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REVIEW AND COMPARISON OF DIFFERENT TIMBER BUILDING PRODUCTS' EMBODIED EMISSIONS USING FREE DATABASES.

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ABSTRACT: This paper aims to present a brief review of sources of information for studying the variability of embodied carbon emissions in structural wood products commonly used in construction. The review considered 13 primary sources, focused on EPDs and generic databases, and allowed the collection of data for the study of 140 products divided into Sawn lumber, Glulam, OSB, and Plywood. The information collected made it possible to identify factors such as the variability of density properties, wood species, the origin of the products, among others. In addition to analyzing the variations in the biogenic carbon of the different products studied. The results allow us to conclude that although the variability of wood products can be significant, like any product of natural origin, when they are studied within the framework of the analysis of the materials of a building, they can present a smaller fluctuation than other materials such as concrete. Moreover, this effect can be accentuated in wood products with greater density or have undergone processes that increase the mass of biogenic carbon per cubic meter in the final product.

KEYWORDS: CO2 Emissions, Embodied Carbon, Global Warming Potential, Biogenic carbon.

1 INTRODUCTION

The building sector is one of the main contributors to the global warming crisis, associated with anthropogenic GHG, with nearly 39% of the global CO2eq emissions. Moreover, when we disaggregate this percentage, we realize that almost 23% of the worldwide CO2eq emissions correspond to building materials production and transport, such as steel and cement, which represent nearly 11% of the global total [1]; while 9% of the emissions to the building's operation, and especially the energy required for space heating [2]. Even more, recent studies have raised evidence that in 2020 the anthropogenic mass became equivalent to the whole planet's biomass. More importantly, approximately 70% of this anthropogenic mass corresponds to concrete and aggregates, the most abundant manmade materials in the world and with the highest environmental impact on the planet's emissions [3].

As a result, the materials we use in our built environment are of utmost importance, since their production and effects on a building's life cycle have been responsible for a good part of the anthropogenic GHG emissions. This could also be extended to other environmental indicators such as energy use, waste production, and water pollution. Therefore, previous research has suggested that replacing steel and concrete with bio-based construction materials could help answer the current construction sector environmental problem. Likewise, studies such as the one led by the researcher Churquina [3] also present a scenario in which massive timber buildings and cities could not only reduce CO2eq emissions but also help to capture it from the environment. Turning cities into long-term carbon storages and promoting a more sustainable forest sector that could foment reforestation and afforestation processes worldwide, also helping to keep capturing carbon from the atmosphere and eventually even returning it underneath the Earth.

On the other hand, although there have been attempts to reduce the building sector's GHG emissions during the past decades, these have been insufficient and carried out primarily in developed countries. Moreover, developed countries' new and increasing attempts to reduce building sector emissions during the following decades might still be unsuccessful. This is because it is expected that the world population will increase by nearly 20% by 2050, although this will not be concentrated in developed countries but developing countries. In this matter, the need for new housing and infrastructure, in regions such as Asia, Africa, and Latin America, will be decisive if we want to decrease anthropogenic GHG emissions and limit global temperature rise under 2°C before the 2050 tipping point.

Developing countries, such as Chile, have made great efforts to commit to achieving carbon neutrality before 2050. Mostly relying upon increasing their renewable energies share, from the current 40% to an ambitious 70%

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by 2050; but also by increasing their CO2 sequestration through new forest plantations, capturing almost 50% of the total country's emission. Moreover, this presents a scenario where buildings would benefit from a cleaner energy source, drastically reducing their operational emissions. Still, it also means that buildings' embodied emissions would become more relevant to achieve carbon neutrality emissions in the Chilean building sector. Also, creating an opportunity to get the advantage of the new forest plantation and the promotion of low embodied carbon timber buildings, which may kickstart a more sustainable development model.

2 GLOBAL WARMING POTENTIAL AND TIMBER PRODUCTS

CO2 is the most common anthropogenic GHG emission and a by-product of burning fossil fuels or biomass, being determined as the reference by which other GHG are compared in their effects on the Earth's radiative balance and global warming over a known period. Therefore, the global warming potential or GWP defines the amount of energy that the emissions of 1 ton of a determined GHG will absorb compared to 1 ton of CO2 over 100 years. In this matter, gases such as methane tend to have a GWP twenty times higher than CO2, while hydrochlorofluorocarbon gases can reach tens of thousands more GWP.

To compare the effects of different GHGs emissions with independent GWP, it is usual to multiply the GWP for a 100 years period by the total gas emission, this way obtaining a CO2 equivalent or CO2eq value. This equivalent emission allows comparing the radiative and global warming effect of different GHG, or even mixed emissions from the same or different production process. Moreover, diverse GHG emissions associated with a specific building product manufacturing can be grouped under a total global CO2eq value.

This CO2eq emission data, associated with GHG GWP factors, is usually used by designers and investors to select building products to reduce a project's overall CO2eq emissions in the early design stages. This is done mainly by comparing the buildings products' embodied equivalent CO2 emissions; when considering raw materials extraction, transport, and manufacturing prosses. Generally corresponding to a cradle-to-gate stage analysis of the life cycle or "Product stage" A1-A3 according to the EN 15978's "System Boundary."

For the designers to obtain the embodied emission information of building materials, they usually must ask manufacturers for the Environmental Product Declaration or EPD for their specific products. EPDs that consider technical standards, such as EN 15804, give detailed information on the product's environmental impact and declare the stages considered on the system boundary for evaluation. Another way to obtain the emission data is to check building products' emissions inventories databases or use specialized tools to estimate emissions through a specific material manufacturing process analysis. Although depending on the data source, emissions could drastically vary their results between products and manufacturers, depending on the process or methodology applied.

It is also important to state, especially for this review, that materials such as wood can also have biogenic carbon sequestration, considered in EPDs and databases that use more up-to-date standards, such as EN15804. This biogenic carbon corresponds to carbon captured from the CO2 in the atmosphere when the tree grows and becomes part of the final timber product structure. Therefore, depending on the process involved in timber product manufacturing and the methodology used to account for emissions, the balance between emissions and CO2 capture can be negative.

Nevertheless, obtaining the embodied emission data can be challenging, especially for timber building products. Data gathering for producing EPDs, or product inventories, is extremely time-consuming and too expensive for many companies. Moreover, free access databases are rare, limited, outdated, and usually constrained to some regions in developed countries. Thus, this is especially complicated in developing countries, where data is almost non-existent, and designers have few tools to select building materials according to their embodied CO2eq performance.

3 METHODOLOGY

This document seeks to review the most used and free access, building product's embodied emission catalogs, focusing on databases that gather EPDs and generic product inventories. Thus, comparing the GWP CO2eq emission variability of more common timber structural products with fewer production prosses, such as saw wood, and those more sophisticated such as plywood or CLT. Meanwhile, other private or paid access databases are not considered since; although they might be more comprehensive, updated, and have a friendlier user interface; they are less used by designers and project managers. A situation that is most frequent in developing countries where the requirements for this analysis are less usual, and paying for this information is not part of a project's budget.

For this purpose, the reviewed sources prioritize first more detailed data from EPDs Program Operators under the ISO 14025 standard; and second, generic environmental impact data from public catalogs and databases worldwide. Moreover, it is important to notice that the catalogs presented later are the ones that declared timber construction products at the moment of the review. In contrast, other discarded catalogs did not have timber products or any construction data, or it was impossible to access them or the information within their platforms. Also, the information needed to be accessed remotely and

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in English to be useful for designers' decision-making worldwide. Yet, some specific countries' databases were language exclusive for global use purposes and, therefore, not considered.

Although data from the EPDS's Program Operators and catalogs might have differences that could make their study difficult, such as their Product Category Rules (PCR) conventions, an effort is made to homogenize de data for comparison. This is done by applying data selection criteria, simplifying their analysis, and converting functional units for comparison. Moreover, a minimum of ten different data sources is required to have representative data to analyze a specific structural timber product, such as glulam. This way, a product with little information that might distort the comparative analysis is not considered.

The criteria for selecting the data and subsequently compare results, from the mentioned sources, consider; i) selecting information from timber structural products commonly available in the market, non-structural timber products such as floors or sheathing are not considered; ii) that the EPD data considered the inclusion of EN 15804:2012+A1:2013, EN 15804:2012+A2:2019 or ISO 21930:2017 standards, which are specific for building products and give more comparable information; iii) that the LCA data consider at least product stage information, modules A1-A3 regarding extraction, material transport and manufacturing; that the global warming potential data available for the product stage, includes separate wood biogenic information; iv) that the wood spices, water content and/or density is declared, in order to identify if the product consists of softwood or hardwood; v) that the functional unit is in cubic meters or there is enough information to make a suitable conversion; vi) that the data is not older than five years, in accordance with international standard. If any previous criteria are not fulfilled, the product is not included in the study. Moreover, timber building products EPDs that could be part of multiple Program Operators or Catalogues are assigned to only one data source to avoid duplicated information.

In addition, to uniform data, functional units expressed in kilograms or square meters, when available, are transformed to cubic meters using equivalent density data and product thickness. Moreover, for timber products that declare their biogenic carbon in kilograms, in accordance with EN 16449:2014 and the atomic weight of carbon and CO2, a factor of 3.67 is used to transform it to CO2eq. Even more, for specific timber product cases, where the total Global Warming Potential excluding the biogenic carbon is not given, this is estimated by resting the informed biogenic CO2eq from the total GWP.

At last, to identify the impact of using different GWP data in a specific case, a Chilean timber frame representative 6-story dwelling building is also studied. Therefore, allowing the understanding of using different timber products' embodied emissions data versus a traditional concrete structure. Moreover, considering the overall effect of the structural material quantities analysis in a complete building evaluation.

4 RESULTS & DISCUSSION

4.1 Timber structural database.

A total of 34 EPDs Program Operators, catalogs, and databases are reviewed, remaining only 13. Most of the sources reviewed considered a specific section for construction material data and filters that allows identifying particular materials such as wood products or capabilities as structural performance. Also, most sources consider digital EPDs documents in PDF format, and only a few have additional data in other forms, such as spreadsheets or HTML data.

Table 1: *Data source*

Data source	Type of data	Source origin	N° products
Environdec	EPDs	Europe	40
EPD Hub	EPDs	Europe	3
ASTM	EPDs	America	10
SPOT UL	EPDs	America	5
EPD Irland	EPDs	Europe	8
EDP Denmark	EPDs	Europe	8
EPD Norway	EPDs	Europe	1
INIES	EPDs	Europe	26
INIES	Generic	Europe	3
IBU EPD	EPDs	Europe	4
ECO Platform [a]	EPDs	Europe	2
ICE 2019	Generic	Europe	7
Quartz	Generic	America	5
ÖKOBAUDAT	Generic	Europe	18

[a] *Although ECO Platform is one of the most significant sources of EPDs information, the data comes from other Program Operators and therefore are assigned to the original source. The remaining data correspond to EPDs that were not accessible through their Program Operators.*

The final list of EPDs Program Operators and catalogue data bases, that can be seen with more detail in table 1, consist of the EPD Environdec System [4], owned by EPD International AB, and part of the Global EPD program for publication of ISO 14025 and EN 15804 compliant EPDs; the EPD Hub [5], based in Europe and in compliant with ISO 14025; the ASTM EPD program [6], managed by the ASTM International, North American organization devoted to standards development; SPOT UL [7], program operated by UL Solutions; EPD Ireland [8], consisting of a program managed by the Irish Green Building Council; EPD Denmark [9], focused in the construction sector and with del EN 15804 European standard; EPD Norway [10], established by the Norwegian Confederation of Business and Industry; INIES EPDs data [11], French national organization which gathers materials and construction system environmental data; IBU.dat [12], which is a data base created by the Institut Bauen und Umwelt oriented to the

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European region (IBU EPD); and ECO Platform [13], International association of private and public EPD's Program Operators. Meanwhile, regarding generic data for timber construction products, the sources compromise of the University of Bath ICE 2019 database [14], which collects data from reports and EPDs; Quartz project [15], which gathers information from EPDs, the Pharos project, and GaBi database; the ÖKOBAUDAT platform [16], from the German Federal Ministry for Housing, Urban Development and Building; and the INIES's generic data [11], built from French EPDs representative data.

Regarding the revised structural timber products, more than 30 products were discarded from the study, primarily due to lack of information, having old data, being innovative products with low market share, and/or not meeting other methodological requirements for this study. Also, some product types, such as Laminated Veneer Lumber (LVL), Nailed Laminated Timber (NLT), Dowel Laminated Timber, Laminated Stand lumber (LSL), and I-joist beams, did not meet the minimum number of product data to be included.

Consequently, the remaining list consists of 140 entries, with information not older than 2018, representing five different structural timber products. Thus, they separate into 40 sawn wood products, finger-joints are not included in this group because of the lack of representative data; 35 glued laminated timber (Glulam), this combining different elements such as columns and beans; 26 Cross Laminated Timber (CLT) products, considering panels of various sizes; 26 Plywood boards, with different representative thickness and manufacturing process; and, 18 Oriented Strained Board (OSB), with different origins and layers.

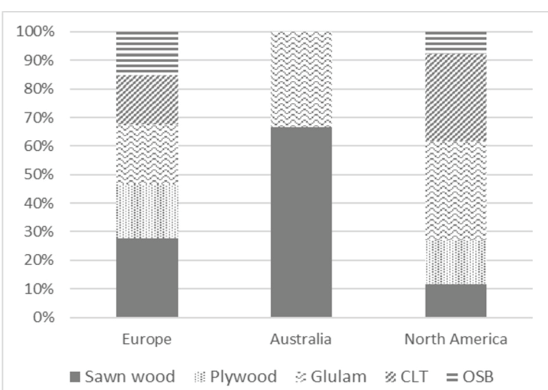

Figure 1: *Timber product share by region of origin. South America is not considered since it only has two EPDs.*

4.2 Timber products properties.

It is well known that wood, as a natural product, presents different properties depending on various factors such as the species, growing considerations, carbon capture, water content, among many others. This has meant that many researchers have concluded that determining the global warming potential of wood products is particularly difficult. However, the properties of structural wood products are more similar to each other when compared to other non-structural products such as flooring, cladding, furniture, tools, decoration, etc. This is mostly due to the types of wood used for building structural purposes, which commonly consist of softwoods with similar properties. Moreover, engineering wood products used in building structures often have production standards that set similar physical properties to control their humidity and strength.

Therefore, from the data collected from EPD information and generic data, it is possible to identify that most of the timber structural products evaluated in this study consist of dried softwoods with an average density between 471kg/m^3 and 623kg/m^3, depending on the product type. Although some wood, such as Cypress, can have a density of more than 800kg/m^3.

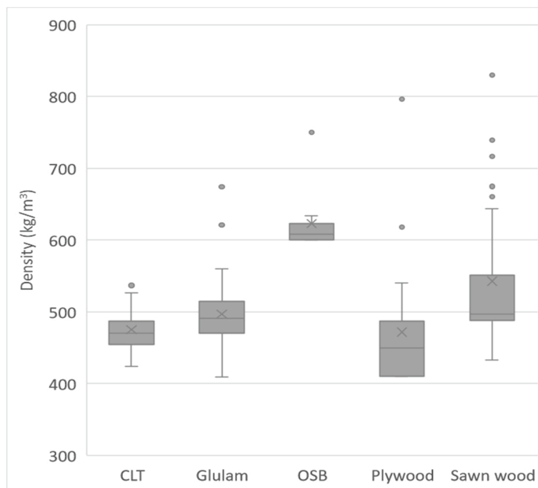

Figure 2: *Timber products and their density range.*

Moreover, the most common species within this study are different softwoods such as Spruce, Pine, and Douglas-Fir. Other hardwoods such as Poplar, Beech, or Oak are also present in products like plywood or sawn wood; nevertheless, they only represent less than 13% of the whole sample.

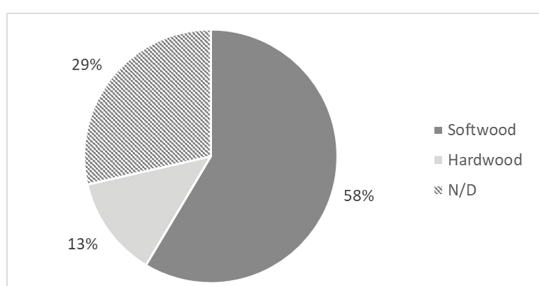

Figure 3: *Wood classification by softwood or hardwood, according to EPDs' data.*

4.3 Global Warming Potential and biogenic carbon

The wood products' Global Warming Potential results show that when biogenic carbon sequestration is considered in the product stage, the total GWP is negative in all the cases. Despite the variability in results within each timber product and the important difference that arise between product types. By comparison, products that require more manufacturing processes, have a higher adhesive or additives to wood mass relation, and present a more significant range of wood species, such as Plywood and OSB, tend to have considerable variability in their GWP results. While on the other hand, timber products with a lower manufacturing process, reduced adhesive to wood mass rates, and more consistent wood species use, such as the sawn wood, CLT, and glulam, present more consequent GWP results. Nevertheless, products with a more complex manufacturing process, such as OSB, still present lower GWP values than sawn wood.

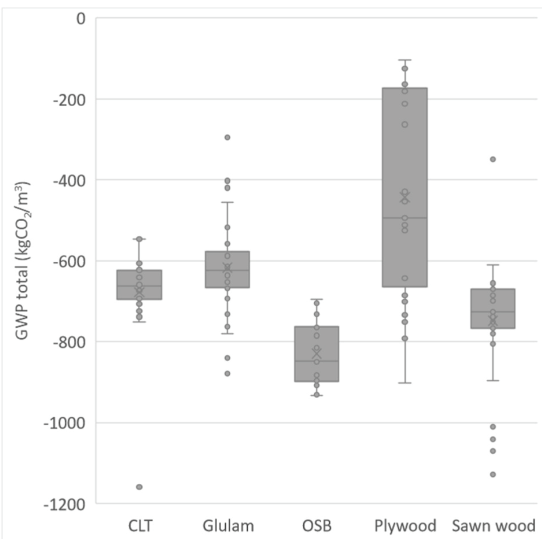

Figure 4: *GWP total by timber product, for product stage (cradle to gate), considering carbon biogenic captured in the wood mass.*

Regarding the manufacturing process, it is essential to notice that less complex manufacturing products will present lower GWP results when biogenic carbon is not considered. Explaining why, in this scenario, the sawn wood has a lower impact than the OSB and Plywood. Therefore, the final dry wood density of the product, regardless of the original wood product density before the manufacturing process, is a crucial factor to consider when studying the GWP of wood base products.

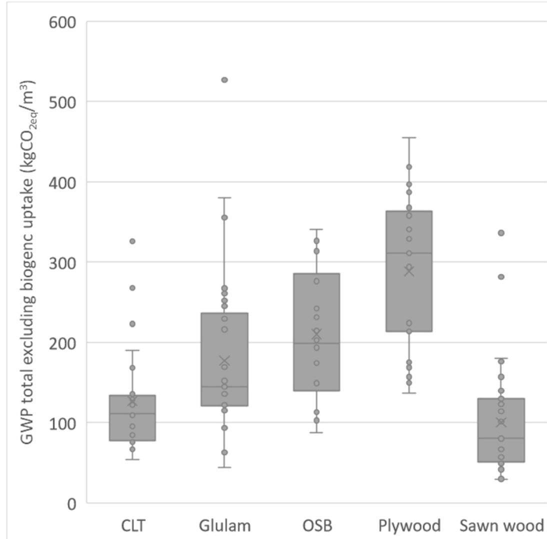

Figure 5: *GWP total by timber product, for product stage (cradle to gate), excluding biogenic carbon uptake by the wood mass.*

However, density and moisture content are crucial to determine the carbon captured in wood products, as presented in EN 16449 standard. Therefore, since structural timber products must be dry, the wood mass density would be the main factor in determining a product's biogenic carbon content. In this sense, the denser the wood used in a product, the more biogenic carbon and CO2eq are sequestered. For example, a cubic meter of dried saw Pine wood with a density of 450kg/m3 and 12% moisture content would have approximately 200.8kg of carbon or a biogenic GWP of -737.3 kgCO2eq. In comparison, a cubic meter of dried sawn Beech wood with a density of 740kg/m3 and a 12% moisture content would have 330.3kg of carbon and a biogenic GWP of -1,212.4 kgCO2eq.

Depending on the product manufacturing process, the amount of dry wood may vary. Therefore, timber products that compress wood might have a higher density than the original piece of wood used for its manufacturing and, therefore, more biogenic carbon by the cubic meter of product. On the other hand, the mass of an engineering timber product could be conformed of wood and other products such as adhesives or preservatives, reducing the amount of biogenic carbon by volume of product. For example, the density of an OSB board could be higher than the pine wood used for its production, but it is also important to take into account the adhesive density in the product to determine the total biogenic carbon. Nevertheless, and weighing their production process, an OSB board made from Pine could have a lower GWP than a Sawn wood piece of the same Pine when biogenic carbon is considered by volume in the product stage.

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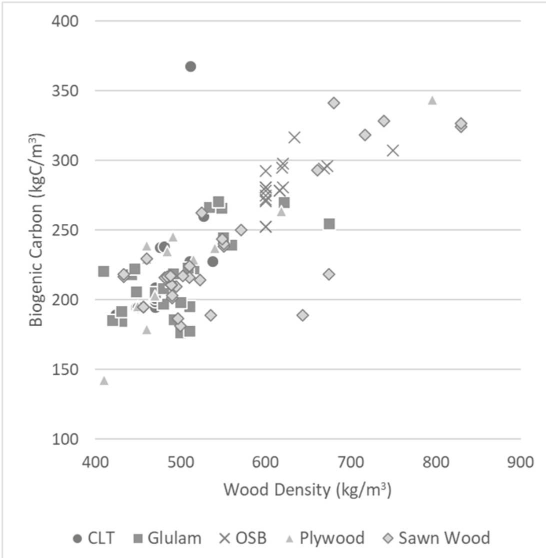

Figure 6: Timber products' density and biogenic carbon content.

4.3.1 Chilean case

As it is stated at the beginning of this document, the Chilean renewable energy growth scenario for the next decades is a particularly interesting case to evaluate buildings' embodied carbon versus operational emissions. Consequently, Chilean buildings that rely completely on electricity for their operation might become, in the future, almost net-zero without any important upgrades. And therefore, new building GWP emissions would mainly depend on the embodied emissions of materials.

On the other hand, Chilean structural timber is produced almost entirely in sustainable certified forests, making it possible to presume that carbon sequestration is taking place in the life cycle of a wood product. Moreover, Chilean structural timber consists exclusively of Radiata Pine, a softwood similar to the one found in the northern hemisphere market, allowing the promotion of knowledge transfer with other countries.

Nonetheless, Chile lacks information regarding the environmental impact of building materials, and the use of international EPDs or generic data is the only option in many cases. Most of the time, presenting uncertainty about the adequacy of the data and doubts about the obtained results, especially for wood-based products that also need to consider carbon sequestration as a critical factor. Moreover, the only two structural wood base products EPDs registered in South America by this study are Plywood boards from Chile, made from softwood Pine and with GWP results raging from -525kgCO2eq and -454 kgCO2eq.

Figure 7 presents the GWP totals of three 6-story buildings' structure materials, one with a timber frame construction system, a second with a mass timber structure in CLT, and a third with a traditional reinforced concrete configuration. It is essential to notice that this data does not consider a whole life cycle assessment, and it is only intended to compare the GWP of three structural building products to verify if wood-based products have higher variability in a project. For this purpose, non-wood product-stage carbon emissions are obtained from the international Institution of Structural Engineers [17] and used in the analysis along with the building's structure mass quantification.

Table 2: *Material GWP product stage (cradle to gate) in kgCO2eq/m³*

Material [a]	Avg. GWP	Min. GWP	Max. GWP	Var. GWP
Concrete C32/40 [b]	420	333.6	504	170.4
Steel plate [c]	12,403	4,451	19.233	14,782
Steel bar [d]	15,386	3,100	31,164	28,064
CLT	-678.6	-750.8	-546.7	204.1
Glulam	-617.2	-780.0	-456.8	323.2
OSB	-829.7	-933.3	-694.9	238.4
Plywood	-443.5	-901.7	-103.7	798.0
Sawn wood	-748.9	-897.2	-611.0	286.2

[a] Concrete and steel data obtained from the Institution of Structural Engineers.
[b] density of concrete 2400kg/m³
[c] Steel plate min and max GWP correspond to UK data, while average value to global data. Density 7850kg/m³
[d] Density of Steel bar 7850kg/m³

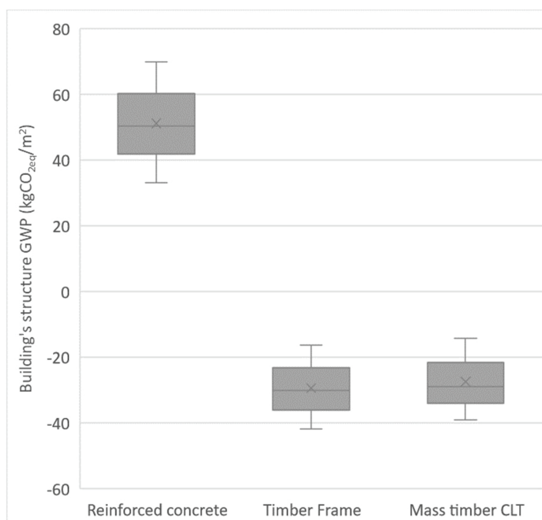

Figure 6: Timber products' density and biogenic carbon content.

The buildings' structural material analysis shows first, as expected, that the overall CO2eq emissions of the timber structures are lower than the reinforced concrete alternative. It also presents that timber building structural materials' total emissions are negative, despite considering steel connectors and concrete foundations in their carbon balance. But what might be more interesting is that the variability of the CO2eq emissions is lower in the timber cases than in the concrete. This condition is explained by the higher mass of concrete in the buildings, compared to timber, and its greater importance contrasted to the structural products' GWP variability.

In the same way, although the volume of wood is higher in the mass timber case, the greater density of wood in OSB boards compensates for the embodied biogenic carbon. This makes the two structural timber systems have almost the same emissions performance for this 6-story building case. This raises the question of which timber structure is most suitable for reducing materials' carbon emissions when building mid-height structures. Tambien entre maderas mayor densidad.

5 CONCLUSIONS

First, it is relevant to remember that this is a brief study of the most popular free-access carbon emissions database for timber structural materials. Therefore it was never intended to address all the information available. Also important, it only focuses on the product stage emissions, not taking into account other important stages in a whole life cycle analysis, such as maintenance or renovations during the life span of the building product or disposal of the material at the end of life. Nevertheless, the previously mentioned stages will depend drastically on design and operation considerations and the scenarios defined for waste management. For example, burning wood products at the end of life would release biogenic carbon, although if it is reused, recycled, or buried in landfills, it might prolong the capture or even become permanent.

The study shows that most data comes from European sources, presumably because of more developed regulations and standards, along with a more informed population and industry. A condition is also reflected in the products data covering, having a similar number of EPDs available for common products such as sawn wood and more innovative products like CLT. Moreover, regions such as North America and Australia have fewer data and, in some cases, concentrate on a couple of timber structural products. Nonetheless, other developing areas have little or no data available at all, like South America, where only two timber structural products' EPDs were identified.

On the other hand, the known variability in wood's Global Warming Potential properties might be less in timber structural products than in non-structural elements. This might be explained by a more standardized manufacturing process and the preference for a small number of softwood species. Therefore spices such as Pine and Spruce are the most mentioned in the EPDs reviewed. Also, the higher density of the wood or timber products, the more significant the reduction in the total GWP associated with the biogenic carbon uptake.

Consequently, considering biogenic carbon and its mass in structural wood products used in a building shows that, although wood may have a higher GWP variability, this is offset by the lower mass required by other materials such as concrete. Thus, a concrete building may have a higher variability in its overall performance, despite concrete having more limited GWP data variability. Therefore, timber structural average GWP data, like the one presented by this study, might have less variability than other traditional material data, such as concrete, when a whole structure building is considered.

Finally, when comparing timber-frame and CLT structures, it is interesting that although their mass volume may vary, the greater density of products such as OSB boards make them have almost the same CO2eq emission for a 6-story building. Because even though the CLT and the OSB can be made of the same tree, the density of the second would have more biogenic carbon per cubic meter due to the manufacturing process and the increase in density. Nonetheless, there are several other factors to consider when studying timber products' environmental impact, apart from GWP, which could have significant implications in a whole life cycle assessment of a product and building. Therefore it is expected that more complete and detailed studies in this matter will follow the present work.

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