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Integrating Regionalized Socioeconomic Considerations onto Life Cycle Assessment for Evaluating Bioeconomy Value Chains: A Case Study on Hybrid Wood–Concrete Ceiling Elements

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Abstract: As bioeconomy strategies strive to integrate industrial sectors for achieving innovative materials alternative to the ones produced from non-renewable resources, the development of monitoring systems and tools to assess the implementation of such value chains is still a work in progress. This work intended to integrate the traditional life cycle assessment with a regionalized social life cycle assessment method to evaluate alternative production scenarios of a hybrid construction system with a wood-based lightweight concrete panel as a core component currently in its final stages of technical development. The life cycle impact assessment was carried out by comparing the relative advantages of two product development scenarios against the reference system's results. The social life cycle assessment was carried out using the model "REgional SPecific cONtextualised Social life cycle Assessment" (RESPONSA), which was developed for assessing wood-based value chains under a regional scope. The results showed that both alternative scenarios present large advantages when compared to the reference system. Moreover, the implementation of the production value chain was found to imply positive socioeconomic advantages in the region, in particular, due to the quality of the jobs found in the organizations associated with the production system.

Keywords: regionalized social life cycle assessment (LCA); integrated LCA; regional LCA; hybrid wood-cement construction materials; bioeconomy

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1. Introduction

Understanding the potential impacts of transforming the current production system is of utmost importance for the actual implementation of the bioeconomy. Especially when planning towards a system with higher shares of renewable resources processed in coupled and cascade production and substituting extractive resources. As a matter of fact, as the bioeconomy is embedded in regional natural and industrial-production systems, the conditions for its development may vary considerably from one region to the other. This variability may be characterized by resource availability, industrial and social infrastructures, human capacities, among other regional characteristics [1]. Therefore, such understanding on a regional level may support regions and their relevant stakeholders to define their regional sustainability strategies, e.g., the forest-based bioeconomy and the supporting policy incentives and initiatives [2,3]. On the other hand, the goal of transforming society into a post-fossil carbon and equal society is currently being catalyzed through several initiatives at global and national scales, such as the circular economy and bioeconomy strategies [4,5]. They provide the fundamental principles for using available biomass resources from local to regional and national to global scale [6–8]. However, although the implementation of national bioeconomy strategies (BES) will take place first at a regional level, its impacts on future agricultural systems are largely unclear [9,10].

Therefore, the first step to determine the potential implications of BES is the analysis of the regional systems to enable the identification of potential trade-offs between biomass utilization alternatives [11,12]. Understanding the potential implications of these trade-offs will allow stakeholders to build up the regional policy agendas for implementing the BES [13].

In this regard, the building sector is a resource-intensive branch that contributes to a large share of anthropogenic emissions [14], e.g., the cement production accounted for around >12.300 kt/a of CO2-equiv. of GHG emissions in Germany in 2015 [15]. Emission-causing areas of the building sector are mainly the high primary energy demand (a large part of this is the energy consumption of a building in operation) and indirect emissions resulting from the provision of construction services and materials. The CO2 emissions of the global construction sector account for 23% of the CO2 emissions of all economic activities worldwide [16].

The use of timber construction products and other materials made from renewable resources offers the opportunity to reduce building construction's environmental impact. From the perspective of climate change, the ability of wood to store carbon and the possibility of using wood to replace emission-intensive and non-renewable materials (e.g., aluminum, steel and concrete) is becoming more relevant in terms of the feasibility of these applications [17–21]. Wood and timber construction products are far more energy and resource-efficient in the extraction and processing of raw materials than conventional fossil materials used in the construction sector. For this reason, the inclusion of wood-based materials could lead to an overall sustainability enhancement of the construction system. Furthermore, the just transition and decarbonization of the building sector and the use of biogenic carbon sources for permanent carbon storage within building envelopes becomes a field where sustainable building product developers are bundling their strategic actions for climate mitigation [22–27].

Life cycle assessment (LCA) is a tool that has been accepted as a standard process for evaluating the potential effects of production systems on a global scale and is currently a major tool for the design and evaluation of sustainable pathways in all economic sectors. However, for achieving this understanding on a regional level, there is still a need to further refine the current life cycle assessment tools [28–32]. Nowadays, the concept of regional LCA is still in its infancy, and there are scattered efforts to develop and validate life cycle based tools to address the challenging task, as well as to integrate them as part of a regional life cycle toolbox to address the complexity of a regional case study [33].

One key issue for the future development of the bioeconomy is establishing a knowledge basis of the socioeconomic issues associated with the implementation of bio-based technologies on a regional level [34–37]. Siebert et al. [38,39] proposed considering the relative social performance of the organizations involved in the value chains associated with a production system. The developed social life cycle assessment model (sLCA), called RESPONSA, allows the evaluation of the organizations against regional performance benchmarks [38,39], thus helping to identify social hotspots (e.g., relative social performances that can be improved) within regional production systems [11,39,40].

This work aims to integrate a regional socioeconomic life cycle model with an environmental life cycle assessment to evaluate a bio-based value chain in Central Germany to identify the value-added that such a regional perspective could bring to sustainability evaluation processes.

2. Materials and Methods

2.1. Definition of the Case Study

The extended life cycle assessment approach conducted in this study for integrating sLCA and LCA results is part of a series of sustainability assessment studies, which were performed as accompanying research activities within the leading-edge cluster bioeconomy in Central Germany (SCBE) (Bioeconomy.de).

Within the SCBE, industrial representatives and material scientists from research institutes were co-developing prototypes for engineered wood products (EW), i.e., glued-laminated timber and novel wood-based hybrid solutions based on beech wood.

The prototypes, which were selected for this case study are belonging to a type of product group for hybrid building elements, which were innovated for increasing the high value-added use of beech wood resources in durable building materials. The assessed prototypes are combining high-performance beech wood hybrid elements, which are an innovative solution for modern timber construction with the constructive strengths of wood-based lightweight concrete ceiling elements developed within the framework of the SCBE.

In general, due to their positive constructional characteristics, wood–concrete-composite systems (HBV) can be used in many ways in the construction sector for modular buildings using prefabricated elements. Especially for ceiling systems, the construction method of combining cassette systems with wood–concrete composites achieves excellent load-bearing (an increase by up to 400% compared to original wooden ceilings is achieved through the hybrid ceiling system) and represents an alternative to conventional construction methods [41–46]. Moreover, the stiffness, as well as the sound insulation and vibration characteristics of the assessed material, are also improved compared to the traditional wooden ceiling.

The developed prototype is produced on a semi-industrial scale and can be used as a ceiling element, being able to bridge a span of 10 m at usual loads when implemented in a cassette system, thus making it suitable as construction material for residential and commercial buildings. Furthermore, all requirements of multi-story buildings regarding sound insulation and fire protection are fulfilled [47].

2.2. Systems Definition for the Case Study

The case study system consists of load-bearing elements made from glued-laminated timber (glulam beams) and steel-reinforced concrete cassette systems, and non-load-bearing elements made from wood–concrete composites. The wood-based elements are all either characterized with different ratios of beech wood to coniferous wood in the glulam product or with the definition of the overall content of wood fiber supplements in the concrete composite. This subsection explains both the product compositions of these functional elements and the processing involved in the manufacturing of these building materials. The general description of the processing operations for the production of the HBV hybrid construction component is presented in Figure 1. As it may be observed, the process starts with the management of forests in the region of Central Germany and the harvesting of beech wood and coniferous wood resources, which are mainly found in the Thuringian forest, the south of Lower Saxony, the north of Hessen and the east of North-Rhine Westphalia. The harvested logs are stored and transported to the sawmill facilities.

Further upstream processes of fossil-based additives are the production of melamine–formaldehyde resins as adhesives for engineered wood components and the production of reinforcing steel and cement mixtures for prefabricated concrete ceiling elements.

Considering the fiber fractions within the wood–concrete composites, the chipping of wood and the processing of beech wood fibers from fresh wood chips with stationary refiner plants and the processing of wood flakes with stationary disc flaker units are major processes involved in the manufacturing of the assessed building materials. From the upstream processes, only the production of steel, the extraction of cement minerals and the production of melamine–formaldehyde as well as the transport fuels are produced outside of the Central Germany region.

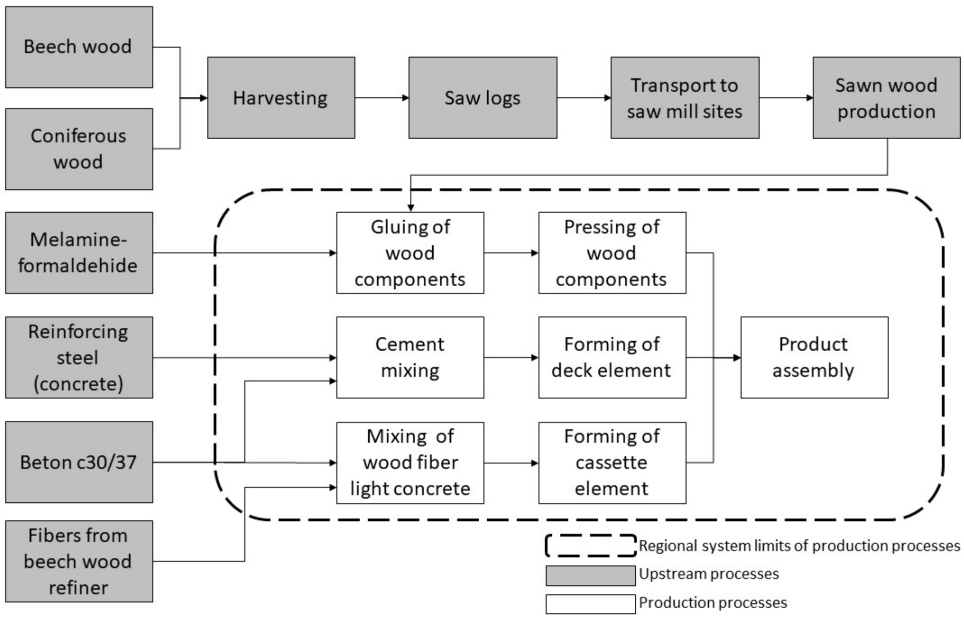

Figure 1. Overview of the upstream processes and production processes of the case study to produce a light concrete, HBV hybrid construction component.

2.3. *Life Cycle Assessment*

2.3.1. Goal and Scope Definition

The goal of the environmental life cycle assessment (eLCA) is to compare two different demonstrator systems for lightweight wood-based concrete elements, which are produced as prefabricated floor cassette systems and are specified by inventory data from the cradle-to-factory gate. The two demonstrator systems differ in the type of wood fraction used for reinforcement of the lightweight concrete. One demonstrator type relies on the use of wood flakes produced from wood chips further conditioned in a disc flaker process (demonstrator 1), and the other one relies on wood fibers also produced from wood chips, which are processed into fine fractions based on a refiner process (demonstrator 2). These two wood-based lightweight concrete systems are then assessed considering their relative advantages in further comparison against prefabricated concrete elements, which do not include any wood constituents.

2.3.2. System Definition

The system boundaries of the LCA include the wood resource mobilization chains of harvesting and the chipping of industrial wood, the flake production in a disc flaker process for demonstrator 1 and the fiber production from wood chips in the refiner process and fiber drying process for demonstrator 2.

The fiber wood assortments as feedstocks for the refiner process and the disc flaker process demands industrial wood chips. The storage of wood chips takes place directly at the individual production sites. The refiner process is a mechanical process, and the fiber drying is a thermal process. The disc flaker process is also a mechanical process requiring mainly electric energy. The system boundary spans from the cradle (i.e., wood harvesting) to the factory gate (i.e., delivery of lightweight concrete elements to construction sites). It considers potential impacts caused by provisioning of wood and energy resources, through transport, by cement production and in general through the production of the functional unit of 10 m broad elements. Further downstream and logistic processes and the use phase and decommissioning phase are not part of this assessment. As a functional unit, 30.6 m^2 was chosen and is related to a thickness of 250 mm and a specific density between 1400 kg/m^3.

2.3.3. Specification of Demonstrator Compositions and Definition of a Functional Unit

Given that the functional unit for the prefabricated floor cassette system elements of 30.6 m^2 is the same for all alternatives, the specification of the specific wood flake and fiber contents and the specific density has a crucial role in setting up the right inventory analysis. In Table 1, the relevant parameters for the material composition of the three prefabricated floor elements are presented.

Table 1. Specific product composition of the demonstrator types of wood-based lightweight concrete elements.

Parameters of Material Composition	Value	Unit	Source
Specific weight of a demonstrator element	10,710	kg per element	Own calculations
Possible range of solid concrete density	1250–1400	kg/m^3	Leading-edge cluster bioeconomy and parameters from [47]
Length	9300	mm	Leading-edge cluster bioeconomy/Fraunhofer WKI
Width	3000	mm	Leading-edge cluster bioeconomy/Fraunhofer WKI
Thickness	250	mm	Leading-edge cluster bioeconomy/Fraunhofer WKI
Fraction of flakes of fibers in relation to solid concrete density	15–250	% by weight related to solid concrete	Leading-edge cluster bioeconomy/Fraunhofer WKI and parameters from [47]
Bulk density of wood flakes	230	kg/m^3	Leading-edge cluster bioeconomy/Fraunhofer WKI
Density of wood flakes in the element production process	Approx. 280	kg/m^3	Leading-edge cluster bioeconomy/Fraunhofer WKI

2.3.4. Data Collection and Life Cycle Inventories

In Table 2, the unit processes used for constructing an LCA model from the cradle-to-factory gate and the used life cycle inventory data sources are presented. The data for upstream processes, such as provisioning of beech wood resources, were modeled using data sets available in the ecoinvent and the GaBi databases valid until 2021. The specification of material compositions of the demonstrator types is based on an on-site appointment at the Company Universalbeton Hering together with Fraunhofer WKI and the cluster management of the leading-edge cluster bioeconomy in 2015 as well as on the project reports of Fraunhofer WKI on the projects "Bucherhybrid" [47]. The share of beech wood in the glulam beams accounts for 30 Vol % and 70 Vol.-% of coniferous wood, respectively. The degree of steel reinforcement was set to 0.15 tons of steel per m^3 of the concrete-based cassette system.

The modeling of the refiner process for fiber provisioning was conducted according to the communications with the Fraunhofer Institute for Microstructure of Materials and Systems (IMWS) in Halle (Germany) from previous and general studies as accompanying research team in the leading-edge cluster bioeconomy and was relying on a generic modeling approach using data from technology providers and plant manufacturers, such as Pallmann/Dieffenbacher/Andritz and others. Thereby, publicly available general energy consumption coefficients for different refiner technologies were used, e.g., from Krug [48,49]. Furthermore, datasets for natural gas-based steam production and datasets for the national electricity mix available from LCA databases completed the modeling.

Table 2. Overview of the unit processes and data sources used for their life cycle assessment (LCA) modeling.

Subnet/Intermediates	Unit Processes	Source
Production of beech wood fibers for wood-based lightweight concrete system demonstrator type 1	Natio: refiner <e-ep> Natio: fiber drying <e-ep> RER: wood chips, deciduous wood, u = 80%, stationary chipper <e-ep> RER: chipping of pulp/fiber wood, stationary chipper electric, at the gate RER: deciduous wood, allocation factor, 1 RER: deciduous wood DE: electricity mix PE DE: thermal energy from natural gas PE	- Results of own modeling and using data sources from [47] - Generic energy demands for refiners [48], adapted to beech wood - Life Cycle Inventories of Wood as Fuel and Construction Material. In: Final report ecoinvent data v2.0 Dübendorf, CH 2007. - PE International, GaBi database 2008–2013
Production of beech wood flakes for wood-based lightweight concrete system demonstrator type 2	RER: wood chips, deciduous wood, u = 80%, stationary chipper <e-ep> RER: chipping of pulp/fiber wood, stationary chipper electric, at the gate RER: deciduous wood, allocation factor, 1 RER: deciduous wood DE: electricity Mix PE DE: thermal energy from natural gas PE Disc Flaker process, self-specified	- Results of own modeling - Life Cycle Inventories of Wood as Fuel and Construction Material. In: Final report ecoinvent data v2.0 Dübendorf, CH 2007. - PE International, GaBi database 2008–2013 - Datasheets
Production of load-bearing reinforced concrete element as the outer part of the cassette systems	Natio: ceiling element-reinforced concrete <e-ep> GLO: reinforcing steel World Steel CN: concrete C30/37 ts	ThinkStep data set 2018: mixing of cement, water and aggregates such as gravel, production mix, at plant, Ökologische Bilanzierung von Baustoffen und Gebäuden, 2000, Eyerer, P.; Reinhardt, H.-W.: Ökologische Bilanzierung von Baustoffen und Gebäuden, Birkhäuser, Zürich 2000, data valid until 2021 ThinkStep data set 2018: blast furnace route and electric arc furnace route, production mix, at plant, World Steel Association 2015–2017
	Natio: product mixer Nation: wood fiber lightweight concrete for a cassette system	Results of own modeling based on inventory and material composition and [47]

2.3.5. Life Cycle Impact Assessment

The LCA modeling was conducted using the LCA software GaBi. For impact assessment, the end-point indicators of the EN15804 based on Environmental Foot Print-EF 3.0 were used aggregated based on person equivalents. The methodology of EF 3.0 is assessing 15 impact categories, which are particulate matter, eutrophication, marine, eutrophication, terrestrial, ionizing radiation, human health, human toxicity, cancer*, climate change, land use, human toxicity, noncancer*, ecotoxicity, freshwater* ozone depletion, photochemical ozone formation, human health resource use, fossils, resource use, minerals and metals, eutrophication, freshwater, acidification, water use.

For the sake of comparing the alternative scenarios, the relative advantage or disadvantage of the environmental impacts of the alternative scenarios was compared against the reference alternative, calculating it by dividing the difference of the resulting indicator values of the alternative scenarios ($IR_{C,S}$) and the values obtained for the reference product ($IR_{C,R}$) by the indicator results of the reference product, expressing the result as a percentage (Equation (1)).

$$Relative\ advantage\ [\%] = \frac{IR_{C,S} - IR_{C,R}}{IR_{C,R}} * 100 \quad (1)$$

2.4. Regionalized Social Life Cycle Assessment

The regionalized social life cycle assessment was carried out based on the RESPONSA methodology proposed by Siebert et al. [11], as presented in Figure 2.

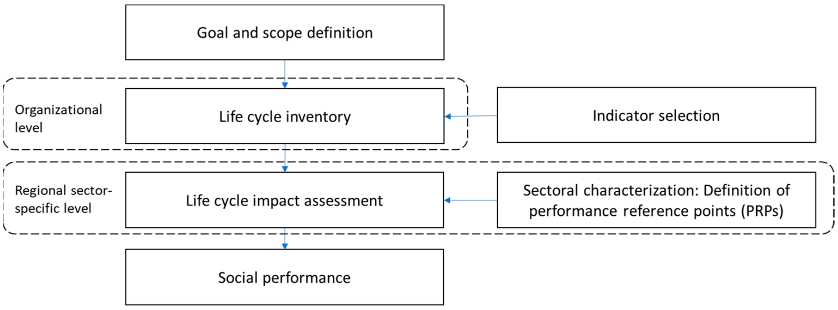

Figure 2. Methodological approach for the evaluation of the social performance of the organizations associated with the case study (adapted from ref. [38]).

2.4.1. Definition of Goal and Scope

As previously mentioned, the RESPONSA model provides an evaluation for the organizations associated with the studied value chain. Since in the case of this study, the production of both demonstrator alternatives contemplates the participation of the same organizations in the assessed value chain, it was decided to use the RESPONSA as a complimentary assessment to the LCA results, as the results of the sLCA activities will be alike for both assessed alternatives. The goal of the social life cycle assessment activity was, therefore, set to complement the results of the life cycle assessment by identifying the potential regional socioeconomic impacts, in terms of a social hot spot and opportunities analysis, of the organizations involved in the value chain of HBV hybrid construction component.

To identify the activities that are carried out in the region, Figure 3 presents the production system associated with the case study, defining the system boundaries for the regional analysis, ranging from the upstream resource extraction processes to the final product assembly, as previously described in Section 2.2.

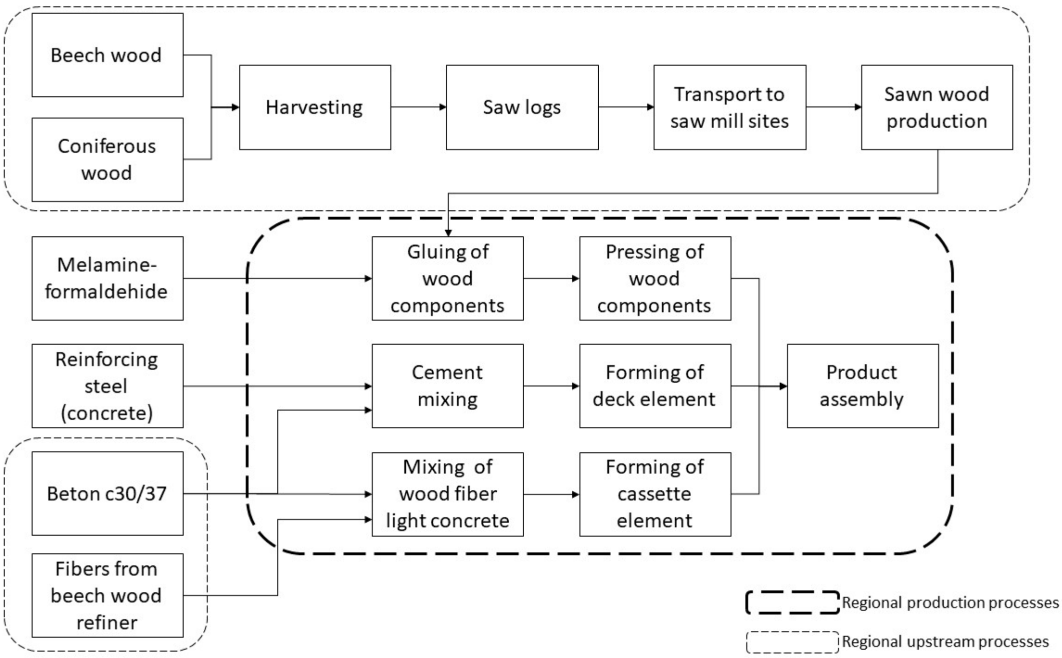

Figure 3. System boundaries for the regionalized social life cycle assessment of the case study.

2.4.2. Inventory Analysis

The indicator set for the sLCA assessment is based on the RESPONSA indicators as proposed by Siebert et al. [38,50]. Table 3 presents the list of the indicators selected for this analysis. The main reason for this selection was the availability of updated and official data for constructing the regional social archetypes. As the case study process is still in a demonstration phase, and therefore, the actual value chain has not yet been implemented, a series of sources were used to identify the most representative characteristics of the potentially involved organizations along the value chain. For this reason, it was decided to define representative organizations for the preliminary assessment of the socioeconomic life cycle impacts.

Table 3. Selected set of indicators for conducting the social life cycle assessment model (sLCA) hotspot and opportunities analysis with the RESPONSA model for regionalized assessment (adapted from refs. [38,40]).

Index Sub-Index	Indicator	Unit	Description	Indicator ID
1. Health and safety				
Sick-leave	Preventive health measures	Cat.	Health measures (e.g., sick-leave analysis, health activities)	I1.1
2. Adequate remuneration				
Payment	Payment according to basic wage Average remuneration level	y/n €	Payment off basic wage Average payment per month per full-time employee per total employees	I2.1 I2.2
3. Adequate working time				
Working time	Contractual working hours	h	Average contractual working hours per week per full-time employee	I3.1
Work–life-balance	Access to flexible working time agreements Rate of part-time employees	% %	Percentage of employees with access to flexible working agreements Number of part-time employees per total employees	I3.2 I3.3
4. Employment				
Job conditions	Rate of qualified employees Rate of marginal employees (max 450€)	% %	Percentage of employees with professional training per total employees Percentage of employees earning max. 450€ per total employees	I4.1 I4.2
Duration of employment	Rate of fixed-term employees Rate of employees provided by temporary work agencies	% %	Number of fixed-term employees in relation to total employees Number of employees provided by temporary work agencies per total employees	I4.3 I4.4
5. Knowledge capital				
On-the-job training	Employees/unity participated in training Support for professional qualification	% y/n	(Qualified) employees/unity participated in training per total employees Assumption of cost or exemption for training programs	I5.1 I5.2
Vocational training	Rate of vocational trainees	%	Trainees/total employees	I5.3
6. Equal opportunities				
Gender equality	Rate of female employees in management positions Rate of female employees	% %	Percentage of female employees in management positions in relation to all employees in management positions Percentage of female employees in relation to total employees	I6.1 I6.2

Legend for units: Nr: number, Cat.: category,%: percent, y/n: yes and no, h: hours.

For this case study, three organizations were identified as the main actors of the value chain. In the first step, organization 1 (O1) corresponds to forest operations and logistics management. Organization 2 (O2) corresponds to a sawmill facility located in Central Germany. Finally, organization 3 (O3) is the facility where the production of structural precast concrete elements takes place. From previous studies [40,51], it was possible to retrieve the data corresponding to the organizations O1 and O2. The data used for Organization 1 is actually a complete primary dataset received from an actual organization in the Federal State of Thuringia [40]. The dataset for organization 2 was constructed upon a literature review based primarily on the information available at the RESPONSA database [38,40,51]. For characterizing O3, the social archetypes constructed based on [38,39,50] were utilized, considering the regional scale of Central Germany.

2.4.3. Impact Assessment

The first step of the impact assessment is determining the performance reference points (PRPs) of the different organizations on a regional level. The PRPs for O1 were taken from the RESPONSA database with a characterization scope of Central Germany. The PRPs for O2 were set according to a national setting from the RESPONSA database. Finally, as O3 was characterized with social archetypes of Central Germany from the RESPONSA database, its PRPs' characteristic values were set to the next regionalized scale of "New federal states of Germany." The latter denotes a region, which comprises all five re-established former East Germany states, and which includes Central Germany (i.e., the states of Saxony, Saxony-Anhalt and Thuringia) together with the federal states of Brandenburg and Mecklenburg-Vorpommen.

Table 4 summarizes the PRPs associated with the evaluated indicators for the case study.

Table 4. Set of performance reference points for the different organizations evaluated in the case study (adapted from ref. [38,40,51]).

Indicator	PRP	PRP	PRP
ID	**O1**	**O2**	**O3**
I1.1	94% yes, 6% no	94% yes, 6% no	50% yes, 50% no
I2.1	22% yes, 78% no	21% yes, 79% no	60% yes, 40% no
I2.2	1016.34	1619.05	2115.34
I3.1	40.85	38.8	40.6
I3.2	14% yes, 86% no	52% yes, 48% no	38% yes, 62% no
I3.3	42.70%	16.67%	8.89%
I4.1	53.11%	63.39%	75%
I4.2	14.29%	5.23%	0%
I4.3	1.62%	6.48%	15.03%
I4.4	No data	5.31%	5.64%
I5.1	33.44%	29.31%	17.89%
I5.2	39% yes, 61% no	76% yes, 24% no	77% yes, 23% no
I5.3	0.00%	0.00%	0.5%
I6.1	21% yes, 79% no	21% yes, 79% no	No data
I6.2	39.50%	47.62%	41.67%

3. Results

3.1. Life Cycle Assessment

The LCA results for the regional bioeconomy developed products are compared with the reference alternative product to assess their relative advantage. The first result of the LCIA analysis is that both alternative scenarios outscore the reference system in most evaluated indicators, as observed in Figure 4.

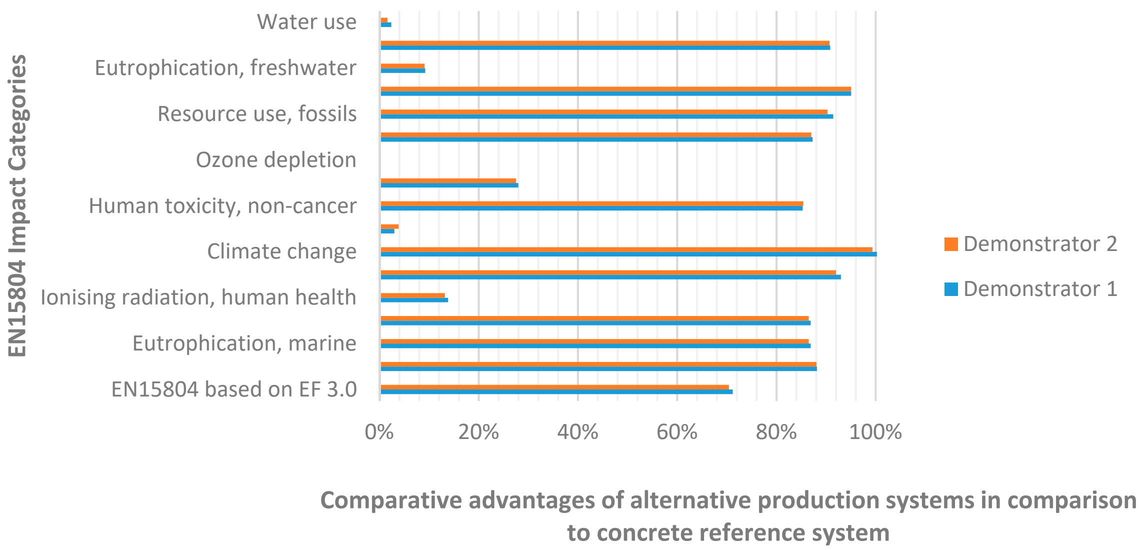

Figure 4. Comparative assessment of the life cycle impacts categories as defined by EN15804, to illustrate the relative environmental advantages of alternative demonstrators of hybrid wood concrete cassette systems for prefabricated ceiling systems concerning the environmental impacts of the standard prefabricated concrete reference elements.

According to the obtained results, both alternative scenarios behave identically, with a difference in their relative advantages of less than 5–10% in all evaluated indicators, which lies still in the range of the basic uncertainties associated with the results. In this sense, it is still not possible to determine the better appropriateness of one alternative to the other at this stage of development.

On the other hand, as observed in Figure 4, the results indicate that the developed innovative construction material in both alternative production scenarios reduces the environmental impacts for the most assessed impact categories. A major contribution is seen in the impact categories "climate change", "resources utilization," and "acidification, terrestrial and drinking water", which show relative advantages over 90% for both assessed alternative development scenarios, whereas the relative advantages of most indicators lie between 25 and 80%. Only four categories show less favorable outcomes for the assessed scenarios, namely, "water use," "freshwater eutrophication," "land use," and "ionizing radiation," with relative advantages of 2%, 9%, 3% and 13%, respectively.

3.2. Regionalized Social Life Cycle Assessment

Table 5 presents the characterization values for the three evaluated organizations participating in both alternative demonstrators assessed in this case study. In addition, the scores of each indicator as a result of the RESPONSA methodology are also presented in this table. By averaging the individual indicators corresponding to each sub-index, it is possible to obtain an overview of the value chain's hotspots.

The resulting hot spot analysis is presented in Figure 5. It can be observed that O1 has a well over-the-average performance compared to the regional benchmark. In particular, O1 exceeds the average socioeconomic performances in the three indices related to an adequate working environment.

In the case of O2, there is a more heterogeneous score distribution, where the indices "adequate remuneration" and "employment" are below the regional average. These indices are, therefore, definitively a source of socioeconomic concern and may be considered as a social hotspot within the regional value chain. In the case of O3, it shows an average-to-good socioeconomic performance, with the exception of the index "knowledge capital," whose score lies below the regional benchmark. Just like in the case of O2, this index must be considered as a negative socioeconomic hotspot within the intended value chain.

Table 5. Indicator values and their associated sLCA scores for the different organizations evaluated in the case study, based on the RESPONSA methodology (adapted from ref. [38,40,51]).

Indicator ID	Values O1	Values O2	Values O3	Scores O1	Scores O2	Scores O3
I1.1	Yes	Yes	Yes	5.6	5.6	7.5
I2.1	Yes	No	No	8.9	2.2	2.5
I2.2	4105	1641	2192	10	4.1	7.5
I3.1	40.0	38.8	37.6	6.6	9.2	10
I3.2	Yes	No	Yes	9.7	2.1	10
I3.3	4.34%	18.23%	4.18%	9.5	4.0	8.51
I4.1	96%	61.7%	72.2%	5.4	4.3	5.36
I4.2	0.23%	7.69%	0%	9.7	4.2	10
I4.3	1.55%	24.7%	15.78%	10	1.6	5.54
I4.4	0%	46.55%	0	5	0.3	10
I5.1	No data	40.63%	13.63%		7.7	2.06
I5.2	No	Yes	Yes	3.1	6.21	6.5
I5.3	3.25%	0.00%	0.2%	7.7	4.8	3.82
I6.1	Yes	No	Yes	9.0	4.1	7.5
I6.2	18.28%	50.0%	33.33%	2.0	5.3	5.67

Figure 5. Hot spot analysis of the value chain associated with the production of the HBV hybrid construction system. Assessment scale as defined by Siebert et al. (Adapted from ref. [38,50]).

Overall, the worst evaluated index resulted in being "knowledge capital", which should be considered as a hotspot throughout the assessed value chain. For overcoming these results, stakeholders involved in the implementation of the intended value chain must make the necessary efforts to foster the further education of employees and to promote programs that involve more vocational trainees in their processes. These two types of measures would directly affect not only the workers of the organizations but could also have a positive effect by involving the local community in the organizations' activities.

4. Discussion

4.1. Life Cycle Assessment

The most decisive aspects in comparison of reduction potentials of environmental impacts in production of wood–concrete elements is the equality of benefits considering structural strength compared to steel-reinforced concrete elements and the decision whether to substitute for 100% of the steel reinforcement and a high portion in the share of cement or not. When the thickness of the ceiling elements is increasing, however, potentials for cement substitution are compromised. In the case of the assessed cassette system, the design decision to not substitute for the full portion of reinforcement steel comes on the cost of a lower ratio of bio-based substitutions in the load-bearing element, but on the benefit that the wood–concrete cassette has not to deliver full structural strength guaranteeing to be the load-bearing element thus the thickness and the share of substituted cement can be optimized. This is achieved because the combination of steel-concrete frame and cross-laminated timber structure is building the load-bearing elements. The intelligent combination of these systems gives a hybrid system that is minimizing the ratio of cement and the associated environmental impacts in the full hybrid system. When comparing the results in the assessment of relative advantages of the hybrid construction material, it is seen that these are in line with results on environmental advantages obtained in other studies for assessing impact-reduction potentials of green buildings, particularly for projects replacing cement components. Whereas fully wood-based building systems outperform steel-reinforced concrete systems normally in the range of 10–55% in most environmental impact categories, the case of wood–concrete systems may differ as they in some cases exhibit even higher environmental impacts as they lack in optimized substitution of cement [52–57]. Here the design of hybrid cassette systems has its intervention point because it can, on one hand, support in optimized substitution of cement, while on the other hand playing out the structural strengths of the individual building materials. The findings are a valuable starting point to enhance the eco-design process of the cement industry and bioeconomy practitioners when aiming to identify design-oriented levers, environmental hotspots and benefits of further minimizing environmental impacts of wood-based lightweight concrete elements by replacing cement with wood-fiber materials in general. Major hotspots are identified in the extraction of limestone, clay and marlstone from open-pit mines, iron ore extraction, the energy demand of cement sintering and the blast furnace processes for steel production. All these processes are characterized by a higher infrastructure intensiveness, land-use intensity and emissions intensiveness than forest management, mobile chipping and stationary fiber refining and disc flaking.

Therefore, the substitution of cement and steel reinforcement by utilizing high shares of wood fibers and wood flakes can contribute to impact reduction for many of the categories related to respiratory diseases, resource depletion, land use and human toxicity and ecotoxicity. The land area used for forest cultivation and the lower density of valuable resources, however, appears to lower the reduction potential when considering water use and land use. In addition, the eutrophication impacts are less significant when observing the potentials for impact reduction. More obvious are advantages considering acidification due to higher share fossil-energy carriers containing sulfuric compounds used in blast furnace and cement sintering operations. In contrast, chipping, fiber refining and flaking can rely on more clean energy sources, such as natural gas and electricity from the German grid.

Finally, it must be pointed out that this assessment only evaluated the system boundary from the cradle-to-factory gate. End-of-life aspects, modular building concepts and reuse strategies also should be considered by practitioners as part of an optimized circular bioeconomy system as we conclude on and describe in a more detailed manner in the conclusions section.

4.2. Regionalized Social Life Cycle Assessment

The results obtained by the RESPONSA are aligned with the outcomes of previous authors in the bio-based field [58,59], in terms of the relevance of the indices health and safety, decent work, labor and human rights, and social acceptability for social life cycle assessment in the bioeconomy field. In this sense, an interesting result in this case study was that the implementation of a regional value chain envisaged in this comparative analysis has the potential of ensuring high-quality jobs in the region. These findings are aligned with the results reported for further case studies on wood-based as well as for sugar-based biorefineries [60,61]. In addition, the suitability for prefabrication in the regional concrete plant ensures that construction sites can be effectively managed and that a high proportion of workload, value-added and expertise stays in the region where prefabricated elements are produced. This is also aligned with previous case studies on the substitution of steel-based systems with wood-based resources [62].

On the other hand, by addressing the issue of the index "knowledge capital" for overcoming the worst evaluated value, the implications are twofold: on the one hand, the socioeconomic indices can be enhanced, which can be reflected afterward in the social rucksack of subsequent product chains. On the other hand, the involvement of trainees can bring further positive impacts in the value chain, such as an increased connection to the local community and thus a better social acceptance towards the production facilities. An issue also addressed as relevant for the socioeconomic life cycle appraisal for the bio-based sector [63]. Moreover, this would help to bridge the gap on skilled workers that nowadays continues to be a major factor in the implementation of high value-added production chains in the Central Germany region.

5. Conclusions

While compiling and structuring the inventory data for evaluating the socio-technical bioeconomy systems, within this study, we identified that valuable conclusions and recommendations could be drawn in three major areas. First of all, considering conclusive findings concerning methodological steps for integrating sLCA and LCA methods: To assess the sustainability of two alternative production systems (demonstrators) of hybrid wood concrete cassette systems for prefabricated ceiling systems, an integrated LCA assessment methodology was established. The proposed methodology is a combination of two life cycle methods. In a first step, the potential environmental advantages associated with the alternative demonstrators were calculated based on a comparative assessment of the demonstrators against standard prefabricated concrete reference elements. This assessment followed the EN15804 standard for assessing construction materials. In a second step, the potential socioeconomic impacts of the proposed value chains were evaluated through the application of the RESPONSA model, a regional social life cycle assessment methodology.

The results of the work have proven that the integration of LCA and the RESPONSA model as a tool for regionalized social LCA provides interesting complementarities, as it allows to cover a wider spectrum of indicators relevant to determine the potential impacts of the implementation of bio-based technologies. It is important to state at this point that although the obtained results for the environmental LCA are in line with the results found in the state-of-the-art literature, there is still a persisting uncertainty. This is due to the scaling effects from a semi-industrial scale (as in this work) to a full industrial scale. Nonetheless, this shortcoming may be addressed by working with potential development scenarios for increasing levels of energy integration and industrial symbiosis. Such a strategy may help in shedding light on the outcomes variances considering future upscaling scenarios and their integrated energy systems and fiber resources cascading system (see [64,65] as an example).

The second area regards the regionalized sLCA approach. An important value that can be derived from this work is the complementarity of the regionalized sLCA methodology to the LCA assessments. In particular, in case studies, which are delimited in a geographical scale smaller than a country. In those cases, the RESPONSA model can bring some advantages over and, therefore, complement the methodology proposed by the sLCA Guidelines [66]. On the other hand, as for the availability of official and reliable data, definitively, the lack of datasets for the RESPONSA model is a deficit that needs to be addressed to move forward on the regional LCA methodology development. Moreover, access to the actually available official data can be often considered a barrier, as the model requires highly disaggregated information. This must be taken into account when developing the regional datasets for the economic activities in the study: if a low number of companies participate in a regional economic sector, a checking protocol must be developed to prevent the possibility of tracing back the data related to individual companies out of the database. These protocols can then be implemented in intensifying the interfaces with statistical agencies in regular project-based cooperation.

When forming future consortia and ideas for complementary research projects out of these findings, we see a strong recommendation for strengthening the regional resolution of sLCA-related data for regional monitoring and life cycle management of bioeconomy networks in the area of collaborative development of bioeconomy monitoring tools in cooperation with federal statistical agencies. In particular, the co-development of sLCA-inventory databases and the streamlining of data interfaces for elicitation and aggregation of socioeconomic data can be a major advancement when calibrating bioeconomy monitoring tools on broad-spectrum of bioeconomy sectors and value chains.

In this sense, the development of the RESPONSA model is an ongoing process. The next step for its development is the expansion of the stakeholder categories addressed by the model. In its current form, the RESPONSA model works with indices related to the categories "workers" and "local community". A further expansion needs to be considered to address the categories "society," "consumers," and "value chain actors." In future applications, it is envisaged to address these categories in a regionalized way as well, to align better to the new sLCA guidelines.

The third and final aspect of consideration deals with the organizational learning for well-coordinated life cycle management within bioeconomy clusters. In this regard, the following research and development activities are advisable: Complementary to strengthening data interfaces for elicitation of socioeconomic data, we conclude that organizational learning of bioeconomy clusters in life cycle management and updating environmental LCA databases needs to be solidified and continuously updated. A major future advancement in this area would be the establishment of continuously updating inventory databases for LCA data and LCA scenarios of industrial process networks in cooperation with industrial actors from cluster networks. Furthermore, the industrial stakeholders from wood-manufacturing industries, from wood fiber production and from prefabricated concrete elements production should be engaged to develop further solutions in modular building design for these hybrid systems to qualify practical reuse strategies how these cassette systems could be reused in a secondary building life cycle. Modular building strategies are valuable life cycle management strategies, which could, in turn, be evaluated again using integrated sLCA-LCA assessment tasks in further accompanying research studies to quantify their socioeconomic and environmental potentials, effects and benefits. This is, in particular, the case as energetic recovery from wood–concrete elements is compromised, which makes further material reuse of these hybrid systems in secondary life cycles advisable.

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References

1. Thrän, D. Einführung in das system bioökonomie. In *Das System Bioökonomie*; Thrän, D., Moesenfechtel, U., Eds.; Springer Spektrum: Berlin, Germany, 2020; pp. 1–19.
2. Hildebrandt, J.; Hagemann, N.; Thran, D. The contribution of wood-based construction materials for leveraging a low carbon building sector in europe. *Sustain. Cities Soc.* **2017**, *34*, 405–418. [CrossRef]
3. Bezama, A. Let us discuss how cascading can help implement the circular economy and the bio-economy strategies. *Waste Manag. Res.* **2016**, *34*, 593–594. [CrossRef]
4. Directorate-General for Research and Innovation (European Commission). *A Sustainable Bioeconomy for Europe—Strengthening the Connection between Economy, Society and the Environment: Updated Bioeconomy Strategy*; European Commission: Brussels, Belgium, 2018.
5. Directorate-General for Research and Innovation (European Commission). *Bioeconomy—the European Way to Use Our Natural Resources: Action Plan 2018*; European Commission: Brussels, Belgium, 2019.
6. Ingrao, C.; Bacenetti, J.; Bezama, A.; Blok, V.; Goglio, P.; Koukios, E.G.; Lindner, M.; Nemecek, T.; Siracusa, V.; Zabaniotou, A.; et al. The potential roles of bio-economy in the transition to equitable, sustainable, post fossil-carbon societies: Findings from this virtual special issue. *J. Clean Prod.* **2018**, *204*, 471–488. [CrossRef]
7. Ingrao, C.; Arcidiacono, C.; Bezama, A.; Ioppolo, G.; Winans, K.; Koutinas, A.; Gallego-Schmid, A. Sustainability issues of by-product and waste management systems, to produce building material commodities: A comprehensive review of findings from a virtual special issue. *Resour. Conserv. Recy.* **2019**, *146*, 358–365. [CrossRef]
8. Bezama, A. Understanding the systems that characterise the circular economy and the bioeconomy. *Waste Manag. Res.* **2018**, *36*, 553–554. [CrossRef] [PubMed]
9. Charles, D.; Davies, S.; Miller, S.; Clement, E.K.; Hoes, A.-C.; Hasenheit, M.; Kiresiewa, Z.; Kah, S.; Bianchini, C. Case studies of regional bioeconomy strategies across europe. *BIOSTEP* **2016**. Available online: https://www.ecologic.eu/14079 (accessed on 10 April 2021).
10. Dubois, O.; Gomez San Juan, M. *How Sustainability is Addressed in Official Bioeconomy Strategies at International, National and Regional Levels—an Overview*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2016.
11. Siebert, A.; Bezama, A.; O'Keeffe, S.; Thran, D. Social life cycle assessment: In pursuit of a framework for assessing wood-based products from bioeconomy regions in germany. *Int. J. Life Cycle Ass.* **2018**, *23*, 651–662. [CrossRef]
12. O'Keeffe, S.; Majer, S.; Bezama, A.; Thran, D. When considering no man is an island-assessing bioenergy systems in a regional and lca context: A review. *Int. J. Life Cycle Ass.* **2016**, *21*, 885–902. [CrossRef]
13. Balkau, F.; Bezama, A. Life cycle methodologies for building circular economy in cities and regions. *Waste Manag. Res.* **2019**, *37*, 765–766. [CrossRef]
14. Riala, M.; Ilola, L. Multi-storey timber construction and bioeconomy—barriers and opportunities. *Scand. J. For. Res.* **2014**, *29*, 367–377. [CrossRef]
15. Strogies, M.; Gniffke, P. *Berichterstattung unter der Klimarahmenkonvention der Vereinten Nationen und dem kyoto-Protokoll 2017—Nationaler Inventarbericht zum deutschen Treibhausgasinventar 1990–2015*; Umweltbundesamt: Dessau-Roßlau, Germany, 2017.
16. Huang, L.Z.; Krigsvoll, G.; Johansen, F.; Liu, Y.P.; Zhang, X.L. Carbon emission of global construction sector. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1906–1916. [CrossRef]
17. Chen, Z.J.; Gu, H.M.; Bergman, R.D.; Liang, S.B. Comparative life-cycle assessment of a high-rise mass timber building with an equivalent reinforced concrete alternative using the athena impact estimator for buildings. *Sustainability* **2020**, *12*, 4708. [CrossRef]
18. Guo, A.F.; Sun, Z.H.; Qi, C.Q.; Sathitsuksanoh, N. Hydration of portland cement pastes containing untreated and treated hemp powders. *J. Mater. Civ. Eng.* **2020**, *32*, 04020148. [CrossRef]
19. Jaaranen, J.; Fink, G. Frictional behaviour of timber-concrete contact pairs. *Constr. Build. Mater.* **2020**, *243*, 118273. [CrossRef]
20. Munoz-Ruiperez, C.; Olivan, F.F.; Carpintero, V.C.; Santamaria-Vicario, I.; Saiz, A.R. Mechanical behavior of a composite lightweight slab, consisting of a laminated wooden joist and ecological mortar. *Materials* **2020**, *13*, 13. [CrossRef] [PubMed]
21. Villas-Boas, B.T.; Iwakiri, S.; Parchen, C.F.A. Production and evaluation of low-density cast-wood-cement blocks for civil construction. *Science* **2020**, *48*.
22. Giesekam, J.; Tingley, D.D.; Cotton, I. Aligning carbon targets for construction with (inter)national climate change mitigation commitments. *Energ. Build.* **2018**, *165*, 106–117. [CrossRef]
23. Giergiczny, Z.; Krol, A.; Talaj, M.; Wandoch, K. Performance of concrete with low co(2)emission. *Energies* **2020**, *13*, 4328. [CrossRef]
24. Karlsson, I.; Rootzen, J.; Toktarova, A.; Odenberger, M.; Johnsson, F.; Goransson, L. Roadmap for decarbonization of the building and construction industry-a supply chain analysis including primary production of steel and cement. *Energies* **2020**, *13*, 4136. [CrossRef]

25. Koh, C.H.; Kraniotis, D. A review of material properties and performance of straw bale as building material. *Constr. Build. Mater.* **2020**, *259*, 120385. [CrossRef]
26. Mata, E.; Korpal, A.K.; Cheng, S.H.; Navarro, J.P.J.; Filippidou, F.; Reyna, J.; Wang, R. A map of roadmaps for zero and low energy and carbon buildings worldwide. *Environ. Res. Lett.* **2020**, *15*, 113003. [CrossRef]
27. Mercader-Moyano, P.; Esquivias, P.M. Decarbonization and circular economy in the sustainable development and renovation of buildings and neighbourhoods. *Sustainability* **2020**, *12*, 7914. [CrossRef]
28. Zeug, W.; Bezama, A.; Thrän, D. *Towards a Holistic and Integrated Life Cycle Sustainability Assessment of the Bioeconomy—Background on Concepts, Visions and Measurements*; Helmholtz-Zentrum für Umweltforschung—UFZ: Leipzig, Germany, 2020; p. 35.
29. Bos, U.; Maier, S.D.; Horn, R.; Leistner, P.; Finkbeiner, M. A gis based method to calculate regionalized land use characterization factors for life cycle impact assessment using lanca (r). *Int. J. Life Cycle Ass.* **2020**, *25*, 1259–1277. [CrossRef]
30. Crenna, E.; Marques, A.; La Notte, A.; Sala, S. Biodiversity assessment of value chains: State of the art and emerging challenges. *Environ. Sci. Technol.* **2020**, *54*, 9715–9728. [CrossRef] [PubMed]
31. Ita-Nagy, D.; Vazquez-Rowe, I.; Kahhat, R.; Chinga-Carrasco, G.; Quispe, I. Reviewing environmental life cycle impacts of biobased polymers: Current trends and methodological challenges. *Int. J. Life Cycle Ass.* **2020**, *25*, 2169–2189. [CrossRef]
32. Lee, M.; Lin, Y.L.; Chiueh, P.T.; Den, W. Environmental and energy assessment of biomass residues to biochar as fuel: A brief review with recommendations for future bioenergy systems. *J. Clean. Prod.* **2020**, *251*, 119714. [CrossRef]
33. Balkau, F.; Massari, S.; Sonnemann, G. Sustainable regional development in a life cycle context. In *Life Cycle Approaches to Sustainable Regional Development*; Massari, S., Sonnemann, G., Balkau, F., Eds.; Routledge: New York, NY, USA, 2016; pp. 9–14.
34. Bezama, A.; Ingrao, C.; O'Keeffe, S.; Thran, D. Resources, collaborators, and neighbors: The three-pronged challenge in the implementation of bioeconomy regions. *Sustainability* **2019**, *11*, 7235. [CrossRef]
35. Albrecht, M. (Re-)producing bioassemblages: Positionalities of regional bioeconomy development in finland. *Local Environ.* **2019**, *24*, 342–357. [CrossRef]
36. Petig, E.; Choi, H.S.; Angenendt, E.; Kremer, P.; Grethe, H.; Bahrs, E. Downscaling of agricultural market impacts under bioeconomy development to the regional and the farm level-an example of baden-wuerttemberg. *Gcb. Bioenergy* **2019**, *11*, 1102–1124. [CrossRef]
37. Befort, N. Going beyond definitions to understand tensions within the bioeconomy: The contribution of sociotechnical regimes to contested fields. *Technol. Soc.* **2020**, *153*, 119923. [CrossRef]
38. Siebert, A.; O'Keeffe, S.; Bezama, A.; Zeug, W.; Thran, D. How not to compare apples and oranges: Generate context-specific performance reference points for a social life cycle assessment model. *J. Clean. Prod.* **2018**, *198*, 587–600. [CrossRef]
39. Siebert, A.; Bezama, A.; O'Keeffe, S.; Thran, D. Social life cycle assessment indices and indicators to monitor the social implications of wood-based products. *J. Clean. Prod.* **2018**, *172*, 4074–4084. [CrossRef]
40. Jarosch, L.; Zeug, W.; Bezama, A.; Finkbeiner, M.; Thran, D. A regional socio-economic life cycle assessment of a bioeconomy value chain. *Sustainability* **2020**, *12*, 1259. [CrossRef]
41. Gonzalez, O.M.; Garcia, A.; Guachambala, M.; Navas, J.F. Innovative sandwich-like composite biopanels—towards a new building biomaterials concept for structural applications in nonconventional building systems. *Wood Mater. Sci. Eng.* **2020**, *16*, 132–148. [CrossRef]
42. Mirdad, M.A.H.; Chui, Y.H. Strength prediction of mass-timber panel concrete-composite connection with inclined screws and a gap. *J. Struct. Eng.* **2020**, *146*. [CrossRef]
43. Molina, J.C.; Oliveira, C.A.B.; Christoforo, A.L.; Boas, D.V.; Calil, C. Influence of the bonding of rebar dowel with adhesive on wood-concrete composite specimens. *Proc. Inst. Civ. Eng.-Str. Build.* **2020**, *173*, 904–913. [CrossRef]
44. Orlowski, K. Verified and validated design curves and strength reduction factors for post-tensioned composite steel-timber stiffened wall systems. *Eng. Struct.* **2020**, *204*, 110053. [CrossRef]
45. Shi, B.K.; Liu, W.Q.; Yang, H.F.; Ling, X. Long-term performance of timber-concrete composite systems with notch-screw connections. *Eng. Struct.* **2020**, *213*, 110585. [CrossRef]
46. Tannert, T.; Gerber, A.; Vallee, T. Hybrid adhesively bonded timber-concrete-composite floors. *Int. J. Adhes Adhes* **2020**, *97*, 102490. [CrossRef]
47. Keilholz, M.; Rüther, N. *Schlussbericht für die öffentlichkeit. Vp 1.13, "Entwicklung eines leichbetons aus buchenholz"*; Fraunhofer-Institut für Holzforschung, Wilhelm-Klauditz-Institut (WKI); Universalbeton Heringen GmbH & Co. KG: Braunschweig/Heringen, Germany, 2017.
48. Krug, D. Einfluss der Faserstoff-Aufschlussbedingungen und des Bindemittels auf die Eigenschaften von Mitteldichten Faserplatten (MDF) für eine Verwendung im Feucht- und Außenbereich. Ph.D. Thesis, Universität Hamburg, Hamburg, Germany, 2010.
49. Paulitsch, M.; Barbu, M.C. *Holzwerkstoffe der Moderne. 1*, Aufl. ed.; DRW-Verlag: Leinfelden-Echterdingen, Germany, 2015.
50. Siebert, A. Socio-Economic Assessment of Wood-Based Products from German Bioeconomy Regions: A Social Life Cycle Assessment Approach. Dissertation' s Thesis, University of Leipzig, Leipzig, Germany, 2019.
51. Jarosch, L. A Social Life Cycle Assessment in Context of the Bioeconomy: The Example of Social Aspects of the Timber Processing Industry in Central Germany. B.Sc. Thesis, Technische Universität Berlin, Berlin, Germany, 2019.
52. Zhou, C.; Shi, S.Q.; Chen, Z.; Cai, L.; Smith, L. Comparative environmental life cycle assessment of fiber reinforced cement panel between kenaf and glass fibers. *J. Clean. Prod.* **2018**, *200*, 196–204. [CrossRef]

53. Wu, T.; Gong, M.; Xiao, J. Preliminary sensitivity study on an life cycle assessment (lca) tool via assessing a hybrid timber building. *J. Bioresour. Bioprod.* **2020**, *5*, 108–113. [CrossRef]
54. Nikolić Topalović, M.; Stanković, M.; Ćirović, G.; Pamučar, D. Comparison of the applied measures on the simulated scenarios for the sustainable building construction through carbon footprint emissions—case study of building construction in serbia. *Sustainability* **2018**, *10*, 4688. [CrossRef]
55. Gámez-García, D.C.; Gómez-Soberón, J.M.; Corral-Higuera, R.; Saldaña-Márquez, H.; Gómez-Soberón, M.C.; Arredondo-Rea, S.P. A cradle to handover life cycle assessment of external walls: Choice of materials and prognosis of elements. *Sustainability* **2018**, *10*, 2748. [CrossRef]
56. Caruso, M.; Pinho, R.; Bianchi, F.; Cavalieri, F.; Lemmo, M.T. A life cycle framework for the identification of optimal building renovation strategies considering economic and environmental impacts. *Sustainability* **2020**, *12*, 10221. [CrossRef]
57. Scope, C.; Guenther, E.; Schütz, J.; Mielecke, T.; Mündecke, E.; Schultze, K.; Saling, P. In Aiming for Life Cycle Sustainability Assessment of Cement-Based Composites: A Trend Study for Wall Systems of Carbon Concrete; Dresden nexus conference 2020—session 4—circular economy for building with secondary construction materials to minimise resource use and land use. *Civ. Eng. Des.* **2020**, *2*, 143–158. [CrossRef]
58. Falcone, P.M.; Imbert, E. Social life cycle approach as a tool for promoting the market uptake of bio-based products from a consumer perspective. *Sustainability* **2018**, *10*, 1031. [CrossRef]
59. Falcone, P.M.; González García, S.; Imbert, E.; Lijó, L.; Moreira, M.T.; Tani, A.; Tartiu, V.E.; Morone, P. Transitioning towards the bio-economy: Assessing the social dimension through a stakeholder lens. *Corp. Soc. Responsib. Environ. Manag.* **2019**, *26*, 1135–1153. [CrossRef]
60. Valente, C.; Brekke, A.; Modahl, I.S. Testing environmental and social indicators for biorefineries: Bioethanol and biochemical production. *Int. J. Life Cycle Assess.* **2018**, *23*, 581–596. [CrossRef]
61. Mandegari, M.A.; Farzad, S.; van Rensburg, E.; Görgens, J.F. Multi-criteria analysis of a biorefinery for co-production of lactic acid and ethanol from sugarcane lignocellulose. *Nat. Sci.* **2017**, *11*, 971–990. [CrossRef]
62. Mair-Bauernfeind, C.; Zimek, M.; Asada, R.; Bauernfeind, D.; Baumgartner, R.J.; Stern, T. Prospective sustainability assessment: The case of wood in automotive applications. *Int. J. Life Cycle Assess.* **2020**, *25*, 2027–2049. [CrossRef]
63. Rafiaani, P.; Kuppens, T.; Thomassen, G.; Van Dael, M.; Azadi, H.; Lebailly, P.; Van Passel, S. A critical view on social performance assessment at company level: Social life cycle analysis of an algae case. *Int. J. Life Cycle Assess.* **2020**, *25*, 363–381. [CrossRef]
64. Hildebrandt, J.; Bezama, A.; Thran, D. Insights from the sustainability monitoring tool suministro applied to a case study system of prospective wood-based industry networks in central germany. *Sustainability* **2020**, *12*, 3896. [CrossRef]
65. Hildebrandt, J.; O'Keeffe, S.; Bezama, A.; Thran, D. Revealing the environmental advantages of industrial symbiosis in wood-based bioeconomy networks: An assessment from a life cycle perspective. *J. Ind. Ecol.* **2019**, *23*, 808–822. [CrossRef]
66. UNEP. *Guidelines for Social Life Cycle Assessment of Products and Organizations 2020*; United Nations Environment Programme (UNEP): Paris, France, 2020.