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# Identification and Trend Analysis of Multistorey Timber Buildings in the SUDOE Region

**Luis-Alfonso Basterra [1], Vanesa Baño [2,3], Gamaliel López [1], Gonzalo Cabrera [3,*] and Patricia Vallelado-Cordobés [1]**

[1] Architectural Construction Department, ETS Architecture, Universidad de Valladolid, 47014 Valladolid, Spain; alfonso.basterra@uva.es (L.-A.B.); gamaliel.lopez@uva.es (G.L.); pvallelado@uva.es (P.V.-C.)
[2] InnovaWood asbl, BE-1000 Brussels, Belgium; vanesa.bano@innovawood.eu
[3] Cesefor, 42005 Soria, Spain
* Correspondence: gonzalo.cabrera@cesefor.com

**Abstract:** The construction sector has one of the most polluting economic activities. In this context, several policies are being launched by the European Union to promote the transition to a sustainable economy, and timber construction is a safe way to contribute to it. Due to the recent development of multistorey timber buildings, the architectural and structural typologies have not been widely studied yet and with not many studies from Southern Europe. In this context, the main objective of this research is to identify and analyse the trends in the use of wood as a structural material in multistorey timber buildings (≥4 floors) in the SUDOE region, i.e., Spain, Portugal, and Southwest France. The methodology involved identifying 28 timber buildings in the SUDOE region and 101 worldwide, most of them in Europe, and sending online information request forms to different actors involved in their design and construction, collecting plans and BIM models, and performing technical study visits to the identified reference buildings. The collected information was included in open-access technical datasheets, and different indicators in terms of building uses, structural system, wood species, and wood volume, among others, were defined. The results showed that there is a tendency to construct taller timber buildings in the SUDOE region with a predominant use of local softwood species, with ratios of wood volume per built area varying between 0.3 and 0.4 $m^3/m^2$. The mass timber typology using cross-laminated timber (CLT) is mainly used for residential buildings, while post and beam are used for educational and offices buildings. In addition, a potential embodied $CO_2$ equivalent depending on the building typology and use was also analysed.

**Keywords:** timber structures; multistorey timber buildings; structural systems; wood; Spain; Portugal; France; SUDOE region



**Citation:** Basterra, L.-A.; Baño, V.; López, G.; Cabrera, G.; Vallelado-Cordobés, P. Identification and Trend Analysis of Multistorey Timber Buildings in the SUDOE Region. *Buildings* **2023**, *13*, 1501. https://doi.org/10.3390/buildings13061501

Academic Editor: Derek Clements-Croome

Received: 30 April 2023
Revised: 6 June 2023
Accepted: 8 June 2023
Published: 10 June 2023



## 1. Introduction

The Circular Economy Action Plan [1] intends to accelerate the change required by the European Green Deal of the European Union (EU), which launched a strategy for the transition to a sustainable economy. The use of sustainable products is essential for the new EU strategy, and it is expected to have a medium-term influence on the forest products market [2], such as wood as a structural material. In addition, the EU Industrial Strategy promotes the green and digital transition of the industry where the construction sector is included [3]. The construction sector is a sector with the most polluting economic activities, the largest consumer of energy for material manufacturing, and a large producer of waste that, according to the United Nations, represents almost 40% of $CO_2$ emissions [4]. Timber construction is a safe way to store carbon and engineered wood products (EWP) and could help ensure sustainable forest management [5].

Wood is one of the first materials used in building construction since prehistory [6], mainly associated with its great versatility for both constructive and structural functions.

However, with the Industrial Revolution in the second half of the 18th century, steel and later concrete replaced timber for structural uses, and the race for the tallest buildings began, resulting in the construction of exemplary buildings, such as the steel structure of 300 m high Eiffel Tower of Paris (1889) and the concrete structure of 381 m high Empire State of New York (1931). At the end of the 20th century, timber started to be recovered for structural purposes thanks to the innovation in EWP as in the case of glued laminated timber (GLT), which allowed overcoming limitations in terms of length and sections of the sawn wood pieces. Engineers, architects, and builders considered these products the ideal solution to cover long spans, resulting in a trend of horizontal growth of structures. However, the vertical growth of timber structures, i.e., multistorey timber buildings, was triggered by the development of cross-laminated timber (CLT) panels [7]. In the present work, the term "multistorey buildings" was used for mid- (4–8 floors) and high-rise (>8 floors) timber buildings.

CLT panels were patented in the 1990s in Europe and designed to be used as floors or walls in mass timber construction, presenting a good performance in buildings up to 10 storeys [8]. In 2017, there were 32 high-rise timber buildings built or under construction worldwide, and several projects were proposed to be built [9], including some skyscrapers. Some of them are currently completed, and the tallest building being the Mjøstårnet building in Norway (85 m height), while others are still in the design phase, such as the Oakwood Tower (300 m height). However, according to the analysis conducted by Leskovar and Premrov [10], most of multistorey timber buildings in Europe have less than nine floors.

Due to the recent development of multistorey timber buildings, the architectural typology has not been widely studied yet [11]. They are being implemented in urban areas; however, most of them are still pilot projects, and specific guidelines, including common understanding, standard procedures, and holistic considerations are not yet developed [12]. In addition, there is a lack of experience and skills in the structural design of multistorey buildings, especially when CLT is used as a structural product. The current version of the structural design codes for timber structures, Eurocode 5 [13] for most of the European countries and Building Design Code [14] for Spain, do not yet include how to design with CLT. For all these reasons, each study-case is of interest for improving the knowledge of the architectural and structural design of multistorey timber buildings. There are some studies identifying and evaluating the existent timber buildings in North and Central Europe as well as in the rest of the world [11,15–19] but few references of those from Southwest Europe. Therefore, the expected outcome of the present work is to contribute knowledge to the design of multistorey timber buildings by analysing the buildings already constructed in this region and characterised by a combination of oceanic and Mediterranean climatic conditions, with no tradition of constructing multistorey timber buildings. Even though the study does not intend to carry out a climatic or socio-economic analysis of the region, it does aim to assess the trends in construction in this region compared to global trends in terms of structural systems and mainly using timber species.

While hardwood species remained constant, softwood species in Europe increased since 2000, being 43% of the total wood destined for construction products (logs and veneers) [20]. From the total of 21 timber species visually graded for structural uses and included in the European standard EN 1912 [21], nine correspond to hardwoods. However, hardwood species are not included in the harmonized European standards providing the manufacturing requirements for EWP, such as GLT or CLT, and therefore, hardwood EWP are rarely used in timber structures. Softwood species included in the harmonized European standards for countries of the SUDOE region are spruce/fir whitewood, larch, Sitka spruce, Douglas fir, and French pine (which can include the species *Pinus nigra subspecies laricio* or *subspecies nigra* and *Pinus sylvestris*) in France; radiata pine, Scots pine, and Salzmann pine in Spain; and maritime pine in Portugal. From this framework originates the present work with the main objective to identify and analyse multistorey timber buildings in Southwest Europe (SUDOE region: Spain, Portugal, and Southwest France) and to study the trends in the use of wood as a structural material in buildings to provide state-of-the-art timber construction in the SUDOE region. To reach this objective, a series of information request forms were sent to the agents involved in the buildings' construction, and technical study visits to the buildings were conducted with the aim of defining a series of indicators in relation to the building use, structural typology, number of floors, timber species used, wood volume per square meter built, and theoretical embodied $CO_2$ per building typology and use. Data collected is included in the open-access technical data sheets of the studied buildings.

## 2. Materials and Methods

To achieve these objectives several tasks were planned, including an overview of state-of-the-art timber construction in the SUDOE region, identifying and analysing multistorey timber buildings in the mentioned area, and performing study visits to reference the identified timber buildings.

In addition and with the aim of comparing timber buildings in the SUDOE region with international trends, a database of 101 buildings from around the world was compiled by obtaining data through a literature review. In order to create an adequately complete database that can be used to obtain relevant output and that enables discussion of the information gathered, the following activities were carried out.

Firstly, a bibliography review and internet research were undertaken to recognize the different timber buildings already built, under construction, or currently in the design phase that are part of the SUDOE area. The search area was extended to a wider geographical area to reach the reference number of 100 timber buildings. They are mainly located in Europe, although four buildings from Canada, two from the US, two from Australia, and two from Chile were included (see Appendix A). The wider area mentioned will be cited hereafter as global area. The buildings located in France, Spain, and Portugal were identified in the "MyMaps" interactive map [22] and included a short description and pictures of each one.

Secondly, once these buildings were successfully identified, a set of important and consistent questions were asked to the principal actors involved in the design and construction of the relevant buildings in the study area. These questions were collected in an online information request form, which was sent to the architects, engineers, public or private promotors, administration staff, or manufacturing companies involved in the design and/or the construction process of every identified building. The forms were organized into five topics:

(i) identification of all the agents involved in the building construction (architect, developer, construction company, structural engineer, timber manufacturer, and timber installer);
(ii) a general description of the building (use, height in m, built-up area in square meters, ground floor area, and number of floors);
(iii) economic and construction process data (total budget in €, the budget of the timber structure expressed in €/$m^2$, and the number of weeks to build the structure);
(iv) wood products used for the structure (engineered wood products used, wood species, and wood volume of the structure in $m^3$);
(v) structural system data (structural system, bracing system, number of concrete floors if the case, and number of CLT floors, if used); and
(vi) plans and BIM models of the buildings.

The information gathered from these forms allowed an initial selection of the buildings to be more deeply studied in terms of the amount of information available and relevance (high percentage of the structure made with wood and number of floors equal to or higher than four, among other architectural and structural issues). In the SUDOE region, an attempt was made to identify every multistorey timber building. This was achieved thanks to the collaboration of all EWP manufacturers in the region.

In order to complete the information obtained through the request forms, the authors and the whole "Eguralt" project group visited the most relevant buildings in the SUDOE area as the study consistently attempted to focus on the SUDOE region. These study visits were guided by some of the main actors involved in the construction of each building with the aim of completing the information collected by the forms and to take photographs, videos, and aerial views using a drone.

As mentioned, the number of global buildings studied was 101, of which 39 are located within the SUDOE region. Technical data from SUDOE buildings were obtained from a literature review (39), complemented by request forms in 28 buildings, and with study visits for 17 buildings. All the buildings are identified in the table of Annex 1 of the present paper.

With the collected information, three types of datasheets were designed. The first type corresponds to a brief description (use and structural system) and a picture of each of the 101 multistorey timber buildings worldwide (AT, AU, CA, CL, DE, ES, FR, IT, NO, PT, SE, SW, UK, and US) chronologically ordered with the building name, city, country, and number of floors. The second type corresponds to a four-page technical datasheet of 28 multistorey timber buildings identified in the SUDOE region containing a description of the building, the agents involved, the technical and constructive information previously defined in the request form methodology, plans, and pictures (both during the construction process and when the building was finished). Finally, the third type corresponds to a 20-page datasheet of the seven most relevant buildings from the 28 of the SUDOE area. The information presented here complements that of the second datasheet with more plans, pictures, and constructive details. The three types of datasheets are available for consultation in Annexes 1, 2, and 3 of the open-access book, Eguralt, written by the authors of the present paper [23].

After collecting all the information, it was classified for analysis. Different indicators were defined in order to make an objective analysis of the available data. These indicators include the following and are explained in detail below: building use, structural typology, timber species, height/floors, slenderness, potential $CO_2$ captured, and the ratio of $m^3$ of wood per $m^2$ built.

### 2.1. Building Use

To classify the buildings according to their main use, the following categories were defined: commercial, cultural, educational, mixed (in case no principal use was identified), residential, private residential (such as hotels or student residences), and transport.

### 2.2. Structural Typology

Five timber structural typologies have been defined and are illustrated in Figure 1: light frame, which commonly uses small cross-section sawn timber; post and beam, mainly uses GLT although LVL and other EWP could be used; mass timber, which uses mainly CLT panels; a combination of EWP; and mixed, which combines wood with other materials, such as steel or concrete. The combination system refers to a structural system that combines some of the first three systems. The mixed system combines timber with other structural materials, such as concrete or steel.


**Figure 1.** Perspective diagrams of the timber structural typologies defined.

### 2.3. Height/Floors

The maximum height is considered to be the highest point reached by the building, including lift shafts, roof parapets, roof installation rooms, etc. When only information on the number of floors was available, it was assumed that the ground floor is 4 m high, and the remaining floors are 3.25 m high. All floors above ground are taken into account.

### 2.4. Slenderness

The slenderness $(s)$ of a building is the ratio between height and base width. The current structural challenge of multistorey buildings is no longer the height they achieve but the slenderness they attain. It is calculated according to Equation (1).

$$s = \frac{\text{total height}}{\text{floor plan narrowest side}} \tag{1}$$

### 2.5. Potential Captured $CO_2$

Tons of $CO_2$ accumulated in the timber structural elements employed in the structure were calculated approximately, as explained below.

The biogenic carbon content is first calculated according to the EN 16449 [24] standard, employing Equation (2).

$$P_{CO_2} = \frac{44}{12} \times cf \times \frac{\rho_\omega \times V_\omega}{1 + \frac{\omega}{100}} \tag{2}$$

where:

$P_{CO_2}$ is the biogenic carbon oxidized as carbon dioxide emissions in kg;

$cf$ is the carbon fraction of woody biomass (default value 0.5);

$\omega$ is the moisture content of the product, e.g., 12%;

$\rho_\omega$ is the density of the woody biomass of the product at that moisture content. Data is taken from [25];

$V_\omega$ is the volume of the solid wood product at this moisture content in $m^3$. For glulam products, a correction factor of 0.95 is applied to this volume.

Transport is not accounted for in this standard despite being a phase with considerable emissions. Therefore, emissions from trucks used to transport the structural elements were subtracted from the biogenic carbon obtained. The methodology applied is as follows: firstly, the number of trucks needed to transport the whole structure was calculated according to Equation (3), and secondly, the embodied $CO_2$ considering the transportation emissions was calculated according to Equation (4).

$$n = \frac{V}{50} \tag{3}$$

where,

$V$ is the volume of wood transported ($m^3$);

50 is the estimated volume that can be transported by a truck in $m^3$.

$$kg_{CO_2} = P_{CO2} - (0.385 \times 2.482 \times n \times d) \tag{4}$$

where,

$P_{CO_2}$ is the biogenic carbon oxidized as carbon dioxide emissions in kg;

0.385 is the average consumption of a truck in L/km [26];

2.482 is the average emissions of a truck in kg $CO_2$/L [27];

$n$ is the number of trucks needed to transport the wood, calculated before;

$d$ is the distance from the factory to the construction site in km.

It was decided not to include emissions during the production phase as no reliable data is available. The analysis of the $CO_2$ embodied in the buildings intends to be a relative indicator for comparing the different timber buildings.

### 2.6. Ratio $m^3$ Wood per $m^2$ Built

This ratio puts into perspective the optimization of wood as structural material and enables the comparison of buildings of various types and sizes. A lower ratio for a building indicates better timber optimization in its structure. The ratio was calculated according to Equation (5):

$$m^3/m^2 = \frac{V_{wood}}{A \times w} \quad (5)$$

where:

$V_{wood}$ is the volume of wood used in the building structure in $m^3$;

$A$ is the building area in $m^2$,

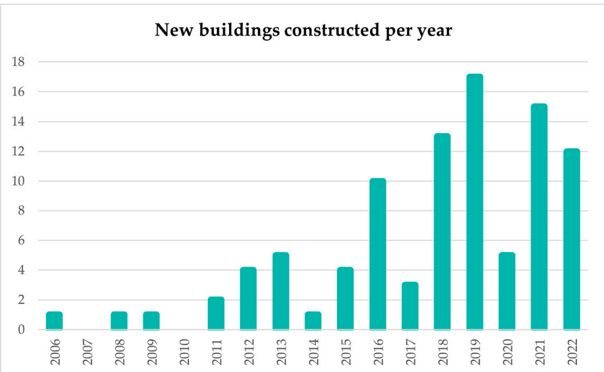
$w$ is the percentage of building area with the structure made of wood as some of the buildings contain concrete and/or steel in their structure (for instance, on the first floor or the communication cores) beyond wood.

## 3. Results and Discussion

In this section, the main results obtained are presented and discussed. These results were obtained through an exhaustive analysis of the aforementioned indicators. Depending on the amount of information available, some of these indicators were studied in the SUDOE region or both the SUDOE region and globally, with the aim of identifying whether there are general similarities or differences between buildings in and out of the SUDOE region in terms of structural typologies or species among others and without distinguishing the buildings from other parts of the globe in the geographical context.

### *3.1. Multistorey Timber Buildings*

The first result observed from the study is a clear upward trend in the use of wood in multistorey buildings. This tendency can be seen both in the overall study and in the SUDOE region as illustrated in Figure 2, which shows the number of mid- and high-rise buildings built per year since 2006 in the global study and in the region already detailed. Nonetheless, it is worth mentioning that the first multistorey timber building identified in the SUDOE region dated 2013, which showcases that multistorey timber buildings were developed here later than in other regions.



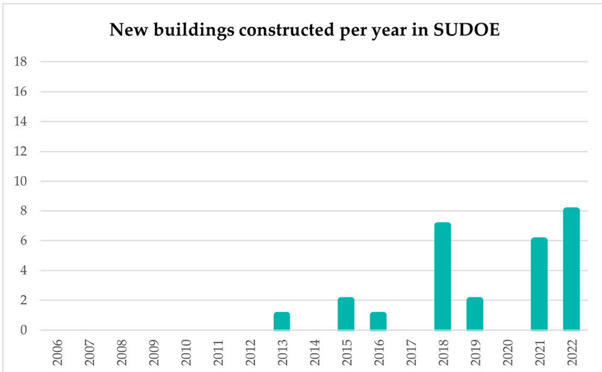




**Figure 2.** Multistorey timber buildings per year in the global study (**left**) and in the SUDOE region (**right**).

### *3.2. Building Use*

In terms of uses of the buildings studied, residential use is dominant both in the global study and in the SUDOE region, representing more than half of the studied cases. To this proportion, private residential use, which includes student residences, hotels, etc., could be added, resulting in more than 60% of the evaluated buildings having a specific residential use (64% global and 68% SUDOE). These percentages of residential use are very similar to that (65%) obtained by Safarik et al. [16]. In an analysis of the mixed use, all the cases include residential use combined with commercial or office space. Office buildings take relevance in the global study (17%), but it is not yet widespread in the SUDOE area (7%). Figure 3 presents the pie chart of building uses for both global and SUDOE region.

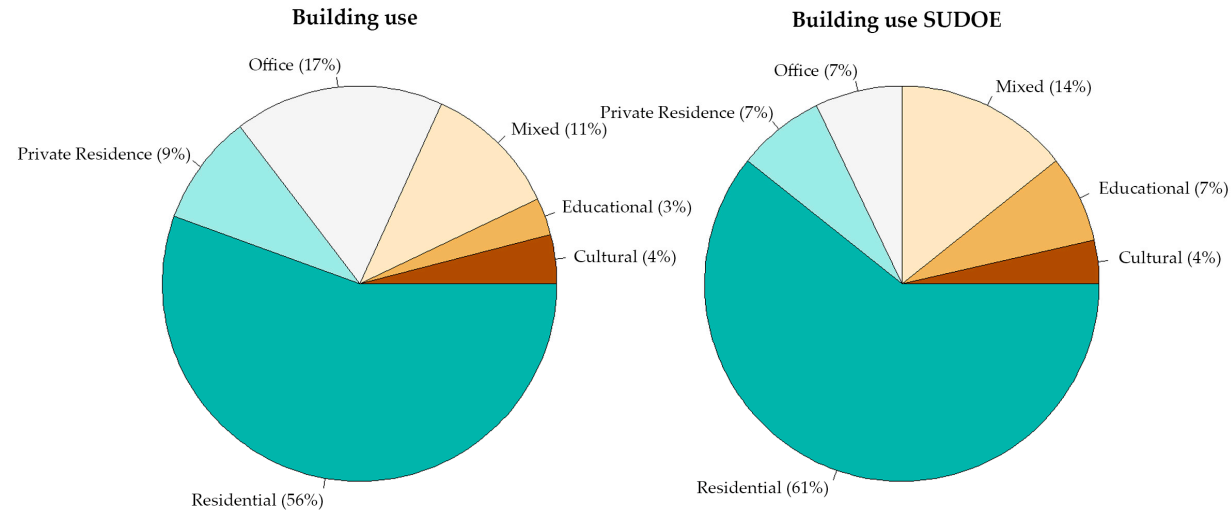



**Figure 3.** Uses of timber building in the global study (**left**) and in the SUDOE region (**right**).

### 3.3. Structural Typologies

When structural typologies are analysed, there is a clear predominance of mass timber buildings in both SUDOE (43%) and global (41%) regions, directly related to the popularization of the CLT panels in the latest years. Light-frame buildings were not observed in SUDOE due to the lack of tradition of light-frame construction, while a small percentage of buildings were found in the global analysis (2%). Regarding the intermediate solutions, SUDOE presented 11% more buildings constructed with the structural system of post and beam than in the global analysis. The comparison between the structural typologies in the SUDOE region and globally is illustrated in Figure 4.

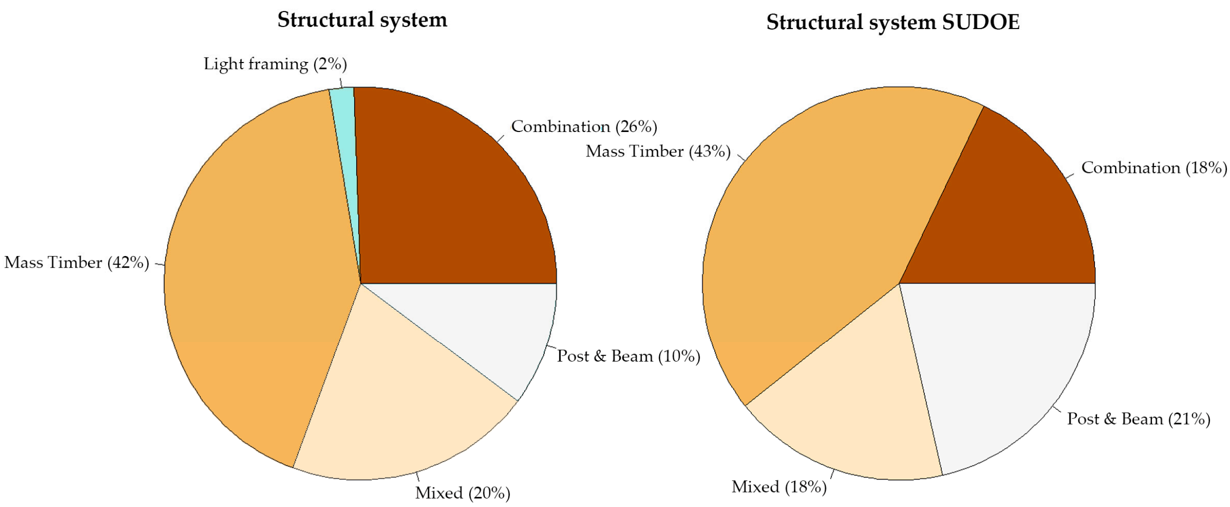



**Figure 4.** Structural typologies in the global study (**left**) and in the SUDOE region (**right**).

The emergence of multistorey timber buildings in SUDOE can be linked to the establishment of CLT manufacturing plants in the region, with the first one dating back to 2007. In contrast to what happened with glulam, which was imported or locally manufactured from imported sawn timber from Central and Northern Europe, mainly spruce, CLT showed a trend of local manufacturing and use of local species from 2018 onwards. Since the first plant was established in the north of Spain, five more CLT plants have been established, and all of them are committed to local timber exploitation as is shown in the next subsection.

### *3.4. Timber Species*

Figure 5 presents a comparison of the wood species used for timber construction in the global and the SUDOE region and concentrates on only four softwood species: silver fir (*Abies alba*), spruce (*Picea abies*), radiata pine (*Pinus radiata*), and Douglas fir (*Pseudotsuga menziesii*). Percentages in Figure 5 show that *Picea abies* is the species more widely used in buildings in both global and SUDOE areas, while this species is only produced locally and available for structural purposes in France and not in Spain and Portugal. *Pinus radiata* and *Pseudotsuga menziesii* are used in a higher percentage of buildings in the SUDOE region, and the first species is produced and structurally graded in Spain and the second one in France. Figure 6 presents the percentages of wood volume per species for both regions, showing the intention to promote the use of local species in the SUDOE region, thus, reducing the carbon footprint.

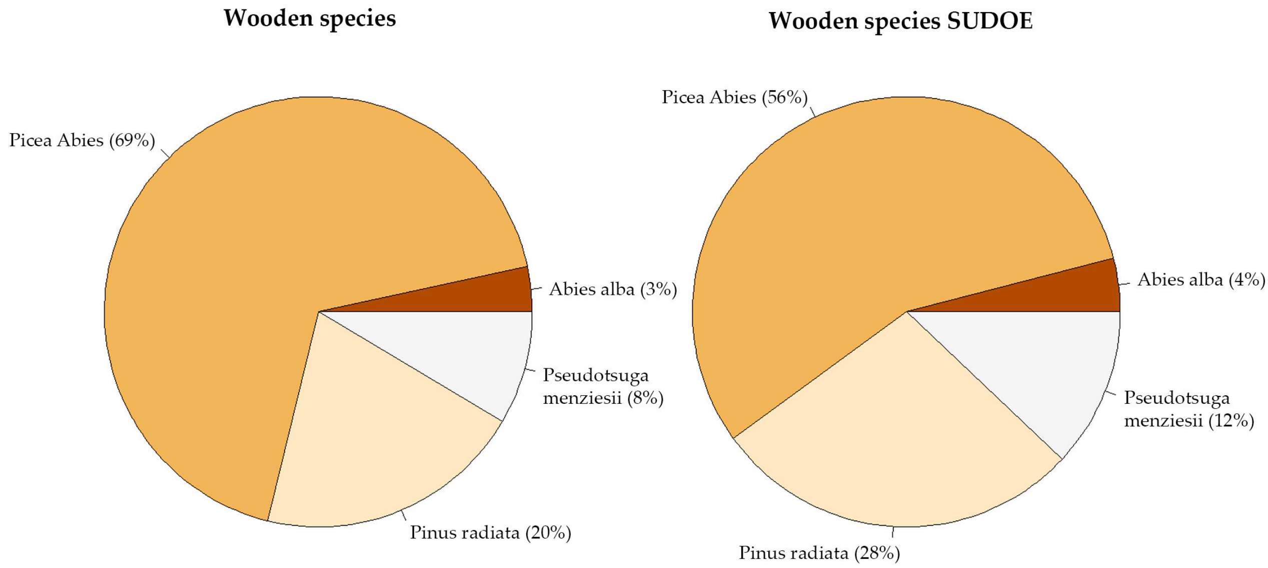



**Figure 5.** Percentage of buildings using a wood species in the global study (**left**) and in the SUDOE region (**right**).

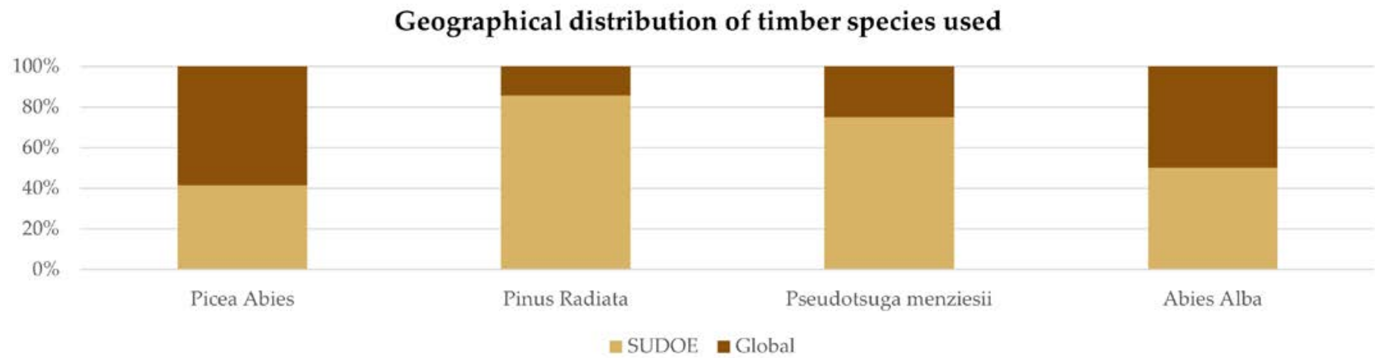



**Figure 6.** Geographical distribution of the timber species used. Percentage of buildings.

The use of radiata pine and Douglas fir in the SUDOE region is associated with their local production and manufacturing. However, the consumption of imported species, such as silver fir or spruce, is very similar in proportion in SUDOE and in the global study.

### *3.5. Height and Slenderness of Wood Buildings*

Figure 7 illustrates the trend in the height increase of timber buildings over recent years. It was not intended to collect information of all timber buildings but simply to show the increasing trend in the construction of taller timber buildings worldwide. Discontinuous lines divide the finished buildings and those under the design phase, which are compared with the iconic steel and concrete buildings, Eiffel Tower and Empire State. The graphic starts in 2009 with the 30 m tall timber building Stadhaus Tower (London, UK) and ends with the ambitious project of the 300 m tall timber skyscraper Barbican Oakwood (London, UK), which showcases the fast development of the timber construction industry. Today, the tallest timber building already constructed is Mjøstårnet Tower, built in Hedmark, Norway, with a height of 85.4 m and is a landmark for future ones.

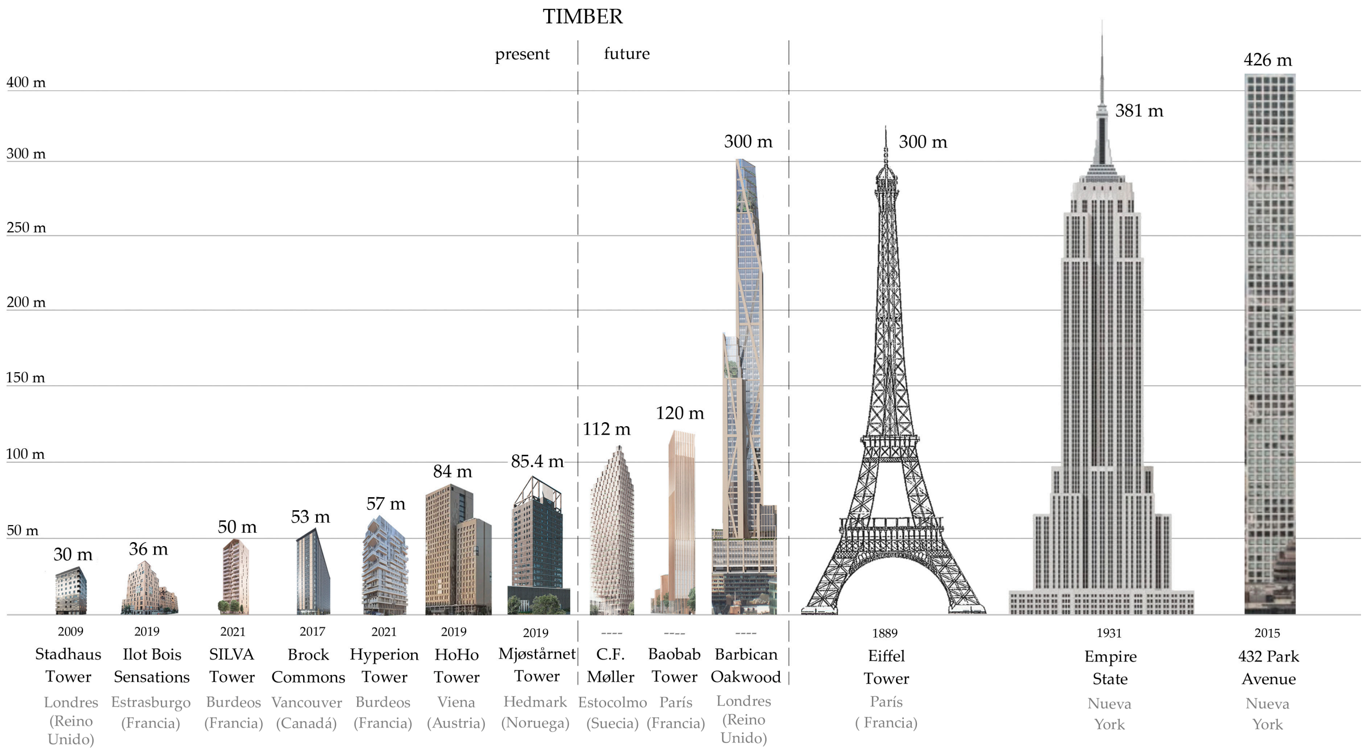



**Figure 7.** Height growth trend of timber buildings compared to iconic steel and concrete buildings.

There is an increasing and evident trend in the SUDOE of constructing taller timber buildings. The first timber building in the region was built in 2013 in Lleida (Spain), 6 floors and 16 m in height, which was destined for residential use. In 2023, two 60 m tall timber buildings were built in Bordeaux: Hyperion residence of 16 floors and SILVA tower of 18 floors (still under construction).

Figure 8 shows the 20 selected buildings of the SUDOE region in chronological order to analyse their height and slenderness. It can be observed that the tallest building of the SUDOE area, Hyperion residence, is also the slenderest with a value of 2.98 over the average value of 1.43. It has a mixed structural system combining glued laminated post and beams, CLT panels for the slabs, and a concrete core, which gives the overall stability to the building.

The trend of increasing building height is not in line with the chronological order, and Hyperion is one of the buildings influencing and modifying this line. Nevertheless, a negative tendency for slenderness can be observed. Taller buildings, such as the Hyperion building, Wood'Art-La Canopée (36 m high and 10 floors), and SILVA tower (50 m high and 18 floors), are built in a mixed structural system, but there is no significant progress in slenderness within the SUDOE area. Taller timber buildings (>30 m) are designed with a mixed structural system.

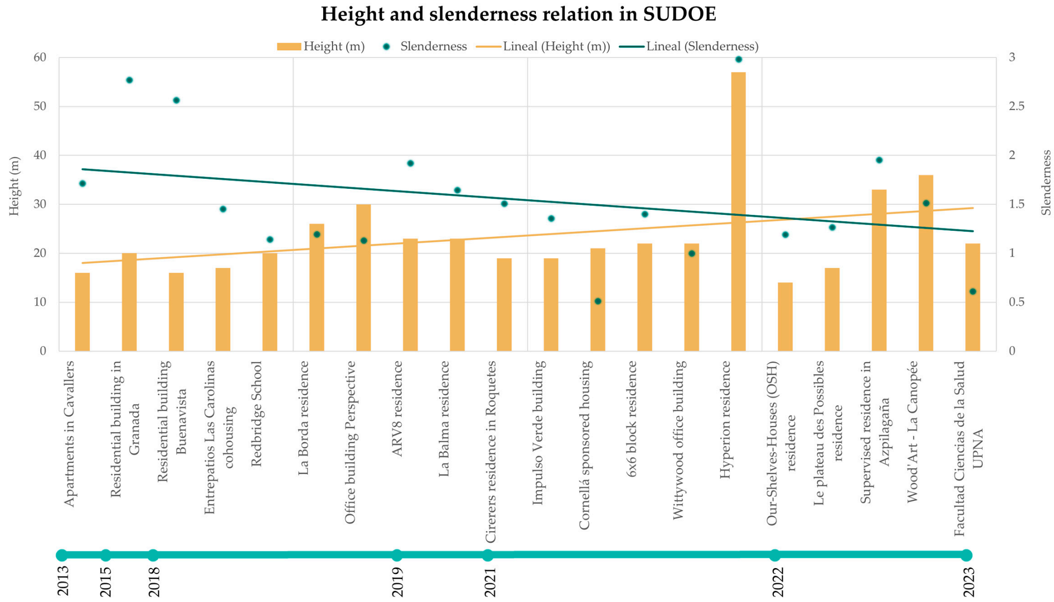



**Figure 8.** Chronological trends in height and slenderness of 20 SUDOE buildings.

## *3.6. Relationships between Indicators*

### 3.6.1. Buildings Use and Structural Typology

The structural typologies defined in 2.2 were analysed in combination with the building uses according to the following categories: cultural, educational, residential, private residence (hotels, student residences, etc.), and mixed. When analysing the correlation between these two indicators for both global and the SUDOE region, the use of mass timber is mostly associated with the residential use of the building, followed by private residential and mixed uses. On the other hand, when looking at cultural, educational, or office buildings, no use of mass timber is detected, as post and beam is the predominant system for these buildings in SUDOE. The use of a mass timber structural system offers less versatility in the use of space, making it less compatible for cultural or educational buildings, since it does not allow to solve as large spans as the post and beam or combined CLT with post and beam system allow (Figure 9).

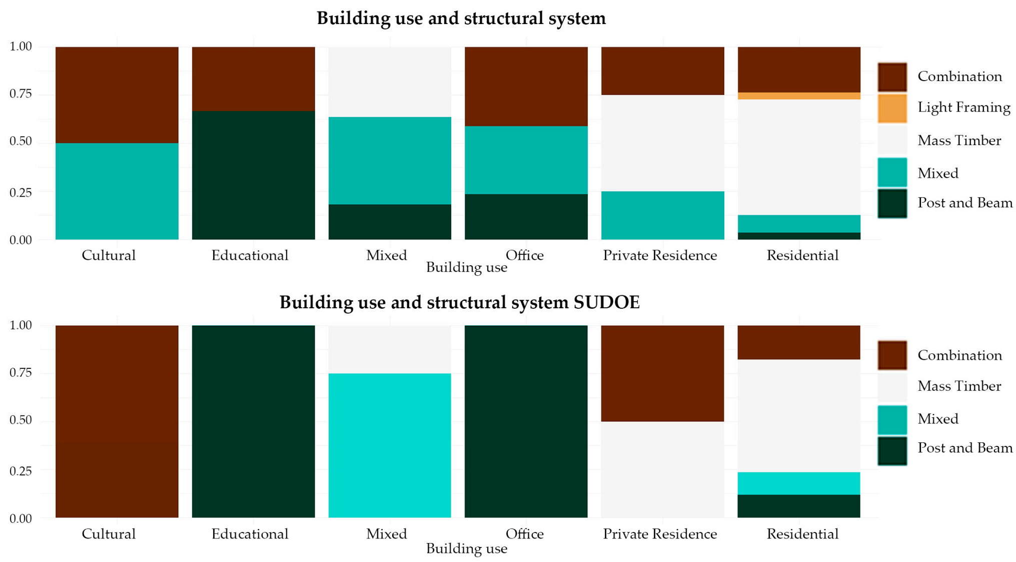



**Figure 9.** Distribution of structural systems in the different uses for the global study (**up**) and the SUDOE region (**below**).

### 3.6.2. Structural Typology and Number of Floors

Figure 10 shows a box and whisker plot of the number of floors per structural typology in both global and the SUDOE region. When these two indicators are correlated, it can be observed that buildings with a higher number of floors are designed in a mixed structure, which is consistent with that shown in the study by Safarik et al. [16], and highlights the need to combine the use of timber with other materials, such as reinforced concrete and/or steel, when greater heights are to be achieved. The appropriate combination of reinforced concrete and/or steel with timber could provide the structure with the stiffer core needed to guarantee the stability of the taller buildings and to act as the wind and seismic lateral load-resisting system, without consuming an excessive volume of wood. Nevertheless, Connolly et al. [28] studied the feasibility of solving the core of the Brock Commons building (53 m high) with a timber structure and concluded that solutions using mass-timber cores could meet the requirements of the standard for this case.

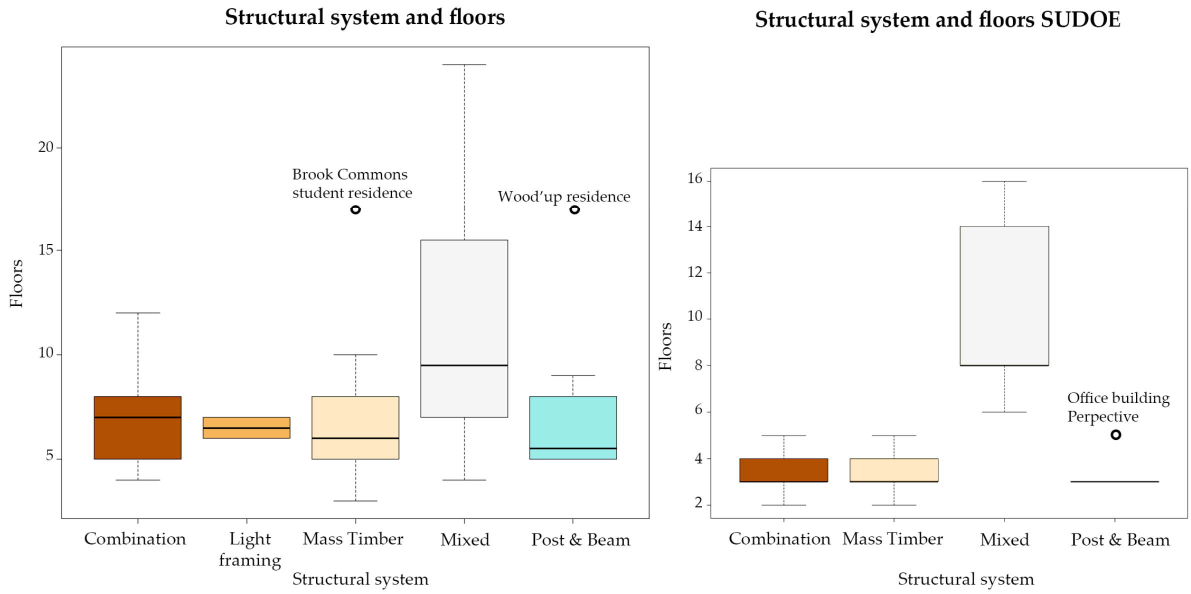



**Figure 10.** Relation between structural systems and the number of floors in the global study (**left**) and in the SUDOE region (**right**).

Within the buildings studied, the one with the highest number of floors in SUDOE is currently Hyperion (Bordeaux, 16 floors); however, this limit will be exceeded by the building under construction that is SILVA tower (Bordeaux, 18 floors). Globally, the building with the highest number of floors is the HoHo Tower in Austria with 24 floors, followed by the Skellefteå Cultural Centre (Sweden) with 19 floors, and the Mjøstårnet Tower (Norway) with 18 floors. The structural typology of all of these buildings is a mixed structure.

The Hyperion building in Bordeaux is a representative example in the SUDOE region of a building with mixed structural typology, designed with a reinforced concrete communication core that acts as the building's stiffening element, and with steel used in the building balconies and some of the perimeter columns.

### 3.6.3. National vs. Foreign Timber Species in SUDOE

Figure 11 plots the transport distance from the wood origin to the building for each species. The relationship between the transport distance and the species used in the SUDOE region shows the difference between using local species and imported ones. The origin of *Pinus radiata* is mainly in the forests of northern Spain, particularly in the Basque Country, which has allowed the development of a strong timber industry in this region. *Pseudotsuga menziesii* can be found in several regions of France, including the Southern area, which belongs to the SUDOE zone.

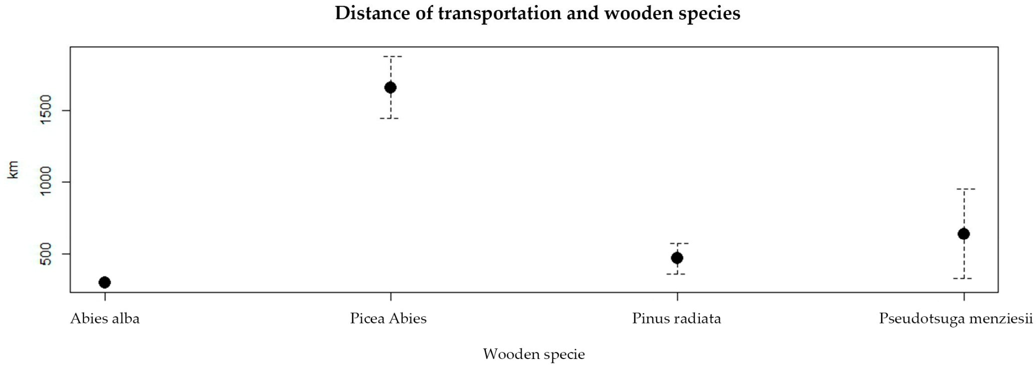



**Figure 11.** Average transport distance of timber in buildings in the SUDOE region according to the species used.

While species from local forests have average values of 540 km (*Pinus radiata*) and 645 km (*Pseudotsuga menziesii*) of transport distance to the buildings, *Picea abies*, whose origin is in Central and Northern Europe, has an average transport distance of 1.820 km. Therefore, the use of EWP that are not made from local species increases the transport distance by 280%. Therefore, it would be desirable to increase the use of local species for contributing towards reducing the carbon footprint. *Abies alba* was not included in the analysis due to the lack of sufficient data to be compared with the other three dominant species.

### 3.6.4. Wood Volume per Square Meter Built

With regards to the wood volume per $m^2$ built, most of the studied buildings have a ratio of wood consumption between 0.3 and 0.4 $m^3/m^2$, with an average value of 0.32 $m^3/m^2$. This can be observed in the graphic presented in Figure 12.

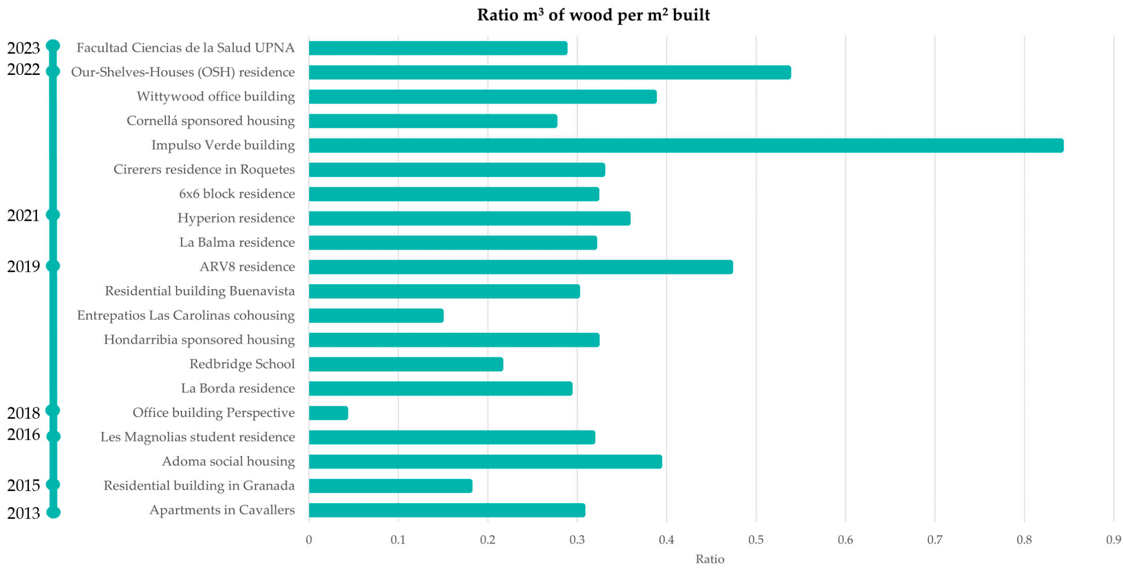



**Figure 12.** Ratio of wood volume per square meter ($m^3/m^2$) in the SUDOE region buildings.

The lowest ratio reached was around 0.05 $m^3/m^2$ and corresponds to the Office Building Perspective (Bordeaux), a building with a post and beam structural typology, while the highest was the Impulso Verde building with around 0.85 $m^3/m^2$, a pioneer building located in Lugo (Spain), that aims to demonstrate the versatility of timber construction, using timber wherever possible; hence, they are not comparable buildings.

This ratio is not only important in terms of structural material optimization but also provides information about the estimated weight of timber structures. If we establish an average timber weight of 5.0 $kN/m^3$, we could obtain a dead load between 1.5–2.0 $kN/m^2$

for timber structures by including the horizontal and vertical structures. This data allows comparisons to be made with concrete structures where the dead load is set between 3–4 kN/m$^2$ and only including the horizontal structure [29]. The dead load would reach 3.5–4.5 kN/m$^2$ in concrete if the vertical structure is included.

A comparison of the ratios according to the structural systems can be observed in Figure 13. There is no significant difference between the average values of the ratios of each structural system. The combination system has more dispersed ratios, which could be because this system has no fixed guidelines, and each building has its particularities when it comes to solving the structure.

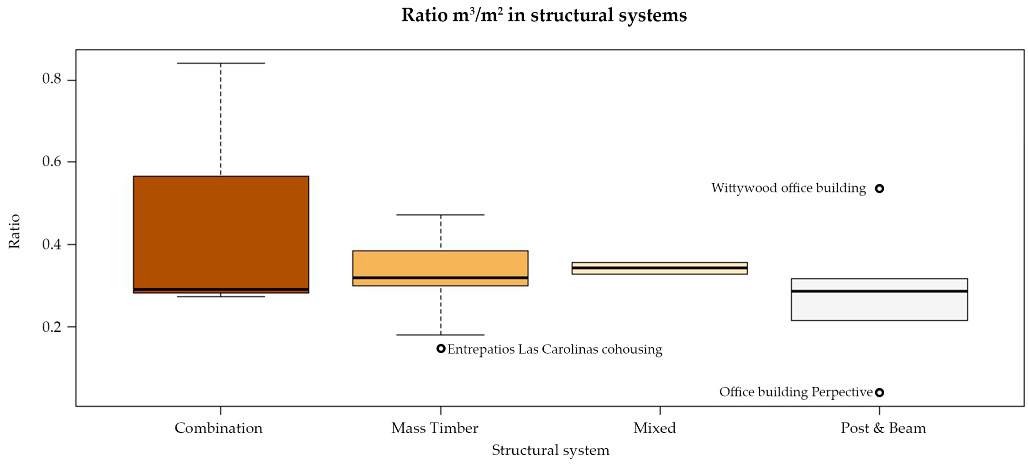



**Figure 13.** Ratio of wood volume per square meter (m$^3$/m$^2$) classified according to the structural systems.

It is worth mentioning the low ratio (the second lowest) of Entrepatios Las Carolinas cohousing, a mass timber construction, that was expected to have a higher ratio due to the higher wood volume of CLT in comparison with GLT. The reason is that the building is destined for social housing that aims to be very economical; hence, the optimization of the structure is key for reducing costs.

On the other hand, the Wittywood building, an office building located in Barcelona, aims to achieve high-quality standards. Therefore, despite the use of a post and beam structural system, which is associated with lower consumption of wood volume, it does not achieve a low ratio. In this building, the entire structure except the foundation is made of timber: glulam posts, beams, and joists and CLT panel slabs. It is also a building with slightly larger spans than those used in housing, hence, larger cross-sections are used.

### 3.6.5. Potential Embodied $CO_2$

Timber structures are distinguished by their ecological nature. Among the various reasons for wood being considered an environmentally friendly material is its ability to store $CO_2$ during its lifetime. It is quite clear that the greater the volume of wood used, the more kg of $CO_2$ is stored. However, the greater wood volume used, the more emissions during its transport are produced. If we also consider that more than half of the wood used in the SUDOE region is imported from other countries, such as Austria, and travels an average distance of 1.820 km, transport becomes a very relevant factor when studying the potential $CO_2$ captured. Timber buildings studied in the SUDOE region potentially store an average of 357.720 kg of $CO_2$.

Buildings, such as Impulso Verde and Entrepatios Las Carolinas cohousing, have a wood volume of around 240 m$^3$. However, the Impulso Verde building has 132% more potential $CO_2$ captured than Entrepatios Las Carolinas cohousing. The difference in transport distance is significant. The timber products used in the Impulso Verde building travelled a distance four times shorter than those usex in the Entrepatios Las Carolinas cohousing. This comparison could be made in 20 of the SUDOE buildings studied by observing Figures 14 and 15.

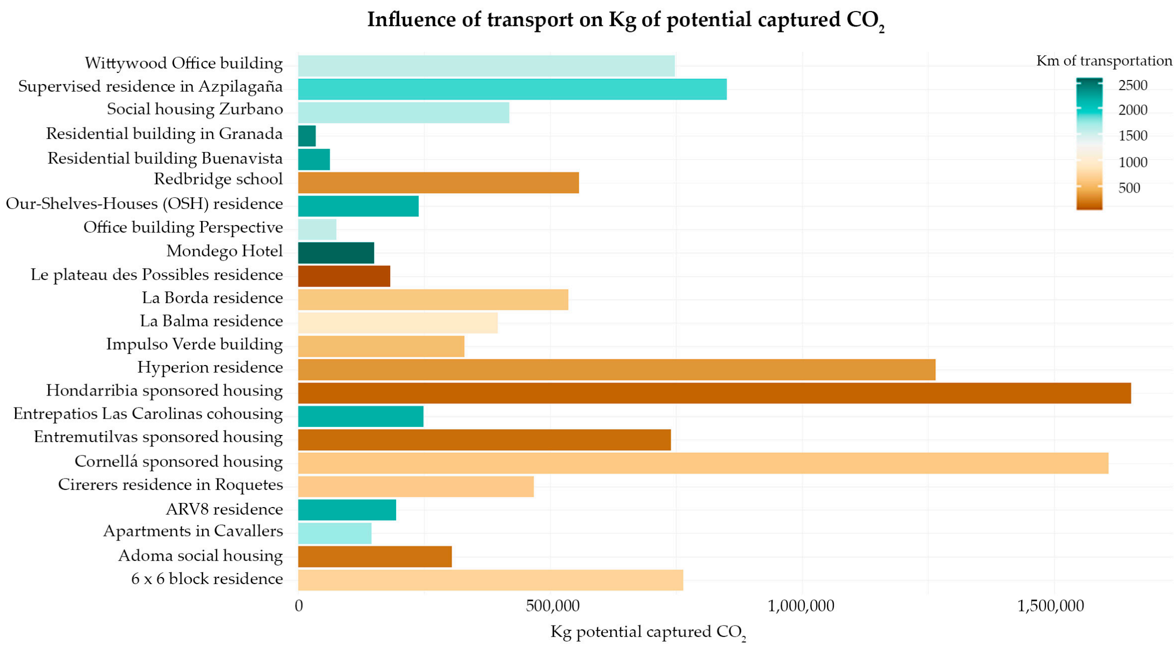



**Figure 14.** Influence of the transportation emissions on the potential embodied $CO_2$.

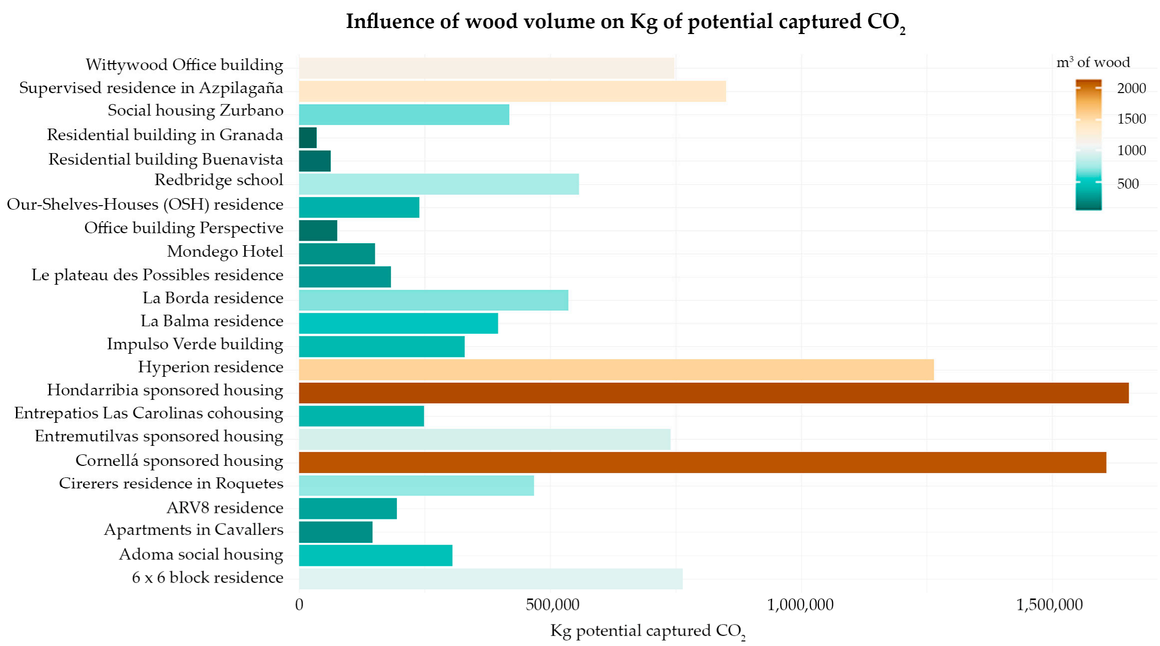



**Figure 15.** Influence of the wood volume of the building structure on the potential embodied $CO_2$.

## 4. Conclusions

The use of timber as a structural material for multistorey buildings (considered in this work as buildings with at least 4 timber floors) is growing in Europe and in the SUDOE area. The number of multistorey timber buildings constructed per year has increased globally, dating from 2013 when the first multistorey timber building was built in the SUDOE region.

Until recent years, timber construction in the SUDOE region involved mostly large-span buildings that employed glulam to solve post and beam structural systems but not multistorey timber buildings. However, this trend is changing, and there are already 39 multistorey timber buildings constructed. This change in trend is associated with the establishment of CLT production plants in the region. The mass timber structural system is currently the most widely used and is consistently associated with residential and mixed uses in both the SUDOE region and the global study. The post and beam structural system is more common in the SUDOE region than globally and is mostly associated with educational and office buildings.

In terms of species, it was observed that even though 21 wood species are included in the European standards for structural purposes, only 4 were observed in the multistorey buildings of the SUDOE region as all of them used softwood species. The predominant species is spruce, in both global and the SUDOE region, but this species is not cultivated in the SUDOE region. However, radiata pine and Douglas fir become more relevant in the SUDOE area, with 28% and 12% of the studied buildings constructed with these locally cultivated species.

The tallest timber buildings (>30 m) are designed with a mixed structural system. The average slenderness ratio of the SUDOE buildings is 1.43, with the Hyperion building (57 m high and 18 floors) being the slenderest, with a ratio of 2.98.

There was no clear influence of the structural typology on the wood volume per square meter in the SUDOE buildings studied, but there was an influence of the building use.

The average ratio of $m^3$ of wood per $m^2$ of built area in SUDOE was 0.32 $m^3/m^2$, with most buildings varying between 0.3 and 0.4 $m^3/m^2$.

It was found that as the wood volume increases, more kg of $CO_2$ are stored in the buildings. However, when more wood volume is used, more emissions are generated during its transport. The benefits of the embodied $CO_2$ in buildings do not take into account material optimisation, i.e., if the structural design is more efficient and less wood is used for the building, less $CO_2$ is embodied in the building, and fewer environmental bonuses are obtained, even if wood volume is saved and remains available in the forests or for other uses. Therefore, further studies analysing both standard criteria together are needed.

**Author Contributions:** Conceptualization, L.-A.B., G.L. and P.V.-C.; Methodology, L.-A.B., G.L. and P.V.-C.; Investigation, L.-A.B., V.B., G.L., G.C. and P.V.-C.; Data Curation, G.L. and P.V.-C.; Writing—Original Draft Preparation, V.B., G.L. and P.V.-C.; Writing—Review & Editing, L.-A.B., V.B., G.L., G.C. and P.V.-C.; Visualization, G.L. and P.V.-C.; Supervision, L.-A.B. and V.B.; Project Administration, V.B. and G.C.; Funding Acquisition, V.B. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Interreg SUDOE program co-financed by FEDER funds through the Eguralt project (SOE4/P1/E1115) and EUFORE project (No 101081788), funded by the European Union through the Horizon Europe program.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors would like to thank the actors involved in the realization of the buildings evaluated, such as architects, engineers, public and private promotors, administration staff, companies, etc., who contributed to this work by providing valuable information.

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

## Appendix A

The following Table A1 presents the 101 timber buildings studied globally. The 39 from the SUDOE region are highlighted in grey colour. A database of the buildings is collected in the annexes of the open-access Eguralt book [23] and is available for download at https://zenodo.org/record/7692175#.ZGdQM3ZBy3A (accessed on 2 March 2023). The last column of the table indicates the page number of the book containing the information on the buildings data sheets. In addition to the technical data obtained from the literature review, buildings whose data were completed with the request form and study visits are identified.

**Table A1.** The 101 buildings studied.

| Id | Building Name | City | Country | Request Form | Visited | Pages |
|---|---|---|---|---|---|---|
| 1 | JO&JOE hotel | Gentilly | France | | | 136 |
| 2 | Îllot Bois Sensations | Strasbourg | France | | | 137 |
| 3 | Office building ZAC Joseph Bedier | Paris | France | | | 130 |
| 4 | Bains-douches in Castagnary | Paris | France | | | 138 |
| 5 | Jules Ferry Residence | Saint-Dié-des-Vosges | France | | | 126 |
| 6 | Lucien Cornil student residence | Marseille | France | | | 131 |
| 7 | L'Etoile des Sybelles residence | Villarembert | France | | | 141 |
| 8 | Office building Palazzo Méridia | Nice | France | | | 144 |
| 9 | Office building Enjoy | Paris | France | | | 132 |
| 10 | Passage Marie residence | Saint-Ouen | France | | | 138 |
| 11 | FILAO residence in Clichy | Clichy | France | | | 142 |
| 12 | Althéa residence | Vélizy-Villacoublay | France | | | 141 |
| 13 | Campus Aquarel | Issy-les-Moulineaux | France | | | 138 |
| 14 | Seine-Ouest residence in Paul Bert | Issy-les-Moulineaux | France | | | 143 |
| 15 | Carre Michelet | Puteaux | France | | | 137 |
| 16 | Pulse in Saint-Dennis | Saint-Denis | France | | | 137 |
| 17 | Office building Perspective | Bordeaux | France | ✓ | ✓ | 167–170 |
| 18 | Woodwork office building | Saint-Denis | France | | | 143 |
| 19 | Amarante à Bezons residence | Bezons | France | | | 142 |
| 20 | Wood'Art—La Canopée | Toulouse | France | ✓ | ✓ | 287–301 |
| 21 | Hyperion residence | Bordeaux | France | ✓ | ✓ | 305–325 |
| 22 | La Borda residence | Barcelona | Spain | ✓ | ✓ | 329–363 |
| 23 | Comunidad Habitacional in Glòries | Barcelona | Spain | | | 151 |
| 24 | Supervised residence in Azpilagaña | Pamplona | Spain | ✓ | | 183–186 |
| 25 | ARV8 residence | Madrid | Spain | ✓ | ✓ | 187–190 |
| 26 | Lignum building | Manresa | Spain | | | 140 |
| 27 | 6 × 6 block residence | Gerona | Spain | ✓ | ✓ | 191–194 |
| 28 | Cirerers residence in Roquetes | Barcelona | Spain | ✓ | | 195–198 |
| 29 | Apartments in Cavallers | Lérida | Spain | ✓ | | 199–202 |
| 30 | Redbridge School | Lisbon | Portugal | ✓ | | 203–206 |
| 31 | Kajstaden-Tall Timber residence | Västerås | Sweden | | | 140 |
| 32 | Tamedia office building | Zürich | Swiss | | | 126 |
| 33 | Skellefteå Cultural Center | Skellefteå | Sweden | | | 149 |
| 34 | Mjøstårnet tower | Brumunddal | Norway | | | 139 |
| 35 | HoHo tower office building | Vienna | Austria | | | 136 |
| 36 | The Stadthaus residence | London | UK | | | 123 |
| 37 | Whitmore Road | London | UK | | | 125 |
| 38 | Via Cenni social housing | Milan | Italy | | | 127 |
| 39 | Moholt 50/50 Towers | Trondheim | Norway | | | 130 |
| 40 | Brock Commons student residence | Vancouver | Canada | | | 131 |
| 41 | 25 King office building | Brisbane | Australia | | | 132 |
| 42 | BC Wood Innovation and Design Centre | Prince George | Canada | | | 127 |
| 43 | MFH Holzhausen residence | Steinhausen | Swiss | | | 123 |
| 44 | Arborea Bègles social housing | Bègles | France | ✓ | ✓ | 207–210 |
| 45 | Hondarribia sponsored housing | Hondarribia | Spain | ✓ | | 211–214 |
| 46 | Hall of residence—Le Luzard II | Noisiel | France | | | 132 |
| 47 | Euratech IBM office building | Lille | France | | | 133 |
| 48 | Entrepatios Las Carolinas cohousing | Madrid | Spain | ✓ | ✓ | 215–218 |
| 49 | Talco cohousing | Madrid | Spain | | | 150 |
| 50 | Bois Debout residence | Montreuil | France | | | 129 |
| 51 | Residential building Buenavista | Madrid | Spain | ✓ | ✓ | 219–222 |
| 52 | Residential building in Hierbabuena | Madrid | Spain | | | 150 |

**Table A1.** *Cont.*

| Id | Building Name | City | Country | Request Form | Visited | Pages |
|---|---|---|---|---|---|---|
| 53 | La Balma residence | Barcelona | Spain | ✓ | ✓ | 367–403 |
| 54 | Residential building in Gracia | Barcelona | Spain | | | 128 |
| 55 | Barbican Oak Tower | London | UK | | | 151 |
| 56 | ExpoMilán 2015 Chile Pavilion | Temuco | Chile | | | 128 |
| 57 | UBC Earth Systems Science building | Vancouver | Canada | | | 124 |
| 58 | Impulso Verde building | Lugo | Spain | ✓ | ✓ | 407–443 |
| 59 | SILVA tower | Bordeaux | France | ✓ | | 231–234 |
| 60 | Siège de la Caisse d'Épargne | Dijon | France | | | 143 |
| 61 | Mondego Hotel | Coimbra | Portugal | ✓ | | 235–238 |
| 62 | Cornellá sponsored housing | Cornellá de Llobregat | Spain | ✓ | ✓ | 447–467 |
| 63 | Forté apartments | Docklands Victoria | Australia | | | 124 |
| 64 | Office building T3 Bayside | Toronto | Canada | | | 150 |
| 65 | Bullitt Center | Seattle | USA | | | 126 |
| 66 | Bridport residence | London | Uk | | | 124 |
| 67 | Residential building in Granada | Granada | Spain | ✓ | | 243–246 |
| 68 | Entremutilvas sponsored housing | Mutilva | Spain | ✓ | | 247–250 |
| 69 | Mining sett. Pérez Caldera—los Bronces | Lo Barnechea | Chile | | | 129 |
| 70 | Sadthaus E3 residence | Berlín | Germany | | | 123 |
| 71 | Residential building in Baleares | Palma | Spain | | | 148 |
| 72 | Dalston Works residence | Hackney | Uk | | | 131 |
| 73 | Rovereto social housing | Verona | Italy | | | 141 |
| 74 | Le Haut-Bois social housing | Grenoble | France | | | 138 |
| 75 | Fair-play residence for athletes | Toulouse | France | | | 141 |
| 76 | Social housing Zurbano | Sabadell | Spain | ✓ | | 251–254 |
| 77 | Wittywood office building | Barcelona | Spain | ✓ | ✓ | 471–505 |
| 78 | Our-Shelves-Houses (OSH) residence | Madrid | Spain | ✓ | ✓ | 259–262 |
| 79 | Baobab skyscraper | Paris | France | | | 150 |
| 80 | Carbon 12 residence | Portland | USA | | | 135 |
| 81 | UPNA Faculty of Health Sciences | Pamplona | Spain | ✓ | | 263–266 |
| 82 | Wooden apartment block | Paris | France | | | 140 |
| 83 | Office building Kibori | Nantes | France | | | 133 |
| 84 | Sous le Signe du Bois residence | Vélizy-Villacoublay | France | | | 142 |
| 85 | Quai de la Borde residence | Ris Orangis | France | | | 129 |
| 86 | Tour Bois Treed it student residence | Champs-sur-Marne | France | | | 147 |
| 87 | Crous Josephine Baker student residence | Pessac | France | ✓ | ✓ | 267–270 |
| 88 | Le plateau des Possibles residence | Bègles | France | ✓ | ✓ | 271–274 |
| 89 | Wood'up residence | Paris | France | | | 146 |
| 90 | Adoma social housing | Toulouse | France | ✓ | ✓ | 275–278 |
| 91 | La Courneuve social housing | La Courneuve | France | | | 136 |
| 92 | Le Conopeé social housing | Bayonne | France | | | 125 |
| 93 | Muros de Nalón Passive social housing | Muros de Nalón | Spain | | | 139 |
| 94 | London Barrets Grove | London | UK | | | 131 |
| 95 | Santa Cruz Campezo social housing | Santa Cruz de Campezo | Spain | | | 124 |
| 96 | Ywood Nexity office building | Rennes | France | | | 136 |
| 97 | Descartes social housing | Tremblay-en-France | France | | | 140 |
| 98 | Abélia residence | Bry-sur-Marne | France | | | 142 |
| 99 | Les Ardennes | Paris | France | | | 130 |
| 100 | Vertou multi-storey residence | Vertou | France | | | 125 |
| 101 | Les Magnolias student residence | Toulouse | France | | | 130 |

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