over the other. The comparisons should rather give insight into the variety of available products and provide base-values for material selection. It is therefore not the aim of the authors to rank the available products.



**Fig. 21.4** Overview of established engineered wood products (EWP) for structural applications based on the used intermediary (<sup>1</sup>Lumber or Sawn timber, <sup>2</sup>Peeled veneers, <sup>3</sup>Strands, <sup>4</sup>Scrim-mats, <sup>5</sup>Particles, <sup>6</sup>Fibres). **a** Typically beam-shaped. **b** Typically panel-shaped. (Not to scale, drawings created by Frederic Lam)

## 21.2 Resource Efficiency

The first section of this chapter gives insight into the utilized raw materials and the resource efficiency from the first breakdown (the first disintegration of roundwood into intermediaries) to the final material yield of the finished EWP. Furthermore, it presents the most common occurrences of by-products during manufacturing. The statements are taken from the literature (see Sect. 21.1.3) and expert interviews in the field.

### 21.2.1 Definition of Resource Efficiency

Resource (process) efficiency, also referred to as material or product yield can be calculated based on the following equation:

$$\begin{aligned} &\text{Resource efficiency or material yield} \\ &= \frac{\text{Intermediaries or material output}}{\text{Roundwood or intermediary input}} \times 100[\%] \end{aligned} \quad (21.1)$$

It expresses the ratio between the output of intermediaries or final material and the input of roundwood or intermediaries. The remaining % to 100% is typically by-product which still can be used in other wood processing streams and end up in different materials. This is an important merit of the wood processing industry. Basically, nothing of the input raw material is wasted in a classical sense but rather transferred to other process streams of typically lower added value compared to structural building products [32]. Furthermore, there are few additional factors that need to be considered when using this metric to compare products and their efficiency in utilizing raw material.

In regards to first roundwood breakdown into different intermediaries, the measuring principle (volume or weight), the measuring standard (different log scales) as well as the consideration of the bark content dictates how one unit of roundwood input is actually calculated. This can lead to significant differences in reported vs. actual roundwood input and significantly influences the reported process efficiencies [33, 34]. According to a recent study by the Food and Agriculture Organization of the United Nations (FAO) [35] different national log scales can cause a deviation from true log volume as high as 32.3% (8.4% on average). Furthermore, when converting 1000 Board Feet (bd. ft.), the traditional unit for sawmill processes in North America, the resulting volume in m<sup>3</sup> can range from 3.87 m<sup>3</sup> up to 17.23 m<sup>3</sup> depending on the log scale and small end diameter [35].

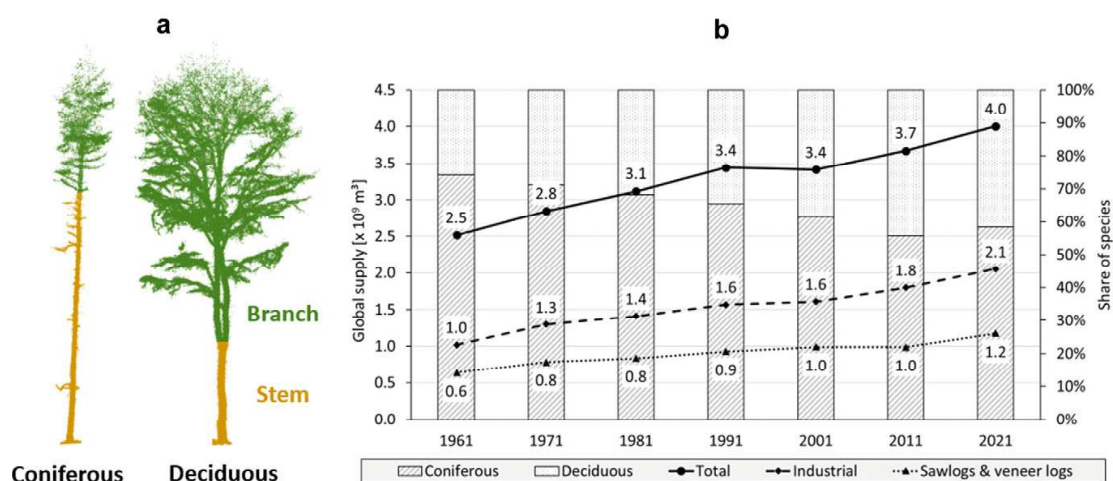
Additionally, the subsequent processing of intermediaries into finished EWPs, the unit (weight or volume) in which the throughput is monitored needs to be considered as well. While lumber-(which can also be referred to as sawn timber) and veneer-based processes are usually controlled only using volume (e.g. m<sup>3</sup> or bd. ft.), the

strand-, particle- and fibre-based processes are monitored using mostly weight (e.g. bone-dry tons also referred to as ATRO) and to some extent also volume. This difference is especially critical when considering the different drying steps to achieve a target moisture content and the compaction (i.e. densification) during the pressing steps. The change in moisture content leads to a change in dimension (volume shrinkage, values for volume shrinkage of selected wood species can be found in literature [31, 36]) and weight (water extraction), while the compaction further influences the dimension (reduced cross-section). Both steps influence the actual density [ $\text{kg/m}^3$ ] of the material, which is the driving parameter when converting output material into different units. The accurate determination of these factors is therefore key when comparing these materials.

### 21.2.2 Raw Material

The predominantly used raw material for the production of EWPs consists of different assortments of roundwood (typically without bark) from forests and, in the case of Particle Boards (PB) and to some extent Fibre Boards (FB), industry by-products (e.g. chips and sawdust) as well as recovered wood from consumers [25]. Depending on the required properties of the final product and the technological processing conditions, relevant quality factors of the utilised roundwood include:

- Wood species (coniferous or deciduous, also referred to as softwood or hardwood, see also Fig. 21.5a)
- Dimension (mainly diameter, length and volume)



**Fig. 21.5** Overview of global roundwood used for the production of engineered wood products (EWP). **a** Typical tree morphology of coniferous and deciduous trees (adopted with permission, copyright by Andreas Tockner, Institute of Forest Growth, University of Natural Resources and Life Sciences, Vienna). **b** Development of global total roundwood supply from 1961 to 2021 as reported by the FAO [22] and amount of industrially used roundwood (incl. the volume of sawlogs & veneer logs) for the production of EWPs

- Growth characteristics (the shape and the quality of the roundwood)
- Biological condition of the tree (is the wood in a healthy condition, e.g. fungal decay or other forms of biological attack).

For the sake of simplicity, the definitions laid out by the FAO [37] for different raw materials of the forest-based value chain will be used in the subsequent comparison of EWPs. More specifically:

- “Roundwood” (roundwood that is removed from the forest),
- “Wood fuel” (roundwood that will be used for the purposes of power production).
- “Industrial roundwood” (all roundwood removed for utilisation, except wood fuel).
- “Sawlogs and veneer logs” (roundwood that will be sawn lengthways or used for the production of peeled or sliced veneers). The terms “sawlogs” and “veneer logs” will also be used on their own.

Furthermore, general terms and definitions for roundwood can be found in ISO 24294 [38] and EN 844 [39], while the measurement of dimensions and volume calculation is standardised in ISO 13059 [40] and further described for Europe in EN 1309-2 [41]. Definitions in regards to growth characteristics (quality) can be found in ISO 24294 as well as in EN 1927 [42–44] for coniferous and in EN 1316 [45, 46] for deciduous species. Definitions concerning the biological condition of the tree are standardised in EN 1309-3 [47]. The previously mentioned quality aspects are to a certain extent already assessed in the forest, before the tree is harvested in order to decide on the target process and potential part of the industry sector the roundwood will be sold to. In that regard it needs to be mentioned that in some instances the market condition may favour certain process streams over others even if the roundwood would fulfil higher quality requirements. In some cases, this can go so far that individual production sites procure all the available roundwood in a region without pre-assessing the quality of the acquired material.

According to the FAO [22, 37], the global roundwood supply has almost constantly increased since 1961 (the earliest recording) from  $2.5 \times 10^9 \text{ m}^3$  to  $4.0 \times 10^9 \text{ m}^3$  in 2021 (see Fig. 21.5b). Similarly, the volume of industrial roundwood has increased from  $1.0 \times 10^9 \text{ m}^3$  in 1961 up to  $2.1 \times 10^9 \text{ m}^3$  in 2021. About  $1.2 \times 10^9 \text{ m}^3$  of “sawlogs & veneer logs” were harvested in 2021, which accounts for 57% of the total industrial roundwood supply and represents a slight decrease compared to the share of 63% ( $0.6 \times 10^9 \text{ m}^3$ ) in 1961. This decrease in relative importance is partly caused by the development of particle-based EWPs like Laminated Strand Lumber (LSL) and Oriented Strand Board (OSB) in the late 1960s and the subsequent installation of production capacities in Europe and North America from the 1980s onwards, which led to the substitution of PLY and other EWPs in some regions [28]. However, from a structural perspective, sawn timber-based EWPs are still dominating the wood-based construction sector. This starts with strength-graded and sometimes finger-jointed timber for timber-frame construction at the lower end of added value, all the way up to prefabricated Cross-Laminated Timber (CLT) wall- and floor-elements, currently offering the highest added value for the wood industry. CLT has seen significant

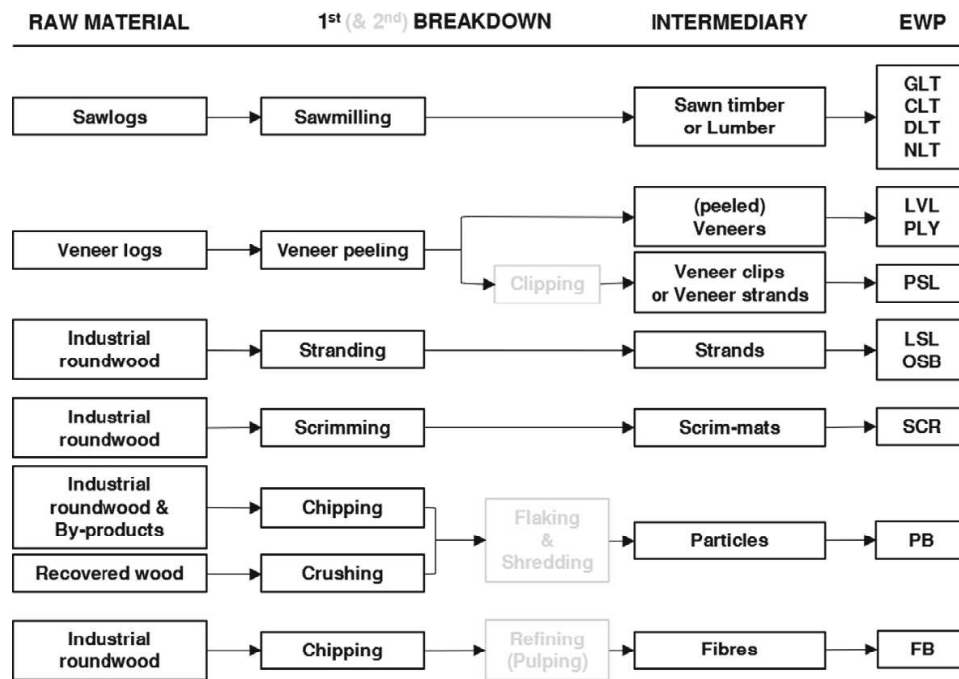


increases in market share in Europe since 2010 [48, 49] and is currently fuelling a hype of so-called mass timber construction in North America which started in 2018 [50]. The roundwood used for these products predominantly comprises of coniferous wood species like Spruce, Pine or Fir and usually requires a uniform/straight trunk shape with little taper and only tolerates small knots (see Fig. 21.5a). However, according to recent studies by Hanewinkel et al. [51] and Thuiller et al. [52] climate change will also impact the species mix of forests in the future, with an expected increasing share of climate-resilient deciduous trees at the cost of currently dominating conifers. This trend is already visible in the supply of industrial roundwood (see Fig. 21.5b), as the share of coniferous wood has decreased from 74% in 1961 to 58% in 2021, while the share of deciduous wood has increased from 26 to 42%. However, this past shift is probably caused by an increase in industrial roundwood used in the pulp and paper industry as well as other industrial roundwood used for poles, posts, fencing, pitprops, shingles and shakes, wood wool, tanning, distillation, among others. In these areas the share of deciduous species has continuously increased while the supply of conifers has decreased [22]. Nevertheless, this shifting species mix will lead to an increase of, currently considered low-quality, non-sawable assortments. This is due to the fact, that deciduous trees grow more heterogenous compared to conifers, with a higher share of branches and lower share of high-quality stem wood (see Fig. 21.5a) [11, 53]. This shift will require a more diverse combination of processes in order to efficiently cover the potential demand for structural EWPs [2]. It also influences other technological factors like adhesive technology, mechanical performance and dimensional stability.

### 21.2.3 *First Breakdown and Intermediaries*

As mentioned in the previous section, the predominant raw material source for EWPs is roundwood (without bark) from coniferous or deciduous tree stems (see also Fig. 21.5). An exception to this is recovered wood in the PB production. Similarly, by-products from other first breakdown processes like wood chips, sawdust or fines can be seen as raw material for the PB and in the case of wood chips also for the FB production.

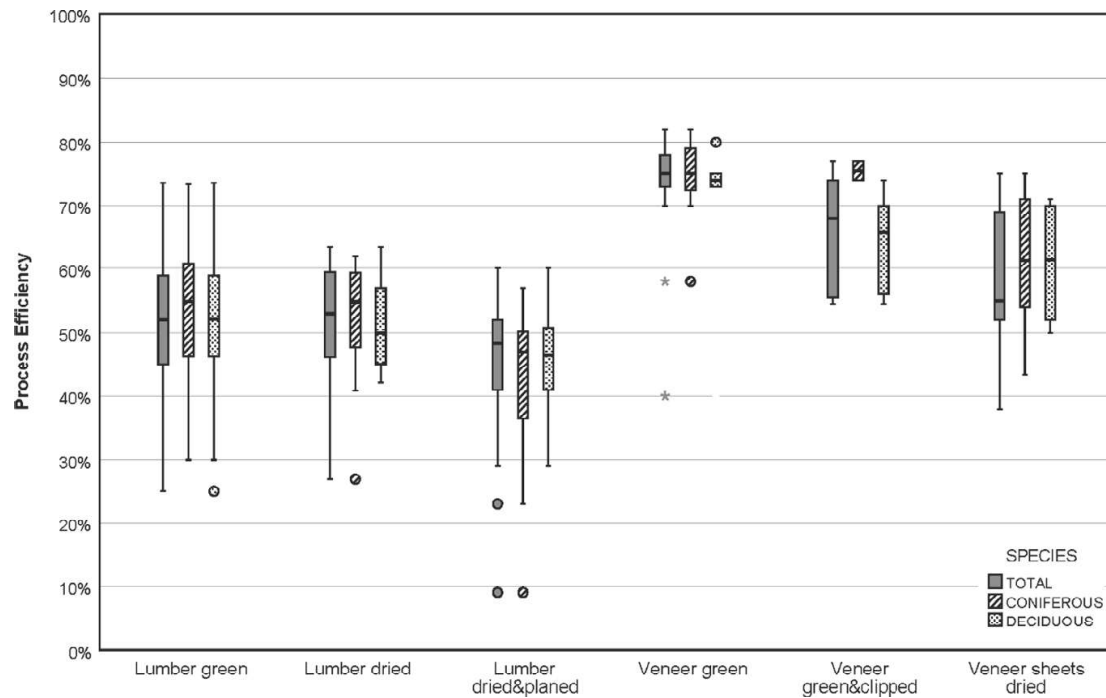
Figure 21.6 summarizes the breakdown steps leading to different EWPs with their intermediaries in a simplified way. The raw material is put through first breakdown by either sawmilling, veneer peeling, stranding, scrimming or chipping. In some cases, a secondary breakdown will occur if the required size of the intermediary needs to be further reduced. This can include for example clipping for PSL, flaking for PB or refining for FB production. Steps like planing, finger-jointing or sanding should not be considered as part of a secondary breakdown, as it does not change the size of the material in a significant way. A concise discussion of the typical sizes of the different intermediaries and the dimensional freedom of the different EWPs can be found in Sect. 21.2.4.



**Fig. 21.6** Simplified summary of utilized raw material, first and secondary breakdown, intermediaries and finished EWPs (based on [25, 37])

This first roundwood breakdown is one of the most dominating factors when it comes to overall resource efficiency. The first breakdown gives the basic dimension of the intermediary and dictates a certain range of resource efficiency due to the underlying technology. Currently, only the sawmilling and veneer peeling (also slicing, for non-structural applications) processes create an intermediary that is also sold as its own product. The production of the strand-, particle- and fibre-based EWPs is normally a fully finished process and the intermediaries are usually not marketed. This is due to the fact that the sawmill and veneer industry has a very long tradition and has historically become more and more integrated by implementing additional value-adding processes over the years. In comparison, the other industries have mainly developed from the need to either utilize a certain raw material or substitute an existing product (e.g. OSB as substitute for PLY). For this reason, there is a lot of literature on the resource efficiency of lumber and veneer production and relatively little on the first breakdown of the other EWPs.

Figure 21.7 summarizes the values found in literature on the process efficiency of sawmilling and veneer peeling and the subsequent process steps to arrive at either dried and planed lumber or dried and clipped veneer sheets. A detailed list of literature dealing with the process efficiency of first-round wood breakdown can be found in the appendix of Pramreiter et al. [24].



**Fig. 21.7** Process efficiency [%] of the first roundwood breakdown and subsequent by-products until the final intermediary material. The base input material is roundwood (without bark), with the input unit being either cubic volume or weight. (Based on [24])

### 21.2.3.1 Sawmilling

The average total green lumber yield related to sawlogs under bark ranges from 25% up to 74% with an average of 52%. In general, sawmilling efficiency increased due to improved process technologies over the past decade's [54–57]. Nevertheless, various factors influencing sawmilling efficiency are summarized in Table 21.1.

Market characteristics (e.g. price of lumber vs. price of by-products) influence sawmilling efficiency by conscious decisions against or in favour of an improved lumber yield [58, 59]. In contrast, mill, roundwood, process and lumber characteristics are predominantly discussed to improve lumber yield. Roundwood characteristics, diameter, length, taper, curvature and local decay are the most important factors influencing process efficiency. Based on findings in the literature [33, 58, 63–65] lumber yield increases with increasing roundwood diameter, while yield generally decreases with increasing length, taper and curvature. To compensate for differing roundwood shapes and sizes, process characteristics like sawing patterns (opening faces) [33, 58, 68, 73], as well as rotation and positioning [74, 75] of the roundwood are usually a direct answer to raw material characteristics to maximize yield on a log-to-log basis. Additionally, general equipment properties like machine set-up [61, 63] and sawing kerf width [33, 58, 63] along with maintenance schedule [58] also influence the process efficiency. However, the ongoing improvements in 3D X-ray scanner technology have enabled the industry to obtain information about the internal

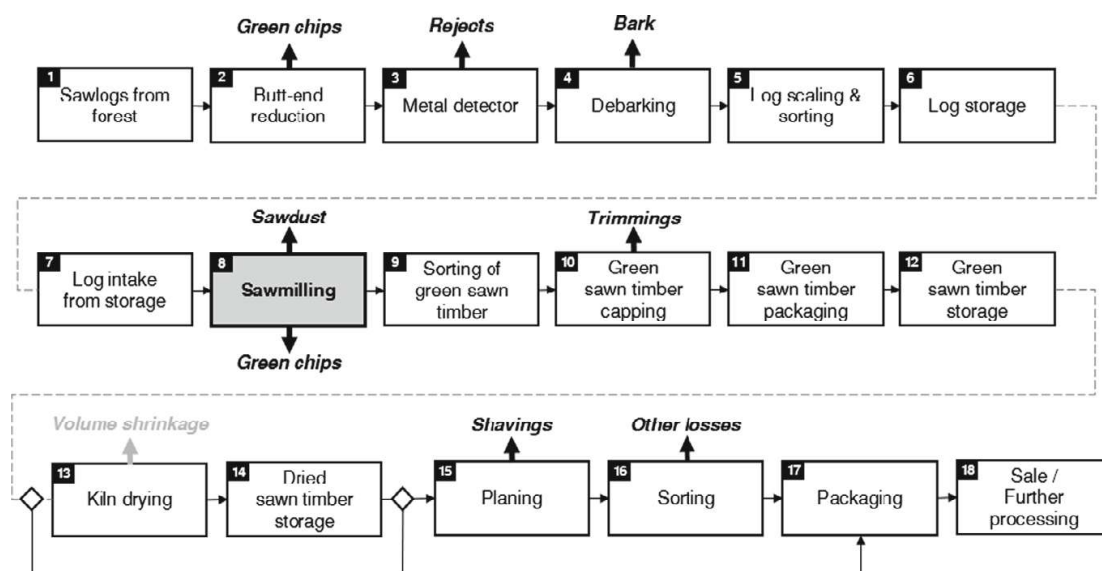
**Table 21.1** Factors influencing sawmilling efficiency

| Factor    | Factors                                                                                                                                                              | References                  |
|-----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| Market    | Product mix, prices, demand and price for by-products, round wood supply                                                                                             | [33, 56, 58, 59]            |
| Mill      | Production capacity, equipment type, age of the machinery, decisions making                                                                                          | [54–56, 58, 60, 61]         |
| Roundwood | Species, origin (native or plantation forest), diameter, length, taper, curvature, knottiness, position of crosscut                                                  | [33, 54–56, 58, 62–71]      |
| Process   | Cutting pattern, accuracy, saw kerf, rotation and positioning, curve sawing capabilities, condition and maintenance of equipment                                     | [56, 58, 59, 63, 68, 72–75] |
| Lumber    | Species, target size (nominal vs. actual), moisture content (drying), visual characteristics (twist, bow, knots, ring width, checks, wane), applied sorting criteria | [33, 58, 59, 67, 70, 76–83] |

structure of the raw material and have led to a shift towards value-focused processing rather than yield-based [84].

In order to discuss the subsequent processing steps of green lumber into dried & planed lumber, Fig. 21.8 gives an overview of typical sawmilling operations and indicates where by-products occur.

Literature reports an average total dried & planed lumber yield from 9% up to 60% with an average of 46%. The lowest reported dried & planned lumber yield of 9% [85] is based on an assumed distribution of process efficiencies and very likely reflects only a theoretical worst-case scenario. Similar to round wood volume,



**Fig. 21.8** Typical operations and by-products during sawmilling. Sawn timber can also be replaced with lumber

the methods of measuring lumber volume influence the reported process efficiency. Most commonly, actual dimensions of lumber are used to determine the cubic volume (length  $\times$  width  $\times$  height). One exception can be found in North America, where nominal dimensions are used to calculate board feet (bd. ft.) of lumber [33, 35, 54]. One bd. ft. is defined as a 1-inch (2.54 cm) thick and 12 by 12 in. (30.48 cm) long board, which would lead to 1 m<sup>3</sup> being 424 bd. ft. [33]. However, as these nominal sizes sometimes ignore dimensional changes due to drying and planing of the lumber actual volume could be as low as 0.66 m<sup>3</sup> [35]. Besides these variabilities, drying (6% average drying loss [35, 59, 64, 78, 85–90]), planing (13% average planing loss [35, 59, 64, 78, 85–93]) and sorting [59, 78–83] significantly decreases the final intermediary yield of the sawmilling process (also see Fig. 21.8).

### 21.2.3.2 Veneer Peeling

The total green veneer yield ranges from 40% up to 82% with an average of 72%, showing lower variability compared to sawmilling (see Fig. 21.7). Similarly, technological advancements increased veneer recovery over the last decade significantly. The chipless peeling of veneers leads to a generally higher material yield compared to lumber from sawmilling and similarly veneer yield increases with increasing small end diameter. However, this requires uniform raw material of preferably high diameter and high quality. In addition, the machine configuration also plays an important role. Currently, spindleless lathe technology is the state of the art, enabling the log to be peeled down to a residual diameter of about 25 mm. In comparison, older literature discusses suitable core diameters to be around 80 mm and above, also depending on the potential utilisation of the peeler cores for other products (e.g. poles for fencing) [33]. After peeling, green veneers are usually clipped and dried to target moisture content as depicted in Fig. 21.9.

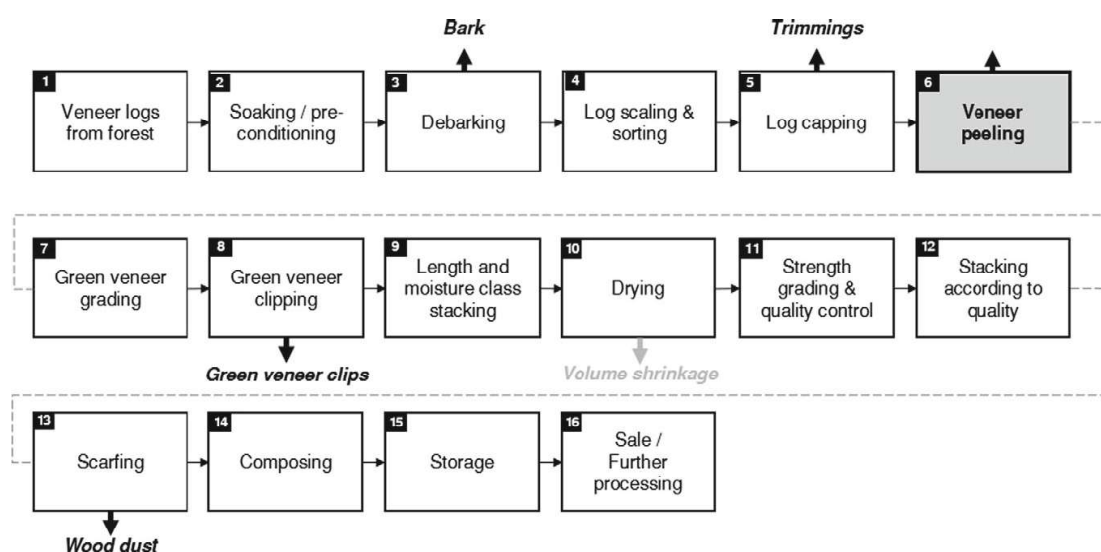


Fig. 21.9 Typical operations and by-products during veneer peeling



As depicted in Fig. 21.7 total yield of veneer sheets dried ranges from 38% up to 77% with an average of 57% showing higher variability (Fig. 21.3) compared to green veneers. As with the sawing process, there are also different ways in which the veneer volume is determined. The cubic volume is either measured based on actual dimensions (length  $\times$  width  $\times$  thickness) or based on the surface area on an equivalent thickness basis [35]. For example, a veneer with 1.25 m<sup>2</sup> and a 1 mm thickness would equal 0.00125 m<sup>3</sup>, including a small plus or minus thickness tolerance [33]. As both methods are based on actual dimensions the variability in reported veneer yield should be negligible. More importantly, the loss due to clipping is reported [33, 64, 94, 95] to be the most severe factor in decreasing veneer yield. According to findings by Woodfin [94] as well as Fahey and Woodfin [64] roughly 20% of material is turned into by-products, whereby the clipped volume (mainly cracked and defective areas) is significantly influenced by the applied clipping strategy [96]. Final veneer drying further reduces the overall yield, with the target moisture content ranging from as low as 2% up to 15% [28]. The lower target moisture content is usually dictated by the target size [33] and possible bonding conditions for subsequent Laminated Veneer Lumber (LVL) and Plywood (PLY) production [26].

### 21.2.3.3 Influence of Wood Species on the First Breakdown

Based on Fig. 21.7, the influence of wood type (coniferous vs. deciduous) is negligible for the first roundwood breakdown. This underlines the greater influence of the principal technology on the level of achievable resource efficiency as compared to the processed wood species. Considering sawmilling and veneer peeling, a key factor in process efficiency [58, 97] is the optimization of mills to process either coniferous or deciduous roundwood. This emphasizes the importance of a plannable and steady supply of comparable roundwood assortments for these industries. Currently, the smaller share of deciduous wood species processed by the industry (see Fig. 21.5) is either subjected to a stricter degree of pre-sorting compared to softwoods, with the non-sawable and non-peelable assortments being either used for wood fuel or pulp and paper, or is directly felled for these low-added value sectors [22]. Therefore, the attainable roundwood quality of deciduous trees will be a key issue in the future [98, 99] and could significantly reduce the process efficiency of sawmilling [71] as well as veneer peeling [97]. Furthermore, a closer look at other process-related factors like productivity, energy demand, necessary pre-treatment and resulting intermediary quality is needed to get a full view of the effect of the changing raw material situation.

### 21.2.4 Typical Sizes of Intermediaries and Finished EWP

At this point, the typical sizes of the intermediaries and finished EWPs will be presented briefly in order to provide an overview of the achievable dimensions. To utilise different EWPs in construction, a certain dimensional freedom is required

to support an array of different building types and designs, while also ensuring the necessary structural safety. Furthermore, the high degree of prefabrication in the wood-based construction industry also requires a certain flexibility when it comes to logistics. Based on currently available literature and building projects, Table 21.2 summarizes the typical sizes of the used intermediaries (sawn timber, peeled veneers, strands, scrim-mats, particles and fibres) and indicates the typical dimensional ranges for the finished EWPs.

Looking at the typically beam-shaped EWPs, Glued Laminated Timber (GLT) currently offers the highest flexibility in regards to the size of the final members. It ranges from standardized dimensions up to singles beams for timber engineering, not only covering great spans but also 3D-shaped constructions [121, 122]. Today, the construction industry can access a wide knowledge-base in regards to design and manufacturing but also in the field of connectors and logistics (on and off the construction site) when it comes to GLT. LVL, Parallel Strand Lumber (PSL) and Laminated Strand Lumber (LSL) on the other hand are predominantly used in standardised lengths. However, LVL recently gained interest for timber engineering due to the higher mechanical performance at smaller dimensions [123], while LSL and PSL are mainly used in North America with standardised dimensions. SCR is currently not produced on an industrial scale and it has been largely ignored since the last push to bring a product onto the market in 2003 [118]. However, the scrimber process has received renewed attention in recent years due to its ability to process small-diameter and low-quality roundwood [124].

Considering the panel-shaped EWPs, CLT is currently generating the most attention in the industry as well as research, which has significantly increased its dimensional flexibility while also offering multiple degrees of pre-fabrication. PLY, OSB, PB and FB are still mainly used with standardized dimensions and rather as one component of a construction element. However, companies started producing PLY [111] and OSB [116] as single load bearing element with bigger dimensions and design flexibility in the recent past. DLT and NLT are currently only manufactured to a limited extent with standardised dimensions [104, 105, 125]. However, they have a long history as structural EWP and offer an adhesive-free alternative to the established EWPs and are comparatively easy to manufacture and recycle.

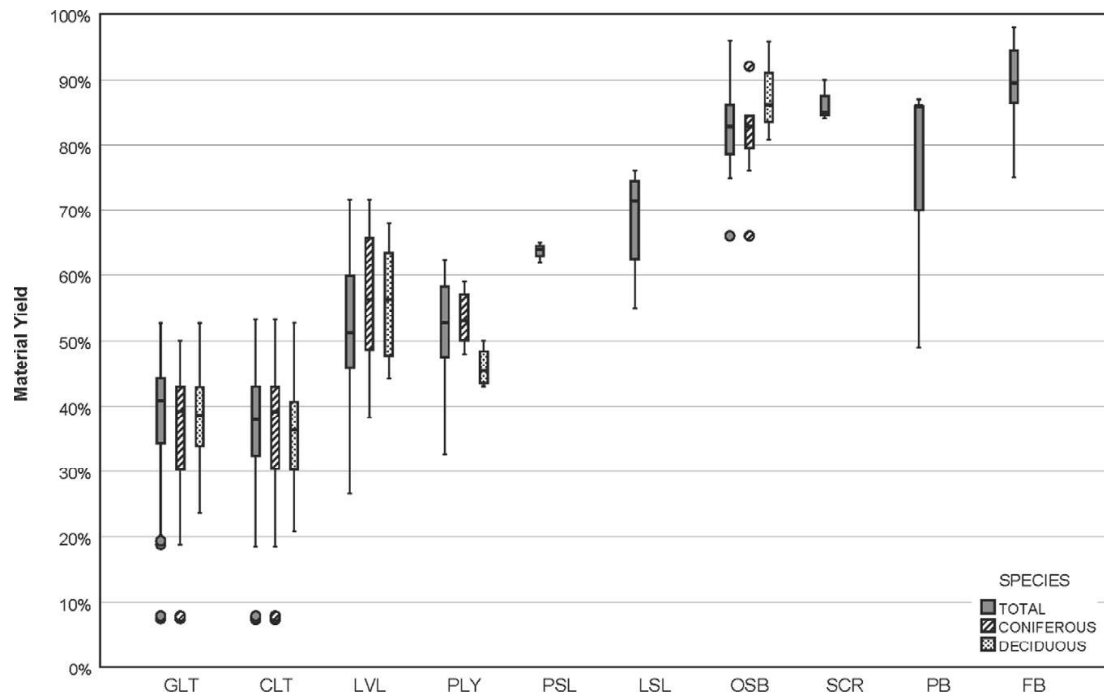
### ***21.2.5 Further Processing and Finished EWPs***

After the first and secondary roundwood breakdown the intermediaries can be either stored for later use or directly processed into the finished EWPs. Figure 21.10 summarizes the values found in literature on the material yield of different EWPs.

**Table 21.2** Typical sizes of intermediary material and engineered wood products (EWP)

| Intermediary       | Length (mm) | Width (mm) | Thickness (mm)   | EWP | Length (m) | Width (m) | Thickness (m) | References            |
|--------------------|-------------|------------|------------------|-----|------------|-----------|---------------|-----------------------|
| Sawn timber/Lumber | 1000–6000   | 40–300     | 6–45             | GLT | ≤ 150      | 0.08–0.24 | ≤ 2.0         | [25, 28, 100, 101]    |
|                    |             |            | 6–47             | CLT | ≤ 18–30    | ≤ 3.0–4.8 | ≤ 0.3–0.5     | [100, 102, 103]       |
|                    |             | ≥ 80       | ≥ 20             | DLT | ≤ 20       | 0.305–4.3 | 0.09–0.4      | [104–108]             |
|                    |             | 89–286     | ≤ 38–89          | NLT | ≤ 7.9      | ≤ 2.4     | 0.09–0.29     | [109, 110]            |
| (peeled) Veneers   | 800–2500    | 800–2500   | ≤ 7              | LVL | ≤ 25       | ≤ 2.5     | 0.02–0.62     | [27, 28, 111, 112]    |
|                    |             |            |                  | PLY | 1.2–14.6   | 1.2–3.7   | 0.01–0.31     | [27, 28, 31, 111–113] |
|                    | ≥ 600       | ≤ 19       |                  | PSL | ≤ 20       | ≤ 0.28    | ≤ 0.48        | [28, 31, 100, 112]    |
|                    | ≤ 300       | ≤ 25       | 0.3–0.8<br>(≤ 2) | LSL | ≤ 19       | ≤ 2.4     | ≤ 0.14        | [26, 27, 114]         |
| Strands            | 50–150      | 4–15       |                  | OSB | ≤ 20       | ≤ 2.8     | 0.006–0.25    | [25, 26, 115, 116]    |
|                    | ≥ 380       | ≤ 19       | ≤ 19             | SCR | 5.5        | 0.05      | 0.3           | [117–120]             |
| Particles          | 1–15        | 0.1–5      | 0.1–1            | PB  | ≤ 5        | ≤ 2.5     | 0.006–0.04    | [25, 26, 100, 115]    |
| Fibres             | 1–25        | 0.03–0.5   |                  | FB  |            |           | 0.001–0.03    |                       |

Glued laminated timber (GLT), cross laminated timber (CLT), dowel laminated timber (DLT), nail laminated timber (NLT), laminated veneer lumber (LVL), Plywood (PLY), parallel strand lumber (PSL), Scrimber (SCR), laminated strand lumber (LSL), oriented strand board (OSB), particle board (PB) and fibre board (FB)



**Fig. 21.10** Material yield [%] of established EWPs based on roundwood under bark (excluding bark). Yield for GLT, CLT is based on the minimum, maximum, and average process efficiency of lumber dried & planed (see Fig. 21.7) multiplied by the average further processing loss reported in the literature. Yield for LVL is based on literature and the minimum, maximum and average process efficiency of veneer dried & planed (see Fig. 21.7) multiplied by the average further processing loss reported in the literature. It can be assumed that DLT and NLT either lay in the same range or slightly above GLT and CLT (data taken from [24] and extended with [126–135])

### 21.2.5.1 Influence of Wood Species on Material Yield of EWPs

Depending on the EWP (see Fig. 21.10) no or too little literature is available to provide a general statement regarding the influence of wood species on the final material yield. Taking a look at the lumber-based products GLT and CLT, there was no literature on the processing losses of GLT made from deciduous species and the literature for CLT is primarily based on the same numerical simulation of low-grade yellow-poplar roundwood [76, 136] reporting a lower yield compared to conifers. In addition, the losses through pre-sorting and strength grading of the input lumber are reported to be significantly higher for deciduous [59, 78] than for coniferous species [79, 80]. In regards to the veneer-based EWPs, a similar statement can be made, with no literature available on deciduous LVL and little literature on PLY [35, 127], showing values significantly lower compared to conifers. In addition, total LVL and PLY includes literature [33, 55, 64, 137, 138] reporting a mixture of both coniferous as well as deciduous species, exhibiting a higher variability in yield compared to mere conifers. This indicates that the higher inhomogeneity of deciduous trees also influences the range of achievable material yields of LVL and PLY. In contrast to the lumber and veneer-based EWPs, Fig. 21.10 shows a different picture for OSB, with deciduous OSB having a higher material yield compared to OSB made from conifers.

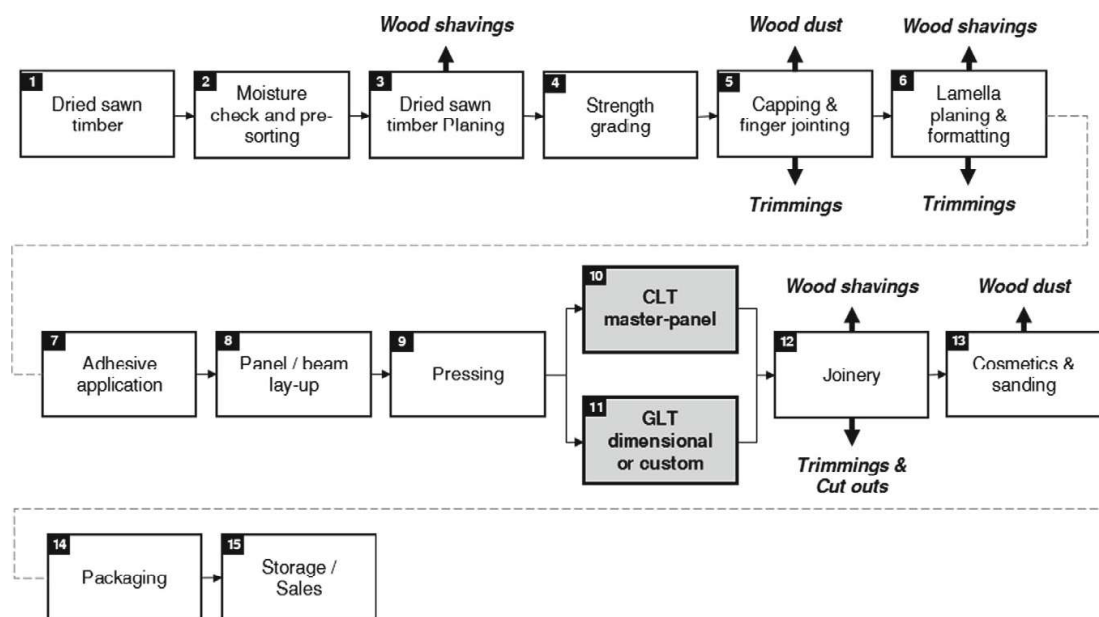
In that regard, results from Feng and Knudson [139] show a significantly higher share of fines from green pine (15.4%) compared to green aspen (4.1%). This indicates, that the production of deciduous OSB could result in a generally higher material yield. Nevertheless, aspen can be considered a low-density deciduous species [140] with technological properties similar to conifers [141]. Therefore, this statement should not be transferred to other deciduous species like oak or beech.

In general, most of the reported values either stem from a process that was optimized for the utilized tree species or are the result of an optimization to utilise a new species. This wide array of investigations underlines the necessity to approach potential changes in the raw material basket with an open eye in regards to the potential processing technologies.

### 21.2.5.2 Glued Laminated Timber (GLT) and Cross Laminated Timber (CLT)

Taking a look at GLT and CLT, comparable efficiencies can be observed, with total GLT yield (GLT dimensional or custom in Fig. 21.11) ranging from 7% up to 53% and an average of 39% and CLT (CLT master-panel in Fig. 21.11) achieving an average yield of 37% ranging from 7–53%. Overall, the further processing losses of GLT and CLT are similar within different literature sources. This is a result of both EWPs having similar processing steps and by-products during manufacturing (see Fig. 21.11).

For total GLT [142–145], the average losses during production amount to about 16% in a range of 12–18% based on timber input. In CLT production [85, 93, 145–150], roughly 16% of input material is transformed into by-products, ranging from



**Fig. 21.11** Typical operations and by-products during the manufacturing of GLT and CLT



12% up to 20%. From this, it can be argued that the main reason for the high variability in yield can be found in the base efficiency of the input timber. In both cases the main steps causing additional losses are lumber trimming and finger jointing, planing of the lamellas and joinery 1 in the case of CLT and cosmetics & sanding in the case of GLT [27, 102]. However, it is important to note that especially planer shavings, which are a big loss factor [57, 85], are probably counted double in some cases for GLT as well as CLT as the process may also be started with rough-sawn lumber [147]. For CLT, this is countered by the fact that the losses caused by the joinery 2 (e.g. cut-outs for windows and doors) are not yet included. Depending on the end-use of the panel this could further bring down the final yield significantly. While floor panels do not require many cut-outs, outer and inner walls require openings for windows or doors, with the total area of these openings mainly driven by design aspects as well as building physics (lighting and ventilation) [151, 152].

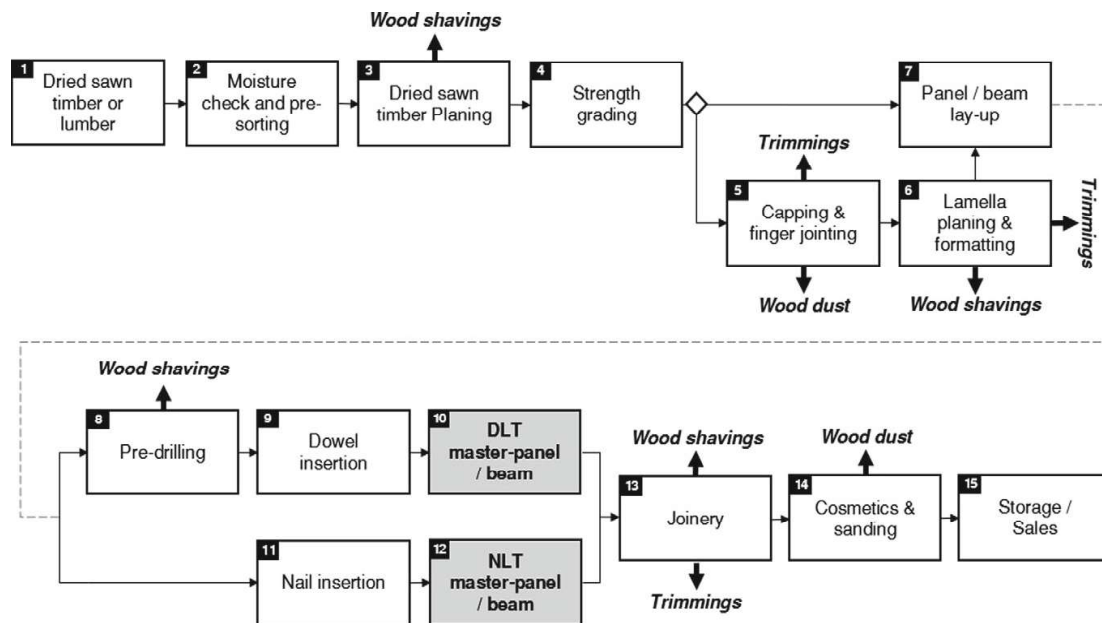
#### **21.2.5.3 Dowel Laminated Timber (DLT) and Nail Laminated Timber (NLT)**

Currently, no publicly available literature deals with the resource efficiency of DLT or NLT. Both products are manufactured from dimensional lumber and instead of an adhesive either wooden dowels (DLT) or nails (NLT) are used to form the finished EWP (see Fig. 21.4). Depending on the producer the typical processing operations (Fig. 21.12) start, similar to GLT and CLT, with dried sawn timber which is in some cases finger jointed before a planing and profiling step to create the final raw lamella. Therefore, similar by-products to GLT and CLT occur. In the case of DLT, the lamellas are then laid up to either a beam or a panel (similar to CLT) and holes are drilled for subsequent dowel insertion. This creates further wood shavings as a by-product. In the case of NLT, the lamellas are directly laid up and nailed together in a repeating pattern. The resulting beam or panel is then further processed in a joiner. However, in the case of NLT, the options for subsequent joining are limited due to the nails within the material. The final EWP can also move through a final cosmetics and sanding step before being either stored or sold directly.

Based on these similarities with GLT and CLT it can be assumed that the overall material yield of DLT and NLT also falls in the same range. More specifically, the material yield tends to be higher compared to CLT and GLT due to the lower requirements on the surface quality of the lamellae. Another potential advantage of DLT and NLT lies in the potential recyclability of beams and panels at the end of their life-cycle due the absence of hard to dissolve adhesive bonds.

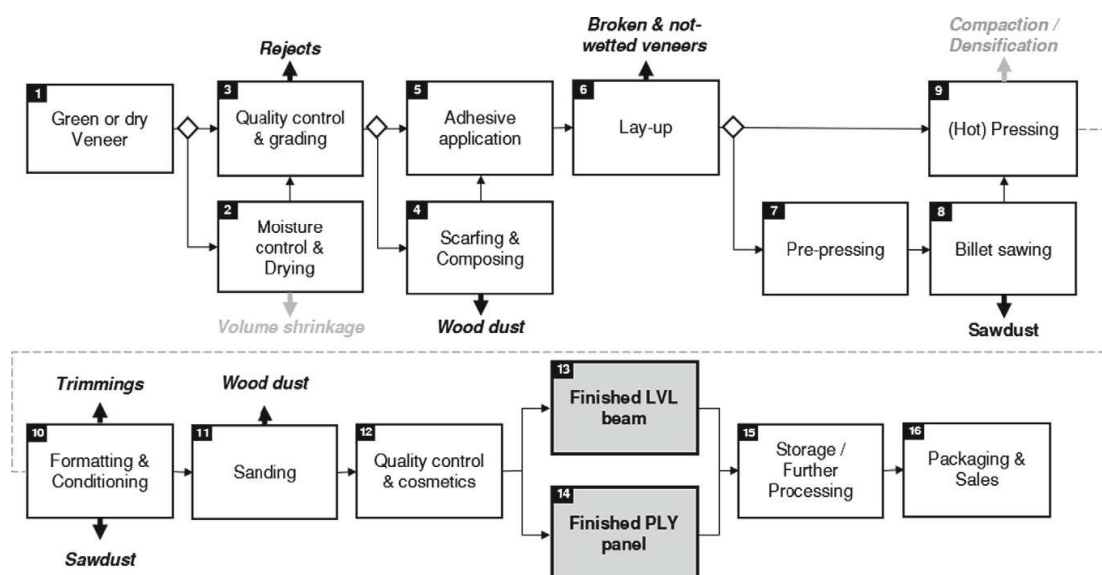
#### **21.2.5.4 Laminated Veneer Lumber (LVL) and Plywood (PLY)**

Taking a look at the veneer-based products, LVL and PLY achieve higher average yields compared to the lumber-based EWPs. Total LVL yield ranges from 27 to 72% with an average of 52% and an average further processing loss of 9% [137, 153,



**Fig. 21.12** Typical operations and by-products during the manufacturing of DLT and NLT

154]. Total PLY typically achieves an average yield of 52%, in the range of 33–62% according to literature. As depicted in Fig. 21.13, the losses from the input green veneers are caused by waste veneer, lay-up scrap, panel trimming and sanding as well as material testing [33, 64, 137, 138, 153], with improved material utilization of roughly 15% compared to the lumber-based EWPs. The higher maximum yield of LVL compared to PLY could be explained by fewer cross-cuts and fewer surfaces for sanding as usually thicker billets are produced [155].



**Fig. 21.13** Typical operations and by-products during the manufacturing of LVL and PLY

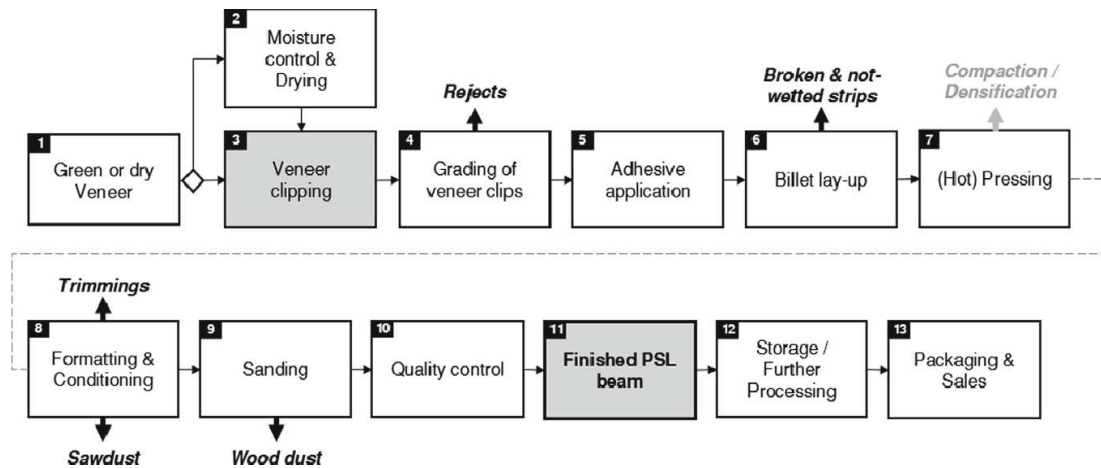


Fig. 21.14 Typical operations and by-products during the manufacturing of PSL

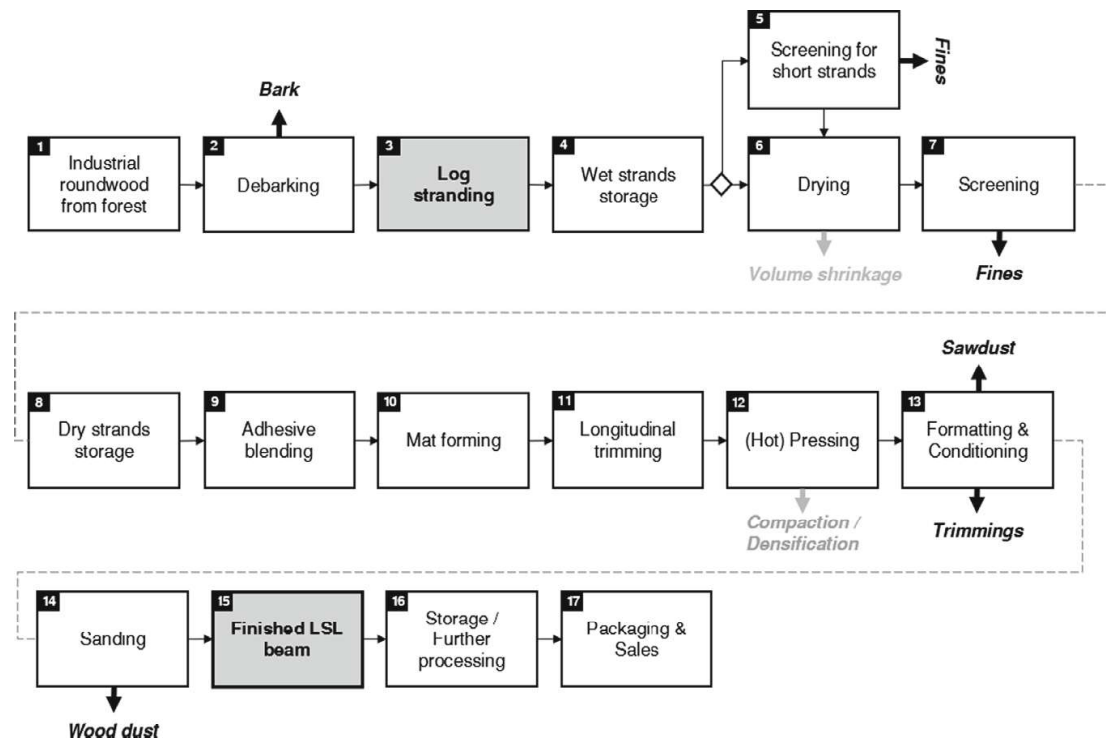
### 21.2.5.5 Parallel Strand Lumber (PSL)

PSL reaches an average material yield of 64%, ranging from 62 to 65%. Within the group of veneer-based products, it can be seen as a special case of EWP. In comparison to LVL and PLY, the production of PSL includes a secondary breakdown of the veneers into veneer clips (see Fig. 21.14). This enables a higher material yield compared to LVL and PLY, as veneer pieces that are not a full-width veneer sheet (roundups, fishtail, etc.) can be utilized [156]. The resulting clips are continuously feed into a hot press to form an endless beam, which is then formatted to the final dimensions.

### 21.2.5.6 Laminated Strand Lumber (LSL)

The material yield of LSL ranges from 55% up to 76%, with an average of 69%. The lower yield compared to OSB (see next section) is due to the unidirectional structure over the entire thickness of the material, demanding generally bigger (see Sect. 21.2.4) and more uniform strands, with high aspect ratios [156]. Therefore, part of the finer fractions which are usually put in the middle layer of OSB cannot be used for the homogeneous build-up of LSL beams. Besides these differences, the main drivers for additional material losses (see Fig. 21.15) are formatting and sanding of the finished panels and beams [27, 138, 157].

In general, the log stranding process does not require high-quality, mature logs and is geared towards small-diameter roundwood of lower quality [27]. Therefore, the process allows for a bigger range in roundwood quality and supports more log diameters and shapes. The factors influencing strand yield partly differ from the previous two first disintegration processes. Increasing log moisture content [139] and ambient temperature [158] significantly decreases the produced fines in stranding and therefore increases strand yield. In regards to machine set-up, the knife angle is reported [158] to be an important factor influencing the share of fines. In addition,



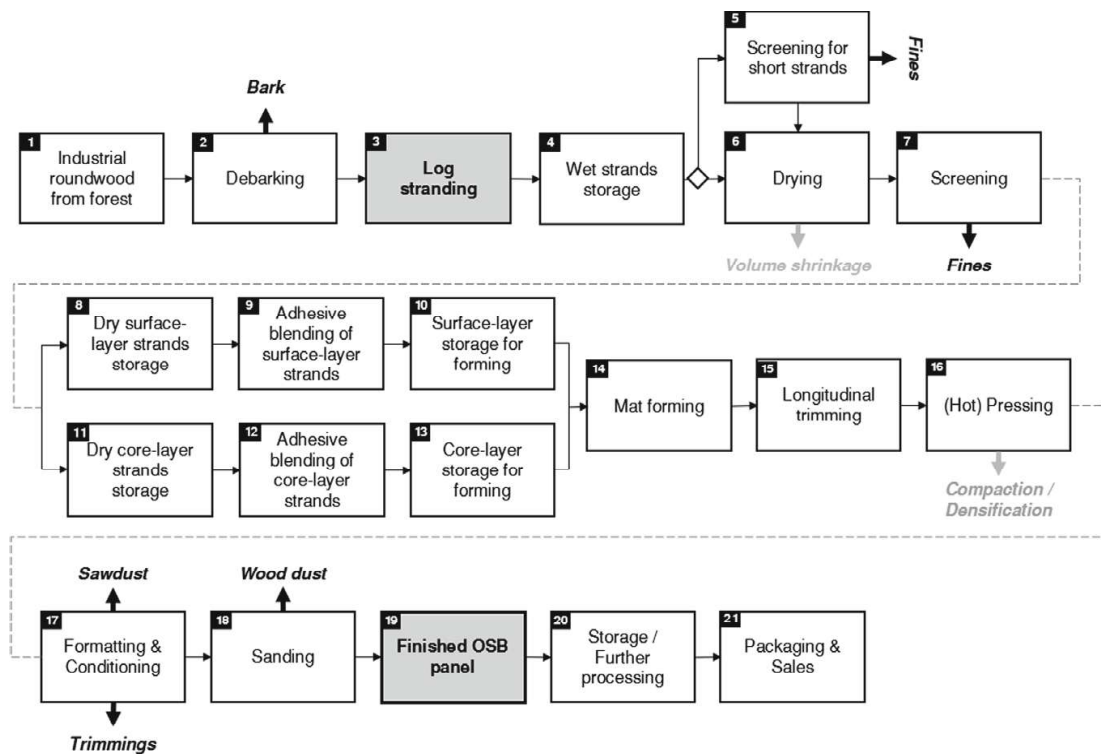
**Fig. 21.15** Typical operations and by-products during the manufacturing of LSL

the positioning of the logs against the rotating knife using of clamps or pushers partly dictates the strand geometry and therefore also influences the strand yield [28]. The fines are normally separated from production and are typically used for the provision of energy as they reduce the strength of the final board and increase the amount of adhesive required. Furthermore, strands that do not fulfil the required sizes are also used for energy, but can also be used for PB.

The final target moisture content of the strands is in the range of 2–5% [27, 28] usually dried from above fibre saturation [159]. As mentioned previously, this could further affect the final material yield depending on the reported input and output unit. This is especially critical when comparing the different processes, as volumetric shrinkage is usually considered a loss in volume-based lumber and veneer production. However, as LSL and OSB production is commonly monitored using (dry) weight, this could lead to inaccuracies when comparing the processes.

### 21.2.5.7 Oriented Strand Board (OSB)

The average material yield of OSB is 83% and ranges from 66 to 96%. Similar to LSL, the main drivers for by-products besides the fines from stranding industrial roundwood are formatting and sanding of the finished panels (see Fig. 21.16). OSB is typically made of three layers, two unidirectionally oriented surface layers and one randomly or perpendicularly oriented middle layer. This was inspired by the orientation of plywood and combines two stiffness-providing surface layers and a



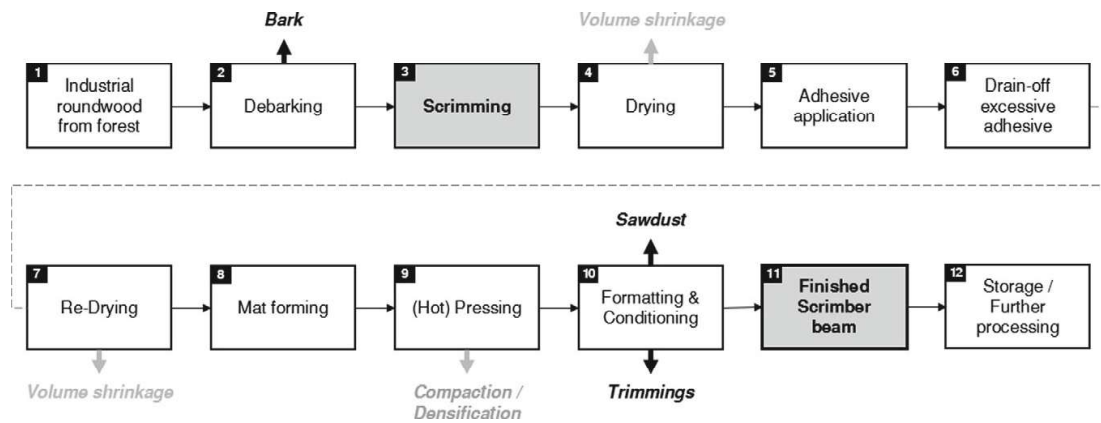
**Fig. 21.16** Typical operations and by-products during the manufacturing of OSB

middle layer which gives additional dimensional stability while also improving shear stiffness. This allows for a bigger range of strand sizes to be used in the production compared to LSL, which explains the higher resource efficiency compared to LSL.

### 21.2.5.8 Scrimber (SCR)

The average material yield of SCR is 86%, ranging from 84 to 90%. These values are partly based on the company that originally produced SCR under the product name TimTek® [160]. Based on the available literature, by-products occur during the formatting and finishing of the final panels (see Fig. 21.17). Additionally, it should be mentioned that it can be assumed that there is a certain share of unusable intermediaries (fines after scrimming and after drying). However, this is not discussed in the available literature.

As of 2024, SCR is the only EWP discussed here that is not produced on an industrial scale. Nevertheless, the process of splitting small-diameter logs has recently gained renewed interest and should therefore also be mentioned here. Especially as it could be one viable way to process the potentially increasing share of non-sawable and- peelable assortments in the future. Furthermore, it could also be used to add value to currently undervalued assortments like branches and crown tops, which were recently found to offer similar technological potential to stem wood [161].



**Fig. 21.17** Typical operations and by-products during the manufacturing of SCR

### 21.2.5.9 Particle Board (PB)

In comparison to the other processes, the production of PB can be seen as having the most flexible input raw material and offers a common utilisation strategy for by-products from sawmilling but also from stranding and possibly also from veneer peeling.

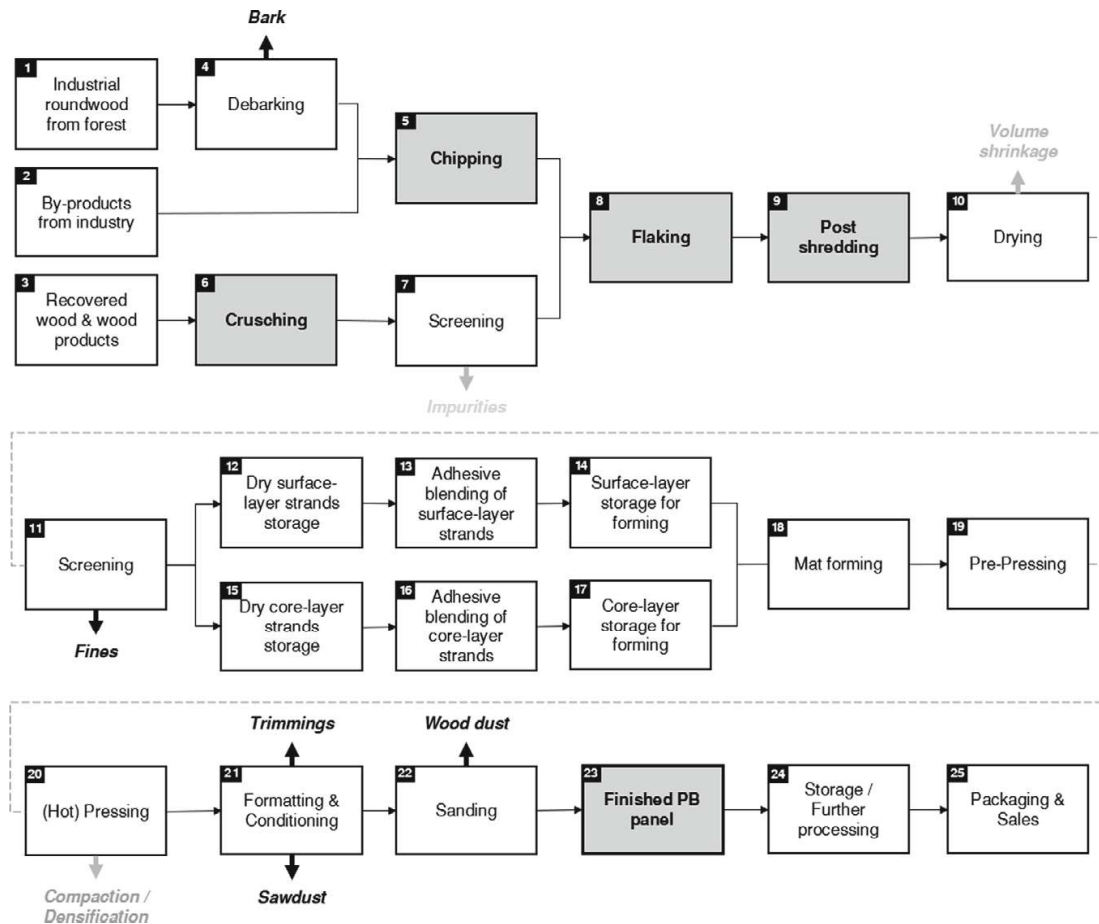
The average material yield for PB is 76% and ranges from 49% up to 87%. The lower end of this spectrum should be taken with a grain of salt as this low value of material yield is not typical for an industrial-scale facility. However, the reported numbers stem from a facility which utilizes mainly low-quality raw materials. According to the study [129], the raw material includes branches and wood from garden pruning, poplar and eucalyptus roundwood, other low-quality deciduous roundwood, forest firewood and industrial by-products, underlining the raw material flexibility of this process. Overall, the production of PB leads to by-products during screening and finishing of the final panel (see Fig. 21.18).

### 21.2.5.10 Fibre Board (FB)

Completing this comparison of different EWPs, the average material yield for FB is 89%, ranging from 75% up to 98%. This also represents the highest potentially achievable resource efficiency of the presented products. However, this, in turn, requires the highest degree of disintegration of roundwood in order to obtain single wood fibres or fibre-bundles as intermediaries. This is typically achieved by combining two major breakdown processes, chipping of roundwood and subsequent refining of the obtained chips into fibres (see Fig. 21.19).

While this has the potential to yield a 100% useable intermediary material for FB production, it also requires the highest total primary energy input of all the processes. With this, the environmental performance, typically evaluated by Life Cycle Assessment (LCA), as well as the mechanical performance needs to be brought into the comparison, as resource efficiency alone does not provide the complete





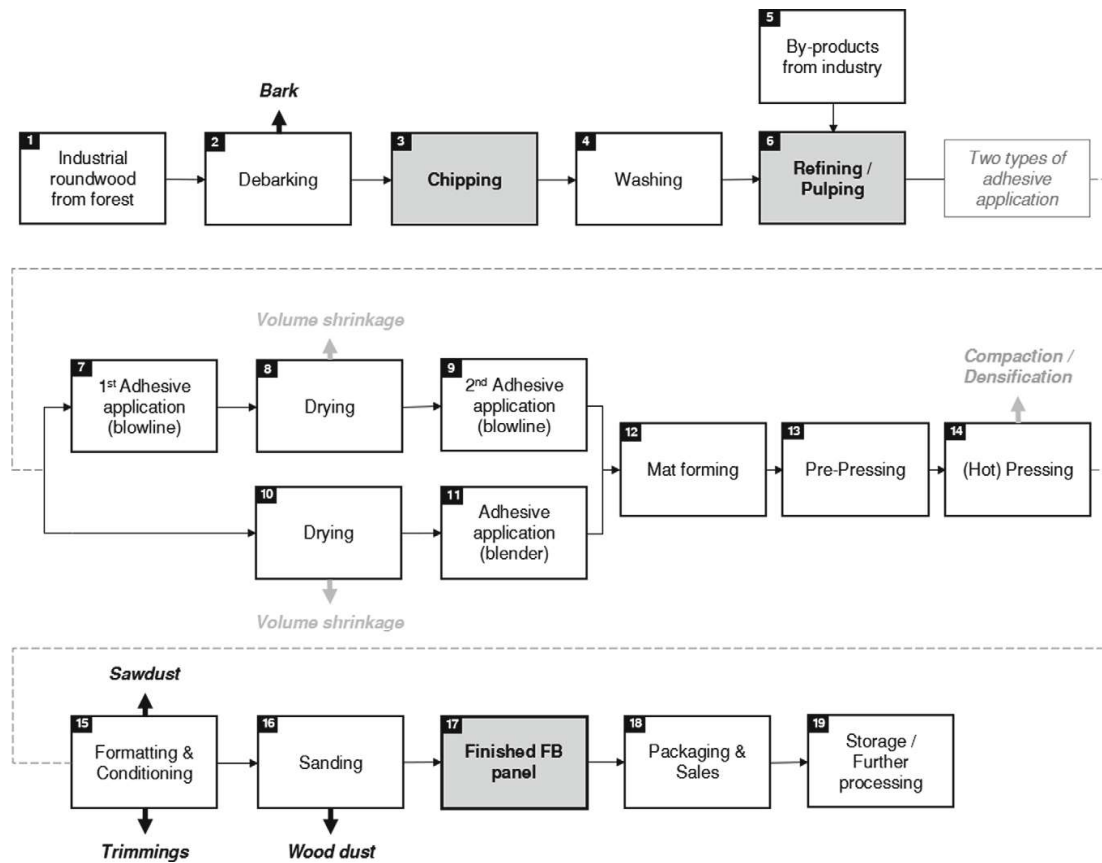
**Fig. 21.18** Typical operations and by-products during the manufacturing of PB

picture in regards to sustainability of wood-based building materials in a broader sense.

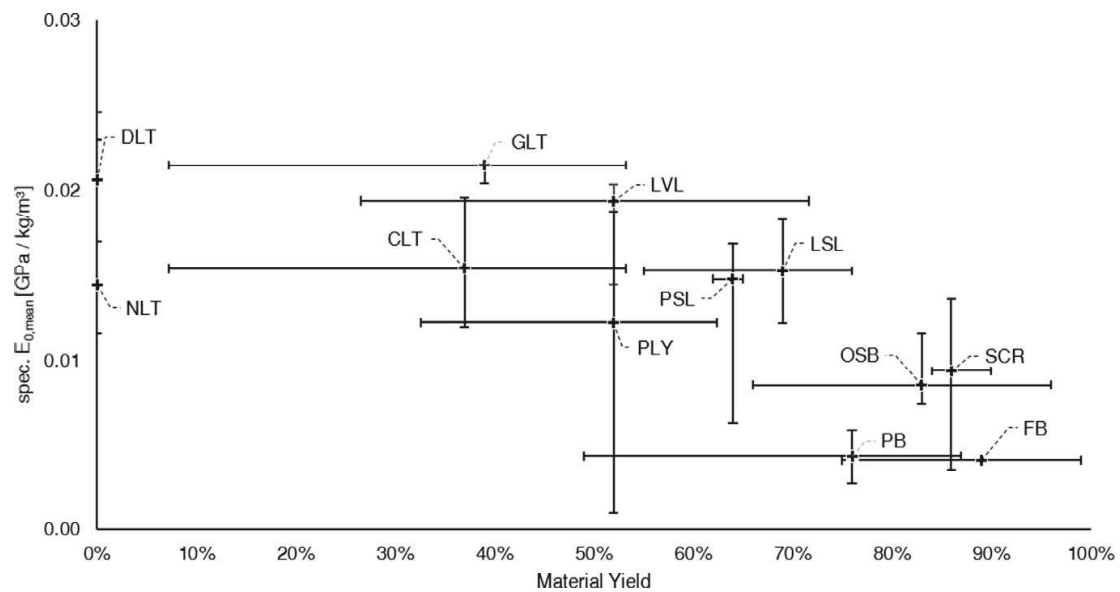
### 21.3 Mechanical Performance

The architectural freedom [162] and design phase [163] of a building demands a certain mechanical capacity of the suitable construction materials [164]. Therefore, the potential mechanical performance of the different EWPs is another important aspect. In addition to the strength, stiffness and long-term behaviour already discussed in Pramreiter et al. [24], the specific modulus of elasticity (spec.  $E_{0,\text{mean}}$ ) [ $\text{GPa/kg/m}^3$ ] in the main load direction is compared with the material yield in Fig. 21.20.

It should become clear that the lower material yield of the lumber-(GLT, CLT, DLT and NLT) and veneer-based (LVL, PLY and PSL) EWPs, can be balanced by the higher attainable stiffness per kg EWP in contrast to the particle-based products [165, 166]. However, this only covers the serviceability side and one load case (bending) of



**Fig. 21.19** Typical operations and by-products during the manufacturing of FB



**Fig. 21.20** Specific mean Modulus of Elasticity ( $\text{spec. } E_{0,\text{mean}}$ ) [ $\text{GPa} / \text{kg/m}^3$ ] versus respective material yield [%]. Based on values in Table 21.3

the design process. Therefore, it is highly recommended to also consider section four in Pramreiter et al. [24] for a more complete picture of the mechanical performance.

## 21.4 Environmental Performance

The evaluation of the environmental performance of materials and products is a very complex topic including different possible approaches and indicators [167]. Therefore, the following LCA indicators [168, 169] (functional unit is “1 m<sup>3</sup> of the respective EWP”) were selected to provide an overview of the environmental performance of the established EWPs:

- Released carbon
- Stored carbon
- Net carbon storage potential (difference between “Stored carbon” and “Released carbon”)
- Global warming potential (GWP)
- Total primary energy.

### 21.4.1 Selected LCA Indicators

Considering remarks by Oneil et al. [170] it needs to be mentioned that the presented values in this section are subject to a certain degree of uncertainty for two main reasons. First, the values include two allocation principles (economic and mass allocation), with economic allocation usually leading to a higher environmental impact of the higher-value product [170]. This significantly influences the outcome, as market prices of the main and co-products can fluctuate greatly over time. Second, the number of values found in the literature varied greatly between the different products. In the case of NLT, PSL and SCR no literature could be found and for DLT only values from one environmental product declaration (EPD) are currently available [171]. A similar issue is present in regards to LSL, with only one available publication [157]. This is especially critical when different production regions (e.g. transport distances and energy mixes) and actuality of the data (e.g. age of the facility) are considered. This underlines the need to study the environmental performance of EWPs in more detail, broadening the investigated regions and raw materials. Furthermore, the underlying LCAs need to be kept up to date much more regularly, as factors like environmental regulations, energy provision and efficiency, data quality and availability are subject to more frequent changes than, for example, mechanical performance and can significantly change the outcome of the assessment. Nevertheless, Table 21.4 summarizes the values found in the literature for the discussed products.

Overall, one m<sup>3</sup> of EWP (cradle-to-gate) offers a net carbon storage potential of 705 kg CO<sub>2</sub> equiv. (192 kg C), by temporarily storing 1019 kg CO<sub>2</sub> equiv. (277 kg C) and releasing 314 kg CO<sub>2</sub> equiv. (85 kg C) into the air during production

(including provision of raw materials). These numbers are in line with assumptions made by Churkina et al. [1], which underlines the potential of EWPs to decarbonise the building sector. More specifically, PB (889 kg CO<sub>2</sub> equiv.), GLT (827 kg CO<sub>2</sub> equiv.) and DLT (823 kg CO<sub>2</sub> equiv.) offer the highest potential of the available EWPs, followed by LVL (781 kg CO<sub>2</sub> equiv.), LSL (751 kg CO<sub>2</sub> equiv.) and CLT (739 kg CO<sub>2</sub> equiv.). FB, OSB and PLY complete the available literature with 671 kg CO<sub>2</sub> equiv., 576 kg CO<sub>2</sub> equiv. and 533 kg CO<sub>2</sub> equiv. respectively. Currently, there are no values available for PSL and SCR. For material selection, the material with the highest net carbon storage potential should be selected.

In regards to GWP, the established EWPs, except for FB, show a rather homogeneous GWP with an average of 232 kg CO<sub>2</sub> equiv. per m<sup>3</sup> material. According to the available literature [131, 172], the high GWP of FB (487 kg CO<sub>2</sub> equiv.) is caused during the manufacturing stage (A3). They don't give a specific cause for this in the discussion, but it is safe to say that the heat required for the drying and (hot) pressing steps as well as the necessary adhesive play a key role. This is also supported by the total primary energy demand (see Table 21.4). While this value may seem very high, it corresponds to the general trend that the GWP increases with decreasing size of the intermediary. In contrary to net carbon storage potential, the goal ought to be to choose the EWP with the lowest GWP [kg CO<sub>2</sub> equiv.]. It should be noted here that GWP is one of the most discussed and accepted indicators in LCA, yet for a full picture, especially when materials from different processes are compared, all the evaluated LCA indicators need to be considered.

A closer look at the total primary energy demand [MJ] in Table 21.4 shows a significant difference on two levels. First, the provision of raw material has a significant influence on the reported total primary energy. On average, the raw material supply and transport stages, in LCA are typically referred to as A1 and A2 [168, 169], cause 49% (4037 MJ of 8178 MJ) of the total primary energy demand in EWPs. For the lumber-based products (GLT, CLT and DLT), these stages represent 66% (3320 MJ of 4997 MJ) of the total primary energy demand. In the veneer- (LVL and PLY) and strand-based products (OSB), they constitute 51% (3885 MJ of 7577 MJ) and 45% (3614 MJ of 8114 MJ) respectively and they account for 50% (3585 MJ of 7118 MJ) in PB and 28% (5540 MJ of 20,043 MJ) in FB. Second, the total primary energy demand for the manufacturing stage, in LCA typically referred to as A3, significantly increases with decreasing size of the intermediary. This is a well-known correlation in wood technology [25] and can be explained by the fact that the disintegration of roundwood into ever smaller intermediaries and the subsequent re-assembly to composites typically causes greater expenditure of energy and requires more energy-intensive auxiliary materials (e.g. synthetic adhesives and hot pressing instead of pressing at room temperature). It also explains the decreasing share of total primary energy demand for the provision of raw materials.

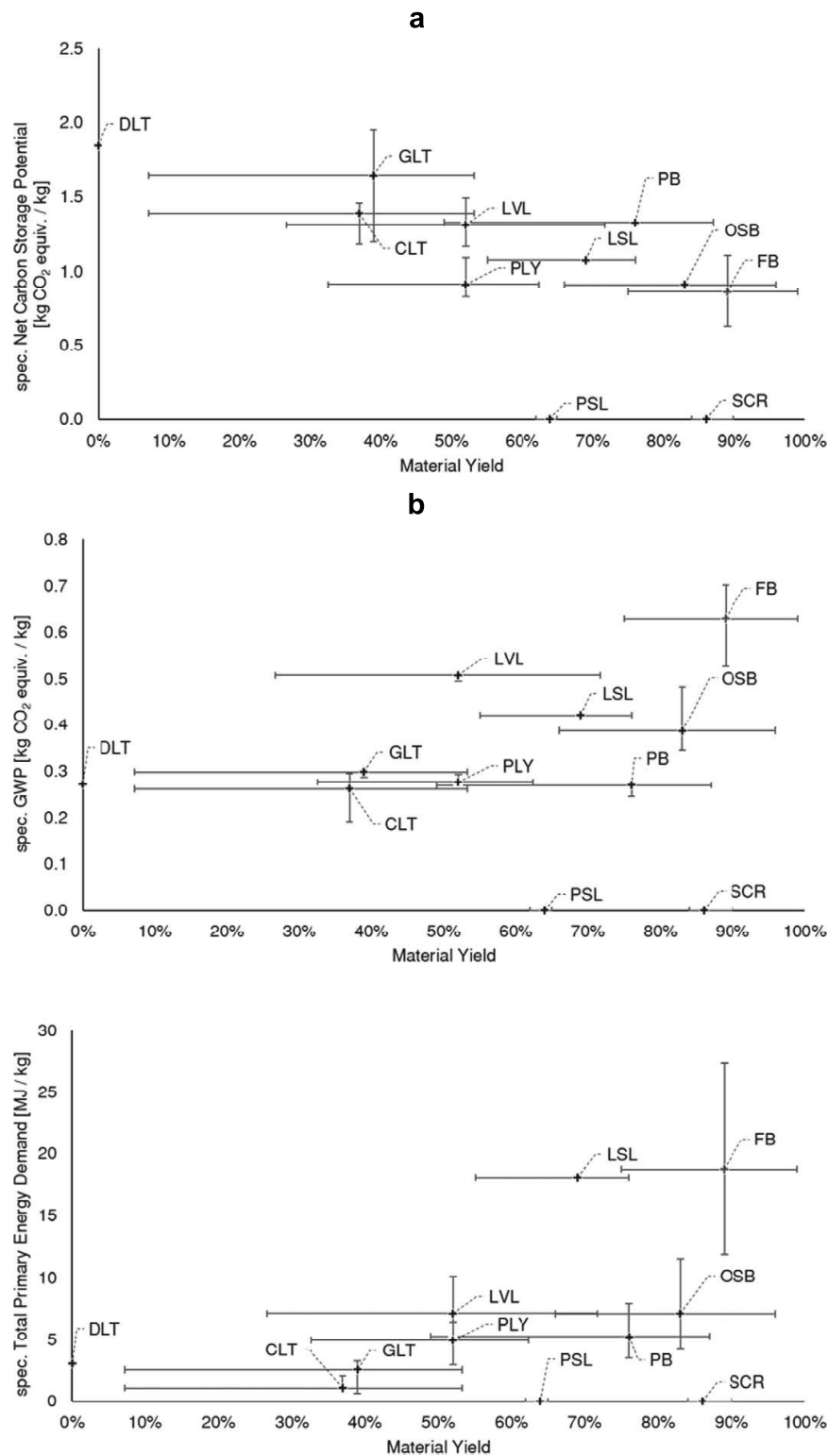
### 21.4.2 *Specific Environmental Performance*

Considering the typical functional unit of “1 m<sup>3</sup> EWP” and the different densities of the EWPs, a comparison based on a specific environmental performance similar to the specific mechanical performance is also of interest. Therefore, Fig. 21.21 shows the specific net carbon storage potential (Fig. 21.21a), specific GWP (Fig. 21.21b) and specific total primary energy demand (Fig. 21.21c) in relation to the respective material yield from Sect. 21.2. It needs to be mentioned that the density was taken from Table 21.3 instead of the respective LCA literature. This was done due to the fact, that not all references on LCA had a clear description of the corresponding density of the final product.

Taking a look at Fig. 21.21, an influence of the intermediary size is still visible, with smaller intermediaries leading to a higher environmental impact. LSL and FB seem to also have a particularly high total primary energy demand compared to the other EWPs. In regards to LSL, this high demand is caused by the log storage in ponds to heat the logs before processing and the subsequent stranding as well as the drying process. Furthermore, the typical panel thickness of 75 mm and above requires the use of a steam injection press in order to maintain suitable cycle times. However, as noted earlier this is only based on one publication [157]. Considering FB, the high energy demand is caused by the refining and drying process, which requires significant amounts of energy [126, 131].

### 21.4.3 *A Three-Dimensional Comparison of Established EWPs*

Together with the previous comparisons, it should become even clearer now that there is no such thing as one ideal EWP but rather a balance of factors that needs to be achieved. Therefore, the end of this section presents a three-dimensional comparison of established EWPs (see Fig. 21.22). This comparison serves as blueprint for a material selection process which incorporates the discussed material yield, mechanical performance as well as net carbon storage potential. For future investigations it should be extended with other mechanical properties, LCA indicators as well as not yet discussed indicators (e.g. production costs or recyclability) in mind. Especially, aspects like recyclability and different cost factors might further support a more balanced material selection. While it might be difficult to discuss the cost factor using reliable values from industry (not commonly accessible), the aspect of recyclability or circularity has gained significant interest in recent years. Therefore, the last section of this chapter will give a brief comment on the circularity aspects of the discussed EWPs.



**Fig. 21.21** Specific environmental performance of established EWPs versus respective material yield [%]. **a** Specific net carbon storage potential [kg CO<sub>2</sub> equiv./kg]. Numbers are based on LCA containing results on stored as well as released carbon. **b** Specific global warming potential (GWP) [kg CO<sub>2</sub> equiv./kg]. **c** Specific total primary energy demand [MJ/kg]. Based on values in Table 21.4 and densities from Table 21.3. Convert [kg CO<sub>2</sub> equiv.] to [C] using the molecular weight ratio of 44/12 CO<sub>2</sub>/C



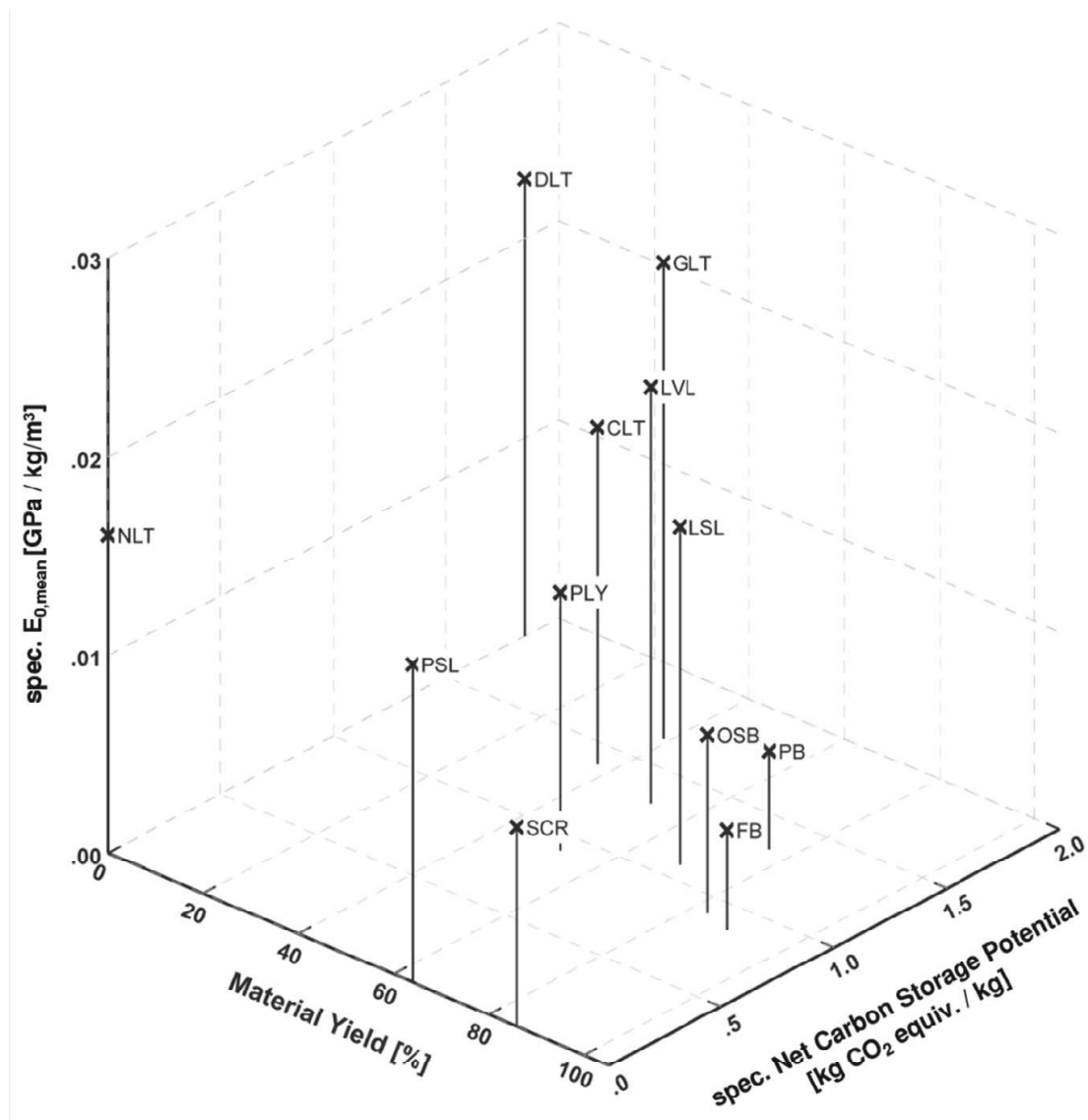
**Table 21.3** Mean modulus of elasticity ( $E_{0,\text{mean}}$ ) and raw density (density at a moisture content of typically 12–15%) [ $\text{kg/m}^3$ ] of established EWP

| EWP | $E_{0,\text{mean}}$ [GPa] |      |      | Raw density [ $\text{kg/m}^3$ ] |      |      |
|-----|---------------------------|------|------|---------------------------------|------|------|
|     | Min.                      | Avg. | Max. | Min.                            | Avg. | Max. |
| GLT | 8.3                       | 12.3 | 16.8 | 370                             | 521  | 828  |
| CLT | 5.5                       | 9    | 15   | 420                             | 532  | 698  |
| DLT | 5.4                       | 7    | 11.6 | 425                             | 441  | 459  |
| NLT | 6.9                       | 10.1 | 13.8 | 370                             | 446  | 510  |
| LVL | 7                         | 12.7 | 17.9 | 440                             | 596  | 800  |
| PLY | 0.5                       | 7.8  | 14   | 459                             | 582  | 680  |
| PSL | 4.2                       | 11.8 | 15.2 | 614                             | 727  | 820  |
| LSL | 9                         | 11.7 | 14.5 | 673                             | 698  | 722  |
| OSB | 4.9                       | 5.9  | 8.4  | 600                             | 631  | 660  |
| SCR | 2.1                       | 8.5  | 15.9 | 540                             | 826  | 1063 |
| PB  | 1.8                       | 3.2  | 5    | 600                             | 670  | 780  |
| FB  | 2.7                       | 3.5  | 5    | 600                             | 775  | 1080 |

**Table 21.4** Selected indicators for the environmental performance of  $1 \text{ m}^3$  EWP

| Indicator                                | Unit                        | GLT  | CLT  | DLT  | LVL  | PLY  | LSL    | OSB  | PB   | FB     |
|------------------------------------------|-----------------------------|------|------|------|------|------|--------|------|------|--------|
| Released carbon<br>(cradle-to-gate)      | [kg CO <sub>2</sub> equiv.] | 104  | 147  | 155  | 212  | 374  | 295    | 429  | 392  | 714    |
|                                          | [kg C]                      | 28   | 40   | 42   | 58   | 102  | 80     | 117  | 107  | 195    |
| Stored carbon<br>(cradle-to-gate)        | [kg CO <sub>2</sub> equiv.] | 931  | 886  | 978  | 952  | 866  | 1046   | 1033 | 1145 | 1334   |
|                                          | [kg C]                      | 254  | 242  | 262  | 260  | 236  | 285    | 282  | 312  | 364    |
| GWP<br>(cradle-to-gate)                  | [kg CO <sub>2</sub> equiv.] | 156  | 139  | 121  | 303  | 161  | 295    | 244  | 181  | 487    |
| Total primary energy<br>(cradle-to-gate) | [MJ/m <sup>3</sup> ]        | 5560 | 4588 | 4844 | 9275 | 5878 | –      | 8114 | 7118 | 20,043 |
| Total primary energy<br>(gate-to-gate)   | [MJ/m <sup>3</sup> ]        | 1310 | 580  | 1342 | 4250 | 3133 | 13,386 | 4473 | 3533 | 14,503 |

The numbers represent an average based on literature (taken from [24] and extended with literature from [126, 128, 131, 133, 138, 171, 172]) dealing with Life Cycle Assessment. In the case of stored carbon, a molecular weight ratio of 44/12 CO<sub>2</sub>/C was assumed



**Fig. 21.22** A three-dimensional comparison of Material yield [%], specific Modulus of Elasticity in the main load direction (spec.  $E_{0,mean}$ ) [GPa/kg/m<sup>3</sup>] and specific Net Carbon Storage Potential [kg CO<sub>2</sub> equiv./kg] of established EWPs. The values are based on average values from the previous sections. A value of zero indicates that there is no available literature for the respective property

## 21.5 A Comment on Circularity

Circularity in engineering and architecture has become an important consideration for sustainable design in recent years [173]. Beyond the initial embodied emissions in new products, an increased life span and future reuse of building materials and components can greatly increase the carbon and emission efficiency of new products [174]. Building designs or material systems conceived for an end-of-life scenario with planned deconstruction or reuse (DfD—Design for Deconstruction) have greater chances of being reused or recycled in the future. The selection of EWPs for a new

building design has a large influence on the future resource, process and environmental efficiency of their reuse or recycling, as they all have different potentials for reuse of the raw materials they are made from [175].

Ideally, a building is designed for a longer life cycle than typically provided by building codes (50–100 years) in order to extend the carbon storage and best utilize the spent carbon and emissions for the construction of the building. Next, adaptive reuse of the building can further extend its life cycle, by bringing upgrades that can serve its new performance requirements (such as structural integrity or thermal performance) and accommodate for the new use of the space. If the building has to be taken down, building materials or components can be reused or recycled to feed into new buildings. Otherwise, the product's intermediary can be reused in new EWPs as salvaged intermediary (e.g. salvaged lumber).

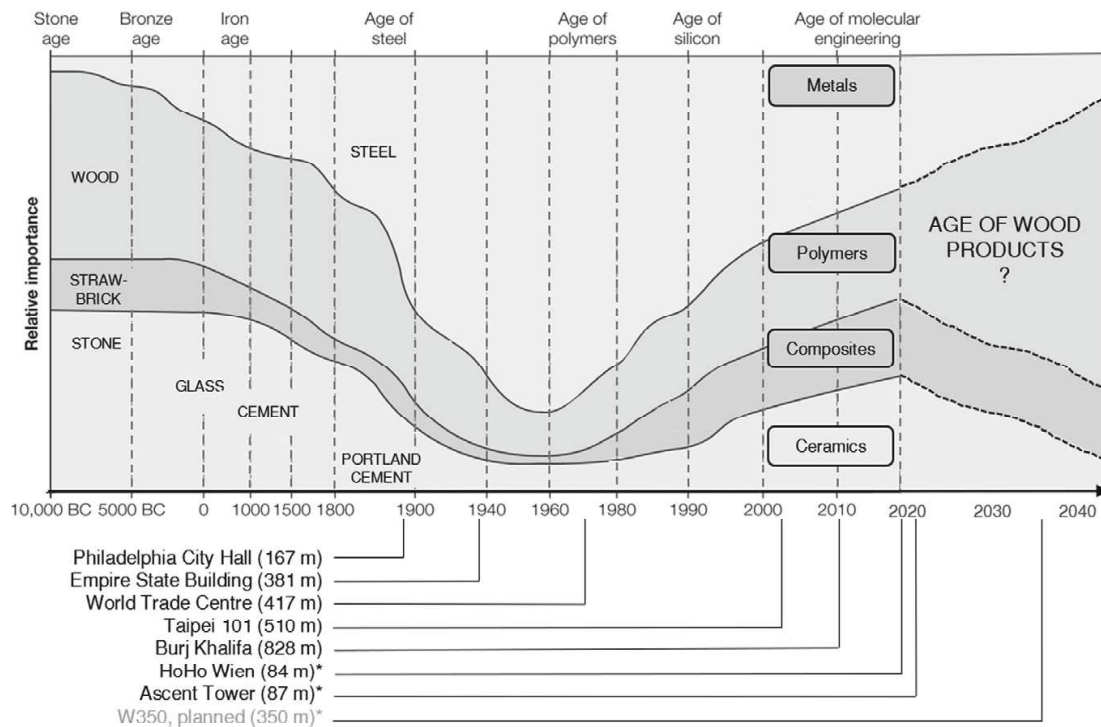
As shown in the previous sections, the selection of suitable EWPs balances a few parameters, such as structural versus environmental performance and material yield. Circularity and reuse of EWPs are currently less quantifiable and hard to include in the analysis but predictions are emerging from current research and references from the past [176, 177]. EWPs made with current adhesive technology might have a lower potential for efficient reuse of the intermediary when compared to EWPs assembled with mechanical fasteners like DLT or NLT. Denailing NLT panels or removing dowels from DLT panels allows for a simple recovery of the product's lumber. Glued products, if not reused as a whole component, will need to be resawn and resurfaced for the production of new EWPs, bringing them back into the same process flow with associated processing losses. Furthermore, information about the durability of the performance of glue over many building life cycles has not been demonstrated. Historical buildings built out of wood demonstrates the durability of the wood fiber itself, as a long-term structural material, like the Hōryū-ji temple in Nara, Japan that has been in use for the last 1300 years.

These predictions don't consider future developments in adhesives and disassembly technologies. However, given the increase appeal for wood-based construction such as mass timber around the world in its current technological state, these considerations should be weighted in to increase the long-term resources efficiency of EWPs.

## 21.6 Concluding Remarks

The widespread application of Engineered Wood Products (EWPs) for not only small residential but also medium to high rise buildings will be key in order to decarbonize the global construction sector. The recent completion of ever higher building projects (see Fig. 21.23) utilizing selected EWPs as one of the main structural components has already shown the advantages of wood-based products along with existing materials like steel and concrete.

However, the potential demand for built environments in the future could put increasing pressure on the world's forests and may jeopardise the sustainable supply



**Fig. 21.23** Past, present and potential future importance of common material categories used in different disciplines of engineering (adapted with permission from [7], copyright by Elsevier).  
 \*Engineered Wood Products as structural components

of sufficient raw materials. Therefore, the construction industry needs to consider the full variety of EWPs and incorporate aspects like resource efficiency, environmental and mechanical performance as well as circularity into their decision process. This chapter summarized this information and shined a light on the currently occurring by-products during production and provided base-values for material selection, not only in construction, but also for other potential applications in the future. It is important to emphasise here that the comparisons should not be seen as a ranking, but rather a demonstration of a potential material-first approach to wood as a raw material and how the by-products of one EWP can be and partly already are the raw material for another. While there are certain aspects of the wood-based value chain that need critical discussion and further research, the authors firmly believe that the shift towards a climate-resilient society requires the sustainably harvested resources of our forests, which are then carefully handled and utilized in long-lasting products. After a century characterised by mainly non-renewable building materials (see Fig. 21.23), the twenty-first century seems to mark the beginning of the age of wood-based building products.

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## References

1. G. Churkina, A. Organschi, C.P.O. Reyer, A. Ruff, K. Vinke, Z. Liu, B.K. Reck, T.E. Graedel, H.J. Schellnhuber, Buildings as a global carbon sink. *Nat. Sustain.* **3**, 269 (2020)
2. M. Pramreiter, T. Nenning, L. Malzl, J. Konnerth, *A plea for the efficient use of wood in construction*. *Nat. Rev. Mater.* (2023)
3. L. Barham et al., Evidence for the earliest structural use of wood at least 476,000 years ago. *Nature* **622**, 107 (2023)
4. OECD, *Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences* (2019)
5. A.L.S. Bais, C. Lauk, T. Kastner, K. Erb, Global patterns and trends of wood harvest and use between 1990 and 2010. *Ecol. Econ.* **119**, 326 (2015)
6. A.R. Martin, M. Doraisami, S.C. Thomas, Global patterns in wood carbon concentration across the world's trees and forests. *Nat. Geosci.* **11**, 915 (2018)
7. M.F. Ashby, *Materials Selection in Mechanical Design* (Butterworth-Heinemann, Oxford, 2011)
8. T.D. Searchinger, T. Beringer, B. Holtsmark, D.M. Kammen, E.F. Lambin, W. Lucht, P. Raven, J.P. van Ypersele, Europe's renewable energy directive poised to harm global forests. *Nat. Commun.* **9**, 10 (2018)
9. U. Mantau, *Wood Flows in Europe (EU 27)*. Project Report Celle 2012 24 (2012)
10. European Commission, *Sankey Diagrams of Woody Biomass Flows in the EU—2021 Release* (2021)
11. I. Alberdi et al., Assessing forest availability for wood supply in Europe. *For. Policy Econ.* **111** (2020)
12. B.J.W. Lerink et al., *How much wood can we expect from European forests in the near future?* *For.: Int. J. For. Res.* **96**, 434 (2023)
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15. A. Mishra, F. Humpenöder, G. Churkina, C.P.O. Reyer, F. Beier, B.L. Bodirsky, H.J. Schellnhuber, H. Lotze-campen, A. Popp, Land use change and carbon emissions of a transformation to timber cities. *Nat. Commun.* **13** (2022)
16. V. Augiseau, S. Barles, Studying construction materials flows and stock: a review. *Resour. Conserv. Recycl.* **123**, 153 (2017)
17. E. Leszczyszyn et al., The future of wood construction: opportunities and barriers based on surveys in Europe and Chile. *Sustainability* **14** (2022)
18. L. Orozco, H. Svatoš-Ražnjević, H.J. Wagner, M. Abdelaal, F. Amtsberg, D. Weiskopf, A. Menges, Advanced timber construction industry: a quantitative review of 646 global design and construction stakeholders. *Buildings* **13** (2023)
19. C. Mergel, K. Menrad, T. Decker, Which factors influence consumers' selection of wood as a building material for houses? *Can. J. For. Res.* (2024)

20. M. Riala, L. Ilola, Multi-storey timber construction and bioeconomy—barriers and opportunities. *Scand. J. For. Res.* **29**, 367 (2014)
21. P. Blanchet, C. Perez, M.R. Cabral, Wood building construction: trends and opportunities in structural and envelope systems. *Curr. For. Rep.*
22. FAO, FAOSTAT: Forest Production and Trade. <https://www.fao.org/faostat/en/#compare>
23. FAO, Global Production and Trade in Forest Products in 2020. <https://www.fao.org/forestry/statistics/80938/en/>
24. M. Pramreiter, T. Nenning, C. Huber, U. Müller, B. Kromoser, P. Mayencourt, J. Konnerth, A review of the resource efficiency and mechanical performance of commercial wood-based building materials. *Sustain. Mater. Technol.* **38** (2023)
25. P. Niemz, A. Teischinger, D. Sandberg, *Springer Handbook of Wood Science and Technology* (Springer International Publishing AG, 2023)
26. M. Dunky, P. Niemz, *Holzwerkstoffe Und Leime* (Springer, Berlin Heidelberg, 2002)
27. M.P. Ansell, *Wood Composites* (Woodhead Publishing, Cambridge, 2015)
28. J.C.F. Walker, *Primary Wood Processing—Principles and Practice* (Springer, Dordrecht, 2006)
29. A. Wagenführ, F. Scholz, *Taschenbuch der Holztechnik, 2, aktual* (Carl Hanser Verlag GmbH & Co, KG, 2012)
30. T.G. Williamson, *APA Engineered Wood Handbook* (McGraw-Hill, 2002)
31. Forests Products Laboratory, *Wood Handbook—Wood as Engineering Material* (U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 2021)
32. R. Sathre, L. Gustavsson, Process-based analysis of added value in forest product industries. *For. Policy Econ.* **11**, 65 (2009)
33. M.A. Fonseca, *The Measurement of Roundwood Methodologies and Conversion Ratios* (CABI Publishing, 2005)
34. E.R. Thomas, N.D. Bennett, An analysis of the differences among log scaling methods and actual log volume. *For. Prod. J.* **67**, 250 (2017)
35. FAO, *Forest Product Conversion Factors* (2020)
36. R. Wagenführ, A. Wagenführ, *Holzatlas* (Carl Hanser Verlag, München, 2022)
37. FAO, *Forest Products Definitions* (2016)
38. ISO 24294, *Timber—Round and Sawn Timber—Vocabulary*
39. EN 844, *Round and Sawn Timber—Terminology*
40. ISO 13059, *Round Timber—Requirements for the Measurement of Dimensions and Methods for the Determination of Volume* (2011)
41. EN 1309-2, *Round and Sawn Timber—Method of Measurement of Dimensions. Part 2: Round Timber—Requirements for Measurement and Volume Calculation Rules* (2006)
42. EN 1927-1 *Qualitative Classification of Softwood Round Timber. Part 1: Spruces and Firs*
43. EN 1927-2, *Qualitative Classification of Softwood Round Timber. Part 2: Pines*
44. EN 1927-3, *Qualitative Classification of Softwood Round Timber. Part 3: Larches and Douglas Fir*
45. EN 1316-2, *Hardwood Round Timber—Qualitative Classification. Part 2: Poplar*
46. EN 1316-1, *Hardwood Round Timber—Qualitative Classification. Part 1: Oak and Beech*
47. EN 1309-3, *Round and Sawn Timber—Methods of Measurements. Part 3: Features and Biological Degradations*
48. J. Hildebrandt, N. Hagemann, D. Thrän, The contribution of wood-based construction materials for leveraging a low carbon building sector in Europe. *Sustain. Cities Soc.* **34**, 405 (2017)
49. R. Sikkema, D. Styles, R. Jonsson, B. Tobin, K.A. Byrne, A market inventory of construction wood for residential building in Europe—in the light of the green deal and new circular economy ambitions. *Sustain. Cities Soc.* **90** (2023)
50. Wood Products Council, *Snapshot of Mass Timber Projects in the U.S.* <https://www.woodworks.org/resources/mapping-mass-timber/>
51. M. Hanewinkel, D.A. Cullmann, M.J. Schelhaas, G.J. Nabuurs, N.E. Zimmermann, Climate change may cause severe loss in the economic value of European forest land—supplementary information. *Nat. Clim. Chang.* **3**, 203 (2013)



52. W. Thuiller et al., Predicting global change impacts on plant species' distributions: future challenges. *Perspect. Plant Ecol. Evol. Syst.* **9**, 137 (2008)
53. T. Gschwanter et al., Harmonisation of stem volume estimates in European National Forest Inventories. *Ann. For. Sci.* **76** (2019)
54. H. Spelter, Conversion of board foot scaled logs to cubic meters in Washington State, 1970–1998. *For. Prod. Lab. FPL-GTR-13* (2002)
55. P. Yang, B.M. Jenkins, Wood residues from Sawmills in California. *Biomass Bioenergy* **32**, 101 (2008)
56. C.E. Keegan III, T.A. Morgan, K.A. Blatner, J.M. Daniels, Trends in lumber processing in the Western United States. Part II: overrun and lumber recovery factors. *For. Prod. J.* **60**, 140 (2010)
57. K.A. Blatner, C.E. Keegan, J.M. Daniels, T.A. Morgan, Trends in lumber processing in the Western United States. Part III: residue recovered versus lumber produced. *For. Prod. J.* **62**, 429 (2012)
58. P.H. Steele, Factors determining lumber recovery in sawmilling. *For. Prod. Lab. FPL-39*, (1984)
59. S. Torno, M. Knorz, J. van de Kuilen, Supply of beech lamellas for the production of glued laminated timber, in *International Scientific Conference on Hardwood Processing, ISCHP* 210 (2013)
60. P.H. Steele, F.G. Wagner, K.E. Skog, Regional softwood sawmill processing variables as influenced by productive capacity. *For. Prod. Lab. FPL-RP-504* (1991)
61. K.A. Kilborn, Lumber recovery studies of Alaska Sawmills, 1997 to 1999. *USDA For. Serv. PNW-GTR-54* (2002)
62. D. Smorfit, S. Harrison, J. Herbohn, Portable sawmills in a high-value rainforest cabinet timber industry in North Queensland. *Small-Scale For. Econ., Manag. Policy* **2**, 21 (2003)
63. M.W. Wade, S.H. Bullard, P.H. Steele, P.A. Araman, Estimating hardwood sawmill conversion efficiency based on sawing machine and log characteristics. *For. Prod. J.* **42**, 21 (1992)
64. T.D. Fahey, R.O. Woodfin, The cubics are coming: predicting product recovery from cubic volume. *J. For.* **74** (1976)
65. A. Clark III., Sawmill residue yields from yellow-poplar saw logs. *For. Prod. J.* **26**, 23 (1976)
66. G.Y. Jeong, J.J. Lee, H. Yeo, S.S. Lee, Predicting lamina yield from logs of different diameters for cross laminated timber production. *J. Korean Wood Sci. Technol.* **44**, 809 (2016)
67. G.R. Middleton, B.D. Munri, *Second-Growth Western Hemlock: Product Yields & Attributes Related to Stand Density* (Forintek Canada Corp., 2001)
68. P.A. Shenga, P. Bomark, O. Broman, D. Sandberg, Simulation of tropical hardwood processing—sawing methods, log positioning, and outer shape. *Bioresources* **10**, 7640 (2015)
69. S.-Y. Zhang, Q.-J. Tong, Modeling lumber recovery in relation to selected tree characteristics in jack pine using sawing simulator Optitek. *Ann. For. Sci.* **62**, 219 (2005)
70. I. Pinto, A. Usenius, T. Song, H. Pereira, Sawing simulation of maritime pine (*Pinus Pinaster* Ait.) stems for production of heartwood containing components. *For. Prod. J.* **55**, 88 (2005)
71. B. Perkins, R.L. Smith, B. Bond, Solid wood and residue yield analysis of small-diameter red oak logs. *For. Prod. J.* **58**, 97 (2008)
72. F.P. Vergara, C.D. Palma, H. Sepúlveda, A comparison of optimization models for lumber production planning. *Bosque* **36**, 239 (2015)
73. P.C. Kersavage, M. Savsar, R.J. Meimban, A mathematical analysis to determine the volume of residues and lumber produced in the sawmill edging process. *Wood Fiber Sci.* **22**, 271 (1990)
74. C.G. Lundahl, A. Grönlund, Increased yield in sawmills by applying alternate rotation and lateral positioning. *For. Prod. J.* **60**, 331 (2010)
75. P. Hamner, M. White, P. Araman, The effect of curve sawing two-sided cants from small-diameter hardwood sawlogs on lumber and pallet part yields. *For. Prod. J.* **56**, 80 (2006)
76. U. Buehlmann and R. E. Thomas, Estimating component yield for CLT production, in *IEEE International Conference on Industrial Engineering and Engineering Management* (2017), pp. 470–474

77. G.Y. Jeong, J.J. Lee, H. Yeo, J.P. Hong, H.K. Kim, W.T. So, W.Y. Chung, Optimized lamina size maximizing yield for cross laminated timber using domestic trees. *J. Korean Wood Sci. Technol.* **41**, 141 (2013)
78. P. Schlotzhauer, A. Kovryga, L. Emmerich, S. Bollmus, J.W. Van de Kuilen, H. Militz, Analysis of economic feasibility of ash and maple lamella production for glued laminated timber. *Forests* **10** (2019)
79. J. Edlund, H. Lindström, F. Nilsson, M. Reale, Modulus of elasticity of Norway Spruce saw logs vs. structural lumber grade. *Holz Als Roh - Und Werkstoff* **64**, 273 (2006)
80. C. Fischer, G.I. Vestøl, A. Øvrum, O.A. Høibø, Pre-sorting of Norway Spruce structural timber using acoustic measurements combined with site-, tree- and log characteristics. *Eur. J. Wood Wood Prod.* **73**, 819 (2015)
81. A. Rais, E. Ursella, E. Vicario, F. Giudiceandrea, The use of the first industrial X-ray CT scanner increases the lumber recovery value: case study on visually strength-graded Douglas-fir timber. *Ann. For. Sci.* **74**, 1 (2017)
82. A. Ranta-Maunus, *Strength of European Timber—Part 1. Analysis of Growth Areas Based on Existing Test Results* (VTT Publications, 2009)
83. A. Ranta-Maunus, J.K. Denzler, P. Stapel, *Strength of European Timber—Part 2. Properties of Spruce and Pine Tested in Gradewood Project* (VTT Publications, 2011)
84. M. Green, P. Lister, F. Brüchert, F. Giudiceandrea, A. Katsevich, J. Oja, K.-J. Johansson, *From Imagining to Imaging—High Speed 3D Scanning of Logs*, in *Symposium 2016: The Marcus Wallenberg Prize* (2016)
85. K. Lan, S.S. Kelley, P. Nepal, Y. Yao, Dynamic life cycle carbon and energy analysis for cross-laminated timber in the Southeastern United States. *Environ. Res. Lett.* **15**, (2020)
86. R.D. Bergman, Gate-to-gate life-cycle inventory on hardwood sawmills in the Northeastern Region of the United States By, Master Thesis, University of Wisconsin (2007)
87. R.D. Bergman, S.A. Bowe, Environmental impact of manufacturing softwood lumber in Northeastern and North Central United States. *Wood Fiber Sci.* **42**, 67 (2010)
88. R.D. Bergman, S.A. Bowe, Life-cycle inventory of manufacturing hardwood lumber in Southeastern US. *Wood Fiber Sci.* **44**, 71 (2012)
89. ASMI, *A Cradle-to-Gate Life Cycle Assessment of Canadian Surfaced Dry Softwood Lumber* (2018)
90. ASMI, *A Cradle-to-Gate Life Cycle Assessment of Eastern Canadian Surfaced Dry Softwood Lumber* (2018)
91. P. Döring, S. Glasenapp, U. Mantau, *Rohstoffmonitoring Holz - Sägeindustrie 2015 Einschnitt- Und Produktionsvolumen* (2017)
92. M.R. Milota, C.D. West, I.D. Hartley, Gate-to-gate life-cycle inventory of softwood lumber production. *Wood Fiber Sci.* **37**, 47 (2005)
93. Y. Han, J.H. Park, Y.S. Chang, Y. Park, J.K. Oh, J.P. Hong, J.J. Lee, H. Yeo, The effect of controlling the drying distortion of laminas on the production yield of cross-laminated timber (CLT) using *Larix Kaempferi* Wood. *Eur. J. Wood Wood Prod.* **74**, 519 (2016)
94. R.O. Woodfin, Wood losses in plywood production—four species. *For. Prod. J.* **23**, 98 (1973)
95. Raute Group, *Data-Driven Veneer, Plywood and LVL Production—Improving the Production Through Intelligence*
96. J.W. Funck, M.G. Babb, Green veneer recovery as influenced by clipping strategies. *For. Prod. J.* **37**, 23 (1987)
97. Raute Group, *5 Ways to Improve Yield.*
98. M. Hanewinkel, D.A. Cullmann, M.J. Schelhaas, G.J. Nabuurs, N.E. Zimmermann, Climate change may cause severe loss in the economic value of European Forest Land. *Nat. Clim. Chang.* **3**, 203 (2013)
99. UNECE and FAO, *The European Forest Sector Outlook Study II* (2011)
100. A.A. Marra, *Technology of Wood Bonding: Principles in Practice* (Van Nostrand Reinhold, New York, 1992)
101. ÖNORM EN 14080, *Holzbauwerke - Brettschichtholz Und Balkenschichtholz - Anforderungen*

102. R. Brandner, G. Flatscher, A. Ringhofer, G. Schickhofer, A. Thiel, Cross laminated timber (CLT): overview and development. *European Journal of Wood and Wood Products* **74**, 331 (2016)
103. ÖNORM EN 16351, *Holzbauwerke - Brettspertholz - Anforderungen*
104. ESR-4069, *ICC-ES Evaluation Report: Dowel Laminated Timber (DLT)* (2022)
105. ETA-13/0785, *Solid Wood Slab Element—Element of Dowel Jointed Timber to Be Used as a Structural Element in Buildings* (2018)
106. ETA-18/0960, *Vorgefertigte Holzbauelemente- Elemente Aus Mechanisch Verbundenen Kanthölzern Für Tragende Bauteile in Gebäuden* (2018)
107. T. Bell, *A Detailed Investigation into the Engineering Properties and Challenges Affecting the Potential Introduction of a UK Grown Dowel-Laminated Timber Floor Panel into the Domestic Construction Market*, Ph.D. Thesis (2018)
108. ETA-11/0338, *Solid Wood Slab Element—Element of Dowel Jointed Timber Boards to Be Used as a Structural Element in Buildings* (2017)
109. BSLC, *The Nail-Laminated Timber Design and Construction Guide* (2017)
110. BSLC, *Nail-Laminated Timber Design & Constr Uction Guide I v1.0* (2017)
111. PR-L325(C), *FRERES Mass Ply Panel (MPP), and Mass Ply Lam (MPL) Beams and Columns*, (2023)
112. ÖNORM EN 313-2, *Plywood Classification and Terminology—Part 2: Terminology* (2000)
113. Finnish Forest Industries Federation, *Handbook of Finnish Plywood* (2022)
114. ESR-1387, *Structural Composite Lumber and Oriented Strand Board*
115. EN 12369-1, *Holzwerkstoffe - Charakteristische Werte Für Die Berechnung Und Bemessung von Holzbauwerken - Teil 1: OSB, Spanplatten Und Faserplatten*
116. ETA-13/0784, *Swiss Krono Magnumboard*, Deutsches Institut für Bautechnik
117. S.C. Kitchens, T.L. Amburgey, H. Michael Barnes, R.D. Seale, Mechanical and durability properties of steam-pressed scrim lumber. *Bioresources* **11**, 5343 (2016)
118. Mississippi State University, *TimTek Process*. <https://www.cfr.msstate.edu/timtek/process.asp>
119. T. Joščák, A. Teischinger, U. Müller, R. Mauritz, *Production and Material Performance of Long—Strand Wood Composites*. *Wood Research*
120. H. Michael, B.R. Dan, S.J.M. Linton, Steam-pressed scrim lumber (SPSL), in *Proceedings of the International Convention of Society of Wood Science and Technology* (2010)
121. Swedish Wood, *Swedish Glulam—New Possibilities for Halls, Arenas, Commercial Buildings and Bridges* (2012)
122. Studiengemeinschaft Holzleimbau e.V., *Sternstunden Des Ingenieurholzbaus*, 2017
123. Studiengemeinschaft Holzleimbau e.V., *Aufbauen, Umbauen, Nachverdichten: Neuer Holzbau in Bestand Und Fläche*, (2023)
124. V. Çavuş, A.Ç. Konukçu, Innovative approach for engineered wood products: Scrimber, in *Academic Research and Reviews in Agriculture, Forestry and Aquaculture Sciences*, edited by A. Atik (Duvar Publishing, 2021)
125. ETA-18/0960, *Brettstapel(Element), Dübelholz/Element), Dowel Laminated Timber, DLT, DowelLam*
126. S.K. Diederichs, 2010 Status Quo for life cycle inventory and environmental impact assessment of wood-based panel products in Germany. *Wood Fiber Sci.* **46**, 340 (2014)
127. T. Enters, *Trash or Treasure? Logging and Mill Residues in Asia and the Pacific*. FAO
128. ASMI, *A Cradle-to-Gate Life Cycle Assessment of Canadian Particleboard- 2013 Update Final*, (2018)
129. H. Kouchaki-Penchah, M. Sharifi, H. Mousazadeh, H. Zarea-Hosseiniabadi, A. Nabavi-Pelesaraei, Gate to gate life cycle assessment of flat pressed particleboard production in Islamic Republic of Iran. *J. Clean. Prod.* **112**, 343 (2016)
130. B. Rivela, A. Hospido, M.T. Moreira, G. Feijoo, Life cycle inventory of particleboard: a case study in the wood sector. *Int. J. Life Cycle Assess.* **11**, 106 (2006)
131. R. Bergman E. Oneil, *Cradle-To-Gate Life Cycle Assessment of North American Hardboard and Engineered Wood Siding and Trim Production* (2016)

132. U. Saal, H. Weimar, U. Mantau, Wood processing residues. *Adv. Biochem. Eng. Biotechnol.* **166**, 27 (2019)
133. ASMI, A cradle-to-gate life cycle assessment of Canadian medium density fibreboard (mdf), in *Review of 3D Printing and Potential Red Meat Applications*, vol. 1 (2013)
134. H. Kouchaki-Penchah, M. Sharifi, H. Mousazadeh, H. Zarea-Hosseinabadi, Life cycle assessment of medium-density fiberboard manufacturing process in Islamic Republic of Iran. *J. Clean. Prod.* **112**, 351 (2016)
135. B. Rivela, M.T. Moreira, G. Feijoo, Life cycle inventory of medium density fibreboard. *Int. J. Life Cycle Assess.* **12**, 143 (2007)
136. R.E. Thomas, U. Buehlmann, Using low-grade hardwoods for CLT production: a yield analysis, in *6th International Scientific Conference on Hardwood Processing (ISCHP2017)*, 199 (2017)
137. R.D. Bergman, S. Alanya-Rosenbaum, Cradle-to-gate life-cycle assessment of laminated veneer lumber production in the United States. *For. Prod. J.* **67**, 343 (2016)
138. D. Kaestner, *Compile a Life Cycle Assessment of the OSB and Plywood Industries in the U.S. & Analysis of the OSB and Plywood Industries in the U.S. Based on a Life Cycle Assessment* (2017)
139. M.W. Feng, R.M. Knudson, Effect of Log Rehydration on quality of OSB Strands manufactured from Beetle-Killed Lodgepole Pine. *For. Prod. J.* **57**, 35 (2007)
140. R.J. Ross, *Wood Handbook—Wood as an Engineering Material* (Forest Products Laboratory, Madison, WI, 2010)
141. F.F.P. Kollmann, W.A. Cote, *Principles of Wood Science and Technology* (Springer-Verlag, Berlin, Heidelberg, 1968)
142. ASMI, *A Cradle-to-Gate Life Cycle Assessment of Canadian Glulam Manufacture* (2018)
143. M.E. Puettmann, J.B. Wilson, Gate-to-gate life-cycle inventory of glued-laminated timbers production. *Wood Fiber Sci.* **37**, 99 (2005)
144. T. Bowers, M.E. Puettmann, I. Ganguly, I. Eastin, Cradle-to-gate life-cycle impact analysis of glued-laminated (Glulam) timber: environmental impacts from Glulam produced in the US Pacific Northwest and Southeast. *For. Prod. J.* **67**, 368 (2017)
145. K. Brandt, A. Wilson, D. Bender, J.D. Dolan, M.P. Wolcott, Techno-economic analysis for manufacturing cross-laminated timber. *BioResources* **14**, 7790 (2019)
146. M. Fredriksson, P. Bomark, O. Broman, A. Grönlund, Using small diameter logs for cross-laminated timber production. *BioResources* **10**, 1477 (2015)
147. ASMI, *A Life Cycle Assessment of Cross-Laminated Timber Produced in Canada*
148. G. Jauk, *CLT | Special*, *Holzkurier* (2020)
149. M. Puettmann, A. Sinha, I. Ganguly, *CORRIM Report—Life Cycle Assessment of Cross Laminated Timber Produced in Oregon* (2017)
150. C.X. Chen, F. Pierobon, I. Ganguly, Life cycle assessment (LCA) of cross-laminated timber (CLT) produced in Western Washington: the role of logistics and wood species mix. *Sustainability (Switzerland)* **11** (2019)
151. D. Mumovic, M. Santamouris, *A Handbook of Sustainable Building Design and Engineering: An Integrated Approach to Energy, Health and Operational Performance*, vol. 10 (2009)
152. J. Cremers, *Building openings construction manual—windows vents exterior doors* (2016)
153. R.D. Bergman, S. Alanya-Rosenbaum, Assessment of Laminated Veneer Lumber (LVL) Produced in the Pacific Northwest Region of the United States
154. J.B. Wilson, E.R. Dancer, Gate-to-gate life-cycle inventory of laminated veneer lumber production. *Wood Fiber Sci.* **37**, 114 (2005)
155. T. L. Laufenberg, Parallel-laminated Veneer: processing and performance research review. *For. Prod. J.* **33**, 21 (1983)
156. S. Smulski, *Engineered Wood Products: A Guide for Specifiers, Designers & Users* (Pfs Research Foundation, 1997)
157. CORRIM and WoodLife Environmental Consultants, *Cradle to Gate Life Cycle Assessment of North American Laminated Strand Lumber Production* (2015)

158. P. Stiglbauer, T.E. Conners, S. Banerjee, Influence of knife angle and ambient temperature on fines generation from flakers. *For. Prod. J.* **56**, 86 (2006)
159. E. Benetto, M. Becker, J. Welfring, Life cycle assessment of oriented strand boards (OSB): from process innovation to ecodesign. *Environ. Sci. Technol.* **43**, 6003 (2009)
160. TimTek LLC, *TimTek: The Process*. <http://timtekllc.com/process.html> (Webpage not available anymore)
161. T. Nenning, A. Tockner, J. Konnerth, W. Gindl-Altmutter, M. Grabner, C. Hansmann, S. Lux, M. Pramreiter, Variability of mechanical properties of hardwood branches according to their position and inclination in the tree. *Constr. Build. Mater.* **419** (2024)
162. D. Parker, A. Wood, *The Tall Buildings Reference Book* (Routledge, Oxon, 2013)
163. ÖNORM EN 1995-1-1, *Eurocode 5: Design of Timber Structures Part 1: General—Common Rules and Rules for Buildings*
164. M. Sarkisian, *Designing Tall Buildings: Structure as Architecture* (2016)
165. EN 338, *Bauholz Für Tragende Zwecke - Festigkeitsklassen*
166. EN 14374, *Holzbauwerke - Furnierschichtholz Für Tragende Zwecke - Anforderungen*
167. B.G. Hermann, C. Kroeze, W. Jawjit (2007) Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. *J. Clean Prod.* **15**, 1787 (2007)
168. ISO 14044, *Environmental Management—Life Cycle Assessment—Requirements and Guidelines* (2021)
169. ISO 14067, *Greenhouse Gases—Carbon Footprint of Products—Requirements and Guidelines for Quantification* (2019)
170. E. Oneil, R.D. Bergman, M.E. Puettmann, CORRIM: Forest Products Life-Cycle Analysis Update Overview. *For. Prod. J.* **67**, 308 (2017)
171. EPD157, *EPD for Dowel Laminated Timber Produced by StructureCraft in Abbotsford*. BC Canada (2020)
172. M. Puettmann, J. Salazar, *Cradle to Gate Life Cycle Assessment of North American Medium Density Fiberboard Production* (2019)
173. E. Stricker, G. Brandi, A. Sonderegger, Baubüro in Situ AG, Zirkular GmbH, M. Angst, B. Buser, and M. Massmünster, *Reuse in Construction: A Compendium of Circular Architecture* (Park Books, 2022).
174. D. Densley Tingley, B. Davison, *Developing an LCA methodology to account for the environmental benefits of design for deconstruction*. *Build. Environ.* **57**, 387 (2012)
175. V. Nicholson, A. Miatto, *Architects as catalysts of reuse in construction*. *Nat. Cities* **1:3** **1**, 179 (2024)
176. C. De Wolf, E. Hoxha, C. Fivet, Comparison of environmental assessment methods when reusing building components: a case study. *Sustain. Cities Soc.* **61**, 102322 (2020)
177. C. Totman, *The Green Archipelago: Forestry in Pre-industrial Japan* (University of California Press, 1989).