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Background Data in the Context of *Pinus sylvestris*, L. Glued Laminated Timber Manufacturing in Spain

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Abstract: The construction sector is achieving its goal of decarbonization. Bioproducts are known to reduce the environmental footprint of the building process, but it is necessary that we determine their exact environmental value. However, assessing the environmental impact relating to buildings is challenging due to a lack of data. The objective of this study was to generate background datasets contextualized to *Pinus sylvestrys*, L. glulam manufacturing in Spain and apply those datasets to a cradle-to-gate life cycle assessment (LCA) to evaluate both embodied energy (EE) and carbon (EC), as well as biogenic carbon and emissions to air. The corresponding raw materials and energy flows required to apply the LCA methodology were gathered and processed from information from the Spanish forest and wood industry. The resulting background datasets include 27 vehicles and machines, which allowed the quantification of four impact category indicators: renewable primary energy (resources), non-renewable primary energy (resources), use of renewable secondary fuels and global warming potential. Biogenic carbon was also calculated. Based on those five values, the embodied energy and carbon of *Pinus sylvestris*, L. glulam were quantified: EE = 1401 MJ/UD and EC = −724 $kg_{CO2\text{-}eq}$/UD. The generation of background datasets and environmental information is innovative and of great interest, and it is a powerful tool for prescribers and technicians.

Keywords: life cycle analysis; glulam; inventory database; embedded energy; embedded carbon; biogenic carbon; global warming potential; greenhouse gasses

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1. Introduction

According to [1], the construction sector generates 10% of the EU's total added value and 25 million jobs. But it requires vast amounts of energy and resources, accounting for 40% of the EU's total energy consumption, 30% of its annual waste generation and 9.4% of the total domestic carbon footprint. Consequently, this is a key sector if the EU is to achieve its goal of higher levels of sustainability.

Thus, interest is growing in the environmental impact assessment (EIA) of buildings [2]. Improving the efficiency of the systems responsible for the operational energy consumption of a building has shifted the potential for reducing greenhouse gas (GHG) emissions throughout the different stages of its life cycle. Thus, the focus has been shifted from the use stage to those stages related to the energy embedded in the materials and products that make up the building, such as the stages of raw material extraction, manufacturing, transport, site installation, demolition and end of life. Decisions on the design and selection of building materials taken during the design stage have a strong influence on the GHG emissions that will be generated during the life cycle of the building. Life cycle assessment (LCA), at the level of both the design and building, at an early project stage greatly benefits environmental, social and economic sustainability [3]. To assist technicians and prescribers in their task of selecting products at this early stage, it is necessary to provide them with environmental information that complements existing performance information.

One of the challenges that the construction industry faces is obtaining reliable and transparent information about the carbon footprint of building materials, as well as an environmental product declaration (EPD) and other environmental labels included in the standard ISO 14025. Achieving these will enable users and consumers to compare the environmental performance levels of different building products [4].

The complex interaction between ecosystems and human well-being is an added difficulty in the definition, quantification and evaluation of the different ecosystem services provided by forests, as well as the conceptual and technical limitations of its evaluation and its integration into LCA [5]. Nowadays, according to current standards, when calculating the global warming potential balance, only carbon storage (or biogenic carbon) is accounted for among all the ecosystem services supplied by forests; this could mean that bioproducts have a comparative advantage compared to other products of non-biological origin.

The quantification of environmental value was conducted using the LCA method, an environmental assessment method for products and services that support decision-making in order to reduce the environmental impact of construction processes. It is important to highlight the need to apply the LCA method in the construction sector and its importance as a tool in decision-making [6].

To this end, the LCA methodology is presented as a tool that classifies products by mean of verifiable, precise and unequivocal environmental information obtained on a scientific and standardized basis. This process is based on impact category indicators defined by the standard UNE-EN 15804:2012+A2:2020 "Sustainability in construction. Environmental product declarations. Basic product category rules for construction products" [7] and adapted to the particularities of each construction product family through its corresponding product category rules. Timber construction products must comply with the standard UNE-EN 16485 "Sawn timber and roundwood. Environmental product declarations. Category rules for wood and wood-based products for use in construction" [8].

The different impact categories included in [7] are quantified through a series of intermediate or midpoint impact indicators that are related to the environmental effects of emissions and which require a certain amount of knowledge in the field for their correct interpretation. This means that they are not always well received by the industrial or construction sector, so it is interesting to translate them, at least partially, into other widely recognized and accepted indicators, such as embedded energy, carbon and biogenic carbon. These can be very useful in the early stages of the construction project for the comparison and selection of products used.

There are different interpretations of the concepts of embedded energy (the quantity of energy required to process and supply the material under consideration to the construction site [9]) and operational energy, as well as the corresponding embedded and operational carbon. Operational carbon is defined in [10] as the set of carbon emissions associated with operational energy consumption during the use stage of the building, including regulated load (air conditioning, ventilation, lighting) and unregulated/plug load (ICT equipment, appliances, electronic accessories). Embedded carbon corresponds to carbon atmosphere emissions associated with embedded energy and chemical processes during the extraction, manufacturing, transport, assembly, replacement and demolition of building products.

The sum of embedded and operational carbon, together with emissions occurring at the demolition stage, give the whole life cycle carbon emissions of the product in terms of GHGs released to the atmosphere. However, in the case of bioproducts, biogenic carbon is another factor that contributes to their final carbon cycle balance. Biogenic carbon is the carbon contained in biomass [8] as a result of the gas exchange that occurs during photosynthesis and which fixes atmospheric carbon in the new tissues created during tree growth.

One of the biggest problems the construction industry faces when conducting the EIA of buildings is a lack of data. The environmental values of natural products have a great importance to the construction sector as they are known to reduce the environmental footprint of the construction process through the incorporation of wood or other natural and recycled products, which fix carbon during their formation or reduce the amount of raw materials required in the production process. The LCA of timber products has demonstrated that they usually require less energy to manufacture than alternative construction products, resulting in a lower environmental impact when the complete life cycle is considered [11]. In this context, the use of wood products should be enhanced due to their environmental value [12]. Therefore, it is necessary to ascertain the environmental value associated with these materials and products and to incorporate them into a high-visibility, open and free-to-use database.

As already mentioned, the LCA has emerged as a useful methodology for the objective, methodical, systematic and scientific analysis of the potential environmental impacts associated with each stage of the complete life cycle of a product, from cradle to grave [13]. These impacts are calculated after compiling the inputs of materials and energy at each stage of the life cycle, as well as the corresponding outputs of emissions, waste, discharges, co-products and others. This methodology involves the enumeration of a large number of flows and their associated effects.

An LCA can involve different databases, depending on the specific information and analysis needs: life cycle inventory (LCI) databases, environmental analysis databases and governmental and statistical databases. LCI databases are called inventory databases (or background databases) and contain information on these input and output flows at a disaggregated level. They are specific to certain industrial sectors (agriculture, construction, electronics, etc.) and can be free of charge or commercial. These inventory databases generally belong to commercial LCA software that incorporate them within the tool itself. Some of the well-known examples are Agribalyse, ELCD, Ecoinvent and GaBi. However, there are no specific LCI databases for the forestry sector or its industry, so the application of LCA, whether with free or commercial databases, always suffers from deficient geographical, temporal and/or technological contextualization.

Environmental analysis databases provide information about the environmental impacts of certain processes, products or materials. The information they store is obtained in accordance with the EPD, a document that provides information on their environmental performance in a transparent and verified manner based on LCA, following the UNE-EN ISO 14025:2010; Environmental Labels and Declarations—Type III Environmental Declarations—Principles and Procedures standard [14]. Examples of these environmental databases are ÖKOBAUDAT, INIES, IBU and OpenDAP.

Finally, governmental and statistical databases provide relevant data on resource consumption, emissions and other environmental indicators from governmental organizations and agencies. They provide data of a more consensual and generic nature, representing a specific geographical and technological context. Examples include data from the US Department of Energy, Boverkets Climate DB in Sweden [15] and ThinkStep in Germany.

Environmental concerns have led to developments in legislation around the world aimed at addressing environmental challenges, promoting sustainability and protecting natural resources. Environmental assessment using the LCA methodology examines a multitude of parameters and consequently generates many uncertainty factors [16]. These should be acknowledged when conducting an LCA, and limitations and assumptions should be transparently communicated in the reporting of results so that decision makers can properly interpret the findings and take these uncertainties into account in their decisions. In addition, sensitivity and scenario analyses can be performed to assess how results vary with different assumptions and inputs [17].

There is a strong preference for one type of database over another depending on the regulatory framework in each country. For example, in Germany, France or Sweden, information from EPDs is preferred as the first choice for input data. Priority is given to product- or process-specific EPDs, and to collective EPDs as a second option, whether from associations or other groupings. The last option is data from inventory databases. Studies such as the one carried out by Loli et al. [18] show differences of more than 15% in the impact results for the use of generic products from LCI databases versus EPD databases, and increases of more than 56% in CO_2 emissions according to the resulting global warming potential (GWP) indicator in a cross-laminated timber floor if the data are obtained from Ecoinvent or from a particular EPD.

Information that is not related to a specific product but to a generic type of product is clearly useful for the early design and project stages. These early stages, where the products to be used in the building have not been defined in detail, are key to minimizing the impacts in a simple and effective way. At these stages, the LCA requires methodological simplifications in order to be applicable in the initial design [2].

In the final LCA of a building, the data must be as reliable as possible, however. The input data are a highly sensitive factor and must, therefore, be extremely transparent and simple so as not to interfere with the results [19]. Geographical and technological contextualization encourage the development of national databases for early design stages or when higher-quality data are not available. The random use of different databases alters the results and prevents homogeneous comparisons of buildings [20].

One of the goals of the project, "The Recycled and Natural Materials and Products to develop nearly zero energy buildings with low carbon footprint—ReNaturalNZEB" (LIFE17-ENV/ES/000329), was to obtain environmental values for construction products (embedded energy and carbon) to be incorporated in the Extremadura Regional Government's NZEB construction price base (pdf, xls and BC3 formats) so prescribers could integrate those data with the rest of the criteria used to select products in the early stages of building projects. Those values can be accessed freely and openly at the website of the ReNaturalNZEB project (https://www.liferenatural.com/en/nzeb-construction-price-base, accessed on 13 November 2023). The background datasets are available on request and will soon be accessible at www.maderia.es (accessed on 13 November 2023).

The objective of this study was to generate an LCI database (background database) related to the manufacturing process of *Pinus sylvestris*, L. glulam in Spain and, subsequently, carry out a case study of its cradle-to-gate LCA, to obtain its values for embedded energy, carbon and biogenic carbon.

2. Materials and Methods

2.1. Selected Tree Species and Wood Product Peculiarities of the Study Area

Glued laminated timber is the resistant wood product that is most widely used in the European construction sector, as it is efficient to use and presents good mechanical performance.

Although glued laminated timber is mainly used in construction, it can also be used for other applications such as rural infrastructures (fences, poles, benches). Furthermore, datasets obtained in this research for glued laminated timber can be used for the LCA of other laminated timber products that at least partly share the industrial process, such as laminated panels and boards. Thus, the furniture sector could use some of the datasets with proper contextualization.

Scots pine (*Pinus sylvestris*, L.) is the most abundant pine in Spain as well as the most widely used for wooden construction products. It is also remarkably important at a European scale as it is—together with *Picea abies*, (L.) H. Karst—the most commonly used species for construction products. This research is limited to the geographical scope of the distribution area of Scots pine in Spain.

Scots pine has the widest distribution area of all the pine species in the world, covering most of northern and central Eurasia and reaching its southwestern limit in the Iberian Peninsula. Thus, this pine grows in temperate and Mediterranean forest biomes under significantly different growing conditions. The specific growing conditions in Spanish stands (Mediterranean biome) demark this pine typically as a mountain species, with mountainous conditions suitable for it to avoid the summer drought.

These differential characteristics of the geographical area of study, and consequently of the growth conditions of this species, constitute a key aspect in the contextualization of the use of the data generated in this study.

2.2. Methods

The values of the inventory data (background data) were obtained on the basis of [7,8,14]. The aim of these standards is to obtain EPD according to the LCA methodology by quantifying a series of indicators of the different impact categories included in [7]. Although the objective of this study was not to obtain an EPD, it is true that some of these impact category indicators allowed us to obtain the embedded energy and carbon. Likewise, the biogenic carbon content was calculated based on [8] for the definition of the system boundaries between nature and the product system, [7] for the definition of the biogenic carbon calculation components (as well as their relationship with the GWP indicator and UNE-EN 16449:2014; "Wood and Wood-Based Products—Calculation of the Biogenic Carbon Content of Wood and Conversion to Carbon Dioxide") and [21] for the definition of the mathematical model to calculate its value.

Firstly, the system boundaries and the declared unit were defined. This declared unit was the reference unit for the normalization of matter and energy flows, as well as for the results of the impact category indicators. To model these matter and energy flows, it was necessary to define a standard product and the scenarios for each module. These scenarios were defined by the unit processes involved and the operations that these include, so that all the machines and vehicles involved could be identified, as well as the flows of raw materials and energy necessary for the manufacture of the declared unit of product. In the definition of these scenarios, the greatest possible representativeness of the structural sawn timber sector of *Pinus sylvestris*, L. in Spain was sought. In addition, cut-off and exclusion criteria were defined according to [7], not considering, for a given unitary process, flows for which data were unknown as long as they did not exceed 1% of the renewable and non-renewable primary energy and 1% of the total incoming mass of raw material. For each module, the set of flows not considered could not exceed 5% of the energy use and mass. Flows related to final product packaging, machinery and vehicle maintenance or replacement of worn parts were not considered in this study.

Appendix A summarizes the scenario definition constraints for each module and Figure 1 shows the product system framework.

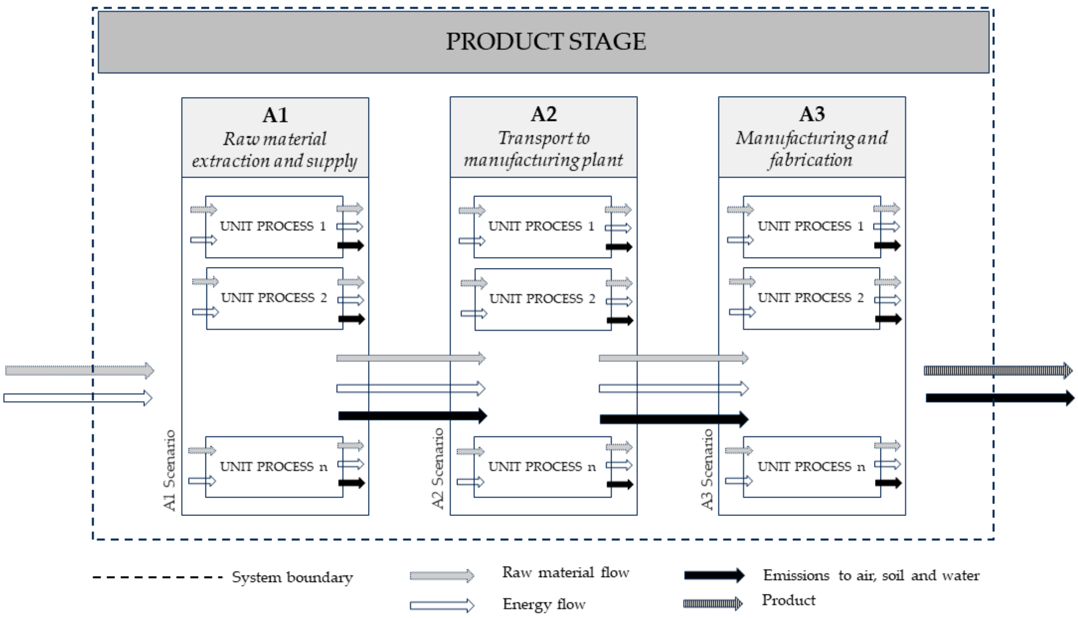

Figure 1. Product system framework.

On the basis of manufacturers' data sheets, the specialized literature, case studies with real data and machinery catalogs, material and energy consumption values were obtained for all these unitary processes that make up the product system. As a result, energy consumption values were obtained from fossil fuels, electricity and lubricants. The energy consumed by the machinery of module A3 was obtained from data on power demand, performance and hourly consumption from practical experience, with real data, data from manufacturers of the product types and the specialized bibliography. The data on additives were taken from the technical data sheets of commercial brands commonly used in the sector, as well as from data provided by national manufacturers of the standard products. Likewise, the energy consumption data for the raw material extraction and transport phases were estimated on the basis of real machinery data obtained from catalogs and the specialized bibliography, which includes practical cases where the yield of forestry machinery was estimated according to specific characteristics of related works derived from tree species, stand density or terrain slope. In any case, the selection of data and consumption estimates was carried out seeking the greatest representativeness of the reality of the forestry sector and of the *Pinus sylvestris*, L. structural sawn timber industry in Spain.

In general, the data on consumption flows were obtained from companies with a high technological level, and in order to be conservative in the results, a penalty of 30% was applied. Thus, these results can certainly be considered an upper limit for the values of the impact category indicators obtained.

The consumption data obtained were subjected to quality assessment in accordance with Annex E of [7], based on their geographical, technical and temporal representativeness.

Once these consumption flows were defined, the indicators of the impact categories related to energy and embedded carbon were calculated using the calculation methodology set out in Annex E of [7]. To this end, a self-developed spreadsheet was used, multiplying the consumption flow data by the conversion factors listed in Appendix B. Embedded energy was derived from the impact category indicators "renewable primary energy used as feedstock", "non-renewable primary energy used as feedstock" and the "use of renewable secondary fuels", while embedded carbon corresponded to the value of the "global warming potential" indicator minus biogenic carbon. Table 1 defines these indicators.

Table 1. Description of the impact indicators considered for the quantification of embedded energy and carbon, and emissions to air.

Indicator	Unit	Description
Primary renewable energy (materials)	MJ	Use of renewable primary energy resources as raw materials
Primary non-renewable energy (materials)	MJ	Use of non-renewable primary energy resources as raw materials
Use of renewable secondary fuels	MJ	Renewable fuel recovered from previous use or from waste which substitutes primary fuels
Global warming potential	kg $CO_{2\text{-eq}}$	Indicator of potential global warming due to emissions of greenhouse gases to the air

In this study, embedded carbon was considered as the difference between carbon emissions to the atmosphere from embedded energy and biogenic carbon. To ensure the transparency of the environmental reporting of bio-based products, the values of carbon emissions to the air due to embedded energy and of the biogenic carbon of the bio-based product are provided separately. Furthermore, it must be taken into account that no net emissions are generated by the heat energy produced from biomass in the dryer due to its carbon-neutral cycle, in accordance with [21].

The emissions to the atmosphere due to embedded energy correspond to the GWP value as defined in [7]. For the calculation of this indicator, all energy consumptions throughout the product stage of the LCA (modules A1-A2-A3) were considered and the conversion factors listed in Appendix B applied.

For the calculation of the biogenic carbon content, the expression contained in [21] was used, based on the volume of the product at the moisture content at delivery and considering a carbon content of the anhydrous mass of 0.5, according to Equation (1):

$$PCO2 - eq = \frac{44}{12} \times fc \times \frac{dw \times Vw}{1 + \frac{w}{100}} \quad (1)$$

where:

fc is the fraction of carbon in biomass (0.5);

dw is the density of wood at moisture w (kg/m^3);

Vw is the volume of wood at moisture w (m^3);

w is the moisture content of the wood (%).

Finally, the results were obtained from the expressions shown in Table 2.

Table 2. Definition of impact category indicators for the quantification of embedded energy and carbon, biogenic carbon and emissions to air.

Indicator	Unit	Description
Embedded energy	MJ	Renewable and non-renewable primary energy of materials and use of renewable secondary fuels
Emissions to air	kg $CO_{2\text{-eq}}$	Global warming potential
Biogenic carbon	kg $CO_{2\text{-eq}}$	Amount of atmospheric carbon dioxide fixed in the wood and bark of trees during their growth
Embedded carbon	kg $CO_{2\text{-eq}}$	Net atmospheric emissions incorporating biogenic carbon [1] in the balance sheet

[1] The calorific energy of the dryer is excluded as it meets the requirements of [21] to consider the carbon-neutral cycle of biomass and, therefore, does not produce net emissions to the atmosphere during the drying of wood.

3. Results

3.1. System Boundaries

The product system considered includes the product stage of the LCA, covering modules A1 Raw Material Extraction and Supply, A2 Transport and A3 Manufacturing, as shown in Figure 1 of the methodology section. These are, by definition, the LCA modules involved in quantifying the embodied energy and carbon, as well as the biogenic carbon of the products incorporated in a building.

3.2. Declared Unit and Product Type

The declared unit (DU) was defined as 1 m^3 of lasur-treated glued laminated timber of *Pinus sylvestris*, L. for structural use with a 12% moisture content at the time of delivery.

The product type was defined as an element with the characteristics of the declared unit and dimensions of 13,500 × 140 × 180 mm.

3.3. Definition of Scenarios

The manufacturing process of the DU was defined for this study as shown in Figure 2.

The scenarios corresponding to each module were defined as follows (Appendix A details the exclusion and cutting criteria, as well as the particular characteristics with which each scenario was defined):

- A1 Extraction and supply of raw material: This module covers the operations for the extraction of roundwood in the forest and the manufacture of the board in the sawmill.
- A2 Transport: This module includes the gathering in the forest, the transport of roundwood from the forest to the sawmill yard and the transport of chemicals (lasur) to the sawmill.
- A3 Manufacturing: This module comprises the manufacturing operations in the second processing industry.

Table 3 shows the input and output flows of materials and energy identified in each module of the product system based on the scheme depicted in Figure 2. The consumption flows shown in Table 4 were calculated based on this figure and table.

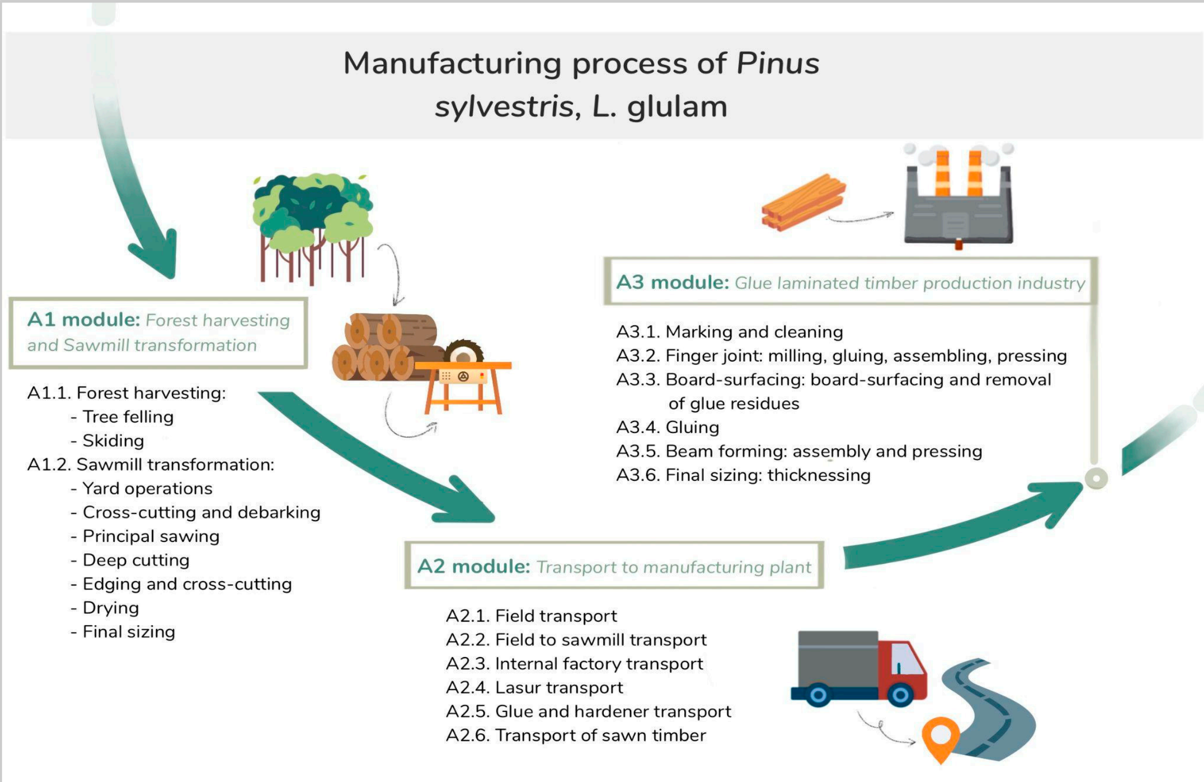

Figure 2. Manufacturing process of 1 m^3 of lasur-treated glued laminated timber of *Pinus sylvestris*, L. for structural use with a 12% moisture content at the time of delivery.

Table 3. List of material and energy input and output flows to each module of the product system.

Module	Matter Flows		Energy Flows	
	Inputs	Outputs	Inputs	Outputs
A1	- Round wood - Lasur - Lubricants	- Sawn wood (4000 × 200 × 150 mm)	- Diesel - Gasoline - Electricity	- Emissions
A2	- Round wood in forest - Sawn wood - Lubricants	- Round wood in sawmill yard - Round wood in second processing manufacturing plant	- Diesel	- Emissions
A3	- Sawn wood (4000 × 200 × 150 mm) - Glue - Glue hardener	- Glued laminated timber (13,500 × 180 × 140 mm)	- Gasoline - Electricity	- Emissions

Table 4. Inventory datasets for the product system under consideration.

Machinery	Operation	Module	Input Flow	Specific Consumption	Unit	Source
Chainsaw	Tree felling	A1	Fuel	0.1558	L/DU	1
			Lubricant	0.0078	L/DU	2
Skidder	Skidding	A1	Fuel	4.7200	L/DU	1
			Lubricant	0.2360	L/DU	2

Table 4. *Cont.*

Machinery	Operation	Module	Input Flow	Specific Consumption	Unit	Source
Cutting-off machine	Cross-cutting	A1	Electricity Lubricant	0.7000 0.0140	kWh/DU L/DU	2 2
Ring debarker	Debarking	A1	Electricity Lubricant	0.6600 0.0132	kWh/DU L/DU	2 2
Two-cutting band saw with carriage	Sawing	A1	Electricity Lubricant	1.6600 0.0332	kWh/DU L/DU	2 2
Circular resaw	Deep cutting	A1	Electricity Lubricant	1.8500 0.0370	kWh/DU L/DU	2 2
Cross-cutter	Cross-cutting	A1	Electricity Lubricant	0.4600 0.0092	kWh/DU L/DU	2 2
Dryer	Drying	A1	Electricity Lubricant	222.74 0.2408	kWh/DU L/DU	2 2
Edger	Edging	A1	Electricity Lubricant	1.1500 0.0230	kWh/DU L/DU	2 2
Matcher	Sizing	A1	Electricity Lubricant	2.0281 0.0406	kWh/DU L/DU	2 2
Aspiration system	Aspiration	A1	Electricity Lubricant	1.3528 0.0271	kWh/DU L/DU	2 2
Compressed air system	Miscellaneous compressors	A1	Electricity Lubricant	1.6846 0.0337	kWh/DU L/DU	2 2
Conveyor belts, rollers	Power supply and machine output	A1	Electricity Lubricant	0.9019 0.0180	kWh/DU L/DU	2 2
Auxiliary elements	Interior lighting and other auxiliary systems	A1	Electricity	0.6466	kWh/DU	2
Forwarder	Field transport	A2	Fuel Lubricant	2.0453 0.1023	L/DU L/DU	1 2
Truck crane 22 Tm	Field to sawmill transport	A2	Fuel Lubricant	2.4887 0.1244	L/DU L/DU	1 2
Forklifts, self-loaders, etc.	Internal factory transport	A2	Fuel Lubricant	0.1173 0.0059	L/DU L/DU	3 2
Citroën Jumpy 180 CV	Glue transport	A2	Fuel Lubricant	0.0924 0.0046	L/DU L/DU	1 2
Citroën Jumpy 180 CV	Hardener transport	A2	Fuel Lubricant	0.0049 0.0002	L/DU L/DU	1 2
Citroën Jumpy 180 CV	Transport of lasur	A2	Fuel Lubricant	0.0064 0.0003	L/DU L/DU	1 2
Volvo FE 350 CV	Transport of sawn timber to 2nd transformation industry	A2	Fuel Lubricant	0.0064 0.0003	L/DU L/DU	1 2
Optimizer	Marking and cleaning	A3	Electricity Lubricant	1.9560 0.0391	kWh/DU L/DU	2 2
Finger joint	Finger jointing	A3	Electricity Lubricant	8.9060 0.1781	kWh/DU L/DU	2 2
Double-sided planer	Board surfacing	A3	Electricity Lubricant	9.8869 0.1977	kWh/DU L/DU	2 2
Gluing machine	Gluing of faces	A3	Electricity Lubricant	2.0200 0.0404	kWh/DU L/DU	2 2
Press	Assembly and pressing	A3	Electricity Lubricant	21.1100 0.4222	kWh/DU L/DU	2 2
Thicknessing planer	Thicknessing	A3	Electricity Lubricant	4.9435 0.0989	kWh/DU L/DU	2 2

1 = Commercial catalogs; 2 = information from manufacturers and industries, 3 = technical reports from industries.

The quality of the calculated consumption flows was analyzed on the basis of Annex E of [7], obtaining the results shown in Table 5.

Table 5. Results of the analysis of the consumption flows obtained.

		Data Quality		
Module	**Type of Data**	**Temporal Coverage**	**Geographical Coverage**	**Technological Coverage**
A1	Means or manufacturer-specific	Very good	Very good	Very good
A2	Means or manufacturer-specific	Very good	Very good	Very good
A3	Means or manufacturer-specific	Very good	Very good	Very good

After obtaining the inventory data (background data) for the LCA of glued laminated timber of *Pinus sylvestris*, L. in Spain, the indicators of the impact categories related to its embedded energy and carbon, and emissions to the atmosphere were calculated. The biogenic carbon content and the heat energy of the dryer were also quantified. Table 6 shows these values.

Table 6. Indicator values of impact categories, biogenic carbon and heat energy for DU.

Indicator	Unit	Value
Primary energy—renewable energy (resources)	MJ/DU	739.00
Primary energy—non-renewable energy (resources)	MJ/DU	594.00
Use of renewable secondary fuels	MJ/DU	68.30
Global warming potential [1]	$kgCO_{2\text{-eq}}/DU$	127.00
Biogenic carbon	$kgCO_{2\text{-eq}}/DU$	−851.19
Heat energy	MJ/DU	210.70

[1] Excluding heat energy.

Finally, embedded energy and carbon values were obtained, as shown in Table 7.

Table 7. Embedded energy and carbon for DU.

Indicator	Unit	Value
Embedded energy	MJ/DU	1401.30
Embedded carbon	kg $CO_{2\text{-eq}}/DU$	−724.19

4. Discussion

Traditionally, the embedded carbon of bioproducts has not considered the value of biogenic carbon under the assumption that its character as a renewable resource does not imply its sustainability [6]. However, standard [8] establishes that we can consider there is no degradation of forest carbon stocks in countries that have signed article 3.4 of the Kyoto Protocol (including all EU countries) or for wood produced under sustainable forest certification schemes. Embedded carbon including biogenic carbon seems to be a more useful value for prescribers to use when selecting from different construction products.

The question could be asked of whether biogenic carbon should not be incorporated in the embedded carbon calculation. If this were the case, it would be a mistake to compare the embedded carbon of a bio-based product with that of a product of non-biological origin without taking into account the additional embedded carbon value of the first. This would lead to decisions based on the misinterpretation of existing environmental information. To ensure transparency in the environmental reporting of bio-based products, in addition to the embedded carbon value calculated under the above assumptions, it might be considered appropriate to provide the value of carbon emissions to the atmosphere due to embedded energy and the biogenic carbon value of the bio-based product. In this way, a comprehensive sustainability analysis can be conducted that does not only include the embedded energy and carbon values, which may lead to the massive use of wood in construction to reduce the carbon footprint of a building without taking into account resource efficiency.

As mentioned above, one of the biggest problems the construction industry faces when conducting an EIA of buildings is a lack of background data associated with bio-based materials and products. Thus, non-contextualized background data are incorporated into LCA more frequently than desired. It is important to highlight that the use of the background datasets obtained in this research is limited to their geographical, technological and temporal context, as well as to the specific considerations and assumptions established during the definition of the different scenarios (see Appendix A) that make up the different modules included in its system limits. When obtaining quality inventory data, the correct contextualization at a technological, geographical and temporal levels is required. In Spain, there are no LCA inventory databases for the forestry sector and its related industry contextualized to the reality of Spanish forests, so the generation of these inventory data is an innovation of great interest. In addition, it is necessary to highlight the importance of public and disaggregated data, which add transparency, ensuring that they are used appropriately. However, the use of commercial databases in LCA is characterized by the inclusion of a wide set of input and output streams, which enriches the detail of the calculations. Nevertheless, it is important to note that in many cases, the consultant's knowledge of these flows may be limited, which may result in a less accurate representation of reality. Calculation automation is common when using databases due to the complexity and opacity of the data, which often leads to the indiscriminate selection of data due to a lack of detailed knowledge [19].

The development of national environmental databases is a growing concept because of they can provide interest insights and are increasingly a necessity. These databases are designed to be used at the national level and are based on technology developed in that country. Using the NativeLCA method, Portugal has developed a method to calculate the so-called Reference Value (REVA), or stable environmental values for the Portuguese environment [22]. Sweden has developed a national environmental database (Climate database from Boverket) [15] that tries to provide stable values for Sweden that can be used for calculating the climate impact of construction while the market evolves and product-specific declarations are generated. Another free environmental database is the ICE Database developed in 2008 by the University of Bath. This is an environmental database that collects embedded energy and carbon data for more than 200 materials from secondary data sources such as journal articles, technical reports and monographs according to criteria related to the use of LCA, the system boundaries used and the geographical and temporal contexts, although it only includes representative standard products. In the case of wood products, the values do not distinguish between sawn timber, plywood and chipboard [9]. This reduces the usefulness of the database to a comparison of product families, and it does not allow prescribers to take into account the specific performance of each product when selecting the most suitable ones during the design phase of their projects. Another example is ÖKOBAUDAT, a standardized database for ecological evaluations of buildings by the German Federal Ministry for Housing, Urban Development and Building. The platform includes an online database with life cycle assessment datasets on building materials, construction, transport, energy and disposal processes, so the entire life cycle of a building can be reconstructed with the help of LCA tools [23]. Although it is a useful tool at the building scale, ÖKOBAUDAT does not provide a background database for performing LCA of building products and is contextualized to the German geographical area. There is also a recent study from the University of Tampere (Finland) that examines different wood fiber insulation alternatives for external enclosures using LCA. However, this work does not develop its own LCA but makes a comparison based on data from EPDs. To find the most suitable EPD, the study uses the baseline data provided by the Finnish Environment Institute as a selection criterion (Rakentamisen päästötietokanta 2022). The Finnish Environment Institute database provides average values of multiple EPDs with publicly available background reports for 200 typical construction materials [24]. This shows that even in countries with a highly developed forestry sector, there is a strong lack of LCA inventory data. The data obtained in this work are related to specific bioproducts, which are defined by their declared unit and product type. This ensures the complementarity of the environmental information generated and the technical performance information of the product.

The Agrybalyse® inventory database, which contains more than 200 life cycle inventories of agricultural products in France, stands out as a reference in this regard. It relies on Ecoinvent data for non-farming processes, such as electricity and transportation, and for imported products (pineapple, Moroccan tomatoes, etc.) [25]. Although there are data on machinery and tools that may be similar to those of the forestry sector (e.g., a tractor), the geographical context and working conditions are very different between the two production sectors and countries (e.g., the slopes of the terrain or the difficulty of access to the work site).

In Spain, it is worth highlighting the OpenDAP initiative being developed by the IETcc CSIC (Eduardo Torroja Institute for Construction Sciences, belonging to the Spanish National Research Council), which is part of the international inData working group. This is a database of environmental information on construction products, currently based on information collected from the EPD. It is open, public and freely accessible. It is aligned with the rules established within the working groups at the European level, intended to generate a working network that harmonizes the exchange, format and quality of environmental data [13].

For all these reasons, the generation of free background data for forest bioproducts in the geographical area of Spain is of great relevance and interest when it comes to promoting the use of forest bioproducts in the construction sector and contributing to the sustainable development of this sector, which is currently seeking alternative products and technologies to enable its decarbonization.

5. Conclusions

The incorporation of biogenic carbon into the embodied carbon balance facilitates the interpretation of environmental information pertaining to bio-based products versus non-bio-based one, highlighting the comparative advantages of wood in terms of sustainability.

To ensure the transparency of the environmental information of bio-based products, it is suggested that the value of carbon emissions to the atmosphere due to embedded energy and the value of the biogenic carbon of the bio-based product should be provided as information additional to the embedded carbon of the bio-based product.

In Spain, there are no LCA background databases for the forestry sector and its industry that are contextualized to the reality of Spanish forests. Therefore, the generation of these data is an innovation of great interest.

There is a growing interest in and need for the development of national environmental databases. These databases are a powerful tool to support prescribers and technicians during the design stage of building projects.

Carbon emissions should be reduced during all the stages of the life cycle. The carbon footprint of timber products can be reduced by improving machinery's efficiency (so energy and raw material consumption is reduced), enhancing industrial processes in sawmills and second transformation industries and enhancing the correct use of timber products via design that improves durability with fewer chemical products.

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Appendix A

During the definition of the scenarios of the stages considered in LCA, it is necessary to define cut-off criteria for the inclusion or exclusion of certain material-energy flows, either because they are of little relevance or because they are difficult to identify and quantify. The UNE-EN 15804 standard establishes these cut-off criteria in article 6.3.6, being 1% of the use of renewable and non-renewable primary energy and 1% of the total mass entering the unitary process in question, not exceeding 5% of the energy use and mass of matter for each of the modules established in this standard. Compliance with these criteria shall be demonstrated through the use of conservative assumptions and expert criteria.

In this study, the following cut-off criteria and consumption hypotheses were assumed for each of the stages considered, according to studies based on real experiences or on the scientific knowledge of the team members. In general, consumption related to the maintenance of machines and vehicles and the replacement of parts worn out by use was not considered:

Appendix A.1. Raw Material Extraction and Supply

- Biomass residues after tree trimming and delimbing in the forest, as well as co-products generated in the sawmill, are assumed to have a destination that is not considered to be included within the boundaries of the system under study.
- The value of fuel and lubricant consumption for tree felling is calculated on the basis of performance and specific consumption data from the commercial catalogs of forestry chainsaws and green wood density.
- The lasur is applied manually.
- Consumption flows due to anti-blue treatment are not considered as they represent 0.14% of the mass of the standard product and reliable data are not available.
- The machinery used is assumed to have corresponding in-feed and out-feed conveyor systems.
- Lubricant consumption is 2% of electricity consumption.
- The consumptions of the compression and aspiration systems are quantified together.
- The moisture content of the wood is considered to decrease from 40% to 12% during drying. The boiler in the dryer is fueled by biomass generated in this module.

Appendix A.2. Transport to Manufacturing Plant

- Lubricant consumption is 5% of fuel consumption.
- Transport from the forest to the sawmill is carried out by a crane truck that also unloads the rolls in the yard. Therefore, it should be noted that the consumption associated with the unloading operation is not included in the estimates for sub-stage A1 (whose results will be reduced) but in stage A2 (whose results will be increased).
- An average distance of 50 km between the forest and the manufacturing plant and an average speed of the truck crane of 50 km/h are considered.
- The fuel consumption of internal transport by forklifts, loaders, etc., including unloading, storage and movement of the wood during the treatment by immersion with lasur is obtained from the manufacturer's data for chestnut wood. For its application to Scots pine, a density of chestnut wood at 40% humidity of 766.6 kg/m^3 and a density of pine for the same humidity conditions of 610 kg/m^3 are considered.
- In order to estimate the fuel and lubricant consumption in the transport of the lasur, a distance of 20 km per trip from the warehouse to the factory is considered, which is covered by a 180 HP Citroën Jumpy van, each time supplying its maximum capacity of a single product.

- Finally, a maximum distance of 50 km and a maximum speed of 80 km/h are considered for the transport of the board produced in the sawmill to the second processing industry for the density at the moisture content of the board (12%). A Volvo FE 350 hp truck is used for this purpose.

Appendix A.3. Manufacturing and Fabrication

- The machinery used at each stage is assumed to have its corresponding in-feed and out-feed conveyor systems.
- Lubricant consumption is assumed to be 2% of electricity consumption.
- The doses of glue and hardener are obtained from the data of the most frequent commercial brands.

Biogenic Carbon

- Packaging accounts for less than 5% of the total mass of the product.
- Work associated with the establishment and management of the forest stand is outside the boundaries of the system.

Appendix B

The values of the conversion factors used in the calculation of the indicators of the LCA impact categories are shown in Table A1.

Table A1. Conversion factors.

Resource	Unit	Conversion Factor	Source of Data
Electricity	kg $CO_{2\text{-eq}}$/kWh	0.3600	1
Glue and hardener	kg $CO_{2\text{-eq}}$/kg product	0.1700	4
Lasur	kg $CO_{2\text{-eq}}$/kg product	1.2790	2
Lubricant	kg $CO_{2\text{-eq}}$/kg product	0.6300	3
Fuel	kg $CO_{2\text{-eq}}$/kg product	3.0900	4

1 = Official data sources; 2 = manufacturers; 3 = other inventory databases; 4 = specialized literature.

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