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# Supply of wood processing residues – a basic calculation approach and its application on the example of wood packaging

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ABSTRACT

Waste reduction, recycling and increased material efficiency are key objectives in complex industrial ecology. The wood processing industry also aims at a more intensive resource recovery and usable residual volumes. Important volumes of wood processing residue potentials can be found at the EU level. However, to date no reliable calculation approach has been established. To fill the information gap, this study presents an approach for calculating the supply of wood processing residues. The methodological approach follows the concept of a material flow analysis. We quantify the material flows based on product-specific conversion factors and the coefficients of material efficiency. This paper intends to develop a calculation approach based on existing statistical data from official classifications such as Prodcom. We perform the calculation approach on standardised wood packaging products at the European level. The calculated supply of wood processing residues the European Union in 2018 was 29.7 million $m^3$f with a total material input of about 70.8 million $m^3$f and a production volume of 40.8 million $m^3$f. A maximum volume of 29.6 million $m^3$f sawnwood is used for the production of wooden containers. Quantification results can be further differentiated – e.g., the share of sawmill by-products. Hence, the calculation approach supports the visualisation and understanding of material flows within the forest-based sector. Wood processing residue coefficients resulting from product specific MFA can be repeatedly applied to annual production data of wood products, wood composites and wood supply chains. Thus, the quantification of wood processing residues improves the results of existing and future wood resource balances including cascade uses by increasing their level of detail.

## 1. Introduction

As a part of the constant analysis of wood resource availability the analysis of the WPR supply coincides with the current research in material efficiency, resource recovery, the cascading use of wood and circular economy (Brosowski et al. 2016; Jacobi et al. 2018). New market areas for wood products and new wood-based products, such as in textile and biorefinery (Jonsson et al. 2017; Hurmekoski et al. 2018), as well as wood-based bioeconomy are expected to influence the demand for wood fibres and wood resources (Mantau 2014; Hetemäki et al. 2017; Schier et al. 2021).

In efforts towards an enhanced bioeconomy and the transition of linear production to circular economy (Hetemäki et al. 2017; Jacobi et al. 2018), the quantification of supply potentials of WPR seems necessary. As regards the emerging wood-based bioeconomy sector and further intensification of the use of wood resources the importance of WPR increases (Hurmekoski et al. 2018). Detailed knowledge on the supply of WPR supports detection of the level of substitution (OECD 2008; Hurmekoski et al. 2018). In addition, increasing the value-added within the wood value chain shows the significance of WPR as a resource for innovative applications (Sathre and Gustavsson 2009). Ultimately, the comprehensive documentation of WPR could increase the availability of data on WPR, and reduce waste in manifold aspects of industrial ecology including wood processing.

In this study we define WPR as a resource which accumulates during the processing and manufacturing of wood and wood products. WPR are an inevitable result of the production process and describe the entirety of the resource. We differentiate between waste and by-products. The term ‘by-products’ is mainly used for WPR which occur during the sawmilling process. Hence, they are a specific subcategory of WPR. Also,

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WPR can be categorised as waste, i.e., an „unserviceable remainder" (Oxford English Dictionary 2015), if they are being disposed. In this case they should be included to the supply of waste wood.

The volume of WPR depends on the type of industry production and roundwood conversion and usually increases with production volumes. WPR comprise chips, dust, slabs, shavings, trimmings, peeler cores, square cuts, and other fine particles. Due to its material characteristics, WPR has mainly been applied for energy use and particular material use (Mantau 2014; Brosowski et al. 2016; Saal et al. 2019) such as the manufacturing of wood-based panels, wood pulp or wood pellets (Vis et al. 2016). We chose the term „Wood Processing Residues (WPR)" based on the wood processing origin of the accumulated residues (Saal et al. 2019).

However, a harmonised research approach and dependable data of WPR supply are not available. Detailed studies on the supply of WPR in general, as well as on the particular supply of WPR from specific processing industries on broader level (such as, e.g., the EU) are rare. Studies on the wood biomass supply on European and global level lack a common methodological approach for the assessment of biomass potentials (Batidzirai et al. 2012). They differ considerably in the applied data, units and terminology (Saal et al. 2019). Data on residue assortments (sawmill by-products, secondary wood processing residues, black liquor) as well as supply characteristics such as material efficiency appear to be insufficient. Most studies on the supply of WPR exclude the quantification of a supply from further processing following the primary processing of roundwood (Perlack et al. 2005; Vis et al. 2016), e.g., in furniture industry and wood packaging industry. In their study on WPR, Saal et al. (2019) propose a structure for the systematic analysis of WPR defined by origin. They concentrate on the data gap and lacking definitions and terminology to provide a basis for further analysis. FAO/UNECE (2020) provide conversion factors for semi-finished wood products, i.e., primary wood products based on a multi-country survey data. Coefficients of shares of WPR are deducible for, e.g., sawnwood and wood-based panels.

Empirical studies have, however, been conducted on a regional level and for specific processing procedures. Alderman et al. (1999) and Szostak et al. (2004) provide empirical results on the supply of WPR from further processing on a regional (Virginia) and national level (Poland). They include results on either wood packaging (Poland) or the pallet industry (Virginia, US). Other studies focus on residual volumes from the furniture industry; however, the studies are based on different contexts and research objectives (Daian and Ozarska 2009; Tatàno et al. 2009; Mendoza et al. 2010). Saal (2010) presented a first approach to estimating the supply of WPR on the European level, including residues from further processing industries. The study includes empirical data on the German wood packaging industry by Mantau and Hartig (2003). Resulting estimations show a great potential of WPR for various utilisation possibilities. This applies especially to an emerging bioeconomy (Marques et al. 2020).

*Objective*

Increased knowledge on the supply of particular volumes of WPR supports regional use as well and improves resource streams with data (Mantau 2014; Da Silva et al. 2020; Marques et al. 2020). As shown with the above literature overview, frequent data and a uniform methodology on the quantification of WPR supply are lacking. We further face the data gap of product-specific efficiency coefficients for the calculation of particular supply along the production process of wood products (Camia et al. 2021).

As studies apply and call for "a range of possible values" of WPR (Camia et al. 2021), we aim to provide a general calculation approach of wood processing residues. Based on that, the calculation provides a comprehensive data basis for continuous monitoring. Further, it allows comparison of countries as well as time series on the basis of international product codes and frequent data (Prodcom). Hence, the main objective of this study is therefore to provide a calculation approach. The results of the study are meant to fill the data gap and to support the harmonised calculation of the supply of WPR.

We apply our general calculation approach to core wood packaging products to calculate the supply of WPR from this particular industry branch. We further derive wood input coefficients and residue coefficients for the wood packaging industry. These can be used to calculate amounts of WPR on different spatial and temporal levels based on official production data.

Globalisation of trade enhances the meaning of wood packaging products. The wood packaging industry plays an essential role within the global trade of daily goods (Albrecht et al. 2013; UNECE 2016). The latest data on sawnwood consumption in the wood packaging sector dates back to 2015 (UNECE 2016). The sector consumed about 25 million $m^3$, which is about 20% of the total sawnwood consumption in Europe (UNECE 2016). We focus on the application on standardised wood packaging products as given in the Prodcom classification based on NACE Rev. 2 (Eurostat 2017b). These comprise flat pallets, box pallets, lightweight packaging including crates and boxes, cable drums and cask and barrel products. Annual production data are available from Prodcom data base [dataset] (Eurostat 2021). Next to relevant availability of production data, the chosen sector is very applicable due to its differentiated product structure and low variation in material composition within its product groups.

The paper is structured as follows: First, we describe the methodological background and present the general calculation approach. Then, we apply the sample approach on the WPR of wood packaging products. We present equivalent data sources as well as the specific assumptions and coefficients on the research example. Results are given in the second part of the study. In Chapter 4 we discuss the results and conclude the paper with the main findings with regard to the use of the calculation approach.

## 2. Material and methods

### 2.1. Methodological frame

The methodological frame of the study covers three parts, starting with the methodological framework of analysis. The second part focuses on the description of the calculation sequences and their application on an example of wood packaging products. The third part covers quantification and data sources of the applied example.

#### 2.1.1. Material flow analysis and material efficiency

The conceptual framework for calculating the potential supply of WPR is based on Material Flow Analysis (OECD 2008). Using MFA, we analyse the material flow for the conversion of ingoing wood resources to outgoing production volumes of each production step, i.e., conversion step. Material flows can be considered on different levels of aggregation. We focus on the analysis of the downstream part of the material flow's core product (Cote et al. 2015; Schweinle et al. 2020). Compared to more frequent MFA on the macro-level (Mantau 2014; Parobek et al. 2014; Bösch et al. 2015; Lenglet et al. 2017; Marques et al. 2020), we apply MFA on meso-level to focus the resource flow of a product (Hirschnitz-Garbers et al. 2014). WPR are produced during all processing of wood or manufacturing of semi-finished and finished wood products. With emphasis on WPR we address the question of resource efficiency and residue output of the particular material wood and the differentiated focus on a particular branch of industry (OECD 2008). Thus, all relevant manufacturing processes of semi-finished and finished wood products are included in the analysis prior to the assessment of their inherent material flows. We quantify the analysed material flows based on material conversion efficiency. Each conversion step of the production process is assigned a product specific material efficiency rate.

We define the length of a considered material flow as the number of conversion steps considering the linear flow of the input wood resource towards the core product output only, without any intermediate cascades or derived uses. Material input is at the roundwood level. Thus, all WPR which accumulate from the conversion steps of initial wood resource input through to final product output are accounted for the analysed flow. Due to the focus on the wood resource input we do not differentiate the origin of initial material volumes. For further differentiation of the material flow, we consider the material composition, i.e., the proportions of different wood resources and production-related additives of the analysed wood product. A product with two or more homogeneous input materials results in parallel linear material flows. All are analysed equally and quantified based on the flows' material conversion efficiency. All values are then weighted based on shares of material composition.

### 2.1.2. Reference unit

Resources and products of the wood industry are reported in various units of mass and volume. All units of relevant data input, e.g., product output units, are converted into wood fibre equivalents ($m^3$f) to calculate a consistent MFA (Lenglet et al. 2017). By calculating on the level of contained wood fibre at the fibre saturation point. we consider possible consistency interference of double counting in material flows (Hirschnitz-Garbers et al. 2014), adhesives and volume changes during the different conversion steps as done in Bösch et al. (2015) and Lenglet et al. (2017).

### 2.1.3. Calculation approach of the supply of WPR

In the calculation approach we define indices for the specific product (*i*) referring to semi-finished and further processed wood products. As part of the material flow, we also define conversion step (*j*). As widely used in MFA (Marques et al., 2020) Fig. 1 shows an exemplary Sankey diagram, visualising the linear flow starting from wood resource input, subsequent material conversion steps and resulting shares of WPR and respective product output. Within the calculation approach of the present study we calculate a potential wood resource supply (Kaltschmitt et al. 2009; Batidzirai et al. 2012). Please note, that the material flow analysis and calculation approach merely focus the supply of WPR. Within this study, we do not analyse further flows or uses of the WPR.

Generally, we define a linear material flow for any specific wood product as:

$$IN_i = P_i + WPR_i + L_i \tag{1}$$

Where $IN_i$ is the wood input to the material flow, $P_i$ is the production volume of the manufactured product *i*, $WPR_i$ is the quantity of WPR and $L_i$ are losses[1] of the production process.

We calculate the specific production volume of the manufactured product Pi in $m^3$f, i.e., a product's wood content, based on given data of mass or pieces of a specific production output. Products are classified according to Prodcom nomenclature (Eurostat 2017b).

Hence, we define WPR as:

$$WPR = IN - P - L \tag{2}$$

We apply the factor $me_i$ for the quantification of product specific material conversion efficiency. Each conversion step of the considered production process is described by an efficiency factor (*me*) within a flow by share of wood product output per wood resource input. Generally, the material efficiency factors depend on the level of mechanisation and technical development of the processing and manufacturing process. Within this study, we assume that they are identical on European level (EU28). Further factors which influence the material efficiency of the initial processing are tree species and log diameter (Steele 1984; Yang and Jenkins 2008). Here, we apply country specific data of material efficiency of primary roundwood processing given by FAO/ UNECE (2020).

We describe $me_i$ for a specific product as:

$$me_i = \frac{P_i}{IN_i} \tag{3}$$

We further define *me* of *n* conversion steps (*j*) of the processing of a product (*i*) as:

$$me_i = me_1 * me_2 * me_n = \prod_{j=1}^{n} me_{ij} \tag{4}$$

Where $me_{iJ}$ describes the product of all conversion efficiency factors $me_j$.

The material efficiency factor for each conversion step is based on references and assumptions derived from the analysis of the material flow of a product. Each wood product or product chain has its specific $me_{ij}$. Moreover, country specific differences of a core product's characteristics can be considered.

As data on the volume of material input of a particular production process are barely available, we invert Eq. 3 and include Eq. 4 to calculate the product specific input on the basis of derived $P_i$ and $me_{ij}$ (4). The material input of a product and product chain is calculated as the quotient of production volume $P_i$ and the product of efficiency rates of all product specific conversion steps j = n.

Considering a specific product, we define the initial material input as

$$IN_i = \frac{P_i}{\prod_{j=1}^{n} me_{ij}} \tag{5}$$

In the calculation approach we include the factor *l* for losses $L_i$ as part of the material flow. In the present study we define losses of 1% over all products and conversion steps. Eq. (6) gives the relation of the factor *l* and WPR.

$$L_i = l * WPR_i \tag{6}$$

Where L is the volume of losses calculated by the general factor *l* for all products and all conversion steps, dependant on WPR.

We define $L_i$ for all calculation steps j for a product based on (1), (5) and (6) as:

$$L_i = \sum_{j=1}^{n} L_j = IN * \frac{l}{(1+l)} * \left(1 - \prod_{j=1}^{n} me_{ij}\right) \tag{7}$$

Finally, we calculate the product specific volume of WPR as:

$$WPR_i = \frac{P_i}{\prod_{j=1}^{n} me_j} * \frac{1}{(1+l)} * \left(1 - \prod_{j=1}^{n} me_{ij}\right) \tag{8}$$

### 2.1.4. Calculation of product specific coefficients

In line with the described calculation approach, we calculate product specific input-output coefficients. These coefficients describe the integrated material efficiency of a flow and define the relation of initial material input per production volume. Applied ranges of material efficiency are implemented based on weighted average (e.g., lightweight packaging).

We define the product specific input – output coefficient $IP_i$ as:

$$IP_i = \frac{IN_i}{P_i} \tag{9}$$

Given the calculation of WPR (8) we define the coefficients of the product specific residue volume dependant on $IN_i$ $R_i$ as well as dependant on $P_i$ as:

$$R(IN)_i = \frac{WPR_i}{IN_i} \tag{10}$$

[1] We use capital letters (IN, P, L, WPR, M for values to distinguish them from factors (*me, l*), given in small letters

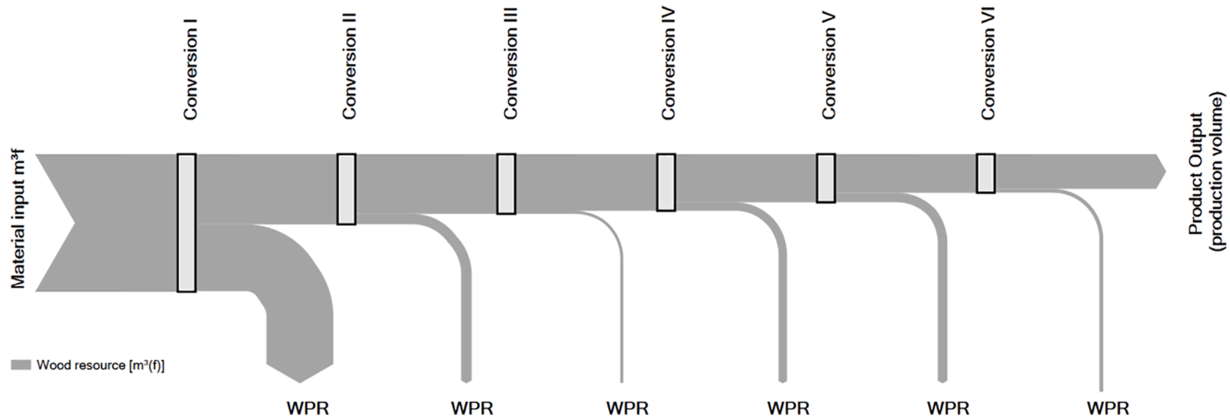


**Fig. 1.** Sankey diagram of a downstream part of wood processing and accumulation of WPR.

and

$$R(P)_i = \frac{WPR_i}{P_i} \tag{11}$$

### 2.2. *Application to European wood packaging*

We exemplify the calculation approach of the supply of WPR on wood packaging products which are classified in European production statistics (Prodcom) (Eurostat 2017b). We comply with chosen Prodcom codes which are assigned to economic activities. First, we focus on the material flow analysis of the core products regarding the definition of all conversion steps. Second, we assign material efficiency rates to the conversion steps and quantify the material flow based on examined data and references to calculate the supply of WPR. Furthermore, due to the structure of the presented calculation approach, we are able to differentiate the supply of WPR into volumes of sawmill by-products (SBP) and WPR from further processing of semi-finished wood products. We refer to this particular assortment of WPR from manufacturing as 'secondary WPR'. Further, we provide specific residue coefficients including the volume of wood input at further processing level.

#### 2.2.1. *Material flow analysis*

We analyse the material flows of five different core products of wood packaging. We base the analysis of the flows on the general assumption of similar production processes in the wood packaging industry of the EU28 (UNECE 2016) in line with similar material input into the different production processes at the EU28-level. The considered core products are standardised products, which are elaborated with no further changes regarding their technological development as well as a high material efficiency (Cote et al. 2015). The analysed downstream parts of the core products' material flows differ in extent, given the number of conversion steps. Roundwood is defined as the initial material input of all analysed flows. The outline of the material flows and their conversion steps within the production processes are shown in the following Table 1. The order of listed conversion steps may vary.

#### 2.2.2. *Quantification and associated data sources*

To quantify the product specific material flows we assign material efficiency rates to the analysed conversion steps. Information on the successive material conversion of the core products and respective data on material efficiency are predominantly derived from references (see Table 1).

Material efficiency rates of particular conversion steps which are not

**Table 1**
Outline of the material flows and conversion steps.

| Product group | Input of | Conversion I | Conversion II | Further processing of | Conversion III | Conversion IV | Conversion V | Conversion VI | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Pallets and flat pallets | Roundwood | Sawing | | Sawnwood<br>Press block | Chamfering | Cutting to length | | | 1 |
| Box pallets and other | Roundwood | Sawing | | Sawnwood<br>Press block | Chamfering | Cutting to length | | | 2 |
| Cases, boxes, Lightweight products | Roundwood | Sawing | Planing I | Sawnwood (rough) | | Cutting/ trimming | | | 3 |
| | | Peeling | | Ply/ veneer sheets | Sanding | Cutting/ trimming | | | |
| Cable drums | Roundwood | Sawing | | Sawnwood rough | | Cutting/ trimming | Circular parts | Assembling | 4 |
| | | Sawing | Planing I | Sawnwood | | Cutting/ trimming | Circular parts | Assembling | |
| | Roundwood | Sawing/ splitting | Planing I | Staves | Planing II | Cutting/ trimming | Circular parts | | 5 |
| Casks, Barrels, vats and tubs | | Sawing | | Sawnwood | Planing II | Cutting/ trimming | Circular parts | | |

References
1 USDA Forest Service 1971; Anil Philip 2010; Bengtsson and Logie 2015; Pfeifer Group 2020
2 see 1 Zamko 2019
3 Barthel and Albrecht 2007; Albrecht et al. 2013; FEDEMCO 2020; Kirschner 2020
4 Sydor et al. 2017
5 Laglasse 2006; Böhm et al. 2013; Flor et al. 2017

given in references are derived from a set of assumptions: Several efficiency rates are based on the volumetric calculation of dimension change due to processing, e.g., cutting to circular surface. In the case of the material flow of lightweight products, and the Conversion Step IV 'cutting and trimming of veneer sheets', we model the conversion efficiency on the basis of roundwood equivalent data (Hunecke 1966). This is done as a stopgap measure based on the known conversion efficiencies of the other conversion steps.

Some flows are differentiated and quantified based on ranges due to possible differences in the number of conversion steps or resource mix, e.g., lightweight products. Furthermore, we differentiate the case of the few producing countries of casks, barrels, vats and tubs. We assume that the data given for European Nordic countries (e.g., Finland, Estonia, and Lithuania) on their volume of produced casks and barrels rather covers sauna and hot tub products than barrels for liquids. We define a shorter length of the material flow, i.e., fewer material conversion steps. We base the conversion efficiency rates on an example calculation on prevalent dimensions of tubs (Baltresto Germany 2021). Here, the range covers the calculation of the same material flow for all considered countries in contrast to the calculation considering country differences.

In contrast to studies focussing on product output (Steele 1984; Lin et al. 2011), we define losses of wood material as a factor decreasing the WPR volume. Empirical studies within the sawmill industry indicate shares material input between 0.5 and 2% of (Sörgel et al. 2006). Saal (2010) included a share of 0.7% (coniferous) and 1.6% (non-coniferous) of losses in the estimation of the supply of SBP in Europe. As given in the methodological frame in chapter 2.1, we define losses as1% over all products and conversion steps. Losses can be volumes which are falsely assorted as waste or not withdrawn by suction. Further, losses may occur by measuring differences e.g., in trade, due to material characteristics such as moisture content (mass).

We finally quantify the analysed flows based on the data of the Prodcom tables [dataset] (Eurostat 2021). The data sets for the considered countries (EU28) and years (2014 – 2018) differ in their completeness. In some cases, missing data were imputed using national statistics.

## 3. Results

### 3.1. Quantification of the material flows

The following chapter covers the results of the quantification of the exemplified material flows of wood packaging products. It is structured according to the calculation approach, indicating material conversion steps for quantification, respective supply volumes of WPR and the correspondent coefficients. The results are differentiated according to the advances of the calculation approach, including results of SBP share, the share of WPR from further processing as well as the volume of sector-specific sawnwood consumption.

As the result of material flow analysis, the following Table 2 shows the product specific material efficiency rates for each conversion step along the material flows. It also presents the results of the assumptions made on the analysed material flows based on references and the described calculation approach (see 2.1).

The results in Table 2 indicate the material efficiency shares of each conversion step of the considered core products. Moreover, we present results on the specific resource mix of the final wood packaging product. Data on the particular weight of a product is given for the calculation of the production volume.

**Table 2**
Product specific data on resource mix, material efficiency of conversion steps and weight.

| Product group | Resource mix | | Conversion [%] | | | | | | | Weight [kg] | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | I Sawing/ splitting | II Planing | III Planing/ sanding/ chamfering | IV Cutting to length/ trimming | V Cutting to Circular surface* | | VI Assembling | | |
| | | [%] | | | | | *me prop. | Share of total volume | | | |
| Pallets and flat pallets | Sawnwood | 76 [1] | 66 [2] | | 96 [3] | 96 [4] | | | | 25 [5] | 1 |
| | Press block | 24 [1] | | | | | | | | | |
| Box pallets and other | Sawnwood (rough) | 100 [1] | 55 [2] | | 95 [3] | 95 [4] | | | | 30 [5] | 2 |
| Cases, boxes, Lightweight | Sawnwood (rough) | 30 [1] | 52 [2] | 85 [3] | | 90 [4] | | | | | 3 |
| | Veneer | 70 [1] | 87 [5] | | 96 [6] | 82 [7] | | | | 0.9 [8] | |
| Cable drums | Sawnwood (rough) | 100 [1] | 51 [2] | | | 95 [4] | 80 [5] | 80 [6] | 90 [7] | | 4 |
| | planed | 100 [1] | 51 [2] | 85 [3] | | 95 [4] | 80 [5] | 80 [6] | 90 [7] | | |
| Casks and barrels | Roundwood NC | 100 [1] | 90 [2] | 40 [3] | 87 [3] | 97 [3] | 95 [4] | 21 [4] | | | 5 |
| vats and tubs | Sawnwood | 100 [1] | 51 [5] | | 85 [6] | 97 [3] | 93 [4] | 28 [7] | | | |

References
1 weighted shares of sawnwood and press block [1] Konsemüller 2016; [2]average of producing countries FAO/ UNECE 2020; [3] own calculation; [4] own calculation based on USDA Forest Service 1971 [5] EPAL 2019
2 [1] USDA Forest Service 1971; Konsemüller 2016; [2]average of producing countries FAO/ UNECE 2020; [3]own calculation; [4] own calculation based on USDA Forest Service 1971; [5]Zamko 2019
3 [1] Albrecht et al. 2013; [2]average of producing countries FAO/ UNECE 2020; [3] Sörgel et al. 2006; [4] own calculation; [5] Albrecht et al. 2013; [6] FAO/ UNECE 2020; [7] Nock and Stegmann 1979; [8] Barthel and Albrecht 2007
4 [1] Konsemüller 2016; Sydor et al. 2017; [2] average of producing countries FAO/ UNECE 2020; [3] Sörgel et al. 2006; [4] own calculation based on Sydor et al. 2017; [5] own calculation; [6] calculation based on Konsemüller 2016
5 [1] Laglasse 2006; Böhm et al. 2013; [2] own calculation based on Hiziroglu and Adams 2017; [3] own calculations based on Laglasse 2006; Böhm et al. 2013); [4] own calculation based on Konsemüller 2016; [5] average of producing countries FAO/ UNECE 2020; [6] Sörgel et al. 2006; [7] own calculations based on product data Baltresto Germany 2021

**Table 3**
Volume of wood processing residues of wood packaging 2018, EU28.

| Product group | WPR [m$^3$f] | | Whereof SBP [m$^3$f] | |
|---|---|---|---|---|
| | Max | min | max | min |
| Pallets and flat pallets | 20,012,982 | | 17,518,101 | |
| Box pallets and other | 6028,084 | | 5390,076 | |
| Cases, boxes, LW | 2380,799 | 1375,057 | 1309,446 | 756,285 |
| Cable drums | 824,798 | 648,932 | 664,190 | 488,323 |
| Casks and barrels, vats and tubs | 518,492 | 516,938 | 75,159 | 73,614 |
| Total | 29,765,154 | 28,581,992 | 24,956,972 | 24,226,399 |

### 3.2. Supply of wood processing residues from the wood packaging industry

Table 3 presents the results of product specific supply of WPR of wood packaging products for the year 2018 in the EU28. Based on the analysed conversion steps, the particular supply of the product specific volume of SBP can be differentiated. The table reveals the residue volume of sawnwood production as a share of the total supply of WPR.

The calculation of the supply of WPR from wood packaging results in a potential maximum of 29.7 million m$^3$f and minimum supply of 28.6 million m$^3$f. The considerable difference of the supply volume of more than one million m$^3$f WPR results from calculation of ranges, mainly of lightweight packaging. For the year 2018 the maximum volume of total losses in the wood packaging industry amounts to 0.36 million m$^3$f.

The following Table 4 shows the results on wood resource input into the European wood packaging industry in 2018. The results are differentiated according to total roundwood input, the volume of roundwood for sawnwood as well as the respective volume of produced sawnwood within the production of wood packaging.

The European wood packaging industry required a total volume of 70.8 million m$^3$f (max) roundwood whereof 54.1 million m$^3$f were used for the production of sawnwood as a resource for the processing of mainly pallets and box pallets, cable drums and components of lightweight packaging. The processing of sawnwood in the production of casks and barrels is limited, e.g., to the production of vats and tubs. Regarding the sawnwood-producing countries, the average material efficiency of sawnwood production is about 53% (based on FAO/UNECE (2020)). Other roundwood volumes are assigned to the production of veneer sheets for lightweight packaging as well as staves for barrel production of non-coniferous roundwood such as poplar and oak (Albrecht et al. 2013; Böhm et al. 2013).

Table 5 combines data on total production output in tonnes given by Eurostat (2021) and results of the total production volume in m$^3$f based on the presented calculation approach (see 2.1).

According to the described calculation approach and exemplary application we provide coefficients of product specific wood resource input and WPR shares in Table 6

The input-output coefficients $IP_i$ as well as the coefficients of WPR $R_i$ are given in ranges, where differences were applied in the quantification of product specific material flows. The coeffients can be applied for further calculations of WPR volumes and supply on the basis of known input data $(R(IN)_i)$ and available production data $(R(P)_i)$.

Fig. 2 presents the product specific volume of roundwood input (max.) and sawnwood production as well as the shares of WPR.

The total roundwood input is highest in the production of pallets and box pallets, whereas the share of WPR is highest in the production of cable drums and casks and barrel products.

The share of pallet production ranks highest on the European level (2018) (see Figure 3) . Although the share of WPR from pallets is the lowest amongst wood packaging products, the highest share by supply volume can be realised. Due to low production volumes, the high shares of WPR of cable drums, and casks and barrels only result in low supply volume of WPR. The production of pallets and box pallets account for 90% of the total production of wood packaging.

**Table 5**
Production output and production volume of wood packaging 2018, EU28.

| Product group | Product output [t] [1] | Production volume [m$^3$f] |
|---|---|---|
| Pallets and flat pallets | 20,621,958 | 31,169,316 |
| Box pallets and other | 3946,324 | 5964,720 |
| Cases, boxes, LW | 1931,524 | 3084,002 |
| Cable drums | 228,388 | 351,123 |
| Casks and barrels, vats and tubs | 162,466 | 212,459 |
| Total | 26,890,660 | 40,781,620 |

Source: [1][dataset] (Eurostat 2021)

**Table 6**
Product specific coefficients of wood packaging products.

| Product group | *IPi* | | *R(IN)i* | | *R(P)i* | |
|---|---|---|---|---|---|---|
| | max | Min | max | min | max | min |
| Pallets and flat pallets | 1.648 | | 0.389 | | 0.642 | |
| Box pallets and other | 2.021 | | 0.500 | | 1.011 | |
| Cases, boxes, LW | 1.780 | 1.450 | 0.434 | 0.307 | 0.770 | 0.444 |
| Cable drums | 3.373 | 2.867 | 0.697 | 0.645 | 2.349 | 1.848 |
| Casks and barrels, vats and tubs | 3.465 | 2.557 | 0.704 | 0.603 | 2.440 | 1.542 |

Reference year 2018, EU28

### 3.3. Wood resource input and WPR of further processing in wood packaging

To close the data gap of wood resource consumption on the level of further processing, we quantify shorter material flows and the product of conversion efficiency $me_i$ of the related conversion steps. Thus, more detailed results on supply volumes of WPR along the production process of wood products can be derived based on particular coefficients. They indicate the material input on the level of further processing (also secondary processing), e.g., initial input of semi-finished wood products such as sawnwood and wood based-panels. Table 7 shows the volume of wood resource input on further processing levels as well as the supply volume of secondary WPR. The coefficients for the quantification of wood resource input on further processing level as well as the quantification of WPR supply based on initial wood resource input and production volume are given in Table 8.

Compared to the results of total supply of WPR in Table 7 and respective coefficients in Table 8, a range of results can only be given for the production of casks and barrels, etc. Here, the results are only based

**Table 4**
Wood resource input of the wood packaging sector in 2018, EU28.

| Product group | Roundwood input total [m$^3$f] | | Roundwood input for sawnwood production [m$^3$f] | | Whereof sawnwood produced [m$^3$f] | |
|---|---|---|---|---|---|---|
| | max | Min | max | min | max | min |
| Pallets and flat pallets | 51,382,428 | | 39,179,102 | | 21,485,819 | |
| Box pallets and other | 12,053,085 | | 12,053,085 | | 6609,108 | |
| Cases, boxes, LW | 5488,609 | 4472,810 | 1646,583 | 1341,843 | 863,633 | 703,797 |
| Cable drums | 1184,169 | 1006,544 | 1184,169 | 1006,544 | 603,926 | 513,337 |
| Casks and barrels, vats and tubs | 736,135 | 734,566 | 4420 | | 2254 | |
| Total | 70,844,426 | 69,649,432 | 54,067,358 | 53,584,993 | 29,564,740 | 29,314,316 |

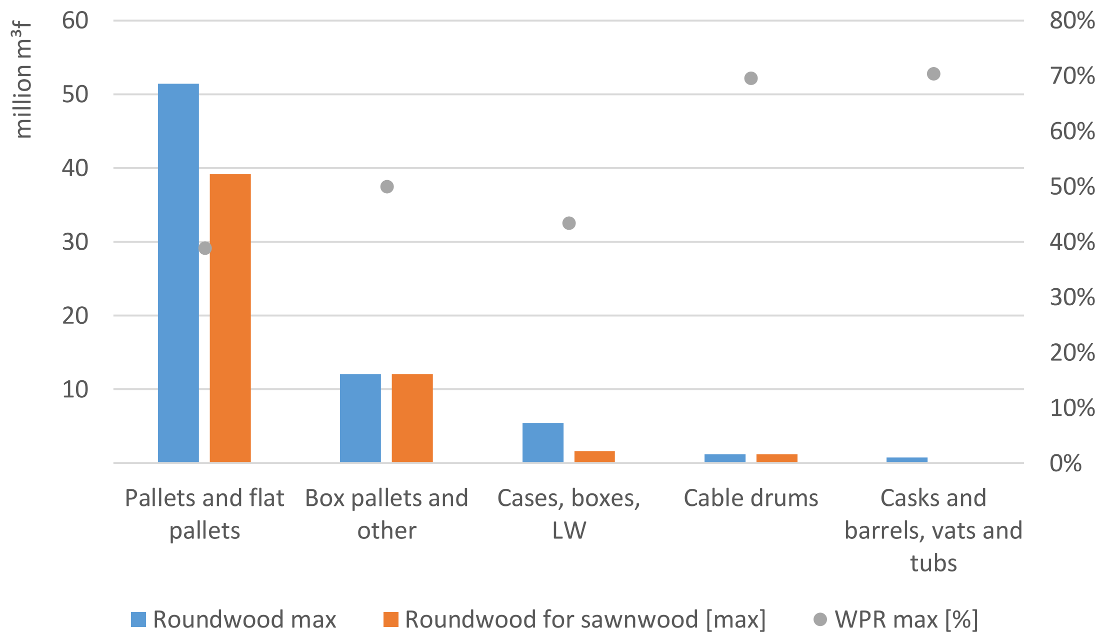


**Fig. 2.** Total roundwood input, sawnwood production and shares of WPR (EU28) 2018
Source: Own calculations based on [dataset] Eurostat (2021).

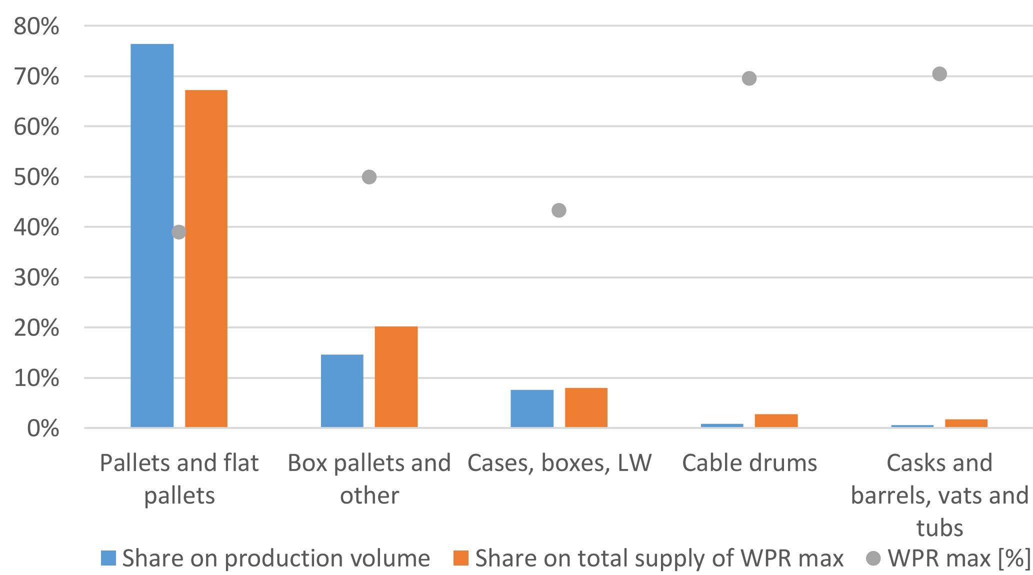


**Fig. 3.** Shares on production volume and supply of wood processing on total production and total supply, shares of WPR (EU28) 2018
Source: Own calculations based on [dataset] Eurostat (2021).

**Table 7**
Wood resource input and WPR on further processing level 2018, EU28.

| Product group | Wood resource input 2nd processing [m$^3$f] | | 2nd WPR [m$^3$f] | |
|---|---|---|---|---|
| | max | min | max | min |
| Pallets and flat pallets | 33,689,146 | | 2494,881 | |
| Box pallets and other | 6609,108 | | 638,008 | |
| Cases, boxes, LW | 3765,659 | | 1071,353 | |
| Cable drums | 513,337 | | 160,608 | |
| Casks and barrels, vats and tubs | 736,135 | 732,400 | 450,063 | 446,922 |
| Total | 45,313,386 | 41,543,991 | 4814,913 | 4811,772 |

**Table 8**
Coefficients of further processing and secondary WPR.

| Product group | *2nd IP$_i$* | | *2nd R(IN)$_i$* | | *2nd R(P)$_i$* | |
|---|---|---|---|---|---|---|
| | max | Min | max | min | max | min |
| Pallets and flat pallets | 1.081 | | 0.049 | | 0.080 | |
| Box pallets and other | 1.108 | | 0.053 | | 0.107 | |
| Cases, boxes, LW | 1.221 | | 0.195 | | 0.347 | |
| Cable drums | 1.462 | | 0.160 | | 0.457 | |
| Casks and barrels, vats and tubs | 3.118 | 1.304 | 0.611 | 0.118 | 2.118 | 0.301 |

Reference year 2018, EU28

on own calculations due to missing differentiation of the material conversion in the references (e.g., Albrecht et al. 2013).

### 3.4. Country specific results

Fig. 4 gives an overview of the total supply of WPR by country in reference to the total production volume. The shares of SBP of the total WPR volume are also presented on country level.

Clear differences in the supply volume of WPR can be seen when looking explicitly at results on the country level. The main producing countries Italy, Poland, France, Germany, and Spain show high production volumes, mainly of pallet production. Differences in the shares of SBP and the respective share of secondary WPR are due to the composition of production of wood packaging products. Italy mainly produces pallets, box pallets and lightweight packaging with lower shares of WPR. The French wood packaging production includes pallets and the highest production volume of casks and barrels – the latter with the highest share of WPR. The following Fig. 5 shows exemplary results on the product composition and dependent volume of WPR of countries with a total production volume over one million $m^3$f, listed according to total production volume.

The country specific results in Fig. 5 show the prevailing production of pallets. Next to high total production volumes, the volume of total WPR ranks highest in countries with products mainly made of sawnwood (pallets and box pallets). Furthermore, the production of cases, boxes and lightweight products also influences the total volume of WPR.

Fig. 6 presents country specific results of the total roundwood volume, the produced volume of sawnwood within the production of wood packaging as well as the volume of WPR and share of secondary WPR from further processing. Countries with a total roundwood volume > 1 million $m^3$f are displayed.

As one of the main producers of pallets and box pallets (see Fig. 5), the total roundwood consumption ranks highest in Italy followed by France and Poland. Moreover, these countries, and also Spain and Germany require the highest volumes of sawnwood for wood packaging. Volumes of secondary WPR are relatively in line with the volumes of WPR. However, the high production volumes of lightweight packaging and casks and barrels in Italy, France and Spain also result in comparably high volumes of secondary WPR.

## 4. Discussion

Current literature and research lack a general approach for the quantification of WPR on the basis of available data sets of forest products. With the present study we are able to present a calculation approach for the quantification of the potential supply of WPR based on material flow analysis. The respective focus is on the analysis of material input, the successive material conversion and related material efficiency of processes. This enables the quantification of process-related supply volumes of WPR, as well as the respective wood resource input on any level of the analysed flow.

Compared to earlier studies by Alderman et al. (1999) Mantau and Hartig (2003) Szostak et al. (2004) we track the calculation approach and serve the application on any wood product. Given the data availability by, e.g., Prodcom (Eurostat 2021), and prior MFA, the presented approach is general. Thus, it can be applied for the analysis of different countries and over time.

As shown, the calculation approach can be applied to production data of wood packaging products for the calculation of the supply of WPR and particular wood resource consumption. The presented approach shows the importance of prior material flow analysis for further quantification and exposition of numbers. High shares of WPR and respective shares of SBP of the chosen example reveal the importance of general quantification of the residual wood resource. Moreover, the exemplary calculation of WPR from wood packaging as well as the sector's wood resource consumption (input) illustrates the potential of the further processing sectors. Generally, the supply volume of WPR of a product grows with the volume of production. The supply volume of a product group, e.g., wood packaging, varies depending on the product composition and respective production volumes. Therefore, differences in the country specific supply of WPR are related to the composition of wood packaging products.

### 4.1. Discussion of the results

The research frame of the present study covers the analysis of standardised wood packaging and represents the calculation of the theoretical potential. However, to elaborate the results we applied ranges to differentiate the assumptions and to follow diverse references, e.g., with lightweight products. Compared to data given by Albrecht

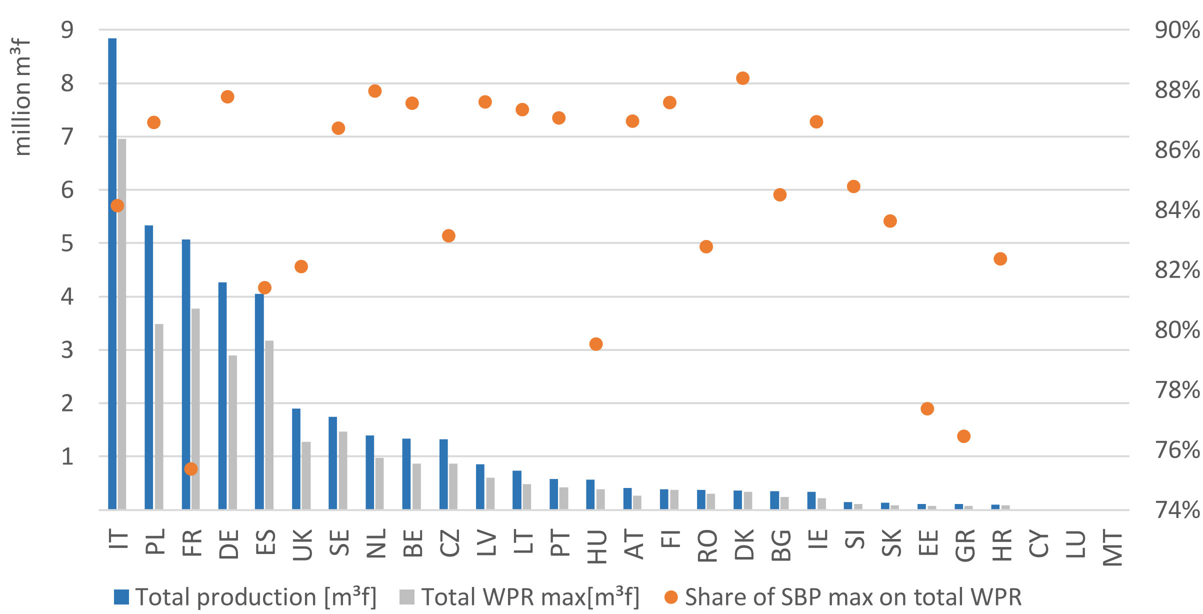


**Fig. 4.** Total production volume and supply of WPR by country, share of SBP (EU28) 2018
Source: Own calculations based on [dataset] Eurostat (2021).

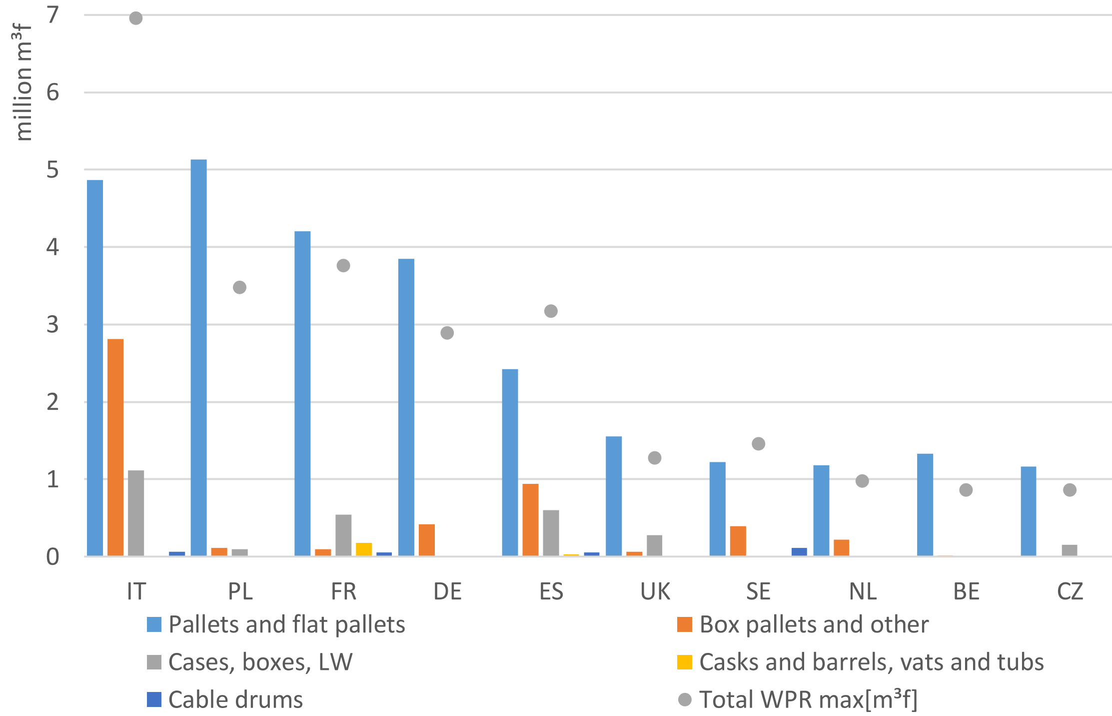


**Fig. 5.** Composition of production volume and total WPR of countries > 1 million m$^3$f, 2018
Source: Own calculations based on [dataset] Eurostat (2021).

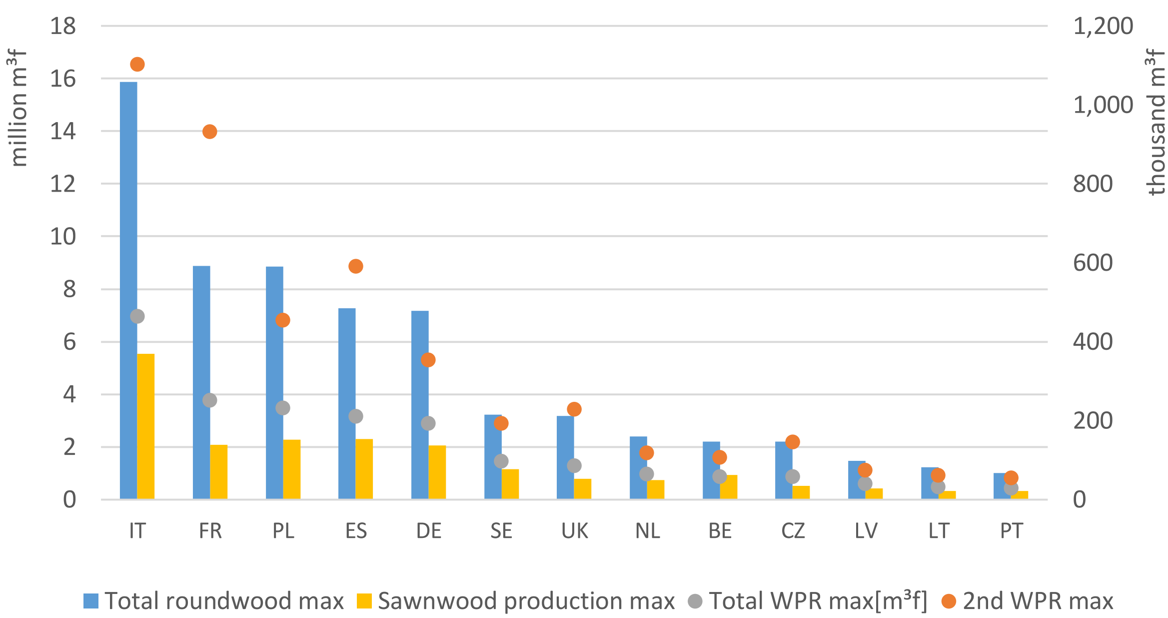


**Fig. 6.** Volumes of total roundwood, total WPR, produced sawnwood and secondary WPR.

et al. (2013) we differentiated the material flow even further and applied a weighted average to consider the material differences of the resource mix. Results of the quantification of the two varying flows show a considerable range of one million m$^3$f in the supply of WPR. For the case of Italy with high production volumes of lightweight products, results show a range of about 360,000 m$^3$f, which equals 5% of total WPR. Whereas the assumptions made on differences in the production of casks, barrels, vats and tubs only result in minor volumes on the total and country level. The ranges equal less than 1% of the countries' total supply of WPR.

As regards the initial wood resource input as well as the lengths of the flows, references show diverse patterns. This applies, e.g., for pallet production (USDA Forest Service 1971; Lübbersmeyer 2021) or production of lightweight products (Albrecht et al. 2013; Kirschner 2020) and covers vertical integration of wood packaging (Lübbersmeyer 2021).

Thus, we basically quantify the complete material flow along its conversion steps by reverse calculation – starting from the given production volume towards the initial wood resource input. Following this approach, we avoid double counting of potential wood resources, i.e., input roundwood and the accumulating WPR volume. In addition, based on the particular differentiation of the material flows into conversion steps, the quantified volumes of wood resource input as well as WPR can be accounted on separate level. Thus, it is very likely to quantify the respective volumes of secondary WPR as well as the particular supply of SBP. These results can be applied to close important data gaps on the particular shares or volumes of WPR from further processing (Vis et al. 2016; Camia et al. 2021).

For the calculation of secondary WPR from conversion of semi-finished wood products, the differentiation of the flows based on ranges was not applicable. Differences in the number of conversion steps mainly occur in the conversion of roundwood to sawnwood at the beginning of the material flow. The detailed analysis of the material efficiency of all conversion steps goes beyond the conversion factors provided by FAO/ UNECE (2020).

In the present study we calculate a total maximum volume of 29.7 million $m^3$f WPR including a volume of 25 million $m^3$f SBP. The volume of WPR equals a mean share of WPR for the manufacturing of wood packaging products of 41 - 42% for the year 2018. Generally, the product-specific shares of WPR range from 30% to 70% (see Table 6). The average share of WPR from wood packaging changes over time and country dependent on the product composition. The range of the coefficients of the analysed product group reveals the importance of a differentiated quantification of WPR based on the application of product specific coefficients. So far, there are no comparable results on the total volume of WPR, except the mean share of the efficiency of European sawmill industry. The industry's respective share of total WPR (assuming 100% SBP) is 45% (FAO/ UNECE 2020).

The calculated maximum volume of produced sawnwood is 29.6 million $m^3$f in 2018 (24.1 million $m^3$f in 2014). This corresponds to the consumed sawnwood in the production of wood packaging and exceeds the latest data of estimated 20 million $m^3$ of the sector's sawnwood consumption in 2015 given by UNECE (2016) considerably. According to UNECE (2016), the wood packing sector used about 20% of the total sawnwood production in EU28. This share basically corresponds to the results of the present study. As a result of the present study, the share of the sector's sawnwood production is about 23% in the year 2015 (24%, 2018) based on FAOSTAT (2021).

Based on the sector's production volume in 2018, the calculated share of secondary WPR is 10.6% in reference to the wood resource input on further processing level. Saal (2010) and Mantau (2012) applied a total share of 9.7% for the calculation of WPR from wood packaging on EU27 level. The share originates from the empirical study on the German wood packaging industry in 2002 by Mantau and Hartig (2003). However, the study does not reveal the composition of data and respondents by product group and thus, is limited in the application on broader level. Vis et al. (2016) present a 'provision volume' of WPR from wood packaging of 4.7 million $m^3$f. The number refers to the estimation of secondary WPR without any further information on data composition, differences in the composition of products or production volume. Both shares refer to the wood resource input on further processing level. Thus, their application on sector specific data is limited, since data on wood consumption on further processing level are not gathered on necessary level. Moreover, results of the application of a mean share of 9.7 % on countries with predominant pallet production are too high. A similar effect results on the application of the share of 4.7% given by Vis et al. (2016) in the case of particular production of lightweight packaging, cable drums or casks and barrel products.

### *4.2. Discussion of method and data*

The assumptions generalise the sector of wood packaging for the purposes of the exemplary application of the calculation approach on European level. Small differences may exist with respect to the level of industrialisation of the processing and conversion steps of the considered countries. Thus, the calculation approach may bear bias or uncertainties in the assumptions on industry structure, material flow patterns and material efficiency. However, we tried to avoid these influences by focusing on the given systematic of product classification (Prodcom) and specific references. Moreover, the described assumptions can be adjusted based on available knowledge, data and future references. This applies also to the set of data. The calculation of product specific input-output coefficients is based on default values given by a study of Diestel and Weimar (2014) and data by Thuenen Institute (2021). Respective background data on the carbon content, product specific density of wood species, as well as the composition of the material, are dynamic and may change over time.

The model could be further validated using very explicit data of manufacturing data. Unfortunately, we did not have these data. What we did was a validation based on the manufacturing of sawnwood and planed wood based on coefficients provided by (FAO/ UNECE 2020). Here, some reliable information was available on the inputs and outputs. For further processed wood products this was not possible. Also, we mathematically checked the calculation approach by conducting the argumentation, see 6.2.

For the evaluation of available data on annual production by Prodcom we roughly analysed the share of data availability of wood packaging products based on the reported data by country [dataset] (Eurostat 2021). Data on the production of 2018 are available to 86% (pallets) and about 36% (casks and barrels). The rough share includes "confidential volumes" as well as zero production. In fact, as described in Eurostat (2017a) some countries report their production as zero as long as their respective production is less than 1% of the community total. That implies that we might miss production volumes and thus supply volumes of WPR within our calculation based on Prodcom data. Moreover, small sized companies with less than 20 employees are excluded from reporting (Eurostat 2017a).

Compared to other end-use products, such as furniture, the chosen sector is assigned to a few, rather homogenous product groups. However, due to the structure of the wood packaging industry, the volume of WPR is even higher since the sample calculation relies on the homogenous production of standardised products. In contrast to standardised wood packaging products, the quantification of WPR from individual wood packaging products, e.g., large tailor-made machinery, can only be based on vague estimates or detailed empirical studies. Other product groups, such as wood-based construction, may show a high variation of material composition and heterogeneity within the product group. Thus, the application of the calculation approach on various wood products, wood composites or wood supply chains requires a prior analysis regarding their material composition of products and production process. Generally, the approach can be applied on any classified wood product, however the analysis of the product or product group may differ in the level of extent.

Thus far, the WPR from further processing industries do not appear as marketable volumes, compared to SBP. However, the volume of WPR from wood packaging is already used and a part of cascading and circular resource flows. Vis et al. (2016) state that the use of WPR in the wood-based-panel production is one of the few established applications of cascading on European level. However, definite amounts of WPR from wood packaging (not to mistake with wood packaging waste) used in the production of wood-based panels are not known. In Germany, approximately 25% of WPR that accumulate in wood packaging production are used for industry internal energy use (Mantau and Hartig 2003). Compared to other wood processing industries, the share is small due to a lower demand of process energy during the production of wood packaging. If not disposed, a share of 75% can be allocated to material use, i.e., cascading use. In terms of climate change mitigation, the $CO_2$-neutral energy use of WPR in general, entails the theoretic substitution of fossil fuels (Sulaiman et al. 2020; Myllyviita et al. 2021).

## 5. Conclusion

The presented general calculation approach and the sample application in this study contribute to filling in the data gap on the supply of WPR (as described, e.g., in Camia et al. (2021)), especially of end-use sectors. Given the general calculation approach, the data set of product specific coefficients can be applied on available data on any spatial or regional level. The advantage of the general calculation approach is its adaptability to different research focus but also to current changes. It is, however, important to know the studied product and product group, to assign reasonable data or individual assumptions on material flow patterns and material efficiency, if there is no adequate data available. Generally, data on resource efficiency, and WPR in particular, would strongly benefit from detailed empirical research. Following the up-to-date objectives of circular economy, the recycling and pooling (e.g., pallets) of wood packaging products as well as the level of repair and recycling of end-use products in general is relevant for further differentiated research of wood resource consumption and supply of WPR. Additionally, the calculation of the possible mitigation effect can be part of further research.

The particular results of the study can be applied for a more detailed analysis of wood resource availability, trade flows and objectives of, e.g., wood-based circular economy and shall be seen as a stimulus to further investigate wood resource flows.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

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## Appendix A

Supply of wood processing residues – a calculation approach on the example of the wood processing residues from wood packaging

*Mathematical derivation of the general calculation approach*

The following equations describe the model of the quantification of the material flows. The main equations of the calculation approach are given in the main paper (see 2.1).

The basic components of the assumed (modelled) production process of a product with index *i* can be described as in equation 1.

$$IN_i = P_i + WPR_i + L_i \tag{A.1}$$

Where $IN_i$ is the wood input to the material flow, $P_i$ is the production volume of the manufactured product, $WPR_i$ is the quantity of wood processing residues and $L_i$ are losses[2] of the production process.

$$L_i = l{*}WPR_i \tag{A.2}$$

Where $l$ is an overall factor, dependent on $WPR_i$. We assume $l = 0.01$

Inserted in Eq. 1, we get:

$$IN_i = P_i + WPR_i + \ l{*}WPR_i = P_i + (1 + l){*}WPR_i \tag{A.3}$$

$P_i$ can be derived from product specific C-factor and density – applied on production output given in mass or volume. The specific content of carbon equals a share of 51.9% wood fibre content. We calculate $P_i$ in $m^3f$.

$$P_i = \left[\frac{P_0{*}\alpha_i}{0.519}{*}\rho_i\right] \tag{A.4}$$

Where $P_0$ is the given product specific production output (mass or pieces[3]), α is the product specific carbon content, $\rho_i$ is the product specific density (Diestel and Weimar 2014).

$P_i$ can also be derived from the factor *me* "material efficiency" and the following relation:

$$P_i = me_i{*}IN_i \tag{A.5}$$

As *me* indicates the material efficiency of a process (conversion step) it is usually used with index *n*.

*Tree diagram*

Following, we describe the calculation approach based on a tree diagram as an example. The shown tree diagram (Figure A.1) presents a theoretical process of three conversion steps. Three edges extend from every "knot" of the tree diagram spread. Formulas are given on the edges to calculate from one knot to the following knot. All three formulas of a knot need to add up to 1. Within the presentation we leave out the product specific index *i*:

Exemplarily we calculate the production volume of the third conversion step $P_3$ depending on the initial input volume $IN_1$, we multiply along the

[2] We use capital letters (IN, P, L, WPR, M) for values to distinguish them from factors (*me, l*), given in small letters

[3] If the production is given in pieces, the average weight of the product is applied as a factor to calculate the mass.

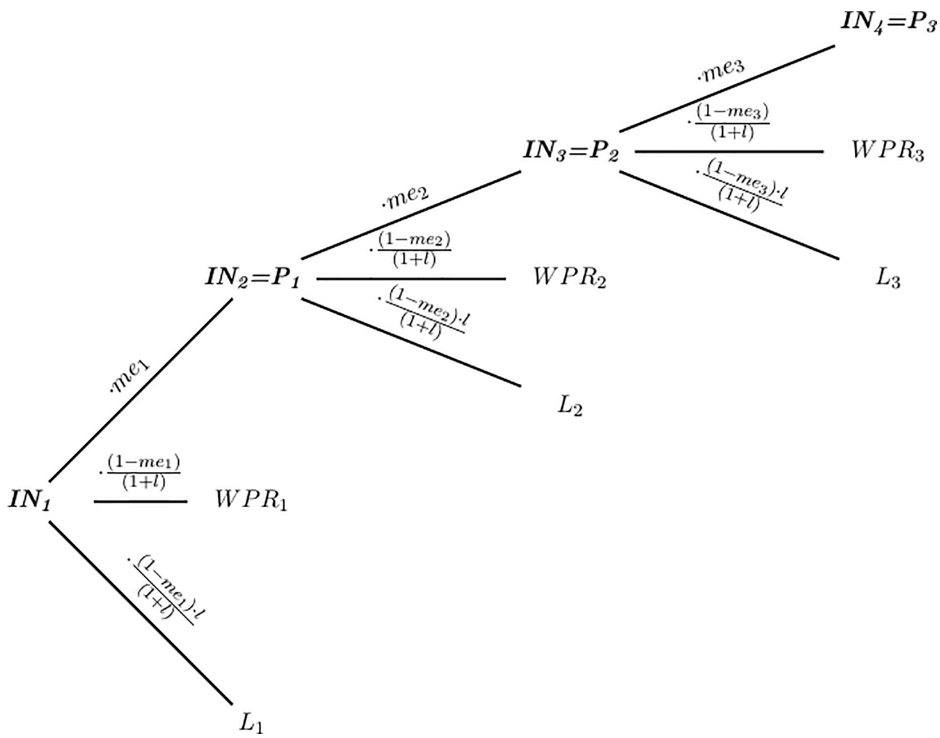


**Fig. A.1.** Tree diagram on wood resource input and output, conversion efficiency, WPR and losses.

upper branch.

$$P_3 = IN_1 * me_1 * me_2 * me_3 \tag{A.6}$$

In general:

$$P_n = IN_1 \prod_{j=1}^{n} me_j \tag{A.7}$$

Where j indices the conversion step of the process.

Converted to $IN_1$ we obtain:

$$IN_1 = \frac{P_n}{\prod_{j=1}^{n} me_j} \tag{A.8}$$

Mathematical evidence =1

**Mathematical derivation of WPR as a function of $IN_1$ based on the tree diagram and $n = 3$:**

$$WPR_1 + WPR_2 + WPR_3 = IN_1 * \frac{(1 - me_1)}{(1 + l)} + IN_2 * \frac{(1 - me_2)}{(1 + l)} + IN_3 * \frac{(1 - me_3)}{(1 + l)} \tag{A.9}$$

$$= IN_1 * \frac{(1 - me_1)}{(1 + l)} + IN_1 * me_1 * \frac{(1 - me_2)}{(1 + l)} + IN_1 * me_1 * me_2 * \frac{(1 - me_3)}{(1 + l)} \tag{A.10}$$

$$= IN_1 * \frac{1}{(1 + l)} * [(1 - me_1) + me_1 * (1 - me_2) + me_1 * me_2 * (1 - me_3)] \tag{A.11}$$

$$= IN_1 * \frac{1}{(1 + l)} * [1 - me_1 + me_1 - me_1 * me_2 + me_1 * me_2 - me_1 * me_2 * me_3] \tag{A.12}$$

$$= IN_1 * \frac{1}{(1 + l)} * [1 - me_1 * me_2 * me_3] \tag{A.13}$$

We obtain the following equation for the general case:

$$WPR = \sum_{i=1}^{n} WPR_i = WPR_1 + \ldots + WPR_n = IN_1 * \frac{1}{(1 + l)} * (1 - \prod_{j=1}^{n} me_j \tag{A.14}$$

Where $\prod_{j=1}^{n} me_j$ is the product of all *me* of a production process.

**Mathematical derivation of *Losses* as a function of $IN_1$ based on the tree diagram and $n = 3$:**

$$L_1 + L_2 + L_3 = IN_1 * \frac{(1 - me_1)*l}{(1 + l)} + IN_2 * \frac{(1 - me_2)*l}{(1 + l)} + IN_3 * \frac{(1 - me_3)*l}{(1 + l)} \tag{A.15}$$

$$= IN_1 * \frac{(1 - me_1)*l}{(1 + l)} + IN_2 * me_1 * \frac{(1 - me_2)*l}{(1 + l)} + IN_3 * me_1 * me_2 \frac{(1 - me_3)*l}{(1 + l)} \tag{A.16}$$

$$= IN_1 * \frac{l}{(1 + l)} + [(1 - me_1) + me_1 * (1 - me_2) + me_1 * me_2 * (1 - me_3)] \tag{A.17}$$

$$= IN_1 * \frac{l}{(1 + l)} + [1 - me_1 + me_1 - me_1 * me_2 + me_1 * me_2 - me_1 * me_2 * me_3] \tag{A.18}$$

$$= IN_1 * \frac{l}{(1 + l)} * [1 - me_1 * me_2 * me_3] \tag{A.19}$$

We obtain the following equation for the general case:

$$L = \sum_{i=1}^{n} L_i = L_1 + \ldots + L_n = IN_1 * \frac{l}{(1 + l)} * (1 - \prod_{j=1}^{n} me_j \tag{A.14}$$

Mathematical evidence: Sum of all P, WPR and L= $IN_1$

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