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Update in LCA data for Cross Laminated Timber

From Tree to Panel – Data for Accurate and Transparent Assessment

Stichting W/E adviseurs
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Summary

To reach climate goals, national and international requirements are or will be in place to reach ambitions in environmental performance of buildings. For each building element, LCA studies provide the necessary information to evaluate this performance. Therefore it is crucial that background data for these LCAs is up-to-date and differences in interpretation of data are prevented. For biobased products, such as Cross Laminated Timber (CLT), the specific question of updating these background data was addressed in this research work. In this report, the results of both a literature and field study are presented. Updates of background data are provided that are related to the production phase of CLT. In particular, the overall conversion efficiency values from literature have been confirmed in a slightly larger efficiency range, resulting in **35-45% production efficiency** for CLT (volume) with respect to harvested roundwood. An improvement proposal to the **methodology of particulate matter impact calculation** has been presented as well. Other **attention points** in the LCA report have been identified as being very case-specific: definition of forest management and exploitation types, transport distances and vehicle type, and the energy source for the drying process of sawn wood. Recommendations are given to implement the results of this study, repeat and expand this type of studies to other wood-based products, and to gain more insight in the (debated) impact category Land use. Additionally, it is recommended to define a **fixed economic allocation factor for by-products in the PCR** to avoid the high volatility in allocation factors, and consider to introduce the **impact allocation** to branches and topwood. Furthermore it is recommended to look into ways to **value biodiversity and carbon storage benefits** within LCAs. Finally, it is recommended to extend the analysis to more LCA phases, e.g. by improving end-of-life scenarios.

Samenvatting

Om de klimaatdoelen te halen, zijn nationale en internationale eisen van kracht of in voorbereiding om de doelstellingen in de gebouwde omgeving te bewerkstelligen. Voor ieder bouwproduct is via een LCA-studie informatie beschikbaar om de milieuprestatie in een gebouw te evalueren en kwantificeren. Hiervoor is het cruciaal dat de benodigde LCA-achtergronddata actueel is, en geen aanleiding geeft tot interpretatieverschillen. De vraag of dit zo is voor biobased producten, zoals Cross Laminated Timber (CLT), is in dit onderzoek behandeld. In dit rapport worden de resultaten van zowel een literatuur- als een veldonderzoek gepresenteerd. Actuele waardes van CLT achtergronddata uit de productiefase worden weergegeven en vergeleken met de literatuur. Specifiek is de resulterende materiaalefficiëntie geëvalueerd, waarbij vastgesteld is dat de gevonden waardes uit het veld variëren tussen **35-45% productie-efficiëntie** voor CLT (volume) ten opzichte van geoogst rondhout. Dit geeft een bevestiging van de al bestaande literatuurwaardes, waarbij de gevonden range iets groter is. In dit rapport wordt een verbetering voorgesteld van de **berekeningsmethode voor de milieu-impact van fijnstofemissie**. Overige genoemde **aandachtspunten** in de LCA-rapportage zijn zeer specifiek van geval tot geval: de definitie van bosbeheer en -exploitatie, transportafstanden en voertuigtype, en de energiebron voor het droogproces van zaaghout. Onder de aanbevelingen doen we de suggestie om de resultaten van dit onderzoek toe te passen in LCA-studies, en vergelijkbaar onderzoek uit te voeren, zowel als herhaling als ook om de scope te verbreden naar andere houtproducten. Verder wordt aanbevolen om het inzicht te vergroten in de (betwiste) milieu-impactcategorie Landgebruik. In aanvulling daarop wordt aanbevolen om een **economische allocatiefactor in de PCR vast te stellen voor bijproducten**, en om **toewijzing van milieu-impact** aan top- en takhout te overwegen. Verder wordt aanbevolen om te beschouwen hoe de **voordelen van biodiversiteit en koolstofopslag in een bos beter gewaardeerd** kunnen worden binnen de LCA. Het is ten slotte ook een aanbeveling om de analyse uit te breiden naar de andere LCA fasen, bijvoorbeeld door de einde-levenscenario's te verbeteren.

1 Introduction

1.1 Background and motivation

In the Paris Climate Agreement, global agreements were made to counter the impact of human activities on global warming. Material use has a significant impact on the environment and CO_2 emissions (embodied carbon). For this reason, there are goals to halve primary material use in the short term (2030) and move towards a fully circular economy (2050). The building sector is responsible for a large part of raw material consumption and needs to become circular. Therefore, there is an urge for the environmental impact of the building sector to be drastically reduced, including in the short term. The use of biobased materials, such as wood-based products, can and should make an important contribution to this.

Construction elements such as cross-laminated timber (CLT) are an important group of biobased products, as CLT is increasingly applied in the building sector and has a high potential for further expansion. Therefore, the environmental impact of CLT is of great importance. Currently, there is a lot of discussion on biobased construction materials concerning the environmental impact that follows from the life cycle analyses (LCAs). This includes the discussion how to account for biogenic carbon storage in (LCA) reports and in national requirements to an environmental performance of buildings to reach climate goals (Nossek et al., 2023). This includes possible misrepresentations due to inclusion of less robust impact categories, outdated background data and differences in interpretation of data. It is therefore key that the background data used in LCAs are accurate and transparent. With this in mind, the 'ToP DATA' *From Tree to Panel – Data for Accurate and Transparent Assessment* research study was selected for funding within Built by Nature's 'From forest to frame' Challenge.

This report discusses the results of our study to provide updates of background data related to the production stage of CLT. It also discusses the effect of the updated data in terms of environmental impact, and gives recommendations for further research.

1.2 Explanation of (Dutch) context

The relevance of good representation of the environmental impact of biobased construction elements is particularly visible in the context of the Netherlands. In the Netherlands, legislation exists on the environmental impact determination of building products and requirements (limit values) to the impact of new buildings. The environmental impact is expressed in costs (MKI), which can be calculated per product and for a complete building. The calculation of the MKI of a building product, a 1-point-score, is based on the total of environmental impact outcomes as the result of an LCA. In this paper a short explanation is given of the LCA method, the use of environmental impact databases, and the Dutch calculation of the MKI.

LCA (Life Cycle Analysis)

An LCA (Life Cycle Analysis) is a systematic approach (Frischknecht et al., 2017) used to evaluate the environmental impact of a product, process, or service throughout its entire life cycle. It considers various stages, including raw material extraction, production, use, and disposal, see Figure 1 for all stages that can be included. Not all stages are considered in all LCAs.

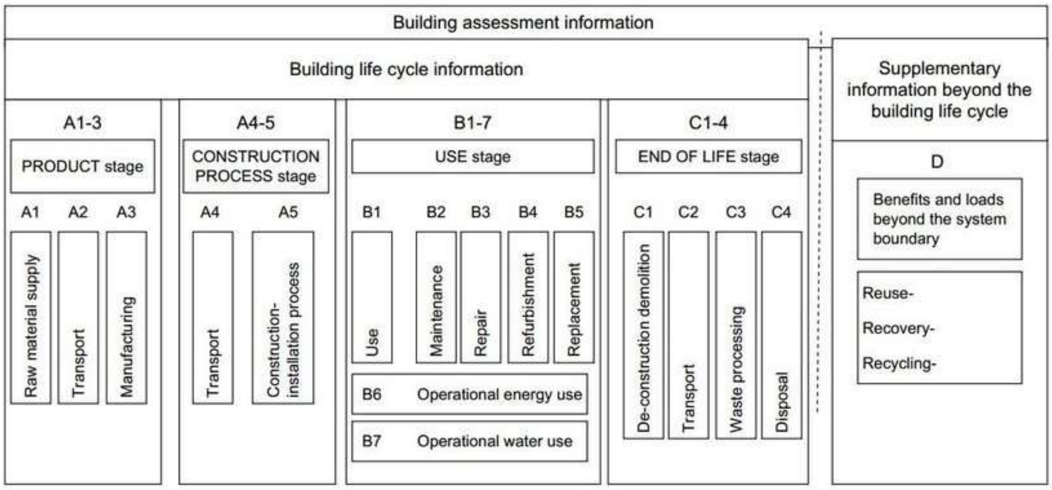

Figure 1: Stages of the life cycle of a building product in an LCA

An LCA can encompass various impact categories, such as climate change, raw material depletion, and toxicity. LCAs can therefore help to make informed strategies to reduce the impact of products and construction projects.

The results of an LCA for a specific product can be provided in an environmental product declaration (EPD). An EPD is a standardized document, conform ISO 14025, in which the results of an LCA are given in terms of environmental impact categories, using specific indicators. Many EPDs are publicly available. For construction products in Europe, the NEN-EN 15804+A2 is the standard providing core rules for filing the EPDs. The impact categories that are mandatory and optional for an EPD of a construction product are given. Both in Europe and internationally ISO 14040 and 14044 are the basis of LCAs.

Ecoinvent

Ecoinvent is a database with background data for LCAs. It contains a large qualified set of environmental data on different background processes of different production processes. The ecoinvent data on background processes often form building blocks of LCAs. In the Dutch national database for EPDs (the NMD), the impact determination is based on the environmental data available in ecoinvent version 3.6. The determination of impact can lead to different results if newer versions are used (3.10 is the most recent version), or if a different database is used (for example GaBi). The prescribed ecoinvent version to use in the Dutch NMD will be changed to version 3.9.1.

MKI (Dutch context)

The Environmental Cost Indicator (in Dutch 'MilieuKosten Indicator', MKI) method aggregates all relevant environmental impacts as calculated in a LCA of a product or set of products into a unified, 1-point-score by applying a monetary weighting factor to each impact category indicator outcome and summing up the weighted impacts. The MKI is expressed in Euros and represents the environmental shadow price or shadow cost. It is proposed that from 2025, all 19 impact categories from the 15804+A2 norm (mandatory and optional) must be included when calculating the MKI of a product in an Environmental Performance calculation for Buildings (in Dutch: Milieuprestatie Gebouw, MPG). This set of impact categories is referred to as the 'A2-set'. The proposed Dutch weighting factors for these 19 impact categories have been published recently (Regeling tot wijziging Omgevingsregeling, 2024), as shown in Table 1. Until the actual implementation of this change, in the Netherlands the impact is calculated using 11 impact categories based on the EN 15804 + A1 plus additional categories ('A1-set'). Current Dutch EPDs need to include the results of both sets of impact categories. In this paper, we consider the impact categories according to the 'A2-set'.

Table 1: Impact categories and weighting factors for MKI determination according to Dutch method, using the A2-set

Impact category	Indicator	Unit	Weighting factor MKI
Climate change – total	Global Warming Potential total (GWP-total)	kg CO_2 eq	0.116
Climate change - fossil	Global Warming Potential fossil fuels (GWP-fossil)	kg CO^2 eq	0.116
Climate change - biogenic	Global Warming Potential biogenic (GWP-biogenic)	kg CO^2 eq	0.116
Climate change – land use and land use change	Global Warming Potential land use and land use change (GWP-luluc)	kg CO^2 eq	0.116
Ozon depletion	Depletion potential of the stratospheric ozone layer (ODP)	kg CFC 11 eq.	32
Acidification	Acidification potential, Accumulated Exceedance (AP)	mol H^+ eq.	0.39
Eutrophication aquatic freshwater	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-freshwater)	kg P eq.	1.96
Eutrophication aquatic marine	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-marine)	kg N eq.	3.28
Eutrophication terrestrial	Eutrophication potential, Accumulated Exceedance (EP-terrestrial)	mol N eq.	0.36
Photochemical ozone formation	Formation potential of tropospheric ozone (POCP)	kg NMVOC eq.	1.22
Depletion of abiotic resources – minerals and metals	Abiotic depletion potential for non-fossil resources (ADP-minerals&metals)	kg SB eq.	0.3
Depletion of abiotic resources – fossil fuels	Abiotic depletion potential for fossil resources (ADP-fossil)	MJ, net calorific value.	0.00033
Water use	Water (user) deprivation potential, deprivation-weighted water consumption (WDP)	m^3 world eq. deprived	0.00506
Particulate Matter emissions	Potential incidence of disease due to PM emissions (PM)	Disease incidence	549750
Ionizing radiation, human health	Potential Human exposure efficiency relative to U235 (IRP)	kBq U235 eq.	0.049
Eco-toxicity (fresh water)	Potential Comparative Toxic Unit for ecosystems (ETP-fw)	CTUe	0.00013
Human toxicity, cancer effects	Potential Comparative Toxic Unit for Humans (HTP-c)	CTUh	1096368
Human toxicity, non-cancer effects	Potential Comparative Toxic Unit for Humans (HTP-nc)	CTUh	147588
Land use related impacts/Soil quality	Potential soil quality index (SQP)	dimensionless	0.000087

2 Problem statement and research objectives

2.1 Problem statement

The motivations to look into the correct representation of CLT construction elements are 1) the quality of the background data of LCAs that is considered questionable, and 2) the observed variation in the MKI results of EPDs, specifically in the production phase (A1-3). Questions on the background data will directly relate to the quality of the impact calculation of the building blocks of the production process. The (emission) parameters and their interpretation may therefore be incorrect or not representative (anymore). Specifically there are questions on the quality of the use of standard values for sawing efficiency and the quality of data in literature and ecoinvent that is used as default values in LCAs. The quality of the background data affects the resulting environmental impact that is calculated for the production process.

2.2 Research objectives

This project aims to gain insight in:

- The environmental background data that can be used for LCAs of Cross-Laminated Timber (CLT) construction products;
- The level of representation of this background data;
- Identification of supply chain's building blocks and the corresponding updates of background data.

Scope

The scope of this project is the production stage of CLT, represented by phase A1-3 within an LCA. The end product that is considered in this project is the CLT construction element as-produced. Geographically, our scope is the European market for CLT construction products. Therefore, we consider the European production of CLT, and the European method for impact calculation, with a special focus on the Netherlands, for which most of the CLT originates from Germany. Although the market for CLT is international, we estimate that the European demand will mostly be covered by production within Europe due to high transportation costs. The impact calculation is based on European norms, and more specifically in this report, on the Dutch monetary method of translating impact values to Euros (the MKI), resulting in impact contributions that can be compared with the same units. In the determination of impact, the Dutch EPDs make use of ecoinvent v3.6. Therefore, in this research, ecoinvent v3.6 processes are used to complement the other literature data (unless otherwise mentioned).

3 Research method

The research method that is used in this project to evaluate existing data and acquire new data for the supply chain's building blocks is a combination of a literature study on background data and field research. In the following paragraphs these studies are explained in more detail. In chapter 4 the results of the literature study, including a defined supply chain scheme, are presented, and in chapter 5 the results of the acquisition of new data are shown, which is followed in chapter 6 by an analysis of the corresponding impact within the context.

3.1 Literature study

Analysis of CLT EPDs

We performed an analysis of the available EPDs in several databases: the Dutch National Environmental Database (in Dutch: Nationale Milieudatabase, NMD) and 2 European EPD databases. In this way, quantitative insight was gained in the impact categories with highest impact, and the variation in the results for the different EPDs.

Supply chain of CLT

Based on a literature review, a detailed overview of the supply chain of the CLT production stage was made. We mapped the supply chain and analyzed the building blocks to determine the quality of the underlying data.

Quantitative data on processes and resources

We performed a literature study on quantitative data on processes and resources that are related to environmental impact. In this way we determined what processes and resources are expected to have a large share in the selected impact categories and correlate this to the building blocks of the supply chain. For example, the type of heat (process) used in the drying process (building block) or the sawing efficiency (process) in the sawing stage (building block). As an addition to this, the data of standard processes in the ecoinvent (Ecoinvent v3.6, 2019) database are added.

3.2 Acquisition of new data

Site visits and questionnaires

Quantitative data on processes and resources directly from CLT producers, including the suppliers of intermediate products, were acquired. Two site visits with in-depth interviews as well as several additional questionnaires were conducted to gain insight into recent data that can be related to the environmental impact.

In the surveys that were distributed to the forest managers, we asked them to specify the data according to stand type (monoculture or mixed) and to give an estimate of their share in the management unit. This division made it easier for them to acquire the data and made it possible for us to give more context to the data. In some cases, incomplete answers to questions could not be taken into account in the analysis. Hence, the number of responses varied between the different topics.

3.3 Analysis of data representation in building blocks

An analysis of the acquired data was performed to gain insight on the representativeness of the data in current LCAs of CLT products. The data is related to the building blocks of the supply chain and when relevant, proposals are formulated to improve the representation of the data. An analysis is done to gain insight into the differences and similarities between the literature-based and the practice data and the overall representation of CLT production in LCAs. Based on this analysis, the building blocks are identified for which the parameters of the CLT production process can be updated.

4 Literature study

4.1 Analysis of impact categories in CLT EPDs

An analysis of several EPDs of CLT construction elements was performed to investigate the main impact categories in the production phase.

Analysis of impact categories in Dutch EPDs

As explained in chapter 1, in the Netherlands the individual impacts are weighted and summed up to a 1-point score, using weighting factors. Such a weighting system allows comparison of the different impact categories, that (without weighting) are expressed in completely different units. In case of housing and offices, a maximum allowed score is defined in the Netherlands. The resulting score from the LCA includes all 19 impact categories (13 mandatory and 6 optional) according to the EN 15804+A2 (A2-set). Based on the analysis of three EPDs from different producers (Derix, Stora Enso and KLH), that are used in the Dutch context, insight was gained into the impact categories that have a high MKI contribution in the production stage (phase A1-3 in the LCA, see Figure 1).

It became clear that, using the Dutch MKI weighting values, three impact categories have the largest contribution: Climate change – fossil, Particulate Matter Emissions, and Land use related impact/soil quality. Together, these three impact categories contribute to 80-85% of the MKI-score (excluding Climate change – biogenic) in phase A1-3 of the three analyzed Dutch EPDs, as shown in Figure 2. The contribution of biogenic carbon to the total A1-3 impact was excluded, as this comprises the high amount of biogenic carbon storage in the CLT which severely dominates the total impact in A1-3. Besides, over the complete life cycle of CLT, the biogenic carbon impact contribution is (close to) 0 in the LCA and therefore has at this moment 0 impact, which is not the case for fossil carbon. Note that the quantified impact in the impact categories may change in the future, in case the EPD is modified by the producer.

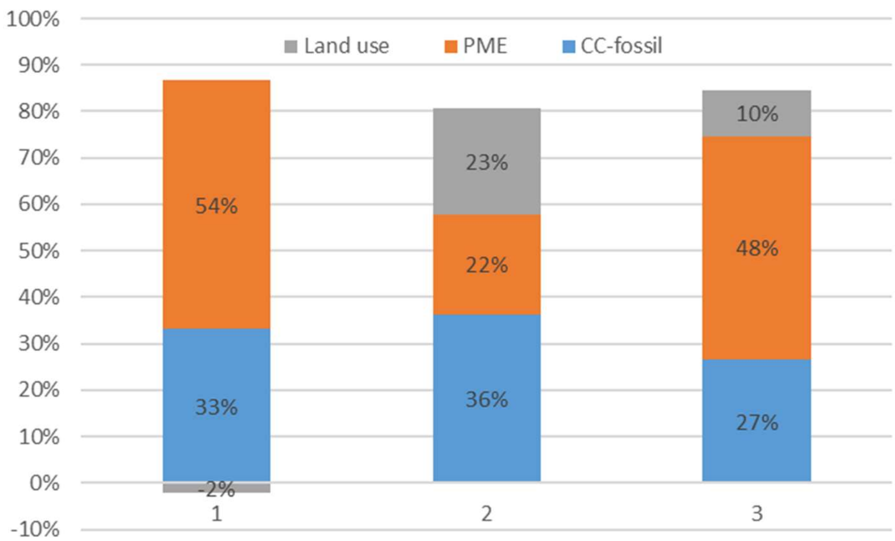

Figure 2 Contributions of the impact categories Climate change – fossil ('CC-fossil'), Particulate Matter Emissions ('PME') and Land use related impact/soil quality ('Land use') to the total MKI of 3 CLT products (1, 2 and 3) in phase A1-3 (excluding Climate change – biogenic).

Although the total relative contribution of the 3 impact categories to the MKI is remarkably similar, the contribution of each category within this 85% varies, as well as the absolute MKI values (factor of 2 difference in absolute MKI values between producers in phase A1-3). Especially the relative differences between the MKI contributions of 'Particulate Matter Emission' and of 'Land use related impact/soil quality' is striking, with contributions between roughly a quarter to half of the total and ranging from a small negative contribution to a contribution of over 20% to the total, respectively. The large variation in impact contributions between these EPDs is not well understood. In the next sections, the meaning and importance of these three impact categories are explained further.

Climate change (CC): fossil

The impact category Climate change – fossil characterizes the global warming potential (this is the indicator for Climate change) from greenhouse gas emissions (or removals) that originate from the burning of fossil fuels or materials that contain fossil carbon. The effect is expressed in kg CO_2-equivalents. However, the impact category is not limited to CO_2-emissions only. The effect of other greenhouse gas emissions is translated into an equivalent amount of CO_2 with the same effect.

Particulate Matter Emissions (PME)

The impact category particulate matter is based on the model that characterizes the disease increase due to the emission of particulate matter (Fantke, 2016). Particulate matter (PM2.5: particulates smaller than 2.5 micrometer) is considered as one of the most important environmental emissions contributing to human disease. The measured quantity is the emission of (primary or secondary) PM2.5. Based on the proposed model this is transformed to inhaled mass and together with the effect factor (disease increase due to inhalation) this results in the characterization factor. Part of this model is the calculation of the inhaled mass depending on the emitted mass. Therefore the location of emission is important, in highly populated areas the number of people inhaling the PM2.5 emissions is larger compared to lowly populated areas. Therefore PM2.5 emitted in lowly populated areas has a significantly lower characterization factor compared to PM2.5 emitted in highly populated areas. As shown in Table 2 below, an unspecified population density (no specification in 'Subcompartment' in the table) has the same characterization factor as for the high population density.

Table 2: Population density and particulate matter emissions

Compartment	Subcompartment	Particulate Matter	Factor	Unit
Air		<2.5 μm	2.3850E-4	Disease inc. /kg
Air	low. pop.	<2.5 μm	3.0176E-6	Disease inc. /kg
Air	low. pop., long-term	<2.5 μm	2.3850E-4	Disease inc. /kg
Air	high. Pop.	<2.5 μm	2.3850E-4	Disease inc. /kg
Air	stratosphere + troposphere	<2.5 μm	0	Disease inc. /kg

Land use

Impacts related to land use are becoming increasingly recognized as an important factor in LCA calculations. However, there exists still a lot of confusion of what exactly land use entails. Two main terms are used to define land use in LCA calculations; land cover and land use. These terms are often mixed or used as synonyms, however, there are significant differences in the terminology. Where land cover refers to the physical material in the area, land use refers to the functional dimensions and describes how an area is used, either for urban, agricultural, forestry or other uses.

The assessment of the environmental impact of land use in forestry and timber products in LCA calculations remains a topic for debate. At the moment this is unclear and there is no well-defined method to assess all impacts. There is a multitude of environmental indicators that are suggested to be used to assess land use impact, ranging from resource depletion, changes in biodiversity and soil quality impacts. Many models aim to reflect land use activities in LCAs, however a balance is not yet found between complexity and comprehensiveness on one hand, and applicability and feasibility on the other hand.
In recent years the awareness of the importance to include soil quality aspects in order to assess land use in LCAs has increased. One model that tries to quantify these soil quality aspects is the LANCA® model (Bos et al., 2016). The LANCA® model provides a set of characterization factors (CFs) for five different soil quality indicators both at global and at country level. The input for these CFs is given by a quality calculation of the corresponding indicators for all impact categories and land use types. This is based on general conditions and characterization factors. This model is used in LCAs to determine the land use impact.

Land use change (or land transformation), as the name suggests, refers to the process of (man-made) change in land use (for instance from forestry to agriculture) and its related impact. Land use change is measured as area from and to (in m^2). This category should not be confused with the impact category GWP-luluc, which considers the possible effect of land use and land use change on global warming.
Land use (or occupation) on the other hand denotes the continuous use of a certain area and time for a specific land use type and related activities Land occupation is measured as area*time (in m^2a). In impact assessments both inventories have to be combined and made comparable in order to assess environmental impacts.

In this study it is assumed that the timber to produce CLT is coming from sustainably managed forests, hence the type of land use will remain forestry. Therefore, in this study the main focus regarding the impact of land-use will be land occupation. In forestry it would most likely comprise one rotation period of a forest stand in case of large-scale forest management. The land use during the growth of the timber, and associated impacts and damages, are required to be allocated to all products created during that rotation period. Therefore, the production rate (how much time is required to produce one unit of product), or harvest intensity is an important factor in LCA calculations regarding land use in forestry.

In current LCA calculations, multiple sub-compartments for forestry regarding land occupation are defined based on forest type and use intensity (Table 3). In this study, managed forests from which timber is extracted are reviewed, hence the forest types intensive and extensive (and unspecified) are most relevant. As to be seen in the table below, the impact of intensive forest management is almost double the impact of extensive management.

Table 3 Land-use types and impact on land occupation (per m^2a)

Compartment	Subcompartment	Unit	Impact
Raw	Forest, extensive	Pt	18,1
Raw	Forest, intensive	Pt	34,1
Raw	Forest, natural	Pt	11,5
Raw	Forest, primary (non-use)	Pt	11,5
Raw	Forest, secondary (non-use)	Pt	11,5
Raw	Forest, unspecified	Pt	21,5

The definition of these types of land use is as follows (Weidema et al., 2013):

- *Forest, extensive: Forests (tree cover >15%), with extractive use and associated disturbance like hunting, and selective logging, where timber extraction is followed by re-growth including at least three naturally occurring tree species, with average stand age >30 years and deadwood >10 cm diameter exceeds 5 times the annual harvest volume.*
- *Forest, intensive: Forests (tree cover >15%), with extractive use, with either even-aged stands or clear-cut patches exceeding 250 m length, or less than three naturally occurring species at planting/seeding, or average stand age <30 years, or deadwood less than 5 times the annual harvest volume.*
- *Forest, unspecified: Forests (tree cover >15%)*

Analysis of impact categories in European EPDs

The meaning of the main three impact categories that show the highest environmental impact contribution are explained in the section on the Dutch EPDs. Now, in addition to the Dutch EPD analysis, a further analysis of EPDs was performed to gain insight into these three impact categories in phase A1-3, because they are particularly relevant for the impact calculation of CLT production. This analysis has been done for 8 additional CLT EPDs (Environdec and Institut Bauen und Umwelt). They have been evaluated with respect to the three main impact categories that followed from the Dutch EPD analysis, and the additional impact category 'Water use', as this is sometimes mentioned as a category with a high impact in case of wood-based construction products. In Figure 3 the result of the analysis is shown, together with impact values from ecoinvent. The reported impact values have been translated to an MKI contribution, using the same weighting factors as for the Dutch EPDs. A wide range of MKI values is obtained for all impacts (except for Water use, which is always close to zero), which confirms the observation of large differences from the Dutch EPDs. The hypothesis of a high impact contribution of the Water use impact category is not confirmed as the MKI contributions are all insignificant.

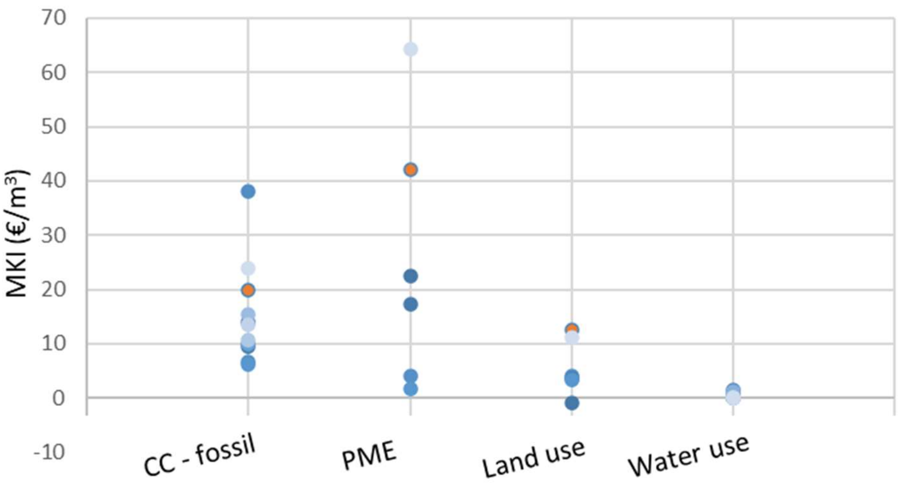

Figure 3 MKI results of 11 EPDs with respect to 4 impact categories in phase A1-3: Climate change – fossil ('CC-fossil'), Particulate Matter Emissions ('PME') and Land use related impact/soil quality ('Land use') and Water use. The orange dots represent the data from ecoinvent v3.6 for CLT.

Because of the high share in the total impact from the three impact categories CC – fossil, PME and Land use, this study will relate the impact analysis to these categories.

4.2 Supply chain

Within the scope of this project, the supply chain of CLT includes the manufacturing processes from the tree in the forest till the final panel (construction and end-of-life scenarios are not covered) (Figure 4). These processes were categorized into three phases, namely: 1) the roundwood production/forest management, 2) sawn wood production and finally 3) CLT production.

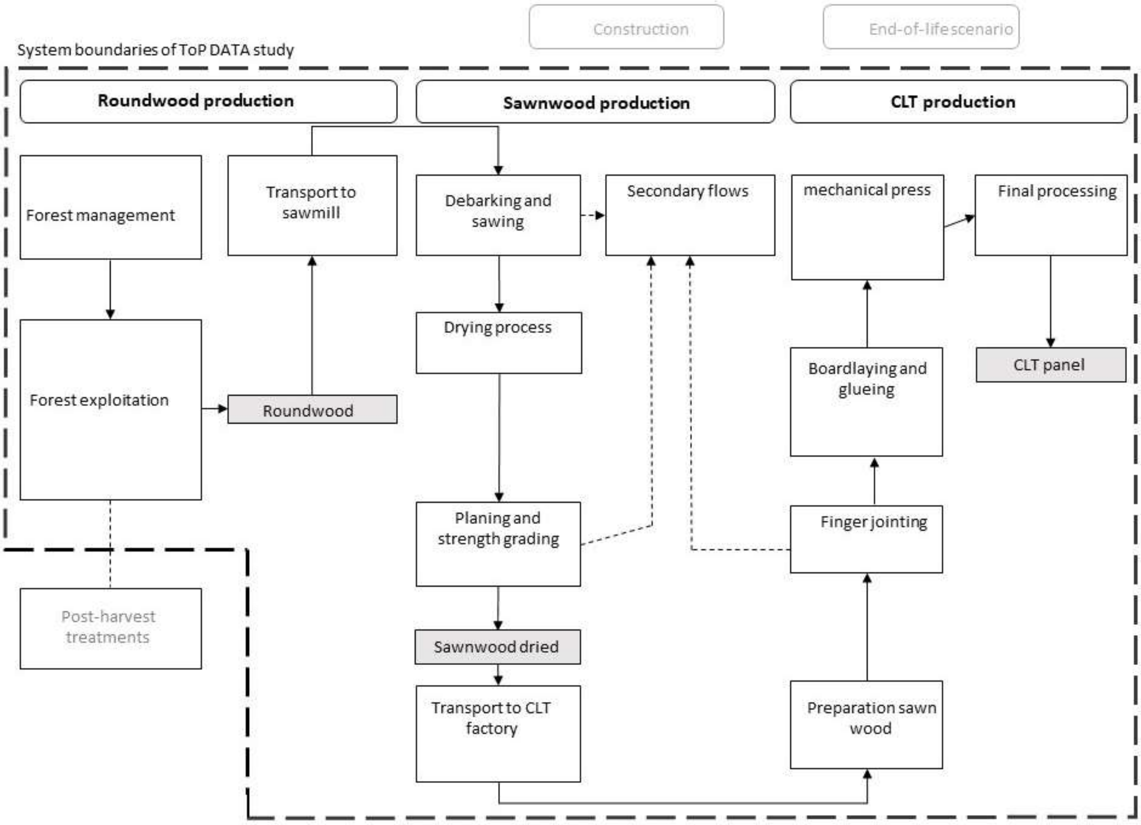

Figure 4: Supply chain of Cross-laminated timber (CLT). White boxes indicate the various processes, while the grey boxes indicate resources. The arrows represent the main resource flows, while the dotted arrows represent residual (or waste) flows.

The processes in Figure 4 of the first two phases were based on the combined authors' expert knowledge of the sector and its common practices. The remaining phase (CLT production) was based on various online sources (Muszynski et al., 2017; De Araujo et al., 2023).

The first phase (roundwood production) starts with the characterization of the forest management, for which many input factors are important that relate to the (land needed for the) harvest. The main parameters needed are the harvest intensity, rotation period and land use intensity, with their associated underlying impacts on the environment. These parameters are influenced by several input factors, such as monoculture versus mixed stands, clear cut versus group selection, log assortments (difference between final cut and thinnings) etc. Another important step to consider is the forest exploitation, which includes the way in which the wood is felled and transported to the forest road. This includes the felling in the forest stand until the skidding to the forest road. Depending on the specific forest type and other factors, different types of machinery (with different energy consumptions) may be used, which ultimately affects the LCA outcome. Depending on the situation, the branches will either remain in the forest or get used as biomass energy. After the wood is felled and skidded, the sawlogs are transported to the sawmill where further processing takes place. In specific cases the logs may be debarked in the forest, but in practice this is usually done at the sawmills.

After the logs are transported to the sawmill the initial step at the sawmill is sorting, scanning and debarking. Thereafter the sawing takes place, which results in a residual flow due to material losses. This flow may or may not be redirected to the supply chain of CLT, depending on the manufacturing process of the specific product in question. For instance, wood chips from sawing may be used for biomass energy in the sawmill as input for a drying kiln. Next, the (green) sawn wood is dried, causing shrinkage. Then, usually the sawn wood is planed and strength graded, which causes additional volume loss.

For the last phase, the sawn wood is transported to the CLT production facility, where the boards are planed and finger-jointed. Finally, the boards are glued together and mechanically pressed. The final processing may include the sanding, producing the openings and pre-drilling of the CLT panels. This depends on the specific product to be manufactured.

4.3 Quantitative data on processes and resources

The supply chain is further supplemented by adding literature-based quantitative data on different processes and resources. The following paragraphs are divided according to the main phases of the supply chain as outlined in the previous chapter, including the transport as part of the corresponding phase. They also include a comparison with data from the ecoinvent database, both for Germany and Sweden.

4.3.1 Roundwood production

Various data sources were consulted in order to paint an overview of the environmental data associated with roundwood production. Most of the imported CLT for the Dutch market originates from Germany (approximately 83% in 2023; Probos, 2024), and we assumed most of the supplied wood for this production to be of domestic origin (as also shown by the field visits). Therefore, we decided to focus our literature study on prevailing German conditions and practises.

4.3.1.1 Forest management

The harvest intensity is expressed as the average yearly harvest over a complete rotation (containing all assortments, such as sawn wood, pulpwood, chipwood, etc.). Based on the available literature, a range of 12.2 – 13.3 m^3 s.o.b. /ha/yr (solid over bark per hectare per year) was found, depending on the specific data source and its assumed management system (Table 4; Annex A). These values are higher than the one used in the ecoinvent database.

The land use intensity is expressed as the land needed to produce 1 m^3 of sawlogs over a complete rotation, a figure which is derived from the total harvest of sawlogs over a rotation and the associated rotation period. The values from the literature are higher than the one used in ecoinvent (Germany), even though the harvest intensity is lower in the latter. This is due to the fact that ecoinvent assumes a higher proportion of harvested sawlogs compared to other assortments (Annex A). Also, the given harvest intensity in ecoinvent for Sweden is considerably lower (meaning a higher land use intensity), which is most likely caused by overall slower growth rates in more northern territories.

Table 4: Key parameters of forest management based on the available online sources (Cardellini et al., 2018; Bundeswaldinventur ergebnisdatenbank, n.d.), in comparison with ecoinvent database (softwood forestry, spruce, sustainable forest management, version 3.6).

Parameter	Literature	Ecoinvent (Germany)	Ecoinvent (Sweden)
Harvest intensity (m^3 s.o.b./ha/yr)	12.2 – 13.3	11.1	7.7
Land use intensity (sawlogs) (ha * yr)	0.14 – 0.16	0.13	0.26

The ecoinvent database expresses volume in under bark, while the literature values are expressed in over bark. In order to maintain comparability, the original ecoinvent values (under bark) are converted to over bark using a conversion factor of 0.88.

4.3.1.2 Forest exploitation

Forest exploitation is characterised by the average productivity of forestry machines over a complete harvesting rotation. In the literature, this is expressed by the amount of productive machine hours (PMH) per harvested m^3 of roundwood over bark. Combining this figure with the average consumption of said machines, impacts (emissions) can be calculated.

From the literature, based on the previous definition, the productivity of harvest operations ranges between 0.22 – 0.28 PMH/m^3 over bark (Table 5), depending on the management scenario. Both felling and skidding is included in this figure, and only assumes the use of a harvester and forwarder, which are often combined in forestry practise, as illustrated in Figure 5. This productivity is considerably higher than the corresponding number expressing effort/m^3 found in ecoinvent for Germany (0.56 PMH/m^3). This is due to the fact that Cardellini et al. (2018) assumes fully mechanised harvesting over a rotation, while in ecoinvent the use of a power saw and tractor (which are both less productive methods) is assumed at final harvest. Here, the final harvest accounts for more than two thirds (66.7 %) of the harvested volume. Literature values are more in line with ecoinvent for Sweden, because here it is assumed that 98% of the harvesting is done using harvester and forwarder.

Figure 5: Pictures showing a harvester (left) processing harvested roundwood into assortments, and a forwarder (right) loading roundwood (source: Ecopedia, n.d.).

Additionally, the energy consumption of the machinery based on literature (Engel, Wegener & Lange, 2011) is calculated, where the required materials for production, life span of the machines and the energy consumption per fuel type are combined (Annex A). Here, there was no difference between the two scenarios, as we did not find any data to make this distinction. These figures can therefore be regarded as an average type of consumption, regardless of harvesting conditions. Overall, the consumption values used in ecoinvent are higher, especially for the forwarder and skidding tractor (Annex A).

Table 5: Key parameters of forest exploitation based on available literature (Cardellini et al., 2018), in comparison with ecoinvent database (softwood forestry, spruce, sustainable forest management, version 3.6).

Parameter	Literature	Ecoinvent (Germany)	Ecoinvent (Sweden)
Effort per average m^3 harvested overbark (PMH/m^3)	0.2222 – 0.2700	0.5579	0.18799
Of which power saw	-	0.445	0.0118
Of which tractor	-	0.0741	0.00249
Of which harvester	0.1111 – 0.1350	0.0166	0.0938
Of which forwarder	0.1111 – 0.1350	0.0222	0.0799

4.3.2 Sawn wood production

The transport of logs is the first step from roundwood to sawn wood production. The impact of the transport is determined by the distance from the forest road (location of log storage in the forest) to the sawmill. This is usually not a long distance, as reported from literature (Rüter & Diederichs, 2012) and ecoinvent (58 and 75 km, respectively).

Sawn wood efficiency and the balance of the remaining residual products is based on the country-specific material balance for coniferous sawn wood, as reported through the 'Forest product conversion factors questionnaire' of 2018 (FAO, ITTO & United Nations, 2020). Here, efficiencies are reported from underbark volume to sawn wood volume (Table 6). The balance of the remaining products (chips/slabs, sawdust, and shavings) are shown in annex A. Overall, the values for Germany are comparable to the ecoinvent values (59.6% and 54.4% in version 3.6 and 3.10, respectively).

Table 6: Efficiencies from roundwood to sawn wood based on the available literature (FAO et al., 2020). Besides Germany, several other countries are shown for reference.

Country	Reported efficiency (% sawn wood of roundwood s.u.b.)	Reported efficiency (% sawn wood of roundwood s.o.b.)[1]
Germany	59	52.7
The Netherlands	53	47.3
Austria	60	53.6
Sweden	49	43.8

[1]Calculated assuming 12% bark volume

4.3.3 CLT production

The data on CLT production that is available in ecoinvent originates from one literature source. Therefore, deviations compared to ecoinvent can easily occur in actual data from other CLT factories. The transport of the sawn wood is the first step from sawn wood to CLT production. The impact of the transport is determined by the distance from the sawmill to the CLT production site. The average distance reported in literature is 259 km. Other relevant parameters are glue use, electricity and fossil fuel use. An average conversion factor (efficiency) from dry planed sawn wood to CLT of 89% is found both in literature and (recent) ecoinvent, which leads to a total efficiency range of 39-42%. A recent analysis of efficiency numbers for several CLT sources (Pramreiter et al., 2023) mentions an average total efficiency from roundwood (under bark) to CLT of 37%.

5 Results of new field data

Two site visits with interviews were conducted and several questionnaires were distributed and filled in. The results from the questionnaires are compared to the literature study and ecoinvent in this chapter, and some more detailed results are presented in Annex B. Per phase in the supply chain, the parameters in the building blocks and in which way they can be updated are identified. The results are found in the following paragraphs. Additionally, we included data from Swedish and Finnish producers, as to gain insight in the expected range in parameter values.

5.1 Roundwood production

Forest management

From the questionnaires spread among the German forest managers it is evident that spruce is predominantly managed in mixed stands, with them occupying 59% of a management unit on average (Annex B, figure B1). The most frequently occurring management system for spruce is selective cut, followed by group selection and lastly clearcut, both in pure and mixed stands (Annex B, figure B2). When asking about the managers' vision on spruce management in the future, various managers stated that the area of spruce will decline in the future and that spruce will only occur in mixed stands or areas with sufficient water supply.

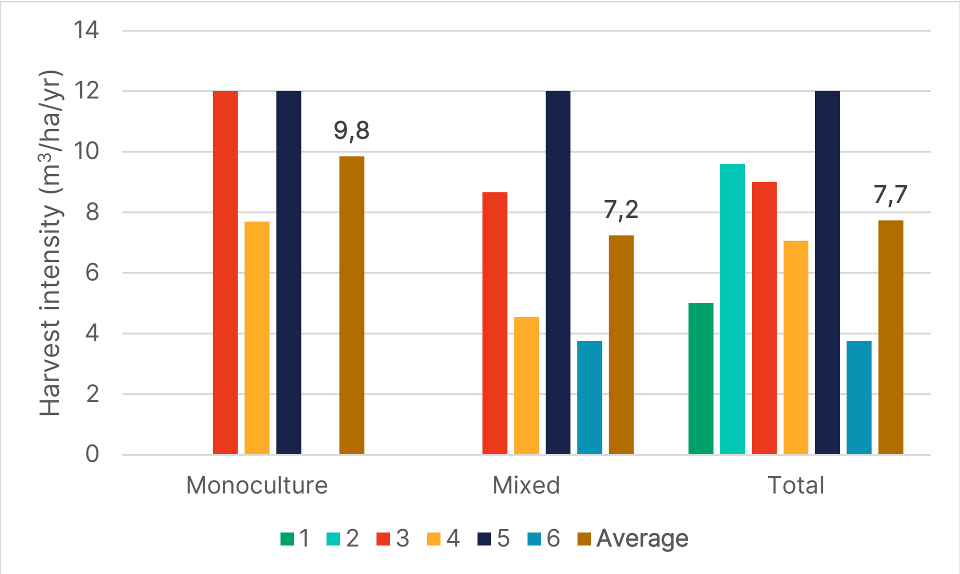

Figure 6: Harvest intensity (m³/ha/yr) among spruce stand types, reported by the different forest managers (n=6).

The reported harvest intensities show a large variation between 3.75 – 12 m³/ha/yr, with mixed stands having, on average, a lower harvest intensity compared to monocultures (Figure 6). At the forest level, the harvest intensity averages at 7.7 m³/ha/yr. These figures are considerably lower than the ones found in literature and used in ecoinvent. However, the average reported harvest intensity in monocultures is reasonably in line with the ecoinvent value. Land use intensity could not be calculated based on the questionnaire responses, as we could not extract information about sawn wood assortment divisions. Also, the reported rotation periods range widely, from 60-70 years till 100-120 years, averaging at 96 years (n=4). For the Swedish producers, the rotation periods were less variable, ranging from 60-75 years and averaging at 72 years (n=3). Both values are comparable to the corresponding country value used in the literature. It should be noted that some managers indicated that there is no actual rotation period, probably due to the increasing complexity of forest management.

Forest exploitation

From the questionnaires, no explicit data on the productivity and energy consumption of forestry machines could be extracted. However, we did gain data on which machines are being used and to what degree. Most of the harvested volume has been reported to be felled by a harvester (58% on average), while the chainsaw is used less often (42% on average) (Figure 7). This division is skewed compared to the literature value used, which assumes fully mechanised harvesting over a rotation (Cardellini et al., 2018). Compared to the ecoinvent database, which assumes motor manual final harvest (which is 66.7 % of all harvested volume over a rotation), the volume harvested by chainsaw can be considered as low. Moreover, chainsaw usage in mixed stands is considerably higher compared to monocultures (61% compared to 14%, respectively; Annex B, figure B3).

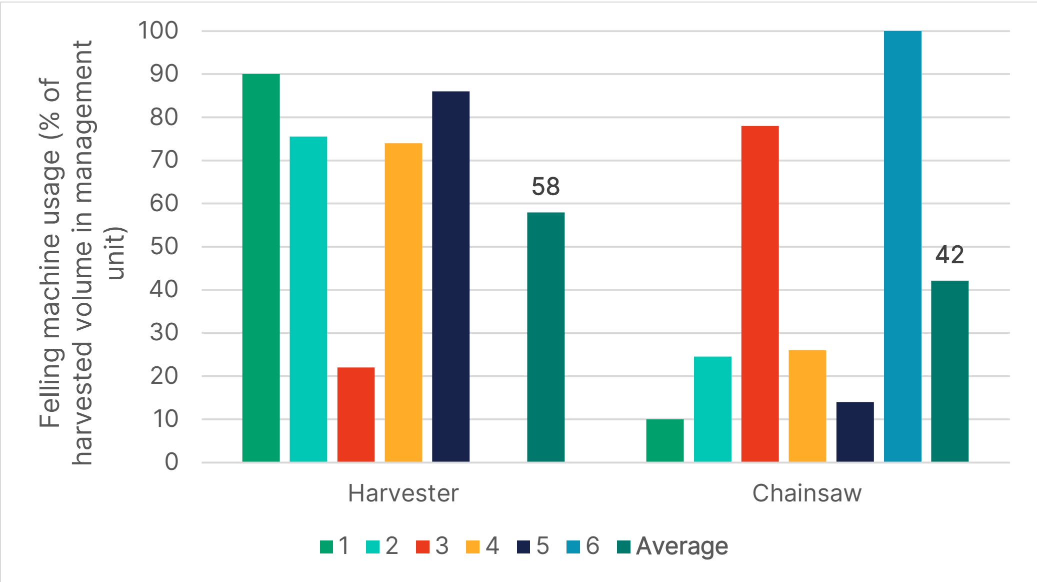

Figure 7: Division of felling machine usage (% of harvested volume) reported by the different forest managers (n=6).

As for the skidding (transporting the logs from the forest stand to the forest road), the forwarder was reported as the most common method (72.5% on average), followed by the use of a winch (25% on average) and skidder (2.5% on average) (Figure 8). This is more in line with the literature value used when it comes to forwarder use, but deviates from ecoinvent, which assumes a significantly higher usage of a skidder. No specification is available on the usage of skidding machines between monocultures and mixed stands.

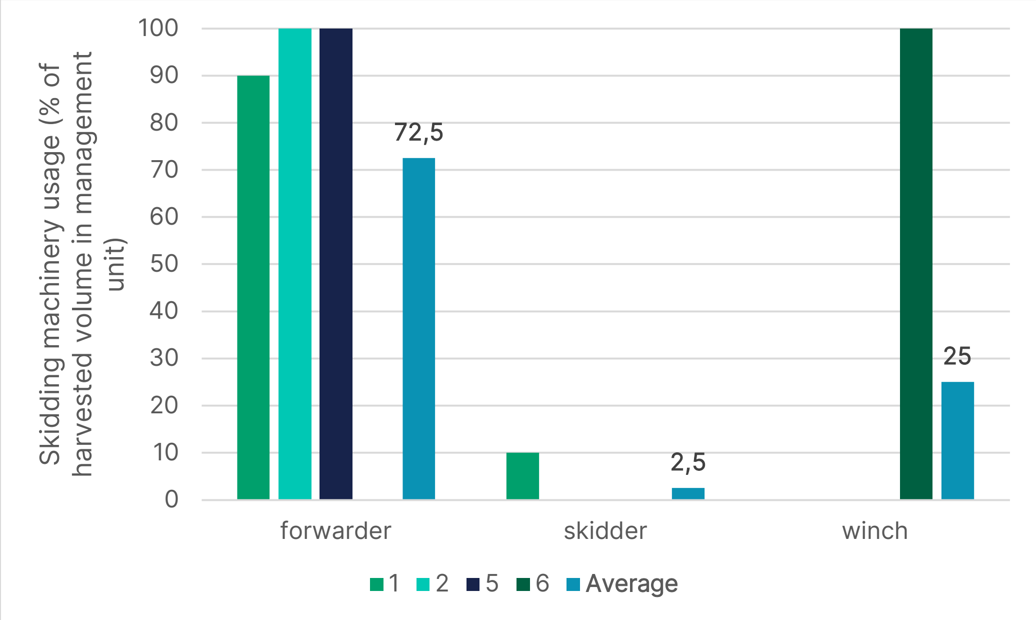

Figure 8: Division of skidding machine usage (% of harvested volume) reported by the different forest managers (n=3).

When it comes to the quality of the data, a few biases must be highlighted. Most importantly, due to practical reasons most of the forest managers who were willing to participate are situated in the state of North Rhine-Westphalia. This means that only a limited geographical area of Germany was covered. Also, most of the respondents were members of an association that promotes 'close-to-nature' forestry, which probably influences their silvicultural practices. For example, they may promote structurally rich and mixed forests to a larger degree than the typical forest manager in Germany. As a result, the degree of small-scale harvesting practises (and therefore the use of chainsaws) is likely overestimated compared to current practices in German forestry as a whole. For instance, an analysis by Lundbäck et al. (2021) revealed that approximately 75% of the harvested industrial roundwood in Germany is fully mechanised, which is considerably higher than the division based on the reported data. This division can be considered intermediate in comparison with for example Sweden and Austria where 95% and 35%, respectively, of the harvested industrial roundwood is fully mechanised (Lundbäck et al., 2021)

However, the data were still highly variable despite these similarities, which points out that the forestry practise is inherently variable and depends on many different factors. This ultimately means that when constructing an LCA, key parameters on forestry should be product/company specific, and that the use of generic values are less meaningful and should be avoided whenever possible.

5.2 Sawn wood production

Transport

From the acquired field data, the reported log transport from forest to the sawmill occurs mostly by truck. There is some transport by train and boat but this is only representative for companies that are close to a railway or port. The reported distances range between 73 and 180 km, which is comparable or higher than the 58 and 75 km found in literature and used in ecoinvent. The average reported emission class of the trucks is Euroclass 5 (which is different from the use of Euroclass 3 and 4 in ecoinvent). For Central Europe the reported emission class for the majority of trucks is Euroclass 6, but for the Baltics the share of Euroclass 5 trucks is higher. The trucks are unloaded at the sawmill with the truck-mounted timber cranes. At the sawmill the logs are measured and sorted based on the diameters.

Electricity

Electricity is used for the sawing and the planing machines. Both renewable and non-renewable electricity sources are reported, and renewable sources contribute significantly (30-100%) to the total. One sawmill manager reported an electricity consumption for the sawing machines of 14 kWh/m^3, which is somewhat higher than the 10.5 kWh/m^3 found in literature.

Heat

Most of the sawn wood is reported to be dried with biomass (either own biomass from production, or bought in biomass). There are different ways to dry sawn wood, however the majority of the installations are conventional drying kilns. These kilns require electricity to power the fans and heat to evaporate the moisture. The required heat as reported in the field, is used for the drying of the sawn wood at the sawmill, or is reported together with the heat used for the CLT production. Drying the sawn wood requires the majority of the heat, it is also the most energy consuming step in the production of dried wood. Values that are reported show a large variation, between 450 and 530 on the lower end, to 900 MJ/m^3 on the higher end are reported. These reported values are lower than found in literature (1302 MJ/m^3) and found for different species (Fir Spruce and Pine) in the US (650-1380 MJ/m^3, as reported by Garrahan, 2008), but higher than or comparable to ecoinvent (376-566 MJ/m^3). No clear explanation is found for these large differences. Possible explanations are that literature reports the input energy, whereas in the site visits output energy is reported (the difference being the efficiency of the boiler). Other possible explanations among others are the different wood species (spruce versus pine), the desired moisture content of the end product, dimensions of the boards and the initial moisture content.

On-site biomass installations produce (biogenic) CO_2, but also other emissions that are relevant for the environmental impact determination. The emission values of different sources are difficult to compare; not only the size of the installation but especially the heat source has a prevailing effect on the emissions and efficiency of the heat plant. For this report, the emissions of ecoinvent processes are compared with the publicly available data from three specific biomass installations, as presented in Figure 9. Other biomass installations also present emission data, however, these are not complete and therefore not useable in this study.
The emissions are compared with the following processes in ecoinvent 3.6:

- Heat, central or small-scale, other than natural gas {CH}| heat production, wood chips from industry, at furnace 50kW | Cut-off, U
- Heat, central or small-scale, other than natural gas {CH}| heat production, softwood chips from forest, at furnace 50kW, state-of-the-art 2014 | Cut-off, U
- Heat, district or industrial, other than natural gas {NL}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U
- Electricity, high voltage {NL}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U

Input per unit heat output	Units	Heat production, wood chips from industry, at furnace 50kW	Heat production softwood chips from forest, at furnace 50kW	Combined heat and electricity	Plant 1	Plant 2	Plant 3
Fuel amount	g (dry)/ MJ	254	251	272		-	-
Fuel Type		Chips dry	Chips wet	Chips wet	Secondary wood and waste from sawmill		
power		50 kW	50 kW	6667 kW	Combined 150kW	49kW	40kW
Emission to air per kg input fuel[1]							
CO	Kg	8.5E-3	8.6E-3	2.8E-0^{4}	5.8E-0^{4}	5.0E-0^{4}	4.2E-04
NH_3	Kg	3.3E-5	3.3E-5	4.7E-0^{5}	4.5E-05		
NO_2	Kg	3.4E-3	1.9E-3	2.2E-0^{4}	8.8E-0^{4}	2.4E-0^{3}	2.2E-03
Organic /NMVOC	Kg	3.3E-4	3.3E-4	7.7E-0^{6}	1.4E-0^{5}	1.2E-0^{6}	2.6E-06
SO_2	Kg	4.7E-5	4.8E-5	6.9E-0^{6}	9.9E-0^{5}	1.0E-0^{4}	3.0E-04
PM	Kg	1.4E-3	1.5E-3	1.4E-0^{5}	1.6E-0^{5}	2.4E-0^{7}	1.1E-05
1. estimated based on 20% mc and the assumption that the normalized m3 equals the numbers reported in m^3.							

Figure 9: Emissions from 3 existing power plants (1,2,3) compared to data from ecoinvent (as described in the text above).

From the gathered data it is clear that the emissions of particulate matter in the 3 plants are lower than data reported from ecoinvent, at least 1-2 orders of magnitude compared to the heat plants and in the same order of magnitude for the combined heat plant. More data is necessary to investigate and compare the efficiency and emissions in relation to plant power, fuel source, building year and application of emission controlling measures (like SNCR and filters).

Conversion efficiency

Efficiency of sawing has a large impact on all impact categories, as sawing is a considerable source of loss. Reported conversion efficiencies from our field research from roundwood to sawn wood range between 49-56% (under bark), while debarking efficiencies range from 88-94% as reported in the field. Literature and ecoinvent show higher efficiencies than this range (59 and 59.6%), although the more recent version of ecoinvent (version 3.10) adjusted the sawing efficiency to 54.4%. The field data translate to an 43-53% efficiency range from over bark roundwood to sawn wood. This corresponds well with the results of an analysis of internal industry data (Probos, 2023), in which an efficiency from over bark roundwood to sawn wood between 42 and 51% was found for sawmills processing mainly spruce.

5.3 CLT production

Transport

The reported transport distances of the sawn wood to the CLT factory shows a much larger variation than the log transport distances from forest to sawmill. The distances reported are between 65 and over 600 km. The transport occurs mostly by truck. In some cases the CLT producer directly uses the logs as input material, which means that the log transport is directly to the CLT factory. The reported transport distances for glue are between 60 and >800 km, whereas ecoinvent reports 451 km. Packaging materials are transported between <50 km and >1300 km, which is a highly variable distance. Although these transport distances can be much higher than the sawn wood transport distance, the impact on the environmental profile may be limited as glue and packaging constitute only a small fraction of the total mass to be transported. The main impact on CC – fossil will therefore be caused by the transport of the sawn wood. Both for impact categories CC – fossil and human toxicity, the total transport in the CLT production chain accounts for about 30% of the total impact per category.

Electricity

Electricity is used at the CLT production site for planing (this can be a second planing step after the first planing step at the sawmill) and for finger jointing, boardlaying and glueing, and for the machine press. Field reported values for electricity use are not always easy to compare between sources, as the input material can vary (roundwood, lightly shaved sawn wood, planed sawn wood) and the electrification of the machines is very dependent on the specific production site. We find a broad range of around 140-220 kWh/m^3 for the total processes from roundwood to sawn wood. The share of renewable electricity is also very site-dependent, as for example the electricity generation of on-site PV can be used instead of a local (or national) electricity mix.

Fossil fuel

Diesel and oil use on-site is reported in two cases to be very low (<1 kg/m3), possibly due to electrification of the machine park, but also a value of 11 kg/m^3 is reported which is closer to the literature reference of 15 kg/m^3. A trend may be that further electrification of the machine park will happen in the future, which can result in further decrease of the fossil fuel use on-site.

Glue

Glue usage is found to range from 4.0 to 4.9 kg/m^3, which in the same range as literature data (4.7-4.8 kg/m^3). Still, the environmental impact of the glue can be decreased by using less harmful, probably biobased glue instead of the regular MUF and PUR based glue types, or apply a strategy to reduce the amount of glue. The use of biobased glue types is reported by a CLT producer.

Conversion efficiency

As mentioned just above, a CLT production site can use either roundwood or sawn wood as input material. The resulting products, side products and residual flows can vary from site to site. Besides different impact of transport distances, this can also lead to large differences in production processes on-site, and the resulting use of machines, as the total production is optimized instead of only CLT production. Overall, the efficiencies that are reported from sawn wood to CLT range from 81-84%. Including the steps from roundwood over bark to sawn wood, the overall resulting efficiency (roundwood over bark to CLT) from the reported field data range from 35-45%. This is clearly on the lower side compared to the previously found literature and ecoinvent values of 37-42%.

6 Analysis and discussion

In this chapter, we analyse the acquired new data in chapter 5 in relation to the previously presented literature data, information from ecoinvent and information in EPDs. We discuss the impact that these new data may have on the three selected impact categories. This is discussed per impact category.

6.1 Climate change – fossil

Fossil fuel use

In CLT production, the contribution CO_2-eq emission by fossil fuel used for (harvesting) machines in the forest (15.2 kg CO_2-eq per 1 m^3 CLT) to the total CC – fossil emission (206 kg CO_2-eq per 1 m^3 CLT) according to ecoinvent is around 7%. From the field reports, no data was available on fuel use by the forest machines (including biofuel), so no updates can be provided. However, a point of attention is that transport distances in the forest may increase if there is a trend to exploit more mixed forest or apply less intensive forest management. As a result, longer distances within the forest cause increased emission of fossil CO_2. For instance, Labelle et al. (2019) found a higher productivity per harvested m^3 of wood by harvester exploitation in selective cut vs. clearcut treatments, which was caused by higher transport distances. The development of forestry machines may have a positive effect (decrease) on the fossil CO_2 emissions. Whereas the shift towards less intensive harvest intensities may lead to increased machine use.
Fossil fuel use by machines at the sawmill and CLT production site is dependent on the production type of the site (the machine park can be different for sites that manufacture additional products, besides sawn wood and CLT) and the level of electrification of the machine park. In general the main impact is due to the use of Diesel, mainly for transport. If relevant for longer transport distances the use train and boat / ferry have a positive effect on the CO2 emissions.

Transport

In the sawn wood and CLT production, the field-reported distances of 73-180 km for log transportation to the sawmill are on the higher side compared to the values in literature (58 km) and ecoinvent (75 km). The transport distance to the CLT factory is a point of attention, as this highly varies from site to site. The lorry transport is reported as mainly Euroclass 5 and 6 whereas ecoinvent assumes Euroclass 3 and 4. Differences in CO_2-eq emissions between Euroclass 4, 5 and 6 are relatively small as extracted from ecoinvent processes. However, the results in other impact categories such as Acidification and Eutrophication and Particulate Matter Emissions are significantly different between the different Euroclasses.

Electricity

Electricity is used for the sawmill and will have an impact on the CC – fossil if the source for the electricity is non-renewable. Reported shares of renewable electricity are considerable, ranging from 30-100% by using renewable electricity from national sources, own biomass plant, or generation from their own PV. From the EPD analysis, half of the EPDs provide a specific declaration of the electricity source, which is typically described as an ecological mix. The impact can differ considerably from a standard (national) electricity mix; use of a higher share of ecological sources will lead to a lower contribution to the CC – fossil impact. This is an attention point for the LCA maker.

Heat

Most of the heat that is used for drying, is reported to originate from burning (own) biomass that is a residual flow of the sawn wood production process. The impact of heat production on the CC – fossil impact depends on heat source: mainly the use of gas, heat networks with non-renewable sources and use of non-renewable electricity contributes to an impact in CC – fossil. Burning biomass, the most common source of heat to dry the sawn wood, emits CO_2, but this is biogenic carbon dioxide and does not contribute to CC – fossil. Biomass as heat source will however have an important contribution to the particulate matter impact, which is discussed in the next section. From the EPD analysis, 2 manufacturers report the use of a biomass installation, and 1 reports the use of a local heat network. The impact can differ considerably between a biomass installation and a heat network, also depending on the source. This is an attention point for the LCA maker.

6.2 Particulate Matter Emissions

The emission of particulate matter is for a large part associated with heat production based on burning biomass (in ecoinvent: around 80% of particulate matter emission is related to heat production). In addition to that, there are also varying amounts of emissions due to electricity production (depending on the electricity mix used), and due to transport and use of diesel (depending on differences in Euroclass truck for log transport), as reported earlier in this report. However, if biomass is used for drying the sawn wood, the drying step will cause the majority of the impact.

Heat (biomass)

Some larger sawmills have a combined electricity and heat production plant, but in general all sawmills use (their own) biomass to generate the heat needed for drying. As already stated in Chapter 2, the population density around the biomass central is important to correctly characterize the impact of the emissions. This is further analyzed using several sources to define a useful statistical methodology, as listed in Annex D. The population density as used in ecoinvent (database versions 3.x) is defined as follows: the number of people in a 2 km radius around a particular point in persons / km^2. The following threshold value is used: a value below 400 persons per km^2 is considered to be a low population density and above 400 persons per km^2 is a high population density.
In order to determine the population density the first step is to determine the point of emission and draw a circle of 2 km radius around this point and determine the cities and villages within this 2 km radius. Once this is done the calculation of the population density is not straightforward, for use in LCA calculations three different approaches are suggested:

1. Search for population statistics of the relevant parts of the cities (districts) and villages
2. Use the population of the whole city and multiply with the area of the part within the 2 km area, divided by the whole area
3. Use the average population density of the area

In case of uncertainty the unfavorable value should be used.
With method 3 especially the population density around a point in the forest can be determined (to account for the emissions of harvester, chainsaw and forwarder) although it is also convenient to use low population density area for these operations, as forest is (unless it is near a city) always lowly populated. In all other cases the use of method 1 and 2 give more reliable results, method 3 should especially be avoided if parts of a city are within 2 km radius while the average population density also includes large rural areas.
In Annex C an analysis is shown for a representative number of the larger German sawmills. It is in this case assumed that a biomass installation is present at each site. The population density is determined with a combination of method 1 and method 2. From Annex C it is

clear that investigating the population density enhances the reliability of the outcomes and in many cases results in a lower environmental impact from particulate matter emissions.

6.3 Land use related impact

The impact calculation of land use in forestry revolves around the area and time needed (m^2a) to produce one unit of product (in case of this study one m^3 of CLT) and its related impacts on the environment. Hence, forest management and -exploitation are important impact contributors in the supply chain of CLT to assess roundwood production and eventually the impacts of land use. In ecoinvent 'forest, intensive' is mainly used for land use.
In order to give insight in the roundwood production, harvest intensities and associated rotation periods play an important role. However, both the literature research and site visits and surveys pointed out that the harvest intensities of different silvicultural systems show major variations (see chapter 5.1 and annex B). Moreover, local site conditions such as soil nutrient richness, geographical location and groundwater levels also influence the harvest intensities, even within similar silvicultural systems.

Besides the harvest intensity, the diameter and quality of the harvested timber plays an important role in the land use assessment. These traits will determine the assortment of the harvested timber. Only logs of certain quality and diameters will be labeled as sawlogs. Only the assortment of sawlogs will be used for the production of CLT. The other assortments, such as logs for firewood or pulpwood (usually called industrial wood), will not be used to produce CLT and hence the timber production per hectare suitable for CLT will decrease.

As mentioned before, only two subcategories of land-use types are in place for managed softwood forests from which timber is extracted; intensive or extensive forest (chapter 2.1). However this does not reflect the variety in silvicultural systems, associated management and related harvest intensities in practice. It goes beyond the scope of this research to divide the German forest area according to the current land use definitions, but based on an analysis of the country average of annual timber harvest and dead wood volume per hectare for Germany (BMEL, 2014), the threshold values in the definition for the 'extensive' categorization seem highly ambitious. This means that most of the forest area from which timber is extracted would be classified as 'intensive'. This is also in line with literature were most sustainable managed forests are classified as intensive forests (Weidema, B.P., 2013).   A more detailed level in the nomenclature that reflects the management intensity is required to properly reflect forestry in practice. This is widely discussed in existing literature. Bos, Horn, Beck, Lindner & Fischer (2016), for instance propose an update for the nomenclature for forest flows that implements this more detailed level of management strategies and silvicultural systems (Figure 10 Proposal for an updated nomenclature for forest flows by Horn et al., 2021.Figure 10).

ID	Land use/cover class from Koellner et al. (2013a)	Management strategy (Nabuurs et al. 2019)	Silvicultural system (Cardellini et al. 2018)
1.1.	Forest, natural		
1.1.1	Forest, primary	Strict nature management	-
1.1.2	Forest, secondary	Close to nature management	-
		Strict nature management	
1.2	Forest, used		
1.2.1	Forest, extensive		
(a)		Low intensity management	Continuous cover forest management (selection felling, or selective logging)
(b)		Multifunctional management	Continuous cover forest management (selection felling, or selective logging)
(c)			Forest management with shelterwood Forest management with clearcutting systems combined with nature considerations in all operations and set aside areas with no management or management in order to maintain or enhance biodiversity values or other values.
1.2.2	Forest, intensive		
(a)		Intensive management	Forest management with shelterwood
(b)			Uniform clearcutting system
(c)			Coppice
(e)		Very intensive management	Uniform clearcutting system
(f)			Short rotation plantations

Figure 10 Proposal for an updated nomenclature for forest flows by Horn et al., 2021.

Such an improved nomenclature, with more levels of detail, would better reflect the variety in management intensities. However the associated characterization factors of these land use types need to be identified.

The LANCA model which is currently used for the calculation of land use in LCAs could be further improved by using country and site-specific characterization factors, as visually explained in Figure 11.

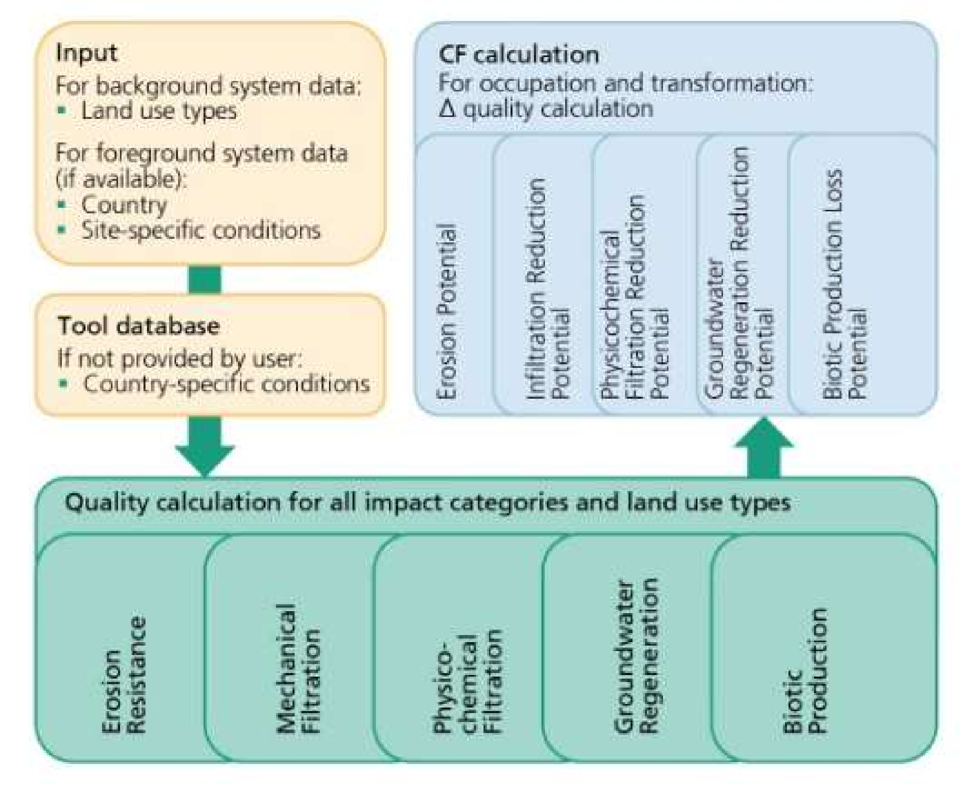

Figure 11 Visual representation of the LANCA model

The use of these types of models is a step in the right direction to better include the wide variety of impacts related to land use. However, incorporating these models in LCA calculations remains challenging since site-specific data for these conditions are difficult to obtain without elaborate research.

Also, the inclusion of other indicators, besides soil quality indicators, such as biodiversity and long term positive effects of forests and forest management for climate mitigation and – adaptation, to name a few, is not yet incorporated in current models but deserve to be investigated in more detail. A more detailed investigation into the land use indicator, also for other products is needed.

6.4 Conversion efficiency and allocation

Conversion efficiency

The overall conversion efficiencies determine the final amount of CLT product that can be obtained from 1 m^3 of roundwood or standing volume. Higher efficiencies automatically relate to lower impact from all impact categories. We have seen that the reported efficiencies for debarking, sawing, drying, CLT production are mostly in line with the values found in literature, and in some cases lower, e.g. depending on the product and the specific source of the roundwood. Therefore, the updated efficiency numbers are hard to convert to single number per stage, and it remains a point of attention to the LCA maker.

Allocation

Allocation of environmental impacts can be performed based on mass or volume fractions, or based on economic value of the different products and secondary material streams. According to EN 15804, co-product allocation 'shall be based on physical properties (e.g. mass, volume) when the difference in revenue from the co-products is low', and in all other cases 'allocation shall be based on economic values'. As guideline for allocation choice, it is stated that a 'difference in revenue of more than 25% is regarded as high'. From the EPD analysis, the following clarifications are made regarding allocation (number of EPDs in brackets):

- Forestry operations: allocated to roundwood only (1)
- In general: impacts are allocated based on economic revenue (2), on economic, physical and energy shares (1) and on product volume (1)

For co-products or secondary flows with fluctuating economic value, the impact calculation according to the allocation rules is not straightforward as the impact share changes with the economic value.

For multi-output processes, allocation is usually applied to divide the environmental impact between products and byproducts. Allocation should, if possible, be avoided. However, in a sawmill it is hard to avoid allocation. During the process of sawing and planing the timber, and constructing the CLT panels, efficiencies of production occur and residual woodflows are created which should not be allocated to the finished CLT-product. A possible approach for sawn wood could be the allocation of the environmental impact of debarking to the bark, allocate the suction of sawdust to the chips and dust, and allocate the sawing and scanning to the sawn wood. The environmental impact of the log should then be allocated based on the economic value of the products and byproducts. However the economic value varies a lot, depending on: location of the sawmill, market demand and season. If the side products (bark, dust) are used for heat generation for the drying process, the impact allocation will ultimately be to the CLT product.
Economic allocation can result in very volatile impact shares. To give an idea of the variability, the allocation factors for 2 different years and two different producers are given: one year the price of the byproducts is roughly 19% of the price of sawn wood, while next year it is 26%. Dried byproducts have a value of 16%-50% of the price of dried sawn wood (average around 33%).
As already discussed above there are several reasons for the high variability:

1. market dynamics and prices;
2. local market demand and transport prices;
3. seasonal effects;
4. quality of the sawn wood products and related price differences.

Therefore it is suggested to investigate whether a combination of economic allocation over the past years and quality differences can be used to come up with a **fixed allocation factor** and publish this in the European wood PCR which then is updated every 5 years.

Also in the forest there is some allocation necessary, as branches and topwood are sometimes removed from the forest and sold as byproducts, to which impact can be allocated. In other cases, the branches and topwood are left in the forest for soil quality and biodiversity reasons. Approximately 23% of the aboveground biomass for the average spruce/fir stand are in the branches (IPCC, 2003). Also, 10% of the standing volume (aboveground volume – branches) is additionally lost during harvest (Stinglwagner et al., 2016), which mainly consists of topwood and remaining stumps. Note that these losses should not be subtracted from the harvested volume in this research, which already accounts for these losses. It is recommended to **see the branches and topwood in all cases as a byproduct to which impact can be allocated**, irrespective of whether it is sold or left in the forest. The byproduct in this case contributes to biodiversity and maintaining (or even improving) the forest health. However, currently this may not be seen as an 'economic' byproduct to which allocation of environmental impact is allowed. Alternatively, the positive impact of leaving branches and topwood in the forest may be valued in a better way, for example in the impact category 'Land use'. We will elaborate on this in more detail in the recommendations section. In general more research is necessary to investigate how the positive functions of forest should be allocated to the wood products.

Another thought is that the impacts of land use should be allocated appropriately following the division of assortments. In literature, approximately 50-70% of the total harvest of spruce stand is estimated to be within the assortment of sawlogs (appendix A), hence only 50-70% of the impacts of the land use should be allocated to the production of CLT.

In general, **allocation strictly based on physical properties** (mass or volume) seems beneficial for decreasing the impact of the CLT product, however, the impact of byproducts with lower economical value (such as pulpwood or saw chips) will increase. **For the wood sector as a whole, this will not lead to a real advantage**. In addition to this, usually a large share of the byproducts with lower economical value are used for heat production and therefore already contribute to the CLT impact.

7 Conclusion and recommendations

7.1 Conclusions

Based on the findings in this report, several building blocks of the supply chain were successfully updated with newly acquired data. Several CLT manufacturers, intermediate product suppliers and forest managers were willing to share their production data with us, which strongly indicates the urge to review these data. We are very grateful for their cooperation. In Figure 12, the supply chain as presented in paragraph 4.2 is shown again, with the building blocks that have been updated with new numbers indicated by dark green boxes, and the building blocks for which we acquired new but highly variable numbers indicated by light green boxes. These building blocks need to be considered carefully by the LCA maker to ensure that the right numbers and interpretation are applied and the correct impact values can be determined. In the following two sections, the new findings are summarized.

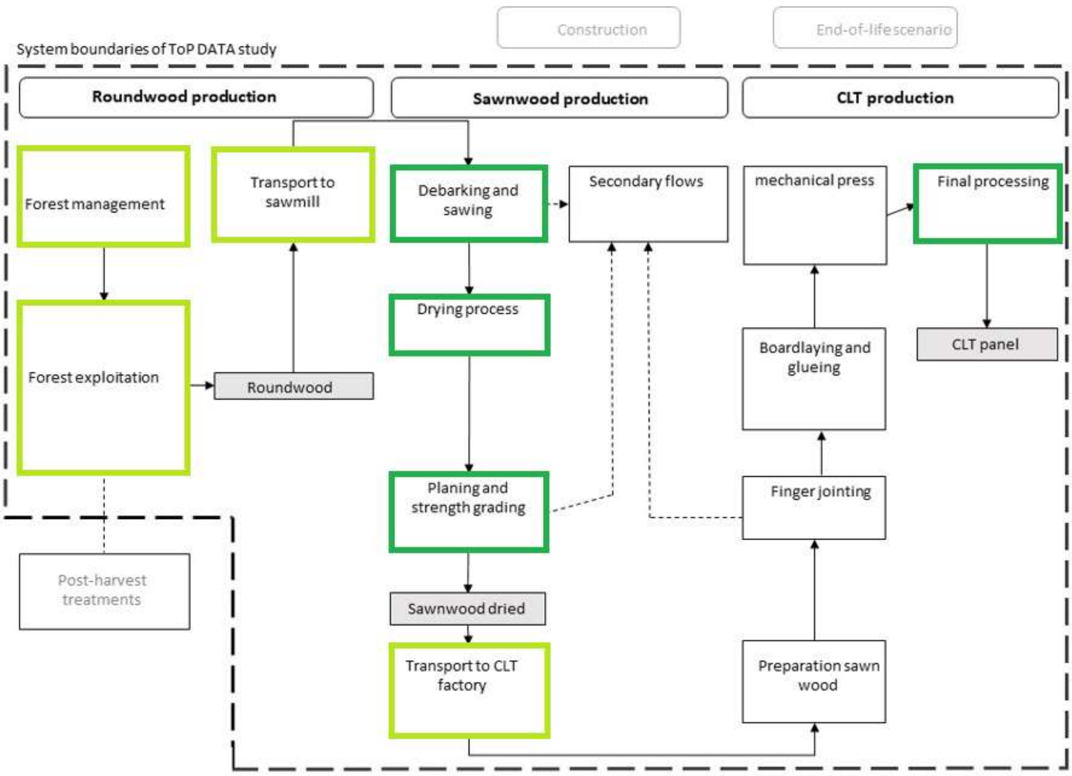

Figure 12 Supply chain of Cross-laminated timber (CLT). Dark-green boxes represent building blocks that were successfully updated, whereas light-green boxes represent building blocks that need serious attention when constructing an LCA.

Identification of new data and methodology

From several producers of CLT and intermediate products, new efficiency data was collected by evaluating the loss percentages in the different stages of the CLT production process. The resulting efficiencies are listed in Table 7 and can be used as a guideline for LCA makers to support the reported efficiency values of CLT (intermediate) products.

A new methodology was identified to determine the impact of fine particulate matter emissions, which is in particular relevant for heat production in biomass installations that is used in the drying process. The population density is key in this method, and performing an actual calculation will help to obtain a more accurate impact determination. Three methods of population density calculation are described that can be used for the impact determination, thereby avoiding the need to use the upper limit for impact. In this way an unrealistic estimate can be avoided.

Table 7 Range of efficiency data of the three main processes from tree to CLT panel, identified from the collected field data

Process	Efficiency	Cumulative efficiency
Harvested roundwood → debarked roundwood	88-94%	88-94%
Debarked roundwood → Sawn wood	49-56%	43-53%
Sawn wood → CLT panel	81-84%	35-45%

Identification of highly variable data

We also identified a number of aspects under each building block that need serious attention when constructing an LCA, as data can vary considerably and therefore the resulting impact is significantly affected.

Forest management:
The current standard choices for land use (intensive and extensive) are too limited to correspond to the actual forest management and stand types. Based on our quick analyses, most of the forest area for German conditions will be categorized as 'intensive'. Based on the collected data, harvest intensity ranges between 3.75 - 13.3 m^3/ha/yr

Forest exploitation:
Especially the division of forest machine use per average harvested m^3 of roundwood needs to be reviewed for each individual case. Energy consumption of forestry machines shows less variation. Based on the collected data, felling occurs in 58-100% by a harvester and in 0-42% by power saw. The transport of the harvested roundwood takes place by a forwarder in 72.5-100% of the cases and only 0-27.5% is transported by either forestry tractor, skidder or winch.

Transport distances:
Especially the distance to the CLT manufacturing site is important to review for each individual case as this distance varies most. Based on the collected data, transport distances from forest to sawmill ranges between 73 and 180 km. Transport distances from sawmill to CLT manufacturing site ranges between 65 and 600 km.

Vehicles for transport:
Vehicles are replaced frequently to more modern versions, including the transition to all-electric vehicles. Based on the collected data, the average emission class of the trucks used to transport the roundwood to the sawmills is Euroclass 5; This is similar for the transport to the CLT factory, in case the transport takes place by trucks.

Sawn wood drying process:
Specifically the share of heat from renewable sources will impact the fossil CO_2 emissions. Within the sources for renewable electricity (used by production machines), the share of PV or wind energy versus the use of biomass affects the impact in the production process, specifically in fine particulate matter emissions.

7.2 Recommendations

Based on the study several recommendations can be given. The first set of recommendations indicates how to use the results of this study. The second, additional set of recommendations represent the (sometimes unexpected) insights gained during the study.

7.2.1 Recommendations on use of results

We recommend the use of the results of this study when making LCAs of CLT construction elements. The conclusions that are given in the previous paragraph give a clear outline of updated data that was found and for which building blocks they are relevant. When making an LCA, these data can form a new reference, with which more representative LCAs can be made. Based on the results it is recommended that specific building blocks of the CLT production process are given specific attention when making an LCA. In the previous paragraph it is noted which data and building blocks it concerns. When possible, the updated data and insights are recommended to be used to make updated versions of existing (LCA) studies;

Based on the results it is specifically recommended to supplement and update data on biomass installations. It is recommended to consider and calculate the population density of the area around the biomass installation location, in new and existing LCAs, especially if the current input for the LCA is set on 'unspecified'. Adjusting the population density in the background data may result in considerably lower impact of particulate matter emissions. It is recommended that, in cooperation with the sawmills, the emissions of biomass installations are determined more accurately. In case of missing information, additional measurements should be performed to update the emission data.

We recommend that new studies will be performed on the context, methodology and data sensitivity for specific impact categories, especially the categories that are rated as highly uncertain. The impact category 'Land use' is a good example. This impact category is meant to represent the situation in the forest, and the effect of forest type in terms of environmental impact. The method to determine the impact is highly non-transparent and unclear. Forests are categorized very roughly, and the categorization will become more representative if more variations can be addressed. A more detailed study will be required for an accurate and transparent way to determine the right parameters, indicator and resulting impact. It is also recommended to review the allocation principles in order to result in a realistic and fair share of the impact to the CLT product. Fixed values for allocation can be presented in the European wood PCR. We recommend that studies such as these are regularly performed, so that data stays up to date and LCAs of CLT element can be as representative as possible.

7.2.2 Additional recommendations

The added value of a forest in terms of enhanced biodiversity, avoided decomposition (and related emissions) and other enhanced ecosystem services is not included in an LCA (Ernst Andersen, 2024). This is due to the set-up of an LCA, which considers the negative environmental impact, and proposes strategies to reduce this impact. Positive environmental impact of production processes does not fit in this set-up. Even though, the positive impacts of a forest is evident, and it is recommended that a new study will be set up how this positive impact can be represented in a better way. This also relates to the fact that forest management in itself can have positive effects in terms of enhanced ecosystem services, when compared to a regular forest. Impact of this is not well represented.

One of the benefits of wood products is the temporary storage of carbon during its life cycle. This added benefit is currently not valued in LCAs, in line with the norm. The reason is that the different points in time of carbon capture (in the tree) and carbon emission (in end-of-life scenario) are not considered. The carbon capture and emissions are simply summed up, and therefore in the total life cycle the net carbon emission is 0. However, the temporary stored carbon has value, as the CO_2 at end-of-life is released at a later point in time and does not contribute to the short term emissions. Especially now that urgent reduction of CO_2-emissions is necessary, it is a recommendation to evaluate how this benefit can be represented and valued in an LCA. In several studies this value and other related issues are discussed (van den Oever, 2024; Fraanje et al., 2021, Keijzer et al., 2021).

This study only encompasses the production stage of the CLT life cycle. It is recommended that in following studies, the representation of the background data of the rest of the life cycle of an CLT construction element is considered. Specifically, it is expected that end-of-life scenarios that are now used when making LCAs of CLT elements are not representative.

Determination of the impact of CLT products can be difficult if there are multiple sources of roundwood or intermediate products that will result in different impact numbers. The use of these sources can be highly variable as well. Taking into account the origin of all materials can be a complex exercise. It is therefore recommended to obtain insight in the material streams within Europe, especially the wood streams that are labeled as originating from a sustainable source (FSC/PEFC).

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Annex A Results literature study

Roundwood production

Table 8: Quantitative data on processes and resources for roundwood production. Scenario 1 is based on even-aged forest management, scenario 2 is based on small-scale forest management. When no data is available in ecoinvent a '-' sign is given. For Eco-Invent the process: "Sawlog and veneer log, softwood, measured as solid wood under bark {DE}| softwood forestry, spruce, sustainable forest management | Cut-off, U" is used from Eco-Invent version 3.6.

Sawlog and veneer log, softwood, measured as solid wood under bark {SE}| softwood forestry, spruce, sustainable forest management | Cut-off, U. Scenario 1 was based on the forest unit 'shade tolerant conifers/even-aged forest with shelterwood', while scenario 2 was based on 'shade tolerant conifers/Continuous cover forest management'.

Round wood production						
Category	parameter	Literature study		Eco-Invent		Unit
		scenario_ 1	scenario_ 2	Germany	Sweden	
Harvest	average harvest over rotation (overbark)	13-13.3	12.2	11.1	7.7	m^3/ha/yr
	total harvest over rotation (overbark)	1.368	61	1110	616	m^3/ha
	of which sawlogs	725	32	789	307	m^3/ha
	of which wood chips	302	15	30		m^3/ha
	of which firewood	57	2	102	44	m^3/ha
	of which industrial wood	284	12	189	265	m^3/ha
	rotation	105	5	100	80	Yr
	land needed to produce 1 m^3 of sawlogs (overbark)	0.14	0.16	0.13	0.26	a*yr
Forest transport	distance to forest for harvesting equipment	75	75	-	-	Km
	forest road density	47	47	-	-	m/ha
	skidding trail density	58	58	-	-	m/ha
	distance between skidding trails	20	20	-	-	m
Felling + skidding	effort per average m^3 harvested (overbark)	0.2222	0.2700	0.5579		PMH/m^3
	of which power saw	-	-	0.445	0.0118	PMH/m^3
	of which tractor	-	-	0.0741	0.00249	PMH/m^3
	of which harvester	0.1111	0.1350	0.0166	0.0938	PMH/m^3
	of which forwarder	0.1111	0.1350	0.0222	0.0799	PMH/m^3
	energy consumption harvester	436.13		489.2[1]	489.2	MJ/PMH
	energy consumption forwarder	303.84		420.4	420.4	MJ/PMH
	energy consumption power saw	71.36		73.6	73.6	MJ/PMH
	energy consumption forestry tractor + trailer	301.86		496.9	496.9	MJ/PMH
Log transport	freight efficiency	40-50		-	-	ton/rit
	distance from forest road to sawmill	58, 104Fout! Bladwijzer niet gedefinieerd.		75	75	km
	Euroclass lorry			Mainly Euro 3 and 4	Mainly Euro 3 and 4	-
Storage	water consumption sprinkler	7.86		-	-	m^3/m^3
	density (wet)	882		731 (70% MC)	731 (70% MC)	kg/m^3
1. Energy use calculated based on 45,5MJ/kg diesel and 46 MJ/kg 2 stroke blend						

Sawn wood production

Table 9: Quantitative data on processes and resources sawn wood production. When no data is available in Eco-Invent a '-' sign is given. The following EcoInvent processes are used (all in version 3.6):

- Sawn wood, board, softwood, raw, dried (u=20%) {CH}| board, softwood, raw, kiln drying to u=20% | Cut-off, U
- Sawn wood, board, softwood, raw, dried (u=10%) {CH}| board, softwood, raw, kiln drying to u=10% | Cut-off, U
- Sawn wood, softwood, raw {CH}| sawing, softwood | Cut-off, U
- Sawn wood, board, softwood, dried (u=10%), planed {CH}| planing, board, softwood, u=10% | Cut-off, U

Sawn wood production				
Category	parameter	Literature study	EcoInvent	Unit
Debarking and sawing	Sawing efficiency from log (incl. 12% bark) to sawn wood	52.7	59.6[1]	%
	energieverbruik zaagmachine	21.77[4]	17.99[2]	kWh/m3
	Diesel use internal transport	37.4[4]	26.9[2]	MJ/m3
	Share of bark (of overbark volume)	12	12	%
	Share of chips/slabs (of overbark volume)	22	-	%
	Share of sawdust (of overbark volume)	11	-	%
	Share of shavings (of overbark volume)	1	-	%
	shrinkage loss (of overbark volume)	2	-	%
Drying proces	Electricity use	21.64[4]	13.3-20 (MC20-10)	kWh/m3
	Heat use	1302[4,5]	376.9-565.9[3] (MC20-10%)	MJ/m3
	Shrinkage	5%[4]	4-8% (tot MC 20 – MC 10%)	%
	uitvalpercentage	[...]	included in shrinkage	%
Planing and strenght grading	efficiëntie schaven	89[4]	93%	%
	Electricity planing	25.64[4,6]	18.6	kWh/m3
Transport to CLT factory	afstand van zagerij naar CLT fabriek		[300]	km
	emissie transport	[...]	Mix of truck, ship, and train transport	CO_2e/km

1. from log (including 12% bark) to sawn wood, in ecoinvent 3.10 adjusted to 54.4% efficiency; 55% reported by Rüter.
2. in EcoInvent 3.10 adjusted to 19.7 kWh/m^3 and 35 MJ/m^3 energy use for 1 m^3 sawn wood.
3. Assuming 7.5 MJ/kg wet wood chips, drying based on boards of less than 40 mm thick and more than 120 mm wide.
4. Rüter & Diederichs, 2012
5. MJ of the fuel as input, depending on process efficiency of the boiler.
6. calculated based on the total electricity use and the electricity for shaving and drying

CLT production

There is no process for cross laminated timber in ecoinvent 3.6, however in ecoinvent 3.10 there is one: cross-laminated timber production RER - cross-laminated timber. This process is based on the Okibilanz data, which is also used as literature source for this report and in the table below.

Table 10: Quantitative data on processes and resources for CLT production.

Category	parameter	Literature study	Unit
	type glue (PUR, MUF, EPI)	All	-

Fingerjointing, glueing, laying up and pressing	Amount PUR	3.382	kg
	Amount MUF	3.983	kg
	Amount EPI	0.189	kg
	Efficiency[1]	89[1]	%
	Diesel use	7.88	MJ
	Heat use	846	MJ
	Electricity use	11.1 (46.86)[2]	kWh/m^3

[1] Efficiency starting from sawn and planed wood.

[2] Electricity use calculated, starting from planed wood. Between brackets starting from sawn wood (so including planing and finger jointing).

Annex B Detailed results field research

In this annex, more detailed results of the site visits and questionnaires are presented.

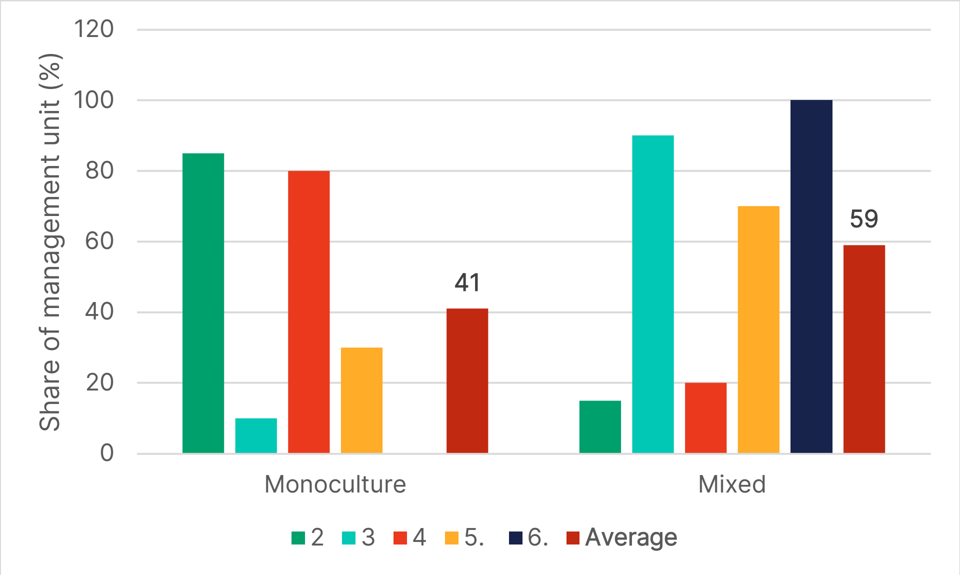

Figure B1. Reported divisions in stand types among the forest managers (n=5).

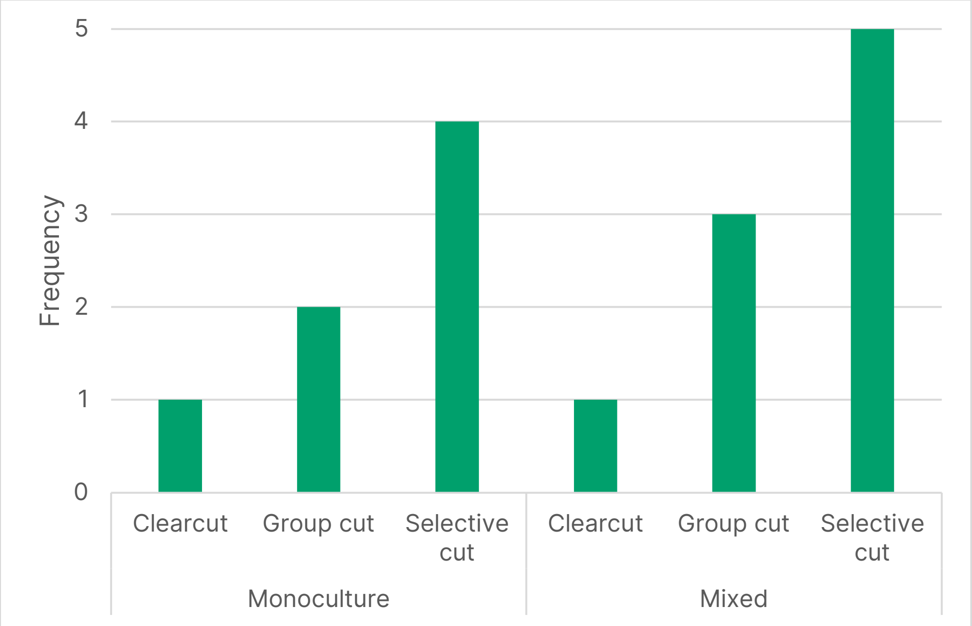

Figure B2. Frequency of management systems per stand type reported by the forest managers (n=6). Note: two management systems may occur twice per stand type, due to a combination of these.

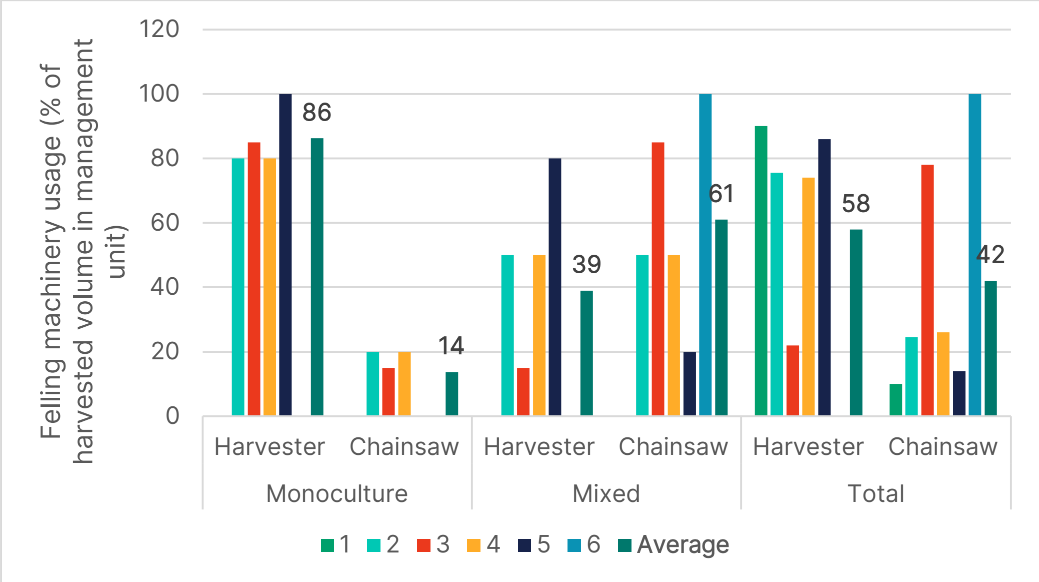

Figure B3. Division of felling machine usage (% of harvested volume) among stand types, reported by the different forest managers (n=6).

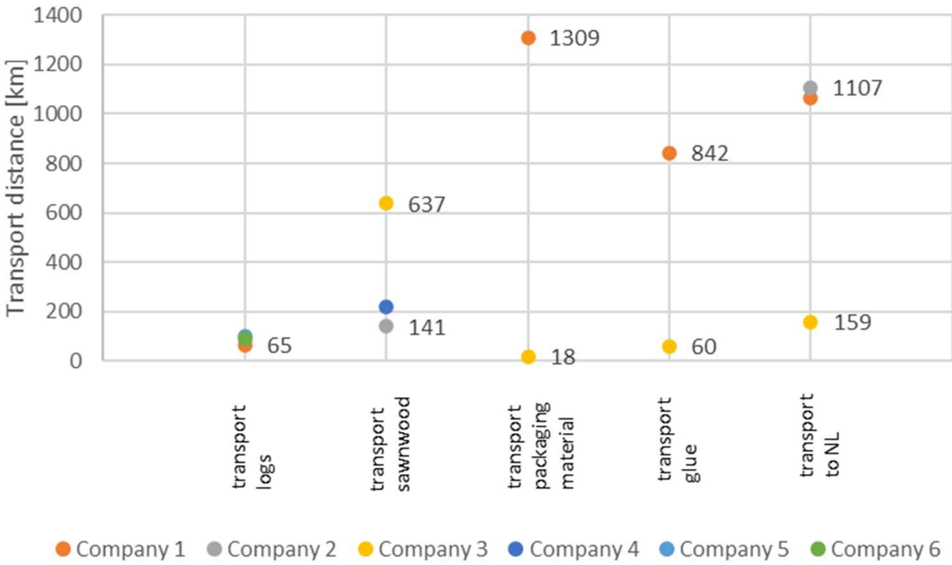

Figure B4 Transport distances as reported by 6 companies.

Annex C Population density analysis

In the table below the population density around the sawmills in Germany is calculated, with the used method indicated. The sawmills highlighted in orange are located in an area with a population density above 400 persons per km^2.

Sawmill	production in 1000m^3 felled timber	Population density (persons/km^2)	Used method
Ziegler Holzindustrie	2100	42	3
Ilim Nordic Timber	1800	1020	3
Mercer Timber Products, Saalburg-Ebersdorf	1450	46 (275)	3 (2, worst case)
ante-holz, Somplar	1350	54 (159)	3 (2, worst case)
ante-holz, Rottleberode	1250	227	1
Binderholz, Baruth	1200	18 (352)	3 (2, worst case)
HS Timber	1200	56 (199)	3 (2, worst case)
Schwaiger Holzindustrie	1140	171 (654)	3 (2, worst case)
Holzwerke Ladenburger, Kerkingen	1000	130	2
Pfeifer Holz, Lauterbach	950	189	2
Ilim timber Bavaria	950	543	2
Mercer torgau	950	229	2
Egger Sägewerk Brilon	907	271	2
Rettenmeier wilburgstetten	900	158	2
Binderholz Kösching	900	246	2
Binderholz Oberrot	900	288	2
Pfeifer holz unterbernbach	855	122	2
Holzwerke weinzierl	650	171	2
Rettenmeier Holzindustrie Ramstein	600	267	2
Pfeifer holz Uelzen	500	239	2
Holzwerke van Roje	310	376	2
I.B.H. sagewerk	300	241	2
Robeta holz	250	119	2
Gebrüder Eigelshoven	226	3017	2
Holz Ruser	210	693	2
Bentheimer-holz	160	420	2
Heinrich Holtmeyer & Sohn	140	182	2

Literature sources

The following sources have been used for statistics of determining the population density.

Germany biggest sawmill, Source: https://www.timber-online.net/blog/germany-s-biggest-sawmills.html#:~:text=Binderholz%20is%20the%20biggest%20sawmill,volume%20of%203.44%20million%20m%C2%B3.

Statistisches Amt M-V – Bevölkerungsstand der Kreise, Ämter und Gemeinden 2020 (XLS-bestand)

Thüringer Landesamt für Statistik (thueringen.de)

Hessisches Statistisches Landesamt: Bevölkerung in Hessen am 31.12.2020 nach Gemeinden (Landkreise en kreisfreie Städte evenals gemeenten, inwonertallen op basis van de census 2011)

Statistisches Landesamt Sachsen-Anhalt, Bevölkerung der Gemeinden – Stand: 31. Dezember 2020

Bevölkerung im Land Brandenburg nach amtsfreien Gemeinden, Ämtern und Gemeinden 31. Dezember 2020

Bevölkerung des Freistaates Sachsen nach Gemeinden am 31. Dezember 2020
Genesis Online-Datenbank des Bayerischen Landesamtes für Statistik Tabelle 12411-001

Fortschreibung des Bevölkerungsstandes: Gemeinden, Stichtage (letzten 6)
https://www.citypopulation.de/en/germany/settlements/badenwurttemberg/ostalbkreis/08136010x0A9M__kerkingen

https://www.schleiden.de/pool/dokumente-rathaus/rathaus/verschiedenes/bevoelkerungsstatistik.pdf?cid=19n4

https://de.wikipedia.org/wiki/Narthauen

Annex D LCA workshop participants

In May 2024, a workshop was organized to present first results of this work, and collect feedback of LCA experts to improve the results presented in this report. We would like to thank the participants for their useful input and discussion.

Participants of the workshop:
Stichting Agrodome
SGS Research
Stichting NMD
Carbon Leadership Forum
Staatsbosbeheer
Built by Nature
Stichting Probos
SHR
Stichting W/E adviseurs