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Monitoring Sustainability Effects of the Bioeconomy: A Material Flow Based Approach Using the Example of Softwood Lumber and Its Core Product Epal 1 Pallet

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Abstract: The transition of our current economic system towards a bioeconomy that is based on renewable materials and energy can be an important contribution but at the same time a threat to mitigate the challenges of the 21st century, such as global warming and resource depletion. To assess societal, economic, and environmental impacts associated with this transition, we propose an approach for a sustainability assessment as an integral part of a future bioeconomy monitoring concept. The assessment approach is based on material flow analyses of the bioeconomy and their core products. As a proof of applicability, the proposed assessment approach is exemplified for the material flow of softwood lumber and its core product 'EPAL 1 pallet'. To simulate a frequent monitoring, material flow analysis and assessment of six sustainability effects are applied for the years 2010 and 2015. Since a frequent bioeconomy monitoring requires regularly updated and quality assured data, official statistics should be the major source of information. Whereas cutoff thresholds, nondisclosure of data, and high level of aggregation are major limitations of official production statistics and for material flow analysis, lack of information regarding environmental effects is the major limitation for material flow related sustainability assessment. We make suggestions on how to overcome these limitations and put our approach in to context with other ongoing monitoring activities.

Keywords: bioeconomy; monitoring; material flow analysis; sustainability assessment; softwood lumber; wood pallet

1. Introduction

The transition of our current economic system that is predominantly based on fossil fuels and nonrenewable materials towards a bioeconomy that is based on renewable materials and energy according to Goven and Pavone [1], can be an important contribution and at the same time a threat to mitigate the challenges of the 21st century. However, there is no common understanding yet of what a bioeconomy is and what it is not. McCormick and Kautto [2], Dieckhoff et al. [3], Fund et al. [4], Fund et al. [5], analyzed the concept of a bioeconomy from a policy and conceptual perspective and found that the definitions vary significantly between organizations, countries, as well as between stakeholder groups. While the definitions of the OECD [6,7] focus on economic growth and welfare based on biological resources, the definition in the EU bioeconomy strategy [8] (p. 16) is more focused on the production and conversion of biological resources. The bioeconomy definition in the German 'National Policy Strategy on Bioeconomy' [9] is rather wide. It defines bioeconomy as the knowledge-based production and use of renewable resources in all economic sectors to provide products, processes, and services. In the Finnish 'Bioeconomy Strategy' [10], the bioeconomy is not seen as a new industry, but the combination of primary production, refining industry and end products markets. In the South African 'Bio-economy Strategy' bioeconomy is seen as ' ... biotechnological activities and processes that translate into economical outputs ... ' [11] (p. 3). These are only a few selected definitions from a few selected bioeconomy strategies. However, although these definitions have a different focus, the underlying concept is the same. That is the shift from non-renewables to bio-based resources and use of biological processes. In addition, the shift should be made by employing advanced technologies, higher efficiency, improved products, generating high value added, creating jobs, and income. Although the cited definitions do not explicitly express that bioeconomy needs to be sustainable or more sustainable, it is a major driver for the shift towards a bioeconomy.

For the development of their bioeconomies only a few countries define explicit, measurable goals, roadmaps or action plans [4] (p. 111), and at the same time promote monitoring the development of their bioeconomies (Australia, EU, France, Malaysia, Spain, Thailand) [3–5]. Argentina, Brazil, Canada, China, Germany, Finland, Italy, Latvia, New Zealand, UK and the USA, however, promote monitoring the development of their bioeconomies without having measurable goals, roadmaps, or action plans [4,5]. Currently only very few of these countries already monitor the development of their bioeconomies. Finland's monitoring concept is based on the Finnish national accounts and quantifies the Finnish bioeconomy in terms of output of products manufactured at basic prices, gross value added, number of people employed, and gross fixed capital formation [12]. Malaysia, as well monitors the development of its bioeconomy solely in economic terms by calculating a so called 'bioeconomy contribution index' [13]. This index consists of the five sub-indicators investment, value added, export, productivity, and employment that are based on national statistics. According to Fund, El-Chichakli, and Patermann [4] countries such as Argentina and Canada are currently developing monitoring systems, but it is not clear yet what their task exactly will be. There is no indication that a more holistic assessment covering also social and environmental effects of bioeconomy is being developed elsewhere. However, from a societal perspective the economic development of the bioeconomy is important but only one aspect among many others. Meier [14] identified universal and equally important themes of societal relevance such as 'health', 'standard of living', 'resources', 'climate change', and 'international responsibility' that should be addressed when assessing effects of products, processes, or economic sectors.

Whether in addition to the monetary quantification of the Finnish and Malaysian bioeconomy the volume or mass of the produced goods is accounted for systematically remains unclear. To understand how and how much biomass and bio-based materials are produced, how interlinked the bio-based value chains are, which sustainability effects bio-based value chains or products have, a good understanding of the material and energy flows of the bioeconomy is essential. Since bio-based materials in general are versatile resources, the variety of uses and products from bio-based materials is numerous. Official statistics on production and processing of bio-based materials and manufacture of bio-based products are available, but the indicators provided do not necessarily allow for the calculation of flows of bio-based-materials processed at different stages of the value chain. Hence, the bioeconomy monitoring concept proposed in this paper is based on a sound Material Flow Analysis (MFA) tracing bio-based products from growing and harvesting of biomass until final disposal or incineration. MFA is used widely to assess resource use, material efficiency, cascade use, recycling quote, etc. at different geographical levels (national, sector, and product-level) [15–21]. With respect to biomass flows MFA have already been conducted for different regions and countries, e.g., biomass use within the European Union [22], Austria [23] or Switzerland [24], or wood material flow in Finland [25], France [26], Germany [27–30], or the Netherlands [31].

In general, a nearly full picture of bio-based material flows in Germany can only be drawn up to the first processing stage. In the case of wood products, the first processing steps are either sawmilling, wood-based panel, or wood pulp production. Beyond that, explicit information on the bio-based material, respectively, wood content in further processed products is hard to find. As comprehensive statistics on material input for manufacturing or further services are missing, a complete picture of a bio-based material flow can be drawn only using a variety of assumptions on the further use, processing, and/or consumption of a bio-based product.

Regarding bioeconomy the analysis of the multitude of existing and future value chains and products is a huge challenge even with a sound database.

As mentioned before, material flow analyses are as well the starting point for sustainability assessment because the amount of material and energy used very much determines the extent of the sustainability impacts.

The methods to assess sustainability effects are numerous [32]. On one side, there are indicator or index-based systems such as the Forest Europe criteria and indicators on sustainable forest management [33] or the Sustainable Development Goals adopted by the United Nations in the year 2015 [34]. Similar to other criteria and indicator or index-based systems (e.g., the wellbeing index or the human development index) they are not associated with any kind of valuation system or a specific material flow or product. Product or material flow related methods are in general based on a Life Cycle Assessment (LCA) approach. Suter et al. [35], Mehr et al. [36], and Kayo et al. [37] used a combined MFA and LCA approach to assess environmental impacts including potential effects from substitution and cascading for wooden material flows of Switzerland and Japan. Although having a system boundary comparable to the proposed monitoring concept, Suter, Steubing, and Hellweg [35] and Kayo, Dente, Aoki-Suzuki, Tanaka, Murakami, and Hashimoto [37] considered environmental impacts only up to the stage of semi-finished products. Impacts occurring after the first processing stage and use are not covered. Mehr, Vadenbo, Steubing, and Hellweg [36] limited all material use only to a wooden house and did not consider its use phase. Softwood and hardwood lumber are not distinguished in all of these studies. None of the abovementioned studies with the similar scope suggested a comprehensive methodology, including environmental, social, and economic assessment for the studied material flows. None of them had a comprehensive recurring monitoring as an evaluation goal, thus keeping in mind recurring data availability.

In addition to the standard life cycle assessment that quantifies environmental impacts related to the product or material flow, also economic and social impacts based on indicators or indices can be quantified. In fact, Life Cycle Sustainability Assessment (LCSA), as introduced by Kloepffer [38], represents the most prominent example for combining MFA with Environmental (LCA), Economic (LCC), and Social (SLCA) assessment methods on a product or service level. However, compared to ISO standardized LCA, a standardisation, as well as case studies, notably regarding social dimension [39,40] are still rare. Guinée [39] introduced a new definition of LCSA, calling it a LCSA framework, which broadens the scope from product-related evaluation to sector or economy-wide analysis. Thus, published case studies using the term LCSA differ significantly regarding used methodology and system boundaries, especially in assessment of economic and social aspects.

Studies assessing the economic pillar of sustainability based on MFA include material flow costing studies [18,41–43] and life cycle costing studies [40,44]. There are also approaches which cannot be clearly attributed to a particular methodology [45–47]. Most of these studies have rather small-scale system boundaries of a product, service or entity, although applications for economy-wide questions (such as electricity generation) exist [48].

MFA for assessment of social sustainability dimension is represented by SLCA studies or similar approaches integrating life cycle thinking in social assessment. Many of these studies use life cycle material flow as a starting point to define stakeholders/organisations affected by the studied process [49,50]. Hosseinijou et al. [51] extended the use of MFA to identify social hot spots for building materials. Statistical sectoral data on the country-level is often utilized even for assessment of products or processes on a smaller regional/organisational scale, since data gathering at organisational level with smaller resolution requires significant effort [49,50,52].

Sustainability assessments based on life cycle thinking and including environmental, social, and economic dimensions have been done for a variety of products and services related to bioeconomy [53–57] and wood-based material flows [58]. Onat, Kucukvar, and Tatari [57] and Spierling et al. [59] extended the scope of analysis to macro-level. Although this approach allows to achieve a desired macro-level assessment, the number of environmental indicators is limited to the available statistical data on sector-level. Furthermore, due to a very high level of aggregation, it fails to trace the environmental impacts of particular materials, which is indispensable for a bioeconomy-related sustainability assessment. To our very best knowledge, there are no studies of social and/or economic assessment which have a comparable scope of material flows on the national scale with a similar resolution (such as coniferous sawn wood) as the assessment concept proposed in this paper.

Indices such as the water footprint [60] or forest footprint [61] proposed by Egenolf and Bringezu [62] as a concept to assess sustainability of bioeconomy are usually not related to a product or single material flow but to the total consumption of a biomass or natural resource of a region or country. To put the indicator or index results into perspective they can be compared to a reference and/or normalized. By normalization it is shown how much the national or regional consumption contributes to a selected reference. Although normalization and/or comparison of indicator values with a reference is not a fully integrated assessment, the selection of a reference is a normative, value-based choice and very much determines interpretation of the assessment results. Fully integrated sustainability assessment methods, however, include a valuation step. This valuation consists of either a weighting process and/or a step that transfers the different indicator scales and units into a monetary value (cost-benefit analysis) or dimensionless digit (multicriteria analysis) [32]. In the end, the assessment method selected should strictly reflect goal and scope, functional unit (e.g., products, material flows, economic sectors), and the system boundary (regional, national, or international) [14].

The first aim of this paper is to present an approach for a material flow based sustainability assessment that is proposed to be an integral part of a future bioeconomy monitoring concept for Germany and possibly other countries, as well. This approach provides information about the total amount of bio-based materials produced, used, and recycled and as well about associated sustainability effects. To our knowledge this approach is currently not applied in any country regarding bioeconomy monitoring. However, due to the high number of material flows and products of the bioeconomy, a total coverage of all material flows from primary production until final disposal is not feasible. Hence, the approach is developed to assess core products that represent the major material flows of the bioeconomy. Regarding a bi- or triannual monitoring, the selection of core products limits data collection and analytical efforts. It reduces complexity to an acceptable level and at the same time covers major sustainability effects of bio-based material flows. In addition, the selection of core products allows comparing sustainability effects of bio-based with other bio-based products or substitutes. As a result, the approach provides information for, e.g., policies fostering and shaping the development of a bioeconomy. Complimentary to the material flow-based sustainability assessment, we also develop a sectoral approach that allows putting the sustainability effects of the bioeconomy into perspective with the economy as a whole or parts of it. This approach will be presented in an additional paper.

As a proof of applicability, the proposed assessment approach is exemplified for the core product 'EPAL 1 pallet' representing the material flow of softwood lumber. EPAL refers to the European Pallet Association, an organization that develops and secures standards in pallet production. To simulate a frequent monitoring, material flow analysis and sustainability assessment are applied for the years 2010 and 2015.

The second aim of this paper is to identify the current limitations and challenges concerning availability and quality of information. Finally, the sustainability assessment approach is discussed critically. Recommendations are given on how to improve availability of information needed for a periodic material flow based sustainability assessment as part of bioeconomy monitoring.

2. Methods

2.1. Definition of Bioeconomy

As pointed out in the introduction, the various existing definitions of bioeconomy are not very operational. They are not as distinctive as needed to delimit the bioeconomy from the rest of the economy. However, this is a prerequisite for a monitoring system. To monitor the development of bioeconomy it must be defined clearly what is part of bioeconomy and what is not. Since the material flow based sustainability assessment introduced in this paper is an extension of monitoring concept described by Iost et al. [63], the same definition of bioeconomy is applied here: 'Bioeconomy includes the production of biomass, bio-based manufacturing along the complete value chains as well as bio-based provision of services, like transport or retail of bio-based products. "Bio-based" refers to products that fully or partially consist of renewable material resources, i.e., biomass' [63] (p. 276). Since it is the task to monitor the material flows of the bioeconomy, the definition is rather narrow. Aspects of bioeconomy such as deployment of biological knowledge and biological systems are not covered. However, if, e.g., the deployment of biological knowledge has an impact on bio-based material flows, the proposed material flow-based sustainability monitoring will cover this impact.

2.2. Material Flow Analysis

In the context of bioeconomy monitoring, we understand Material Flow Analysis (MFA) as a means of describing the flow of a bio-based raw material from harvest to final disposal including all processing, manufacturing, and recycling steps that may take place in between. In contrast, material flow accounting describes the interaction of a national economy with the natural environment and foreign economy in terms of material flows [64]. Thus, in our approach the material flow is subdivided into processes where material is transformed into semi-finished or finished products, recyclate or waste. A process may also lead to aggregation or allocation of a material flow [27].

To monitor the entire bioeconomy and its material flows, in principle, all material flows from raw material production until final disposal need to be identified and quantified. This is a challenge due to the vast amount of material flows and products. It would require huge efforts. To keep the effort to an acceptable level and at the same time to cover bioeconomy as fully as possible, we propose a two-step approach: First step, complete coverage and quantification of bio-based material flows until the first production stage. This gives an overview on the bio-based material flows in a country. In a second step, major material flows represented by a core product should be analyzed completely. This is to get a more thorough understanding about the structure of production, use, recycling, and disposal of bio-based materials.

2.3. Sustainability Assessment

In order to quantify the sustainability effects of a material flow we propose to combine the 'Logical Framework for a Sustainability Assessment' (LOFASA) [14] with LCA and MFA. A schematic workflow is presented in Figure 1. Whereas for definition of scope and goal of the sustainability assessment, functional unit, system boundary and cutoff criteria we refer to LCA and MFA, the selection of indicators follows the LOFASA. Statistical and nonstatistical sources, as well as the MFA of a material flow are used to quantify the selected indicators.

However, to keep the paper as concise as possible, the consecutive steps of the LOFASA, as well as the LCA/MFA based assessment steps are described rather briefly in the subsequent sections.

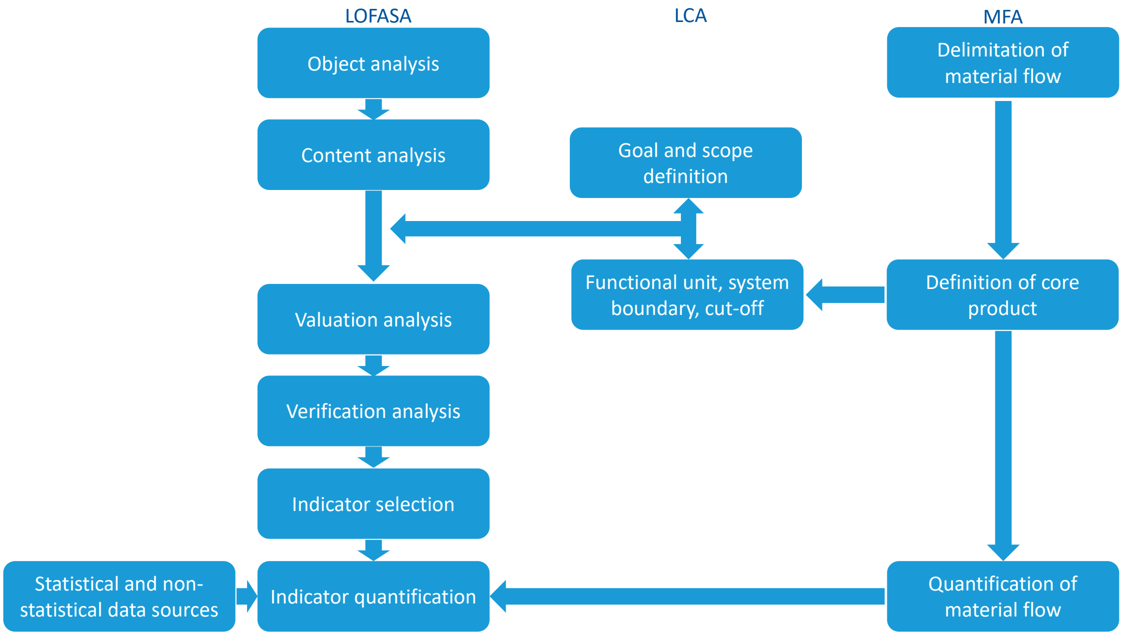

Figure 1. Schematic workflow of the material flow based sustainability assessment (Sources: [14]).

2.3.1. Selection of Relevant Sustainability Aspects Applying Content and Valuation Analysis

It is common understanding that environmental, economic, and social aspects should be regarded in a sustainability assessment. However, what are the relevant environmental, economic, and social aspects that should be addressed and how to select them? To identify and select indicators, we propose to apply the 'Logical Framework for a Sustainability Assessment' (LOFASA) [14]. According to LOFASA, the relevant sustainability aspects are identified based on a thorough qualitative content analysis [65,66] of the current societal discourse in public, stakeholder groups, media, and politics. Qualitative content analysis is a common methodology in socio-empirical studies to systematically structure any kind of communication about a distinct topic. To structure the different kinds of communications, a database is set up with information about the communications' content, sources, search terms used to find them, etc. Next, the communications are structured based on key words or phrases. Content represented by the key phrases is paraphrased and assigned to so- called semantic analytical units. The semantic analytical units are text modules that represent sustainability aspects such as criteria or indicators. As a result, complex communications are narrowed down to a few essential attributes. Finally, the semantic analytical units are assigned to sustainability themes such as health, resources, standard of living, climate change, economic competitiveness, and international responsibility. Coding rules make sure that the assignment process is reproducible and subjective choices of the encoder are minimized.

In the next step of LOFASA those sustainability aspects, that are not relevant for the assessment object, are eliminated in a valuation analysis [14]. The valuation analysis is a heuristic process based on logical and comprehensible causal interrelations. The valuation analysis is a tool to eliminate those analytical units that do not address the object of the assessment. The resulting list of sustainability aspects relevant for the object of assessment is one of the bases for the selection of indictors that are required for the quantification of sustainability effects of the core products.

2.3.2. Goal and Scope Definition

The next step after selection of relevant sustainability aspects is goal and scope definition. In order to meet the needs of the users of a bioeconomy monitoring system, we propose that goal and scope definition should be a participatory process involving the various users [14]. From a methodological point of view, this step corresponds with goal and scope definition in an LCA study [67]. How the participatory process is setup, should depend on the country specific needs and goals.

In addition to the specific assessment goals obtained in the proposed stakeholder process, the proposed sustainability assessment approach such as the whole bioeconomy monitoring concept is designed to be:

- Predominantly based on periodically updated and reliable information,
- Transparent,
- Efficient,
- Goal oriented,
- Flexible enough to cover altered and new material flows and products of an evolving bioeconomy.

A periodical update of information in data sources is a prerequisite to monitor changes of the bioeconomy. Quality insured data guarantee reliability of monitoring results. Hence, official statistics are due to their periodicity and quality assurance a preferred source of information. Transparency is also key since any monitoring step and any calculation must be reproducible and comprehensible. Efficient in the context of bioeconomy monitoring means that the goals of the monitoring should be met in a cost and time efficient way. In addition, the monitoring itself should focus only on relevant aspects of bioeconomy. Relevance must be defined by the user groups of the monitoring and is part of the LOFASA. The setup of the monitoring should address the monitoring goals. Any effort that is not goal-oriented must be avoided. Finally, the monitoring system should be flexible enough to cover altered and new material flows. Consequentially, revision of material flows and products is a prerequisite in the beginning of any new monitoring period.

2.3.3. Functional Unit, System Boundaries, and Cutoff Criteria

Regarding the definition of a functional unit, system boundaries, and cutoff criteria the proposed sustainability assessment combines LCA and MFA (cf. Figure 1).

Since a bio-based material flow differentiates into a multitude of products with different uses, lifetimes, recycling rates, etc., it is not feasible to select a material flow as the functional unit. Instead, we propose to select the amount of a core product produced repaired, recycled, and disposed in one year as the functional unit. The selection is based on the results of an MFA for a certain bio-based material. Typically, the core product is produced using the biggest share of a bio-based material flow. It represents the material flow by means of quantity. Due to the large quantity produced, recycling and waste streams of the core product are also significant. Since many sustainability effects are related to mass, by selecting a core product, consequentially, also a large proportion of the sustainability effects of the material flow are covered.

The technical system boundary is set by delimiting the assessed material flow and core product from other material flows and products (cf. Section 2.2). This is a requirement for MFA to prevent from overlapping and double counting.

Geographically, the system covers a country. To assess the sustainability effects associated with the core product all steps of production, use, recycling, and disposal are assessed.

Sustainability effects associated with services, ancillary materials, and means of production required to produce a core product are in general cutoff from the assessment. However, for components of a core product that do not belong to the material flow, a common understanding is needed whether these should be included in the assessment or not.

2.3.4. Selection of Indicators Applying Verification Analysis

The indicators are selected regarding the specific assessment goals (cf. Section 2.3.3) and the sustainability aspects identified as being relevant for bioeconomy monitoring in the content and valuation analysis of LOFASA (cf. Section 2.3.1). According to LOFASA, the indicators should be checked by experts in a verification analysis for redundancy, adequateness, efficiency, and detail. To limit the efforts for data acquisition redundant indicators must be eliminated. Indicators should adequately address the relevant sustainability aspects. At the same time, they should as comprehensively as possible assess and quantify the cause or causes of the respective sustainability effects.

Finally, the indicators that pass the verification analysis are from a scientific point of view suitable for the assessment and should be put up for discussion and final selection among stakeholders.

2.3.5. Quantification of Indicators

Similar to any other monitoring system, a bioeconomy monitoring is setup to be frequently repeated. Hence, it should be based on publicly available quality assured and frequently updated information. Ideally, this is official and nonofficial statistics because specific data acquisitions would be too costly and time consuming. This holds true not only for the quantification of material flows but also for the quantification of the sustainability indicators. As Figure 1 shows, the sustainability indicators are quantified by combining statistical information with the results of the MFA. In general, indicators should be quantified for each processing, use, recycling, and final disposal step of the material flow in order to show how much a certain step contributes to the sustainability impact quantified by the indicator. However, if information is not available yet, the approach allows for the quantification of only some steps or as a total for the entire material flow and its core product.

2.4. Case Study EPAL 1 Pallets

As mentioned earlier, this paper's aim is to present and proof the applicability of the material flow based sustainability approach. To keep the paper as concise as possible, the focus is first on quantification of the material flow and sustainability indicators and second on testing data availability. Since goal and scope definition, as well as the indicator selection process is not crucial for the quantification, it is not covered by the case study. Regarding data availability, the case study aims to reveal current data gaps and show the consequences for the quantification of the material flow and sustainability indicators.

2.4.1. Material Flow Analysis of Softwood Lumber and Its Core Product EPAL 1 Pallets

The material flow analysis uses the example of softwood lumber for the years 2010 and 2015. As the core product representing softwood lumber, the dominant type of flat pallet, which is EPAL type 1 (EPAL 1 pallet) was selected. It is made of softwood lumber, blocks made of compressed wood particles and nails. According to German production statistics [68], EPAL 1 pallets, which fall under "flat pallets and pallet collars of wood" (Production Statistics code 1624 11 330), are the major finished wood product within the classification of production statistics. It should be noted that products similar to, lumber or planed wood are also major products with even higher production figures. However, although final consumers directly use a certain amount, in the context of this analysis, such products cannot be interpreted solely as finished but also as semi-finished products.

Figure 2 shows the generalized material flow for softwood in pallet manufacturing and data sources needed for quantification of this specific material flow. For the calculation of material flows of other wood-based products other data sources may be necessary. The material flow starts with softwood removed from German forests (production). A major part is processed in sawmills. A certain percentage of the lumber produced is used to manufacture wood packaging (1st and 2nd). Wood packaging can be disaggregated into end-products using official production statistics. As mentioned above, our chosen core product falls under the production code 1624 11 330 "flat pallets and pallet collars of wood". In addition to EPAL type 1, this code subsumes "other flat pallets of wood, pallet collars of wood and pallet collars of wood (assembled, with hinges)" and gives information on the total number of produced pieces within this code [68].

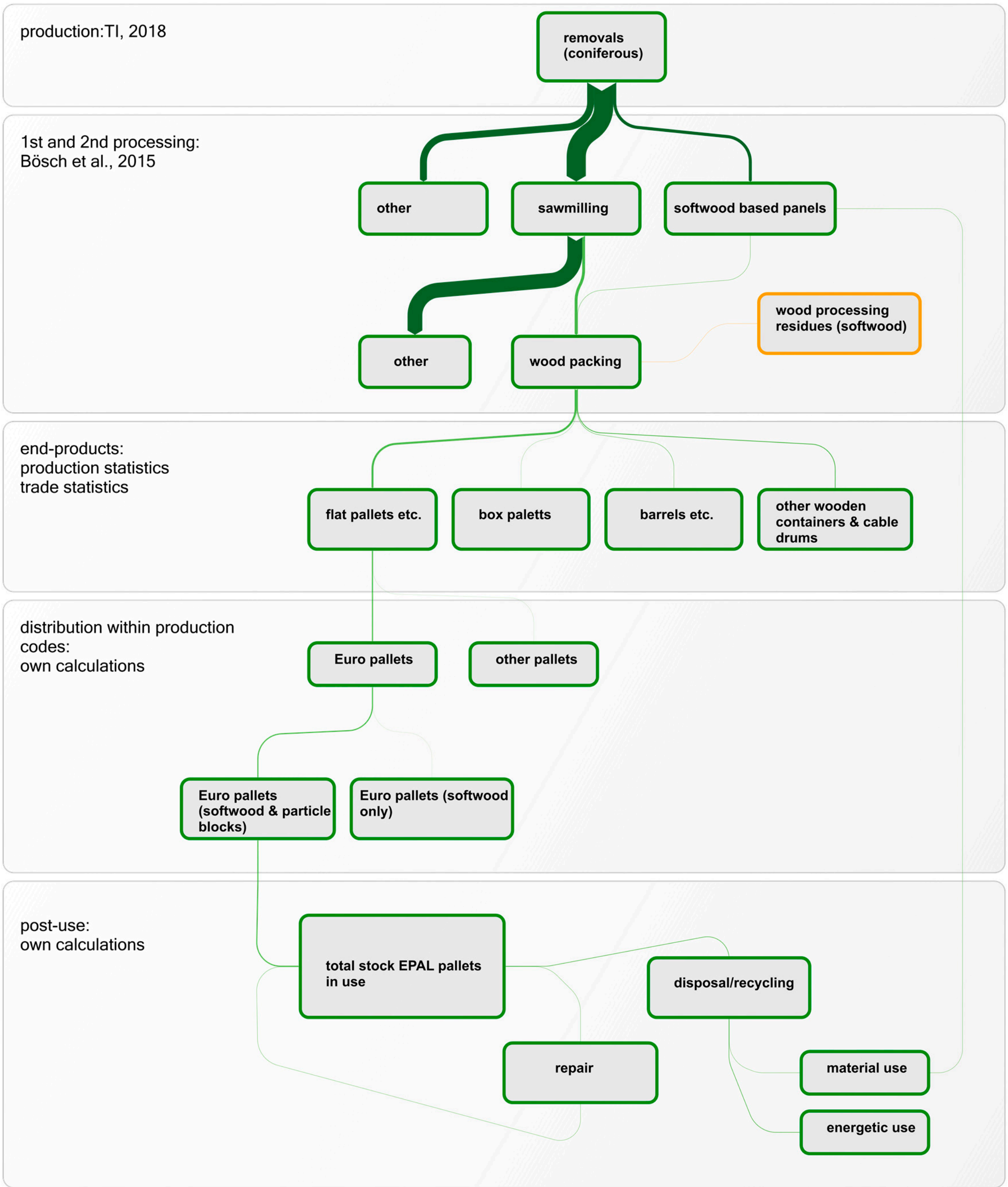

Figure 2. Generalized material flow of European Pallet Association (EPAL) 1 pallets (Sources: [28,69]).

Since under production code 1624 11 330 the production of different types of flat pallets is covered, in a first step it needs to be identified how much EPAL 1 pallets are produced and how much softwood lumber is used for its production. For that, the following assumptions are made: (i) 95% of the products under production code 1624 11 330 are flat pallets, (ii) 95% of (i) are EPAL 1 pallets. Of those, 95% are made from softwood lumber (71.5% of weight), wood particle blocks (26.2%) and nails (2.3%) [70]. The remaining 5% of flat pallets only consist of softwood lumber (97.7%) and nails (2.3%).

Weight and volume of the softwood lumber in the selected type of pallets were calculated based on the calculated number of pieces and the findings of Scholtes and Jansen [70] who dismantled EPAL 1 pallets and measured and weighed each component separately. As a result, for each component volume and weight are available (see Table 1). The authors calculated the average density of one flat pallet as 0.486 g cm^{-3}.

Table 1. Weight and volume of components of EPAL type 1 pallets.

Component	Weight in kg	Volume in m^3
Total weight	22.1	0.0444
Softwood lumber	15.8	0.0331
Particle board blocks	5.8	0.0113
Nails	0.5	

To show the magnitude of the flow of softwood along the processing steps, finally, information about the total amount of softwood, softwood lumber, and wood packaging produced is required. As shown in Figure 2, data for felling and use of softwood is based on [69]. Data regarding 1st and 2nd processing is only available for the year 2010 by Bösch, Jochem, Weimar, and Dieter [28]. To be able to calculate the flow for the year 2015 we assumed that in 2015 the packaging industry used the same softwood/hardwood ratio of sawn wood and wood particle blocks as in 2010. Furthermore, we assumed that the ratio of in- and outputs of the packaging industry are according to the results of Bösch, Jochem, Weimar, and Dieter [28] and also remained unchanged in 2010 and 2015.

Along the general material flow, produced pallets in general and EPAL 1 in particular, enter the total stock of pallets in use (cf. Figure 2). According to [71], the average lifespan of a timber pallet is five to seven years. Hence, we assumed a lifespan of six years. We calculated the stock in use as the sum of produced flat pallets as documented in the German production statistics codes 2040 11 330 (2006–2008) and 1624 11 330 (2009–2015). Data for the years 2006 to 2010 are used to calculate the stock in 2010 and data from 2010 to 2015 for the stock in 2015, respectively.

After use, pallets may be repaired and re-enter the stock in use. Considering the wood material flow, 14.4% of the lumber contained in one pallet are substituted with fresh lumber during repair on average [70]. If they cannot be repaired, pallets are disposed of and usually recycled. According to the German ordinance on waste wood (AltholzV), only untreated waste wood is allowed to be reused. This is true for wood packaging products. Hence, this material flow is an important resource in particleboard manufacturing [72,73]. Pallet-based waste wood is also important for energy generation in biomass plants [74]. Based on [70], we assumed that 33% of disposed pallets went into material uses (particle boards) and 67% were incinerated.

In 2014 and 2016, some 1.20 million t and 1.29 million t of reusable packaging, mainly pallets, were disposed of [75,76]. From the data given by Schüler [75,76] an average for 2015 was calculated. In order to calculate the amount of disposed reusable packing in 2010 and 2015 this average was related to the amount of post-consumer wood used in particle board manufacturing in 2010 and 2015 [77]. We reduced this amount to the post-consumer wood that can be attributed to EPAL 1 pallets by applying the same assumptions as in calculating production of EPAL 1 pallets.

2.4.2. Goal and Scope

As mentioned earlier, goals and scope definition as described in Section 2.3 is not covered by this case study. Hence, the goals selected are proxies that stand for the selection process described in Section 2.3. The goals are:

1. Relevant environmental, economic, and social effects of a material flow and its core product shall be assessed and quantified.
2. The assessment is setup for comparisons with reference material flows and core products.

The first goal reflects the common understanding that all three pillars of sustainability (environmental, economic, and social) should be reflected in a sustainability assessment. The second goal considers that bio-based products must proof that they are more sustainable than other nonrenewable products with the same function.

2.4.3. Functional Unit, System Boundaries, and Cut-off Criteria

The functional unit of the case study is the amount of two versions of EPAL 1 pallets produced, repaired, recycled, and disposed in one year. One version is made of softwood only and the other version with particle board blocks instead of softwood blocks. Both versions are the core products of the material flow of softwood lumber.

Technically, the sustainability assessment of the two EPAL 1 pallet versions covers forestry and logging, sawn wood pallet production, pallet use, repair, and disposal (cf. Figure 2). Pallet use, repair, and disposal are due to nonmatching data sources only assessed for the environmental effects. Geographically, the assessment covers Germany and temporally the years 2010 and 2015. However, regarding the assessment of the environmental effects data specifically for Germany are currently not available.

2.4.4. Indicator Selection

For this case study, six indicators have been selected to exemplify the assessment of sustainability effects of the softwood lumber material flow with its core product EPAL 1 pallet (Table 2). Similar to goal and scope, these are proxies for indicators selected according to the process described in Section 2.3. However, the selected indicators are well established and often used to assess environmental, economic, and social sustainability aspects of products and services.

Table 2. Selected sustainability indicators and associated data sources.

Sustainability Indicators	Data Sources
Environmental	
Global Warming Potential	Scholtes and Jansen [70]
Eutrophication Potential	Scholtes and Jansen [70]
Economic	
Production Value	Eurostat [78,79], Rosenkranz [80]
Value Added at Factor Cost	Eurostat [78,79], Rosenkranz [80]
Social	
Number of Persons Employed	Eurostat [78,79,81,82]
Average Annual Earnings	DESTATIS [83–85]

Environmental Indicators

As two examples for indicators assessing and quantifying environmental sustainability effects of the EPAL 1 pallets Global Warming Potential (GWP100) and Eutrophication Potential (EP) are selected. Both indicators address so-called midpoint environmental impact categories [86]. Midpoint because they do not directly quantify impacts on human health, social assets, biodiversity, and primary plant production. These are the so-called impact endpoints LCAs try to characterize to give a comprehensive environmental impact profile of the system assessed. GWP100 quantifies the impact on radiative forcing of the studied system whereas EP quantifies impacts of nitrogen and phosphorous on waters and soil. Hence, both indicators address two important sustainability aspects: Climate change and protection of waters and soil.

Information on greenhouse gas, as well as eutrophying emissions associated with EPAL 1 pallets based on official statistics or a representative German LCA study are currently not available. Consequently, GWP and EP are calculated based on a LCA study made by the Dutch Institute for Building Biology and Ecology [70]. The study covers the complete life cycle of EPAL 1 pallets including use and disposal. Both indicators are quantified according to the CML-2 method, developed at the Centre of Environmental Science at Leiden University [86] described in Scholtes and Jansen [70]. More details on the main underlying data and assumptions made can be found in Appendix A. Since the study does not contain information about the individual contributions of softwood lumber, wood particle blocks and nails, GWP and EP have to be related to EPAL 1 pallets instead of softwood used in EPAL 1 pallets, only.

Economic Indicators

'Production value' and 'value added at factor costs' are the two indicators selected to estimate economic effects associated with EPAL 1 pallets. Ronzon and M'Barek [87], for example, propose value added to be one of the socioeconomic indicators to assess bioeconomy on EU level. Production value is the total value of all economic activities generated along the assessed material flow. In this case study softwood harvesting, pallet production, and repair are covered. Disposal and/or incineration is not covered, yet. Production value is defined as turnover, plus or minus the changes in stocks of finished products, work in progress and goods and services purchased for resale, minus the purchases of goods and services for resale, plus capitalised production, plus other operating income (excluding subsidies). Income and expenditure classified as financial or extra-ordinary in company accounts is excluded from production value [88].

Value added at factor costs is the gross income from operating activities after adjusting for operating subsidies and indirect taxes. Value adjustments (such as depreciation) are not subtracted [88].

Both values indicate the economic relevance of the material flow and 'core product' as such and in relation with the production value and value added of the German economy. In comparison to the production value, the value added at factor costs indicates the depth of value creation within the material flow since the intermediate consumption is subtracted from the production value.

Contrary to the environmental effects that cannot be quantified based on official statistics, the stages of material flow match with the structure of the economic activities used within the European Union (NACE). This allows for the use of various statistical sources for calculation of socio-economic indicators. The calculation of the selected economic indicators for the processing industry is based on the structural business statistics published by Eurostat [78,79]. These are the only statistics that include small entities with one or more employees and at the same time provide the necessary sectoral differentiation. Since forestry and logging are not covered by the structural business statistics, the German National Economic Accounts for Forestry was used as a data source [80]. Since the production value and value added at factor costs are given per economic activity, the shares for EPAL 1 pallet production in the related economic activities were calculated as the percentage of softwood lumber contained in the finished EPAL 1 pallets as related to the total amount of wood used in the relevant economic activities. For repair, the share was calculated using details on production value for the economic activities 3319 'Repair of other equipment' and 1624 'Manufacture of wooden containers', as well as data and assumptions of the material flow described in Section 2.4.1. The calculation details can be found in Appendix B.

Social Indicators

To exemplify the quantification of social effects, the 'number of persons employed' as well as the 'average annual earnings' of fulltime employees associated with EPAL 1 pallets were selected. The number of persons employed is also proposed by Ronzon and M'Barek [87] to monitor the bioeconomy on EU level.

The calculation of persons employed associated EPAL 1 pallet production is based on structural business statistics. Only these statistics provide the employment data at the required depth [79,80]. For forestry and logging, the labor force survey of Eurostat was used, which is to our best knowledge, the only available official statistics for persons employed in forestry and logging today [81,82]. Since the number of employed persons and the average annual earnings are reported per economic activity, the share for EPAL 1 pallets were calculated using the approach described in the previous chapter.

Average annual earnings of full-time employees are based on the earnings survey for the processing industry [83,84] and the structure of earnings survey for forestry and logging [85]. The results are available upon request at the German Federal Statistical Office. The first survey is the only available data source, which provides the necessary differentiation of data for the processing industry. The latter survey is the only available statistical source for earnings in forestry. It is conducted and published every four years and includes forestry and logging starting from the year 2014. However, due to missing data on earnings in forestry and logging for the year 2010, it was not possible to calculate the average annual earnings for the entire production chain of EPAL 1 pallets for the year 2010. In order to quantify the earnings for the year 2015 it was assumed that the earnings in forestry in 2015 remained at the same level as in 2014. Please, also note that both statistical sources have slightly different scopes and methodology. The main differences are highlighted in Appendix C, which also contains all calculation details.

3. Results

3.1. Material Flow Analysis

Table 3 shows that in 2010 approximately 2.128 million t and in 2015 approximately 2.624 million t wood was used in Germany for the manufacturing of packaging products. 1.048 million t in 2010 and 1.316 million t in 2015 of softwood was used for EPAL 1 pallet production. This amount is equivalent to 35% in 2010 and 36% in 2015 of softwood used for manufacturing of packaging. The produced EPAL 1 pallets (softwood and wood particle blocks), contained 0.978 million t softwood in 2010 and 1.228 million t in 2015. For EPAL 1 pallets made of softwood lumber and nails only, 0.07 million t (2010) and 0.088 million t (2015) softwood were used. In 2010 about 5.7 and in 2015 7.08 million t softwood lumber was stored in both EPAL type 1 pallets. For repair of pallets approximately 0.07 (2010) and 0.08 (2015) million t softwood lumber was used. In 2010 about 0.272 million t and in 2015 0.270 million t softwood lumber that originated from packaging was used as post-consumer wood for particleboard production.

Table 3. Material flow of softwood lumber in pallet manufacturing. Sources: [28,69], Own calculations.

Processing Steps		Softwood Weight million t	
		2010	**2015**
Forest production	Softwood removals	20.686	19.061
1st processing	Sawmilling	13.609	13.095
2nd processing	Wood packaging	2.128	2.624
End product	Flat pallets (EPAL 1)	1.048	1.316
	EPAL 1 (softwood and wood particle blocks)	0.978	1.228
	EPAL 1 (softwood only)	0.070	0.088
Stock in use	EPAL 1 (softwood and wood particle blocks)	5.349	6.605
	EPAL 1 (softwood only)	0.385	0.475
Repair	EPAL 1 (softwood and wood particle blocks)	0.175	0.217
	EPAL 1 (softwood only)	0.009	0.011
Post-use (material)	EPAL 1 (softwood and wood particle blocks)	0.253	0.252
	EPAL 1 (softwood only)	0.018	0.019
Post-use (energy)	EPAL 1 (softwood and wood particle blocks)	0.515	0.511
	EPAL 1 (softwood only)	0.037	0.037

3.2. Sustainability Assessment

3.2.1. Environmental Indicators

GWP as well as EP do not differ much between the two EPAL 1 types when related to 1 metric ton of EPAL 1 pallets. As shown in Table 4, EPAL 1 pallets made with wood particle blocks have a slightly higher GWP and EP per t of product. This is caused by a higher energy demand to produce the wood particle blocks as compared to softwood lumber. However, EPAL 1 pallets with wood particle blocks are the most commonly produced type since it has lower production cost and the same level of quality. Due to the significantly higher production amount of EPAL 1 pallets with wood particle blocks in 2010 and 2015, GWP and EP are significantly higher (cf. Table 4). Total GWP for the EPAL 1 (softwood and wood particle blocks) was 1.724 million t CO_2 eq. in 2010 and 2.261 million t CO_2 eq. in 2015. The EP was 2349 t PO_4^{-3} eq. in 2010 and 2912 t PO_4^{-3} eq. in 2015.

Table 4. Cumulated environmental impacts resulting from the production, use, and disposal of the EPAL 1 pallets in Germany (Source: [70] And own calculations).

EPAL 1 Pallet Type	**Impact of Production, Use, and Disposal per t EPAL 1 Pallet**		**Impact of Production, Use, and Disposal of the Total Amount of EPAL 1 Pallets in GERMANY**			
	GWP t CO2 eq.	Eutrophication kg PO_4^{-3} eq.	GWP thousand t CO2 eq.		Eutrophication t PO_4^{-3} eq.	
Year			2010	2015	2010	2015
EPAL 1 (softwood lumber only)	1.06	1.68	76	100	112	138
EPAL 1 (softwood and wood particle blocks)	1.21	1.76	1648	2160	2237	2774
Total			1724	2261	2349	2912

Figures 3 and 4 show that the use phase contributes most significantly to the environmental impacts. This is caused by fossil fuel combustion during the transportation of loaded pallets. Moreover, production has a significant share in the total amount of GWP and EP in the respective years, mainly due to the energy use during the processing of wood and nails. End-of-life phase partly offsets the global warming impact, since both wood combustion and wood recycling save CO_2 emissions either for energy generation or production of new wood particle blocks. Based on the currently available data, a more differentiated breakdown into processing steps such as in the MFA or for the economic and social indicators is currently impossible. For frequent monitoring this data gap needs to be filled.

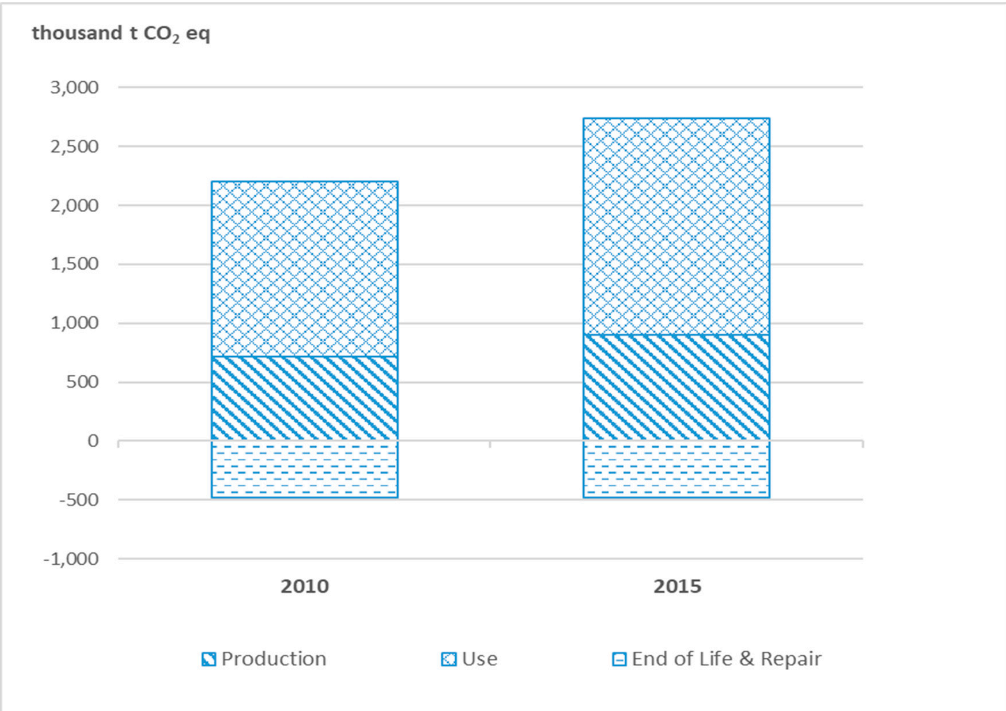

Figure 3. Breakdown of Global Warming Potential (GWP into the process steps of softwood lumber material flow and its core product EPAL 1 pallets in 2010 and 2015 (Source: [70] And own calculations).

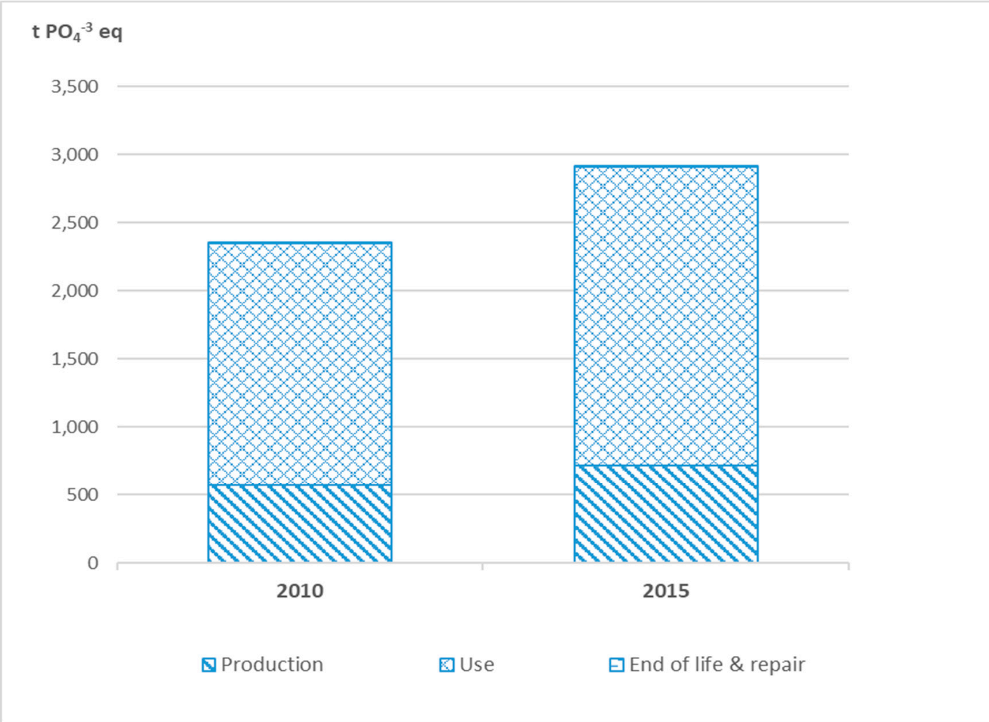

Figure 4. Breakdown of Eutrophication Potential (EP) into the process steps of softwood lumber material flow and its core product EPAL 1 pallets in 2010 and 2015 (Source: [70] And own calculations).

Since GWP and EP are standard LCA impact categories the results can be compared to other material flows of core products or nonbio-based substitutes (such as plastic pallets) provided that assessment goal and scope, as well as the system boundaries are identical. The underlying calculation data and assumptions can be found in Appendix A.

3.2.2. Economic Indicators

As indicated in Figure 5, in 2010 the production value related to the softwood lumber material flow and its core product EPAL 1 pallet was 1060 and 1574 million € in 2015. In 2010 that was equivalent to 10% of the total production value generated in economic activities forestry and logging, sawmilling, manufacture of wooden containers, and repair of other equipment, whereas in 2015 it was equivalent to 11% (cf. Table A1, Appendix B).

The added value generated in the process steps of softwood lumber and its core product EPAL 1 pallets was 336 million € in 2010 and 503 million € in 2015 (cf. Table A2, Appendix B). This equated 9% of the total value added generated in 2010 in the related economic activities of forestry, sawmilling, manufactory of wooden containers, and repair. In 2015 it was 10%.

Looking at the distribution of production value and value added, it shows that assembling EPAL 1 pallets in the economic activity manufacture of wooden containers generates the highest values in the entire material flow. However, it is a common observation that the last processing step in a production value chain generates the highest production value and value added. In line with the higher production value and value added generated in the relevant economic activities of the material flow in 2015 as compared to 2010, also the production value and value added of the EPAL 1 pallets increased significantly. The share of EPAL 1 pallets in the relevant economic activities remained almost unchanged. This is reflected in the increase of production value and value added. Compared to the economic activities sawmilling and planning of wood and manufacture of wooden containers, the difference between production value and value added is rather small in forestry and logging. This is because in the first processing step the connections to other economic activities is low and as a result the amount of intermediate consumption is rather small.

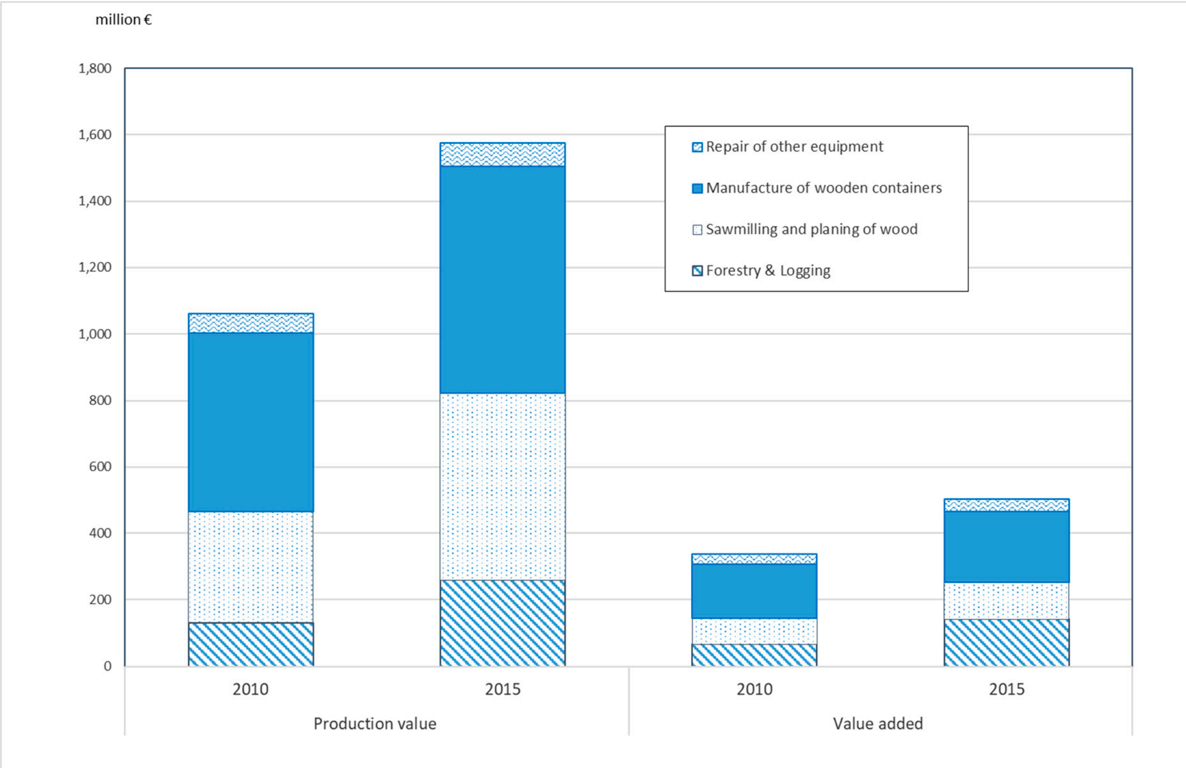

Figure 5. Production value and value added at factor costs of the process steps of softwood lumber material flow and its core product EPAL 1 pallets. Production value and value added at factor costs associated with the production of nails and wood particle blocks are not included. Source: [78,79] And own calculations.

3.2.3. Social Indicators

Similar to production costs and value added, the production of EPAL 1 pallets as part of the economic activity manufacture of wooden containers accounts for the highest employment share of the entire material flow, as can be seen in Figure 6. In line with the increased use of softwood and softwood lumber for the increased EPAL 1 pallet production between 2010 and 2015 the number of persons employed also increased from 7500 persons in 2010 up to 8900 persons in 2015 (cf. Table A4, Appendix C). Within the economic activities, the percentage of persons employed for the material flow increases from 3% in forestry and logging to 6% in sawmilling and planning of wood, 29% in repair of other equipment, and to 35% in manufacture of wooden containers in 2010 (cf. Table A4, Appendix C). In 2015 the numbers differ only slightly.

Manufacture of wooden containers has, however, compared to the other activities the lowest average annual earnings (cf. Figure 3). While in forestry and logging the average annual earnings are 38,000 € and in sawmilling and planning of wood 33,000 €, it is only 32,000 € in manufacture of wooden containers. Compared to the average annual earnings in Germany of 46,000 € in 2014, the average annual earnings of persons working in the sawn wood material flow is with 34,000 € significantly lower. Since only the four-yearly structure of earnings survey provides comprehensive statistical data for average annual earnings including all economic activities (and agriculture, forestry, and fisheries), the average annual earnings of Germany are only available for 2014. Data are unavailable for 2015.

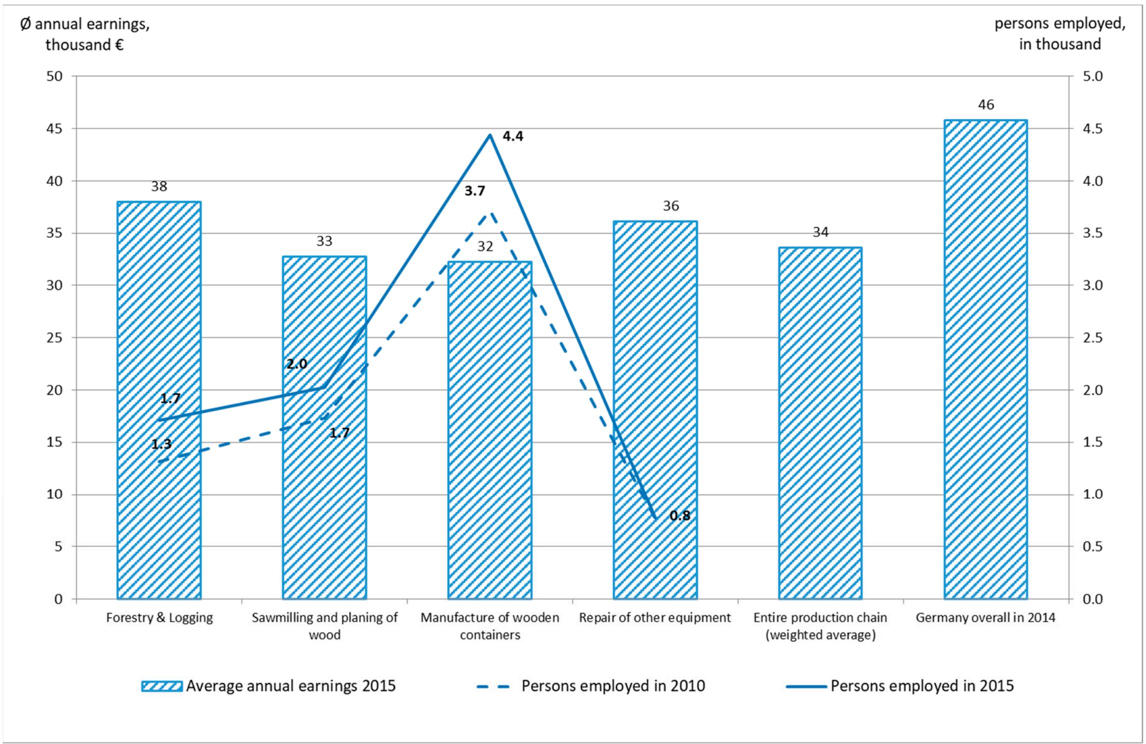

Figure 6. Persons employed and average annual earnings of full-time employees associated with the process steps of softwood lumber material flow and its core product EPAL 1 pallets for 2010 and 2015. Production of nails and wood particle blocks are not included. Sources: [81–85], Own calculations.

4. Discussion

4.1. Material Flow Analysis

The precise quantification of material flows relies on available data on produced goods. For Germany, national production statistics provide most data. However, there are several general limitations. First, cutoff thresholds. Only enterprises with 10 or more employees are obliged to report data for production statistics. Thus, the statistics do not cover Small and Medium-Sized Enterprises (SME) and do not offer the full picture of economic activities [89]. Second, if an economic activity is conducted only by a small number of companies, respective data is not disclosed. For scientific purposes and policy advice such data should be made available under strict obligations on the aggregation level of the results.

In general, production statistics do not provide information on biomass contents of the listed products. Products with different biomass contents are often aggregated under the same product code and it is unknown how the products are distributed within the product code. Thus, the biomass contents of end-products need to be derived empirically through market or LCA studies, expert interviews or other secondary statistics [23]. With regard to material flow based monitoring, the resulting efforts are significant, especially in fast changing or developing bio-based products markets. Comparability of results is not given, as different studies may use different conversion factors for estimating material flows.

To provide production data in different units, often not in t or m^3, which would allow for the direct calculation of volumes, is an additional challenge. As applied in this study, trade statistics allow to calculate the product's weight if production volume is given in number of pieces. In the case of flat pallets, this approach is legitimate because product code and the respective code in trade statistics match unambiguously (Production Statistics: 1624 11 330 = Trade Statistics WA4415 2020). For other products it is not that straight forward. One product code might be linked to several trade statistics codes or vice versa. Hence, to calculate the product's weight depends on estimations of distributions of products aggregated in one code and is less reliable.

In general, our analysis showed that bio-based material flows, as presented in the paper using the example of softwood lumber and its core product EPAL 1 pallets, is possible but requires more official data on material in- and outputs of economic activity. We suggest two alternatives: First, official statistics should be extended to more consistent data on materials in proper measuring units such as cubic meters and tons; second, official and consistent prize indices of relevant materials need to be established. The latter would also need a continuous monitoring of product properties and the respective shares of bio-based materials that are used in production.

Due to the high complexity of all bio-based material flows a precise quantification of all flows is impossible yet and only an aggregated account could be done. Therefore, we consider estimating core products as a suitable compromise. However, for more complex core products such as biochemicals or some agricultural products the efforts to be made in data collection are substantial. Consequently, in the beginning of a material flow based bioeconomy monitoring the number of selected core products will be rather limited.

Finally, consistent estimation of material flows is required to provide a basis for sustainability assessment and to assess the development of resource efficiency, cascade use, recycling. These are important aims of German bioeconomy policies [9].

Regarding the case study, official production statistics provide reliable data for calculating the number of pallets in use based on additional information on pallet lifespan. The numbers calculated here correspond to the data given by EPAL [90]. When interpreting the results, one should have in mind that EPAL is an open pooling system for load carriers worldwide and includes production and repair operations in over 30 countries. Pallets are used for storage and transport of all kinds of goods. Consequently, they travel on regional and global scales and do not necessarily return to its original producer. Thus, post-use phase in the case study was calculated based on empirical data on the use of post-consumer wood that is collected at facilities in Germany. Today's available data on post-consumer wood is an excellent example on how to build a consistent database through empirical studies, market analyses, and secondary statistics. With growing importance of recycling and cascading the need for such data is also increasing and will lead to further studies and data collection outside or additional official primary statistics.

Life Cycle Inventory as an inherent part of LCA delivers material flow data of the concerned product on a micro-level. This data can be cross-checked with the data of MFA on the macro level. It is a helpful procedure to verify assumptions made and to identify any implausibility, as well as data gaps. A combination of LCA and an economy-wide MFA is, therefore, a powerful tool for sustainability analysis for national economies.

4.2. Sustainability Assessment

Using the example of softwood lumber and its core product EPAL 1 pallets, the applicability of the proposed material flow based sustainability assessment could be proven in this paper. It is possible to assess selected environmental, economic, and social sustainability effects associated with a bio-based material flow and its core product based on currently available information. As mentioned before, the efforts to be made for more complex material flows and core products might be significantly higher and currently there might be data gaps, as well. The proposed approach allows also to compare sustainability effects of bio-based material flows and core products with references such as nonbio-based or alternative bio-based material flows and core products over time. For example: The sustainability effects of one unit or all EPAL 1 pallets produced, used, recycled, and disposed in a certain year or over time can be compared with the environmental, economic, and social effects of one unit or all pallets made of bio- or nonbio-based plastics. As a result, the comparative advantages of the compared material flows and core products, as well as trade-offs between different sustainability effects can be presented. Furthermore, the approach allows quantifying effects from cascading, increased efficiency of material use or potential substitution. However, the implementation is not straight forward and requires substantial effort regarding selection of indicators matching the assessment goals, stakeholder needs, as well as data provision.

Despite that the indicator selection process applying LOFASA [14] is not covered in this paper, it is a useful procedure for a successful and consensual implementation of sustainability of the proposed material flow based sustainability assessment. This is line with Bonisoli et al. [91]. They conclude in their analysis of agri-sustainability indicator systems that acceptance among stakeholders and users is key for the successful implementation of any criteria and indicators system. To their understanding, a combination of participatory bottom-up approaches and science based top-down approaches might be the most promising way to implement an assessment framework. This is exactly how the LOFASA works. Hence, prior to a material flow based bioeconomy monitoring, a participatory process should be started that leads to the identification of sustainability themes and selection of indicators.

Since adequateness and accurateness of indicators are substantial for an effective monitoring, the selection of indicators should be based on scientific proof. First, indicators must be able to assess the change of one or several effects directly or as a proxy. Second, indicators need to be adequate for the assessment of sustainability effects of core products and their material flows. If indictors match these requirements, the original purpose of an indicator is not important. As the case study shows, the material flow based sustainability assessment approach presented here is not limited to indicators of a certain origin. Indicators developed for LCA are used, as well as indicators originally designed to quantify economic and social effects. This flexibility is a strength of the approach. Footprint indicators trying to assess the intensity of different land uses such as forestry and agriculture as described by O'Brien and Bringezu [61], O'Brien et al. [92], however, are for example not suited for the assessment of a single material flow and its core product [93]. They are not adequate. Footprint indicators try to quantify the human pressure on a certain natural resource such as biomass, water, or land. This is done by relating a country's or region's total consumption of a biomass or use of a natural resource with a respective reference. The selected reference very much determines the result of the footprint. The proposed material flow based sustainability assessment does not provide any reference or suggests using references to which the results of the selected indicators should be related to. This is intended. The assessment approach is an integral part of a material flow based bioeconomy monitoring. Similar to other monitor systems, it is designed to provide information that enables stakeholders, decision makers, and society to make informed decisions regarding sustainability effects of bioeconomy. For that reason, stakeholder and decision makers are free to aggregate results, apply references, and use evaluation tools adequate (e.g., multicriteria-analysis) to their specific needs.

To provide enough data for the proposed sustainability assessment is a challenge. Especially the systematic assessment of environmental sustainability effects is currently impossible based on official and nonofficial statistics. The only available data source is LCA studies. However, being setup for different purposes than monitoring environmental sustainability effects of bioeconomy, each available study has its specific goal and scope, system boundaries, cutoff criteria, etc. Consequentially, they are no viable basis for a frequent bioeconomy monitoring.

To close the current data gaps either 'uniform' and frequently updated LCA studies or an extension, respectively amendment of official statistics (environmental accountings, production statistics) would be required. 'Uniform' in a sense that they are conducted based on the same settings regarding goal and scope, system boundaries, cutoff criteria, etc. to ensure quality and comparability. The latter will be a rather time-consuming exercise with unpredictable outcome. This is because any extension or amendment within the International Standard Industrial Classification of all Economic Activities (ISIC), respectively, the Nomenclature statistique des activités économiques dans la Communauté européenne (NACE) must be adopted internationally. Since for the proposed bioeconomy monitoring approach material flow analysis and sustainability assessment are interlinked and both require amendment and extension of the NACE, it is advisable to jointly push this forward. This will be a long lasting and open-end process. Setting up an initial monitoring for the most important bio-based material flows and their core products build on 'uniform' LCA studies, official statistics, and other sources might be a realistic way to start. On the long run, however, the monitoring should be based on official statistics since they provide data frequently and quality assured.

Regarding the design, the proposed approach is not suitable for sectoral assessments or analyses. To assess sustainability effects of the bioeconomy compared to the whole economy or sections of it, a sectoral approach is needed. As mentioned in the introduction, our sectoral approach will be presented in an additional paper. While the design of this approach would allow for quantification of regional effects of material flows on jobs, emissions, etc., missing data are the limiting factor. Unless data availability would improve substantially, only some single regional studies might be feasible if financial resources would allow for that kind of empirical studies.

Putting the proposed material flow based sustainability assessment into context with other monitoring activities in Finland and Malaysia, there are two prominent differences. First, the Finnish and Malaysian assessment approaches are sectoral. They quantify sustainability effects of the bioeconomy as a part of the national economy. Consequentially, the sectoral monitoring is not designed to provide information of sustainability effects of certain material flows or products. However, a material flow based assessment does not replace or substitute a sectoral assessment approach. In fact, they are complimentary. Since goal and scope of a sectoral approach reflect the need to assess the bioeconomy as a part of the national economy, the indicators to be selected, consequentially, are partially different from the ones selected for a material flow based assessment. Therefore, we are currently also developing a proposal for a sectoral sustainability assessment. Its goal will be to quantify sustainability effects of the German bioeconomy, to allow comparisons with other sectors of the economy, and to assess the bioeconomy's share of the progress towards the United Nations' Sustainable Development Goals (SDG). It will be based on a sub-set of the indicators provided in the German National Sustainability Strategy [94] to assess Germany's progress towards the SDGs.

Second, the Finnish and Malaysian assessments focus on economic sustainability effects only. The current societal discourse about sustainability, even if a clear concept for social sustainability is missing [95], very much depends on institutional and geographical context [96]. The integration of the findings is a challenge [97] as it goes beyond economic effects. It is common sense that environmental and social sustainability effects should be addressed, too. This is reflected in the proposed monitoring approach applying LOFASA. The participatory process of goal and scope definition, as well as selection process of relevant sustainability themes ensures that the current societal discourse is addressed and a balance between environmental, economic, and social effects of the bioeconomy are assessed.

Author Contributions: N.G. and J.S. setup and conducted the sustainability assessment; S.I., H.W., and D.J. designed and conducted the material flow analysis; J.S., S.I., N.G., H.W., and D.J. wrote the paper. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Overview of the underlying data and main assumptions made for the estimation of the environmental impacts of EPAL 1 pallets.

Assumptions:

- Softwood timber is from Germany (60%), Poland (20%), and Lithuania (20%).
- Wood for repair of pallets is from Lithuania (100%).
- We assume that production, use, and disposal of EPAL 1 pallets in Germany would have the same environmental impacts as in the Netherlands.
- The average transport distance of one pallet throughout its lifetime is 8538 km.

- The use of EPAL 1 pallets (transport activities) occurs linearly throughout the useful life of six years.
- At the end of life 67% of pallets are combusted while 33% are recycled.

Table A1. Calculation of cumulated GWP and EP from production, use, end of life, and repair of EPAL 1 pallets in Germany in 2010 and 2015.

EPAL 1 Pallet Type	**Impact of Production, Use, and Disposal per t EPAL 1 Pallet**		**Amount of Pallets, in million t**		**Impact of Production, Use, and Disposal of the Total Amount of EPAL 1 Pallets in Germany**			
	GWP, t CO_2 eq.	EP, kg $PO_4{}^{-3}$ eq.			GWP, thousand t CO_2 eq.		EP, t $PO_4{}^{-3}$ eq.	
Year			2010	2015	2010	2015	2010	2015
EPAL 1 (softwood lumber only)	1.06	1.68			76	100	112	138
EPAL 1 (softwood and wood particle blocks)	1.21	1.76			1648	2160	2237	2774
Total					1724	2261	2349	2912
Thereof production:								
EPAL 1 (softwood lumber only)	0.37	0.30	0.07	0.09	27	34	22	27
EPAL 1 (softwood and wood particle blocks)	0.51	0.40	1.37	1.72	693	870	550	691
Total production			1.44	1.81	719	903	572	718
Thereof use [1]:								
EPAL 1 (softwood lumber only)	1.13	1.35	0.39	0.49	74	92	89	110
EPAL 1 (softwood and wood particle blocks)	1.13	1.35	7.48	9.24	1413	1744	1687	2083
Total use			7.87	9.73	1487	1836	1775	2193
Thereof end of life and repair:								
EPAL 1 (softwood lumber only)	−0.44	0.02	0.06	0.06	−25	−25	1	1
EPAL 1 (softwood and wood particle blocks)	−0.43	0.00	1.07	1.07	−457	−454	0	0
Total end of life and repair			1.13	1.12	−482	−479	1	1

[1] Please note that the impact per t EPAL 1 pallet (as shown in the columns 2 and 3) includes the impact resulting over the entire lifetime of a pallet while the calculated cumulated impact (as shown in the last four columns) reflect the impact in the respective years only.

Appendix B

Table A2. Production value generated in production of EPAL 1 pallets in Germany in the year 2010 and 2015 excluding nails and wood particle blocks.

	Total Production Value of the Related Economic Activity, million €		**Calculated Share of the Softwood Lumber Material Flow and Its Core Product EPAL 1 Pallets in the Related Economic Activity %**		**Production Value of the Softwood Lumber Material Flow and Its Core Product EPAL 1 Pallets, million €**	
Economic activity/year	**2010**	**2015**	**2010**	**2015**	**2010**	**2015**
Forestry and logging	3776	5546	3%	5%	131	259
Sawmilling and planning of wood	4832	6279	7%	9%	334	563
Manufacture of wooden containers	1533	1902	35%	36%	539	681
Repair of other equipment	194	234	30%	30%	57	70
Total	**10,335**	**13,961**			**1061**	**1574**

Source: [78,79]. Own calculation.

The shares of EPAL 1 pallets in the related economic activities were calculated as the percentage of softwood lumber contained in the finished EPAL 1 pallets as related to the total amount of wood used in the related economic activities. The economic activity "repair of other equipment" subsumes repair of various wooden and nonwooden goods. Therefore, we applied a different approach for this economic activity. First, the share of repair of wood packaging material was calculated as the ratio of the production value of the production statistics code 3319 10 103 'Repair of packaging material, storage containers and load boards from wood' to the total production value of the economic activity 3319* 'Repair of other equipment'. In a next step, the share of repair of flat pallets was calculated as the percentage of the production value of the production statistics code 1624 11 330 'Flat pallets and pallet collars of wood' to the total production value of the production statistics code 1624* 'Packaging material, storage containers and load boards from wood'. We thereby assumed that the number of repaired products is proportional to their production number. Furthermore, we assumed that the goods reported in the code 1624 13 20* 'Cases, boxes, crates, drums and similar packings of wood' are not repaired, since they mainly include one-way wood packaging means. Finally, we calculated the share of EPAL 1 pallets, using the same approach as described in Section 2.3.1. From this, the percentage of weight of softwood lumber to the overall weight of all repaired EPAL-1 pallets was used.

Table A3. Value added at factor costs generated in production and repair of EPAL 1 pallets in Germany in the year 2010 and 2015 excluding nails and wood particle blocks.

	Total Value Added of the Related Economic Activity, million €		Calculated Share of EPAL 1 Pallets in the Related Economic Activity, %		Value Added of EPAL 1 Pallets, million €	
Economic activity/year	**2010**	**2015**	**2010**	**2015**	**2010**	**2015**
Forestry and Logging	1920	3046	3%	5%	67	142
Sawmilling and planning of wood	1120	1239	7%	9%	78	111
Manufacture of wooden containers	465	597	35%	36%	164	213
Repair of other equipment	96	119	30%	30%	28	36
Total	**3602**	**5001**			**336**	**503**

Source: [78,79], Own calculation.

Appendix C

Table A4. Number of persons employed in production and repair of EPAL 1 pallets in Germany in the year 2010 and 2015 excluding nails and wood particle blocks.

	Persons Employed, thousand		Calculated Share of EPAL 1 Pallets in the Related Economic Activity, %		Persons Employed in the Production of EPAL 1 Pallets, thousand	
Economic activity/year	**2010**	**2015**	**2010**	**2015**	**2010**	**2015**
Forestry and Logging	38	37	3%	5%	1.3	1.7
Sawmilling and planning of wood	25	23	7%	9%	1.7	2.0
Manufacture of wooden containers	11	12	35%	36%	3.7	4.4
Repair of other equipment	3	3	30%	30%	0.8	0.8
Total	**76**	**74**			**7.5**	**8.9**

Source: [81,82] And own calculations.

Please note that persons employed in structural business statistics (economic activities sawmilling, planning of wood, and manufacture of wooden containers) are stated as at 30. September of the respective year, while labor force survey (forestry and logging) provides annual averages.

Number of persons employed is defined as the total number of persons who work in the observation unit (inclusive of working proprietors, partners working regularly in the unit, and unpaid family workers), as well as persons who work outside the unit who belong to it and are paid by it (e.g., sales representatives, delivery personnel, repair, and maintenance teams). It excludes manpower supplied to the unit by other enterprises, persons carrying out repair and maintenance work in the enquiry unit on behalf of other enterprises, as well as those on compulsory military service.

The approach for calculation of shares of EPAL 1 pallets in the related economic activities is described in Appendix B.

Please note that the average annual earnings of full-time employees do not include trainees and semi-retired employees. The data is based on the earnings survey for the processing industry and the structure of earnings survey for forestry and logging. The main difference between the two statistical sources arises from the coverage of small enterprises. The structure of earnings survey includes the enterprises with less than 10 employees, whereas the earnings survey normally does not include them. Further, less essential differences may arise from the treatment of workers in minor employment. However, they are not expected to be significant since the indicator considers only full-time employees.

Table A5. Calculation of average annual earnings in production, use, and repair of EPAL 1 pallets in Germany in the year 2015.

Economic Activity	Average Annual Earnings in the Related Economic Activity (thousand €)	Share of Employees in the Related Economic Activity (%)	Calculation of Weighted Average Annual Earnings in the EPAL 1 Pallet Value Chain, (thousand €)
Forestry and Logging	38	16%	6
Sawmilling and planning of wood	33	24%	8
Manufacture of wooden containers [1]	32	52%	17
Repair of other equipment	36	8%	3
Total		**100%**	**34**

[1] Estimated based on earnings survey, which was complemented by ratios from structural business statistics. Source: [83–85] And own calculations.

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