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A review of structural, thermo-physical, acoustical, and environmental properties of wooden materials for building applications

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ABSTRACT

The current environmental and energetic crisis and the resulting regulations led to a new interest in using sustainable materials for building applications. Wood can be a material with high sustainable rates because it is recyclable, reusable and naturally renewable. Moreover, its excellent strength-to-weight ratios, thermal insulating and acoustical properties make it useful for different kinds of applications in buildings, ranging from structural beams and frames, insulating envelopes, windows, door frames, to wall and flooring materials and furniture.

Although wood is commonly classified as a sustainable material, its real sustainability depends on different issues: appropriate forest management, manufacturing methods and site assembly, distance required for transportation and use of glues. Wood has also good seismic performances due to its lightweight and even if timber elements are not able to have a ductile behavior, using steel connection allows to build dissipative structure, as well platform frame and X-LAM panels systems. Insulation properties are related to low thermal conductivity values. Furthermore, wooden elements can be used to minimize sound transmission and they can be employed as sustainable materials as several Life Cycle Assessment studies demonstrate.

This review paper aims to analyze the structural, thermal, acoustical and environmental properties of wooden materials for building applications; other properties such as fire resistance and durability were also taken into account. The work is completed by several tables and graphs with wood properties and by an updated and thorough reference list.

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Nomenclature

CLT	Cross Laminated Timber
GLT	Glued Laminated Timber
LVL	Laminated Veneer Lumber
LSL	Laminated Strand Lumber
K_{mod}	Modification factor to strength values, allowing for load duration and moisture content [-]
K_{def}	Modification factor for the evaluation of creep deformation that takes into account the relevant service class [-]
q	Structure behavior factor
ρ	Density of a material [kg/m^3]
c_s	Specific heat [J/kgK]
λ	Thermal conductivity [W/mK]
U-value	Thermal transmittance [W/m^{2}K]
R	Thermal resistance [m^{2}K/W]
D	Thermal diffusivity [m^2/s]
RH	Relative humidity [g/kg]
g_v	Water vapor flux density [kg/m^{2}s]
p	Water vapor partial pressure [Pa]
δ_0	Water vapor diffusion coefficient in air [kg/msPa]
μ	Water vapor diffusion resistance factor of the material [-]
d	Dry density [kg/m^3]
M	Moisture content (percent of dry weight) [%]
c_0	Specific heat of dry wood [kJ/kgK]
c_w	Specific heat of water [kJ/kgK]
a_0	Constant [m^4/s^{3}K]
a_1	Constant [m^4/s^{3}K]
A	Correction term [kJ/kgK]
k_0	Constant [W/mK]
R_w	Airborne Sound Insulation [dB]
L_n	Impact Sound Insulation [dB]
α	Sound absorption coefficient [-]
LCA	Life Cycle Analysis
EE	Embodied Energy
GWP	Global Warming Potential
CED	Cumulative Energy Demand
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene Insulation

1. Introduction

The application of wood in the history of architecture is characterized by tree main phases [1]. Before 1850 wood was an irreplaceable material for buildings. Since the XIX century a decrease in the use of wood was recorded and new structural and building materials replaced wood. From the 1970s the renewable and versatile properties of wood gained increasing importance, starting a new phase for wood products. In particular, over the past 10–15 years wood architecture has grown and new wood building systems and design strategies have been developed. This led wood to elevate from a mainly single-family residential standard to compete with concrete and steel construction for a several types of building, considering also the high rises. Consequently, it is possible to observe several case studies (e.g. in United Kingdom, Norway, Sweden, Germany, Austria, Italy, Canada, United States, New Zealand and Australia) that show innovative design strategies and construction details in wood applications [2].

In the history of construction wood was the first and for a long time the most important building material for load-bearing structures. If at the beginning using wood was mainly due to its manufacturing and lightness characteristics, today the choice of this material is determined by specific characteristics and properties, such as: realization in environmental friendly conditions, availability and manufacturing options without high energy from fossil fuels employment, valuable ratio between weight and resistance, wide spectrum of density and resistance values, high thermal resistivity combined with good thermal insulation properties, different external characteristics and aspects [3]. Nowadays, the design and construction industries embrace again wood, which has regained prominence through innovations in the construction methodologies. This material is now diffused and often employed in the building construction sector; for instance, it is in use as cross-laminated timber in projects like Curt Fentress's Raleigh-Durham International Airport. Furthermore, wood structural properties are connected to its anisotropic characteristics while its lightweight guarantees low inertial forces during seismic exposure. In addition, the seismic design of timber structures is based on the distribution of many steel connections with small diameters that can dissipate a lot of seismic energy before failure [4]. Many findings in the national and international literature demonstrate the high safety level of buildings completely realized with wood; they are also widely diffused in different parts of the world (North America, Japan, Northern Europe, New Zealand) in which wood is normally used and often preferred for residential and public constructions. In Italy, wood was used until a few decades ago, mainly as renovation material for structural elements in historical buildings and for roofs constructions, but it was not exploited as a building material for structures realization; this due to the replacement of such traditional material with newer materials, such as reinforced concrete and steel (from early twentieth century). Currently, since the improvement in industrial manufacturing lead to a high level of prefabrication, timber structures have found a specific area in the field of structural engineering, starting from residential buildings, up to multi-story structures, bridges, and schools (see Fig. 1). Wood is again taken into account thanks to the various aspects of the working processes, which have led to a large variety of elements and details in terms of geometry and mechanical characteristics, by

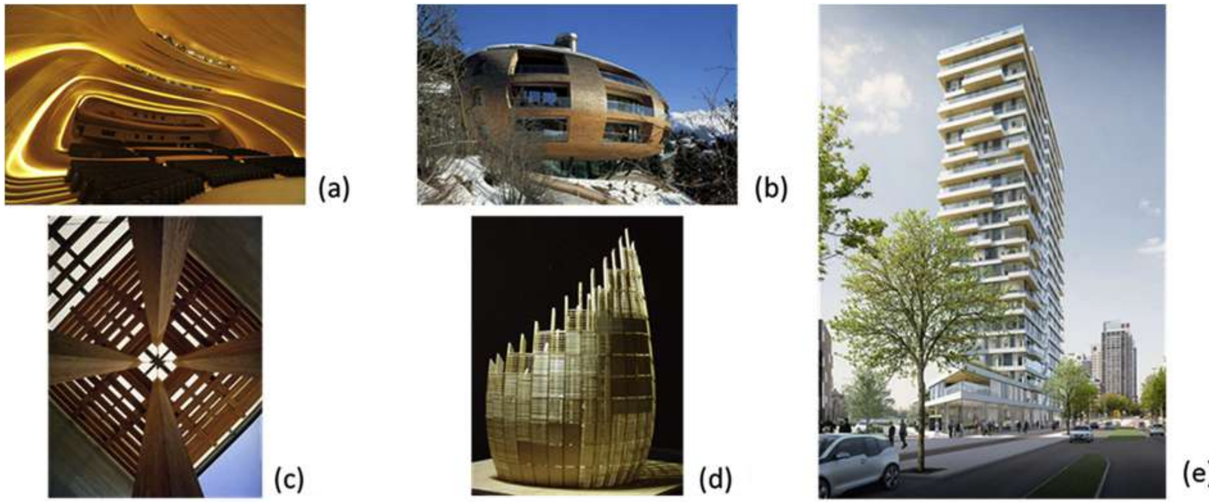

Fig. 1. Examples of different application of timber structures in contemporary architecture: **(a)** Zaha Hadid, Baku Auditorium (2013); **(b)** Norman Foster & Partners, Chesa Futura St. Moritz (2003); **(c)** Tadao Ando Japanese Pavilion, Seville Expò (1992); **(d)** Renzo Piano, copy the wood screen technique of the Jean-Marie Tjibaou Cultural Center, Noumea, New Caledonia (1991–1998); **(e)** ARUP, Haut, the residential tower located in the Amstelkwartier (Netherland).

reducing the presence of natural defects.

Moreover, despite the common opinion, wood has better performance towards fire than other materials such as steel, because its mechanical properties do not change with high temperature. Wood, if properly designed, can last centuries (the roof of churches are an example): in North America 80% of residential buildings, including multi-story, are wooden and some of them exceed 100 years of life. The concept of durability of a structure, defined as “conservation of physical and mechanical properties of materials and structures to ensure that safety levels are maintained along the entire structures life”, according to the Italian and European Building codes [5,6], is an essential requirement for the structures design as the mechanical strength and stability. Taking into account timber structures, the material knowledge and the correct elements design and construction details, together with a proper maintenance schedule, allow reaching the levels of nominal life of the structure prescribed by the Regulations.

The thermal properties of wood as a building material are strictly connected with the interaction with environmental moisture. For this reason it is important to study the hysteresis of sorption of humidity and its dependence with temperature [7]. The incorrect control of sorption hysteresis in wood elements can cause mould growth and the rapid deterioration of the construction elements. Wood has good insulating performance and it is possible to create insulation panels with wood fibers, flakes, and particles of various dimensions. The application of insulating panels is usually in the external part of the wooden buildings to avoid the effects of thermal bridges linked to the discontinuities of envelope materials in wooden frame constructions (e.g. in correspondence of studs). The influence of thermal bridges sometimes can't be neglected and the transmission coefficients given by the catalogues are slightly accurate [8]. Considering an approach in which the aim is to mitigate environmental impacts and climate change, the substitution of energy and CO_2 intensive materials, like concrete, with wood can be a good solution. It has been demonstrated that timber structures cause lower CO_2 emissions during their life cycle in comparison with concrete, steel or brick-based systems [9], even though considering the costs of the material and of the emitted CO_2, timber frames could not be cost-effective in comparison with concrete ones [10]. It is worthy to notice that carbon reduction is an important advantage of wood buildings. One cubic meter of structural lumber stores 0.9 tons of CO_2, which the tree has absorbed from the air. In addition, the glulam in the building's structural frame replaces materials such as concrete and steel. Furthermore, this type of buildings is faster to build and caused less disruption and less waste than a concrete building characterized by the same size. Wood, which is among the oldest building materials employing for construction, has become one of the newest and most innovative constructive technology thank to the use of mass timber technologies (cross-laminated timber and glue-laminated timber) [11].

The use of wood for building applications has advantages and disadvantages that have to be taken into account in the design of architectural wooden details. Therefore, an integrated design of wooden buildings is desirable in order to consider all the different aspects of wood products application. This review paper aims to analyze critically the structural, thermo-physical, acoustical and environmental properties of wooden materials for building applications.

2. State of the art of structural typologies for residential buildings

The main types of timber framed structures can be divided in the following way:

- *Balloon Frame Structures* (Fig. 2a). This technique is no longer used today but was significantly diffused in the past. The Balloon frame is composed by standardized strips, studs and horizontal boards all connected by nails. The main characteristic is that studs are not interrupted by floors slabs and a continuous wall cavity extends from the foundations to the roof.
- *Platform Frame Structures* (Fig. 2b). This system employs shorter, lighter pins that are easy to handle and are interrupted by the insertion of the floors that are distinct horizontal platforms and this makes it an easier method during the construction phase. The applications range from residential building to care homes, hostels and students' accommodations characterized by a cellular-plan and by an up to seven storeys height.
- *Timber Frame Structures* Timber Framing, also called post and beam, is composed by timber beams and columns jointed together with wooden pegged mortises and tenon joints.

Fig. 2. Different structural typologies for residential buildings: Balloon frame (a), Platform frame (b).

Diagonal bracing is used to prevent the movement of structural vertical beams or posts.

- *Block-Bau System* (Fig. 3a). This technique allows to construct a building overlaying square-section trunks to create a vertical wall. Snap fit connections are achieved at the corners and this procedure allows the structure hardening. By employing this technique, the created elements are distinguished by two dimensions smaller than the third one. The applications are manly in the residential sector with one story buildings.
- *X-LAM Structures* (Fig. 3b). This construction system, also known as Cross Laminated Timber (CLT), is based on the use of load-bearing elements consisting of solid wood panels that are crossed glued crossed layers. The use of the X-LAM is very adaptable and it allows constructing walls, floors and roofs for

Fig. 3. Block-Bau System [12] (a), X-LAM structure (b).

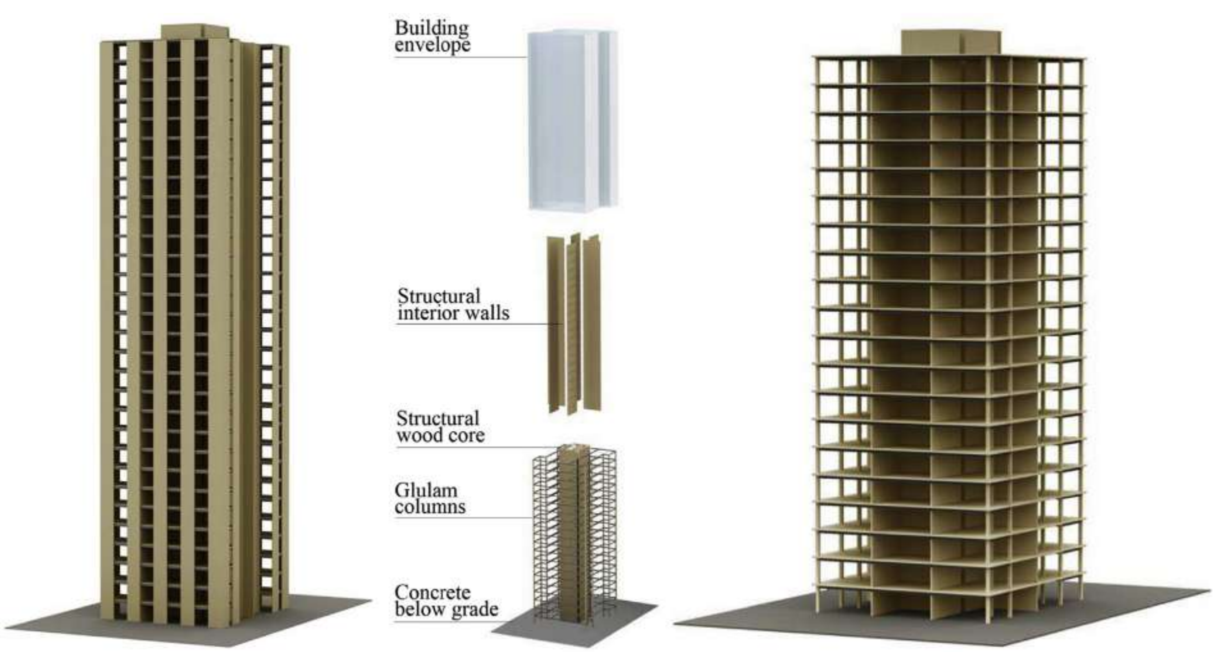

Fig. 4. Tall building structures [13].

buildings of various typologies: multi-storey residential buildings, schools, auditoria, exhibition places, places of workship, sports halls, theatres and commercial buildings.

- *Tall building structures* (Fig. 4). The structural system is generally composed by an external glulam heavy frame coupled with and internal core of CLT units that resist to lateral loads; CLT panels employed in floors or in the perimeter of the building are lateral straightening systems and additional support is also provided by the interior walls. The CLT core is sometimes substituted with a reinforced concrete one, that can also provide lateral stability, connected to a glulam frame straightened with CLT shear walls.

The use of wood for buildings dates back to the prehistoric age when people used to erect stilt houses in order to avoid the contact with the water in the ground. The other system that has strong links with the prehistoric age is the blockbau, or log-house, and it represents still now a traditional construction system in Alps and Scandinavia: even if this type of construction has been overcome since the 90s, there are still cotemporary architectures based on this traditional timber construction system (see Fig. 3a). Block-bau systems have high deformability because wood is stressed in a direction that is perpendicular to the fibers and the high variation in vertical dimension have to be supported by windows and finishes.

The timber frame system can be considered as a subsequent technique but it is also one of the oldest known form of wood construction and no-one knows exactly how it started or when (e.g. Ise Temple in Japan was built in 690 A.D.). Timber frame homes were typical across many American and European cities until the late 1800s. Typically, if the house was built before the 1830s it is probably a timber frame home.

The advent of balloon frame dates back to the beginning of nineteenth century when American pioneers used to build houses with the Balloon Frame technique. From the 1890s until the 1930s it was the most common form of construction in the USA. This kind of framed structures are light and allow rapid constructions with no heavy equipment. On the other hand, these are not strong enough to resist major wind events (tornadoes and hurricanes): they got the name rather dubiously because such a weak form of construction would be carried away like a balloon due to the slightest breeze. Moreover, they are highly flammable: with wall cavities that are typically uninsulated and run the entire height of the building, fire is able to spread quickly.

By the 1930s the risks associated with balloon framing had become apparent so the housing industry came up with the next structural typology called platform framing. A break between each floor, that was not present in the balloon frame, created the fire block and ensures an easier construction of the entire building proceeding floor by floor. The first application probably took place in St. Marie Church in Chicago in 1930. Initially the platform frame system was constituted by light lumber frame for vertical bearing capacity and lumber bracing elements (beams) for supplying horizontal actions (wind and seismic actions). Now the lateral bracings are substituted by shear wall, made by wood based panels such as Oriented Strand Board (OSB) panel. This construction system is rapidly spreading in many European countries, including Italy It is a system that, in addition to the rapid implementation, allows obtaining a good static and seismic safety.

The contemporary architecture shows the spread of X-LAM structure for single storey residential buildings. In 2000 the Italian market did not know this product, today it has spread very fast and it is considered one of the most interesting constructive solutions for the residential building industry. Among the existing buildings systems, the X-LAM construction system aims at defining the performance and potential of a system for multi-story buildings construction characterized by high mechanical performance and low power consumption energy, excellent levels of safety against fire and earthquake, acoustic comfort and durability over time. Compared to other wooden construction methods, in fact, CLT systems are more suitable for multi-storey buildings due to their mechanical characteristics and due to the possibility of achieving the required fire safety. In recent years there has been a trend of constructing tall commercial or residential X-LAM buildings with floors ranging from five to ten [14]. Tall wooden building structures are based on the hybridization of heavy wood structural systems that are able to resist to high loads. These types of constructions are not located in seismic areas and the research about their behavior under lateral loads is developing.

2.1. Classification of wooden materials for buildings applications

Recently the wood productions for building application have shown a progressively reduction of size of the material that characterize them. The original sawn timber sections, as cut from the tree trunks, have been first reduced to laminated boards, then to veneers and finally to strands, particles and fibers. The use of adhesives and fasteners has permitted to reconstruct structural load bearing engineered wood products and different types of panels. The reduction of the size of particles permits to utilize the forest resources in a more efficient way also employing low grade logs getting anyway very much more uniform properties. Engineered wood products in general have better material properties and structural performance than the original sawn timber in term of predictability of performance, large range of available sizes, dimensional consistency, dimensional stability and easy treatability. Fig. 5 reports a classification of the main wood products for building applications.

2.1.1. Solid wood

Solid wood is one of the most traditional materials used in building and currently is mainly being used for restoration and replacement of existing structures but also for new buildings. Solid wood products are extracted from the timber with the best characteristics in terms of size, growth and dimensions. For each trunk it is still possible to derive various elements, different in size and quality. The advantage of a solid wood element is that its structure, compared to the raw material, was subjected to few changes, in particular sawing, natural curing, drying and possibly bonding while the drawbacks are the presence of natural defects (i.e. knots due to the growth of branches, slope of grain) and the limitation on the timber element dimensions depending on the tree dimensions. Massive timber for structural use need to be classified according to its resistance, following the rules reported in the Standard UNI EN 14081 [15]. For timber produced in Italy, the Standard UNI 11035 [16] is applicable and more in general, in order to classify the massive wood from conifers in Central and Southern Europe the DIN 4074 [17] can be applied; unfortunately, some European and extra-European countries did not publish national Standards to categorize timber grown on their territory.

2.1.2. Engineered wood products

These disadvantages of sawn wood in term of length limitations and defects influence on the resistance of the elements are overcome by glulam. In recent years features and quality standards achieved by glued laminated timber (GLT) made it very suitable for its use in structures design and able to meet the needs of the structural design modern approach. The technology is principally based on finger joint, made by cutting a set of complementary rectangular cuts in two pieces of wood and removing the defects; after that they are glued in the transversal direction (see Fig. 6). Defining the efficiency of a wood connection as the ratio between

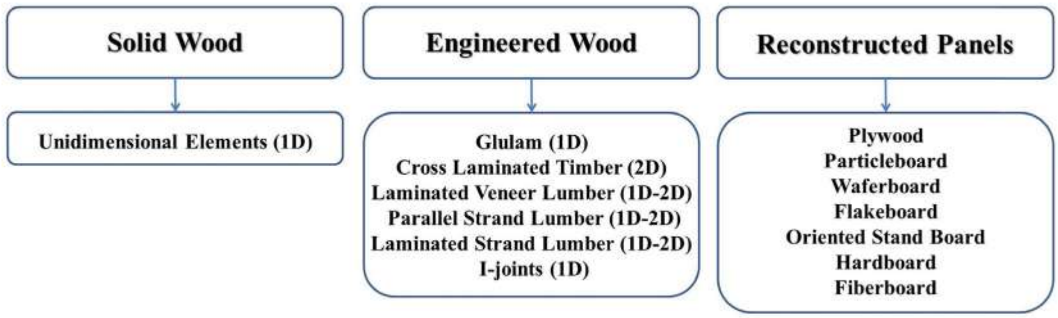

Fig. 5. A classification of wooden materials for buildings application.

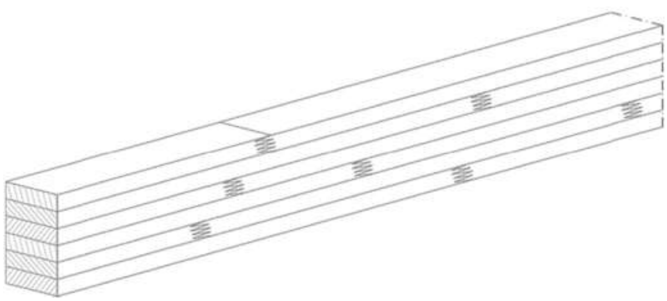

Fig. 6. Finger joints on a glued laminated truss.

the strength of the connection and the strength of the members it connects, the finger joint shows an efficiency of 100%. In general, glued connections guarantee the highest efficiency while the use of steel fasteners like screws and dowels permit to obtain an efficiency of 20–30% [18]. the production of laminated wood elements, manufacturers have to follow the requirements imposed by the Standard UNI EN 386 [19], valid for all European countries, and eventually by more restrictive national regulations. Since 2010 in Italy it has been mandatory to produce and sell elements with CE marking, issued by a Certification Body in accordance to the UNI EN 14080 [20].

The most interesting evolution of structural timber is the “cross laminated timber” (named CLT or X-LAM), which is – as previously said - a panel composed by crossed layers of planks, nailed or glued. This system is characterized by a variable thickness, which ranges from 5 to 30 cm, obtained by gluing crossed layers of boards with an average thickness equal to 2 cm. The panels are carved according to the structural requirements, with openings for doors, windows and stairwells and then connected between themselves in the operating phase. For their characteristics the CLT panels can be used for walls and slabs, creating a construction system named X-LAM panel system (see Fig. 7).

This category of products is very heterogeneous in terms of dimension, composition and production processes and their strong development occurred despite the lack of regulations, both at National and European level.

Laminated Veneer Lumber (LVL) is made from softwood veneers oriented in a single direction or in cross directions to improve mechanical properties and bounded at high pressures and temperatures with a waterproof adhesive. Common used adhesives are phenol formaldehyde and phenol-resorcinol formaldehyde. The requirements for LVL are contained in BS EN 14374:2004 [22].

Laminated Strand Lumber (LSL) is made by long thin strands approximately 300 mm long and 0.8 mm - 1.3 mm thick. The strands are blended, coated with adhesive and oriented so that they are essentially parallel to the longitudinal axis of the section before being reformed by steam pressing into a solid section. LSL is used in I-joints flanges and in similar applications to LVL.

I-joists are made by an OSB web that connects two LVL flanges. I-joists are used in new residential buildings and are preferred to traditional timber joists because of their higher dimension stability.

When considering the engineered wood products, excluding glulam, the absence of uniform normative brings to the absence of a uniform characterization of the mechanical properties and most of the manufacturers provide their own designing tables.

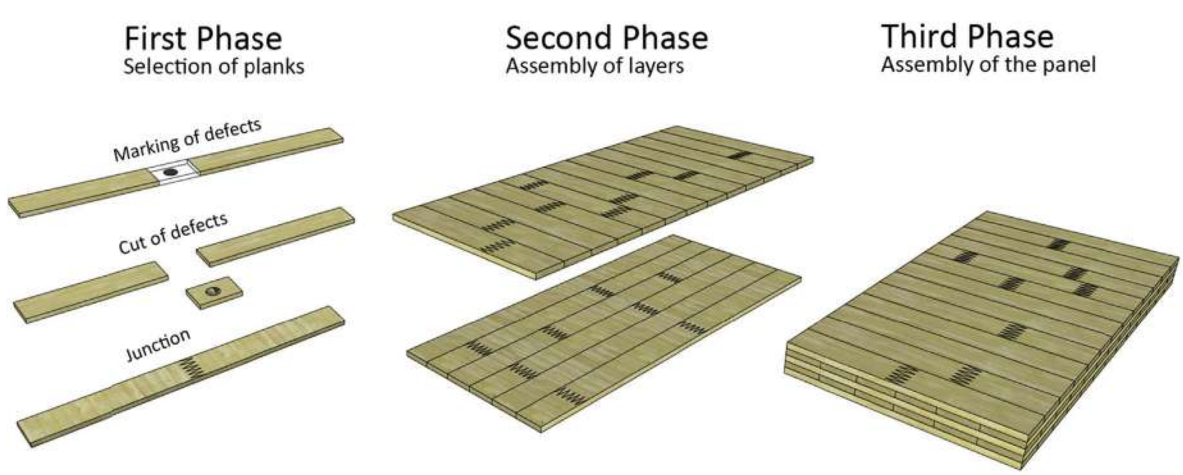

Fig. 7. Fabrication of X-LAM panels [21].

2.1.3. Reconstructed panels

There are many wall panels that can be coupled to wood frames for different purposes like plywood, particleboard, wafer-board, flake-board, Oriented Strand Board (OSB), hardboard, fiberboard (see Table 1). These types can be inserted to add bracing and shear strength to wooden frames or for acoustic and thermal insulation functions. Furthermore, they are very common for finishers (parquet floors, internal coatings, etc.) and furniture. In Europe the wood panels products have to meet the requirements proprieties set by the EN 14915 [23].

3. Structural properties

Wood has good aesthetic and structural characteristics: when comparing it with concrete, wood shows similar properties for both compression and traction that make the pairing with other materials unnecessary; moreover, wooden elements have the same volume as analogous concrete ones but with 1/5 of the weight. The favorable strength-to-weight ratio makes wood an ideal material for all the types of structures that have a high percentage of self-bearing weight in the total loads to be supported. Examples of these kinds of structures are roofs, bridges and tall buildings. Some applications can be tracked in gridded shell structures: wood elements represent an ideal construction material not only for their high strength-to-weight ratio but also for their elasticity that permits an easier site assembly without the need for complex worksite infrastructures. The use of glued connections guarantees the continuity of the shell but in order to improve the environmental burdens of the construction it is also possible to connect the wooden strips with steel elements. Although light structures require, a particular attention for wind loads a minor self-weight is important to reduce the costs in the transportation and construction phase but also for a seismic and foundation point of view because simpler foundations are possible with more and more incidence on costs. Some disadvantages of wood structural applications are linked to the anisotropic behavior with a good resistance in the directions of the fibers and to the heterogeneity characteristics of wood connected to a lot of knots that reduce the resistance performances. Another drawback is the viscous behavior connected to the sorption and desorption of humidity and water that can cause excessive permanent vertical displacements and stresses. Harvested timber, sometimes called "green timber", can have a moisture content of 100% defined as the percentage of water in the timber cell cavities. In order to avoid the dimension instability of green timber when it shrinks and in order to improve its mechanical properties, a natural or accelerated drying is strongly recommended. The Young modulus of wood, that is one third of the concrete, can generate possible problems connected to vibrations,

Table 1
Common sizes and applications of wooden building products.

Product	Elements	Function	Common Size	Applications
Solid wood	Unidimensional: beams, columns, header beams	Load bearing	Length: up to 5,4 m Width: 25–75 mm Depth: up to 250 mm	Structural frames, floors, roofs
Glulam (GLT)	Unidimensional: beams, columns, trusses	Load bearing	Length: no theoretical limit (40 m) Width: from 60 to 250 mm Depth: from 180 up to 2000 mm	Bridges, halls, industrial buildings, arenas, distribution centers, schools, commercial buildings, supermarkets and residential buildings.
Cross Laminated Timber (CLT)	Bi-dimensional: walls, floors, roofs	Load bearing and shear walls	Length: up to 20 m Thickness: 50 –300 mm Depth: up to 4,8 m	Residential and tall buildings, schools, auditoria, exhibition places, places of workship, sports halls, theatres and commercial buildings
Laminated Veneer Lumber (LVL)	Unidimensional: beams and headers beams, columns, trusses, portal frames, post and beam structures, I-joist flanges Bi-dimensional: structural decking, rim boards, stressed skin panels	Load bearing	Length: up to 20 m Width: 19 –200 mm Depth: from 200 up to 2500 mm	Halls, industrial buildings, arenas, distribution centers, schools, residential and commercial buildings and supermarkets.
Laminated Strand Lumber (LSL)	Unidimensional: beams, columns	Load bearing	Length: up to 20 m Width: 30–90 mm Depth: from 90 up to 1000 mm	Post and beam structures
Parallel Strand Lumber (PSL)	Unidimensional: beams, columns	Load bearing	Length: up to 20 m Width: 45 –200 mm Depth: from 200 up to 1000 mm	Post and beam structures
Oriented Strand Board (OSB)	Bi-dimensional	Structural and non-structural	1220 × 2440 mm Thickness: from 9 to 25 mm	Structural sheathing and decking, I-joist web
Particleboard	Bi-dimensional	Non-structural	1220 × 2440 mm Thickness: from 9 to 25 mm	Flooring, ceiling and panel infill
Fibre Board	Bi-dimensional	Non-structural	1,200 × 3,000 –1220 × 2440 mm Thickness: 3-6-12-25 mm	Flooring, ceiling and wind-shield, infill thermal insulation and sound proofing – deadening.
I joists	Unidimensional: floor and roof joists, formwork, ceilings, load bearing or cladding support studs.	Load bearing	Length: up to 20 m Width: 38–97 mm Depth: 200 –500 mm	Principally in new residential buildings.

buckling, instability phenomenon and deformability. Therefore, for timber structures the fulfillment of the service limit state can be more restrictive than the ultimate limit state requirements.

The mechanical design values of wood strength strongly depend on the duration of load application, on temperature and on hygroscopicity. In particular wood has a higher resistance for short term loads than for long loads applications. This effect is linked to the viscoelastic behavior of wood during long periods and due to the humidity of the surrounding ambient. The European Standards [6] considers consider these two effects by reducing the design strength by two coefficients K_{mod} and K_{def}. The latter is used in serviceability limit state to evaluate the long term displacements under quasi permanent loading combination, while K_{mod} for long lasting effects of loads and humidity.

From a seismic point of view and according to building codes [24], in order to account the structural capacity of performing a non-linear behavior, the value of the design response spectrum depends on the behavior factor q that is defined as the ratio between the ductile non-elastic deformation capacity and the linear elastic deformation of a structure. It can be assumed that q accounts for two contributions: the intrinsic inelastic capacity of the structure and the design over-strength that considers both the code partial safety factor and design assumptions [25].

3.1. Seismic behavior of wooden structures

The characteristics that make wood suitable in seismic constructions are: lightness and resistance, viscoelastic properties, deformability. The lightness of wooden structural elements reduces the induced stresses through seismic forces. The viscoelastic properties vary the mechanical properties in function of the duration of load application: in particular, the compression resistance in the direction of the fibers has an increment, in comparison with the design value, of 10% for actions of 20 s duration and of 16% for loads applied for 3 s. The low value of Young modulus makes wooden elements more flexible and deformable and so it influences the sensibility to the seismic action at the operational limit state, corresponding to earthquakes with a short return period.

The wood stress-strain behavior is not ductile and it is a disadvantage from a seismic point of view that brings to the necessity to concentrate the ductility of structures only on steel joints. The structural ductile behavior depends on different variables: the regularity of the structure, the number of storey levels, the number of vertical joints, the slenderness of the structure, the type of connections design. In particular, for timber structures the number of levels increases the number of steel connections in the basis of the walls and the number of vertical joints modifies the ductility and the displacement capacity of the building. Therefore, the mechanism of collapse is strongly governed by the design of the connections based on the capacity design in order to avoid brittle failure. Wooden buildings can manifest good behavior in terms of safety if the connections are right designed: respect of the limits of distance from the borders and between connectors, right type of connection (glue connections have a brittle behavior with respect the ductile behavior of steel connections).

In particular, Loo et al. [26] in their study adapted slip-friction connectors for use as hold-downs in an experimental rigid timber shear wall. The authors demonstrated that this device can be calibrated to cover wall strength to the wanted level. Sarti et al. [27] in their research showed an experimental investigation of the behavior of large-scale posttensioned timber walls. In particular, the authors focused on the system connection optimization of posttensioning anchorage, fastening of the dissipation devices, and shear keys.

In a ductile designed joint the plasticization of connectors precedes the failure of wooden materials. For Eurocode 8 [24] timber structures, as well reinforced concrete and steel structures, must be designed according to the Hierarchy of Resistance Criterion: the structural elements with a ductile behavior must reach the post-elastic phase when the brittle elements are still in elastic phase far from the failure. In platform frame structures three types of collapse appear: relative sliding of the wooden panels, rocking effect and shear deformation. In the last the panels warp maintaining the parallelism of sides and the nailing between panels and frame has high ductile capacity. Rocking effect is controlled through the insertion of hold-downs that are a system with a medium dissipative capacity. Relative sliding causes a brittle collapse of angle brackets and so the hierarchy of resistance is respected if the angle brackets are designed as over strength with respect to hold-downs strength and of nailing. The mechanical characterization of strength and stiffness of angle brackets and hold down has recently been conducted by many authors by means of experimental cyclic tests [28,29]. For cross-lam buildings the hierarchy is ensured if the failure mechanism is governed by hold-downs and vertical joints. Attention must be paid to not over-dimensioned nailing of the hold-downs to prevent brittle collapse. With experimental results Premrov and Kuhta [4] demonstrate the strong influence of fasteners diameters and spacing in walls subjected to lateral forces: decreasing the distance between fasteners is gained a higher failure force. Otherwise the fasteners spacing influences the bending stiffness of the panel. The ductility of the structure is taken into account through q factor [30].

Eurocode 8 [24] classifies structures with $q = 1$ as not dissipative and structures with $q = 3$ as ductile; for sake of safety and luck of knowledge about this new construction system cross-lam structures are actually designed with $q = 2$. The determination of an appropriate value for q factor is not easy because of many source of uncertainty [25]. As an example, the reduced mean q factor values can be observed for cross laminated glued rigid wall panels while higher deformability are observed when glue is replaced by metal staple in cross laminated panels and for layered panels with dovetail inserts.

Many findings in literature present the approach used to analyze the non-linear behavior of structures. Pozza and Scotta [31] in their study present a new numerical model which employs commercial software and shows how it can be used for the estimation of appropriate q factor in multi-storey, cross-laminated timber buildings. Moreover, Pozza et al. [31] show that deformable wooden panels (stapled or layered walls) can be characterized by q factors inferior to 4 while rigid wooden panels (un-joined CLT and joined CLT) can be modeled with a q factor inferior of 3. In particular, CLT joined panels present a higher ductility and displacement capacity connected to the shear failure mechanism instead of rocking one; this guarantees a better behavior during seismic excitation. Sustersic et al. [32] investigate the seismic behavior of four-storey CLT buildings with linear and non-linear finite elements analysis. Values of q factors are derived: it has been shown that the use of more ductile brackets can increase the q factor while the use of non-ductile brackets connections can bring to a decrease in the value of q factor. In seismic timber design the right choice of the proper behavior factor is a fundamental issue but today the seismic codes provide only values for the most common building typologies and different codes usually employ different q factors. Pozza and Scotta [33] shown a new model, based on the application of a commercial software, able to provide a reliable estimation of appropriate behavior factor (q) in multi-storey, cross-laminated timber buildings. Starting from a macro-element approach, the authors demonstrated that the proposed model can reproduce the load–displacement hysteretic response of the steel–wood and wood–wood joints typically used in such structures. Many authors worked on the definition of the q factor by numerical or experimental analyses, among them Ceccotti et al. [25] characterize the q factor of eight different types of timber structures by experimental, numerical and hybrid experimental-analytical methods (see Table 2).

In general timber structures subjected to transversal loads show unacceptable deformations and to increase its stiffness and stability it is useful to insert steel bracings or shear walls. In a lot of multistorey buildings core structures and exterior shear walls represent the structural effective resistance to lateral forces while beam and column framework resist to vertical loads [34]. Several types of innovative shear walls have been proposed by different authors with the frame that support vertical loads and with walls that are designed to resist to horizontal forces [25,35–37]. By an experimental loading cycle, He et al. [35] investigates the lateral performance of a hybrid system composed by a steel moment resisting frame and a light wood frame shear wall. At the initial stage of the loading cycle the infill wood frame causes an initial increase of the lateral stiffness that degrades afterwards when the damage develops into the wood. The connection between the two components guarantees the effectiveness of the infill wood shear wall and the energy dissipation is mainly provided by the wood infill within a drift ratio of 2%.

Another seismic effective hybrid steel-timber structure is presented by Scotta et al. [37]. In this case the vertical loads are supported by steel columns while the seismic behavior is guaranteed by a light timber frame system coupled with OSB panels and an innovative technoprene slab. The quasi static and cyclic loading test [38] and some numerical simulations demonstrate the high values of static ductility and the pronounced dissipative behavior of the proposed shear wall. Pozza et al. [36] presents a new hybrid shear wall formed by platform frame panels with a reinforced concrete shelter screwed at the wooden frames. The seismic characteristics of the proposed wall are determined by a cyclic loading test [38]. The reinforced concrete skin improves the strength and ductility against horizontal loads if compared to the traditional building technologies, like CLT or platform frame systems. According to [38], the q factor can be considered superior to 4.

3.2. Fire resistance

The fire resistance is the ability of a material to maintain for a prefixed time some parameters of mechanical resistance, tightness to smokes and thermal insulation in fire conditions or high temperature. As concerns complete building elements (wall, window or door) on the other hand, fire resistance is defined as the decision criterion in the 13501 Part 2 standard [39]. In the EN 13501 Part 1 series of standards, the reaction to fire of construction and building materials is divided into several classes (Euroclass A1, A2 and B through F).

Nowadays wood is commonly used in the building sector and wooden elements need an adequate fire resistance so that the fire is contained within the environment where it is originated. In order to guarantee the encapsulation of fire, wood walls and floors are usually covered by a layer of gypsum board or other nonflammable materials. Furthermore the active control fire systems, like sprinklers, are embedded in the buildings and they lower significantly the life risk to the occupants in the room where the fire origins [40]. It has also been shown that life safety performance of buildings depends more on design solutions than on the typology of the building (e.g. high or mid-rise, combustible and non-combustible or light framed and CLT ones). The fire structural collapse is not actually very common but in case it occurs it can cause death. Wood has a flash over temperature of about 220–250 °C and generates great energy of combustion (about 4400 kcal/kg). The mechanism of combustion is characterized by four main phases: until 110–115 °C the mechanical properties of wood remain unchanged, then we have the propagation phase until about 200 °C when there is the flash over; after that the effects of fire decrease because of the absence of more combustive materials. The mechanism of diffusion of fire in the wooden material is composed by two directions of heat propagation: the dispersion to the external ambient is governed by convection, transpiration of hot vapors and irradiation; the flux to the interior of the element happens by conduction and radiation. When a stationary condition is reached we have a superficial carbonized part that loses material, a zone of pyrolysis and an integral internal zone that recedes with a velocity of about 0,6–0,7 mm/min. The layer external to the residual intact cross section is called zero-strength layer (see Fig. 8).

Wood is a very bad conductive material and under fire conditions it maintains good properties of resistance; when we compare wood with other conductive materials, like steel, the percentages of residual resistance of sections are higher with the increase of temperatures. Moreover, while in steel sections intumescent paint is necessary to prevent fire collapse, the external carbonized zone of wood acts itself as fire protection. The inner part, under the pyrolysis zone, can so be considered intact. Moreover, the absence of thermal dilatation prevents structural collapse for thermal deformations. According to Eurocode 5, a simple method for the design of timber members exposed to fire is the Reduced Cross-Section Method (RCSM), using an effective cross-section and mechanical properties at normal temperature. The structural approach in the verification of fire resistance is to begin with the carbonization velocity and resistance time in order to define an effective reduced cross section of structural elements. The fire design has a strong influence on the dimensions of structural wood elements.

Although RCSM is very common and easy for applications, in recent years a discussion on the reliability of the method has arisen as some advanced simulations have shown some limitations and contradictions. Schmid at al [42]. recommend a revision of RCSM after a comparison between resistance tests and RCSM results. After the revision of 153 fire tests large variations in the zero-strength layer are observed with good agreement for members subjected to tension differently for members subjected to compression or

Table 2
Structure behavior factor (q) of different timber structures types by experimental, numerical and hybrid experimental-analytical methods [25].

Timber structure	q (mean quasi static test)	q (mean numerical method)	q (mean hybrid method)	Eurocode 8
Blockbau wall	5	1,4	7,2	1,5
Layered wall with dovetail insert	2,5	4,6	3,6	–
Un-joined CLT wall	1,5	2,8	3,6	–
Joined CLT wall	2,4	3,5	3,3	–
Stapled wall	3,3	4,7	3,7	–
Light frame timber wall	4,1	5,0	4,1	5
Heavy frame timber wall	2,6	5,1	3,3	–
Mixed wood-concrete frame wall	5	4,2	5,0	–

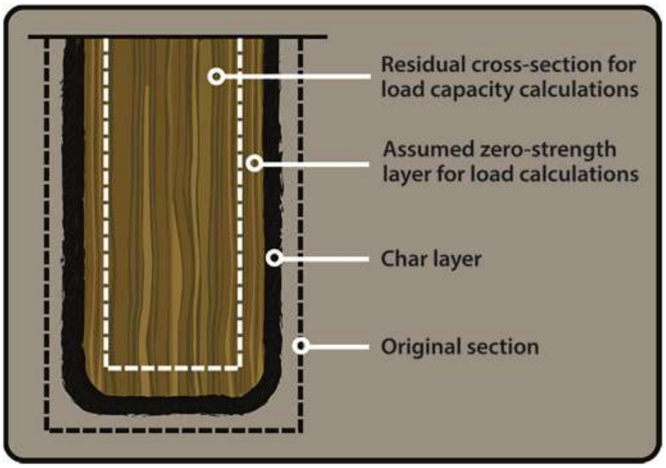

Fig. 8. Illustration of zero-strength layer model of fire-damaged wood beam [41].

bending.

There is a lot of literature about how load-bearing timber elements perform during fire events but there are still some areas where more research is needed, principally about tall buildings behavior in fire [43]. It is well known that greater is the structural demand compared to capacity, that is the load ratio, the worse is the expected fire performance [44] but the tests are based on single elements while in a real fire event the heating involves parts of the structural system. An interesting issue is how the different elements of the structure redistribute loads when they kindle and what is the complete structural response in term of continuity, restraints, connections ductility and failure modes. These kinds of topics require large scale testing that involves frames and assemblies instead of single elements. On the other hand numerical modeling can be complex and more developments are required for a practical use [45]. Modeling permits to assess the temperature distribution in a compartment and, based on this distribution, the structural response determines the structural failure time of an assembly and the deflection of wood beams under constant and cyclic loading and fire [46,47]. By means of a numerical analysis, the determination of the dynamic fire performance of a wooden beam, under ISO 834 [48] and mechanical loads, permits to predict the time to structural failure [49] but it is necessary to validate the model through experimental tests.

In tall buildings composite assemblies, like concrete-timber, are usually employed to provide fire resistance and also acoustics soundness and stiffness. As new composite structures are developing, new fire tests for these systems should be necessary and may include both single elements test and large scale tests. When considering steel-wood assemblies, the weakest parts, in case of fire, are the metallic connections between wooden elements: steel shows a strong reduction of its mechanical properties at high temperature, moreover it is a conductive material and transports heat quickly into the interior parts of the wooden section causing the carbonization not only in the external surface (see Fig. 9). This effect anticipates the collapse of joints while wooden sections are still capable to support loads. The fire resistance of not protected joints doesn't often exceed R30 so it is useful to protect them with a wooden cover or with high performance materials like gypsum boards. Moreover, in tall buildings the contribution to compartment fire dynamics of the use of CLT should be better evaluated and quantified: when exposed to fire CLT chars and separates from the structure increasing the amount of fuel burning material in the room. More research is also needed to prevent fire propagation through timber facades, for fire stopping in concealed spaces and penetrations for services, and for circulation elements in vertical timber cores.

Wooden low density panels are widely used for interior coatings. These elements contribute in a significant way to the fire load in the constructions. Using both Kissinger and Coats-Redfern models Jian Ge at al [51]. studied the kinetic degradation of wooden panels in fire. They ordered the different types of boards simulated by activation energy, carbon residue rates and onset pyrolysis temperature. From the activation energy point of view, the boards were ranked as follows: core-board, pine board, density board, plywood, particle board. The study shows how particle board are the easiest wooden panels to pyrolyse while core-boards have the best thermal stability.

3.3. Durability

The principal factors affecting the durability of wooden building elements are the interaction with water and with biological agents. The durability of wooden building materials is strictly connected to the interaction with moisture and is characterized through the classes defined by the standard UNI EN 350 [52]. Withdrawal and swelling, if bounded, can cause cracks, warping of wood elements, ovality of circular truss sections. Moreover humidity can facilitate fungi spread [53]. This kind of attach happens when the external temperature goes over 5 °C and the relative humidity exceeds the 20% and the common causes are interstitial condensation and upstream capillary flows of atmospheric water. The correct hygrothermal design of envelope is strongly recommended to escape wood durability problems connected to fungi attaches. There are also two types of biological agents that attach wooden building materials: insects like woodworms (cerambycids) and termites (wood-eating insects) [53]. The diffusion of these biological deteriorations don't depend on the relative humidity of wood but on temperature of the ambient, warm and humid climates, and on the type of wood present: low wrought wood rich in sapwood is strongly subjected to insects' attaches. A correct design of durability aspects is very important for wooden materials in buildings applications. The most common way to increase wood durability is through the use of impregnates but it can be not sufficient and not very efficient [53]. Moreover, higher is the quality of the wood used less efficient is the impregnation because it is not absorbed. The most important parameter for wooden building materials conservation is the species of wood used [54]: as shown in Table 3, fir or pine woods have a service life between 5 and 15 years, larch woods between 15 and 25 years, oak woods between 35 and 50 years while chestnut woods exceed 50 years. Another important way to preserve wooden structures and buildings is through an adequate design of architectural details [55]: the goal is to avoid the contact between wood and standing water. Most attention is to be paid to external timber structures, to timber frames in glass walls, to wooden bridges and to wooden applications in buildings with high humidity flows in the internal spaces like swimming pools. The common way to design durable details is paying attention to coverings, overhangs, ventilation.

The treatment of wood can be done in different ways according to consumer requirements and legislative constrains that are increasingly strict about effectiveness and harmlessness of the wood preservatives: CCA (chromate copper arsenate) that was extensively used since few years ago is now prohibited for residential construction and are replaced with “new generation biocides” that are chromium and arsenic free. Different remediation actions can be considered to replace the application of biocides as wood preservatives such as the use of naturally durable wood species or the use of composite materials made of wood fibres and

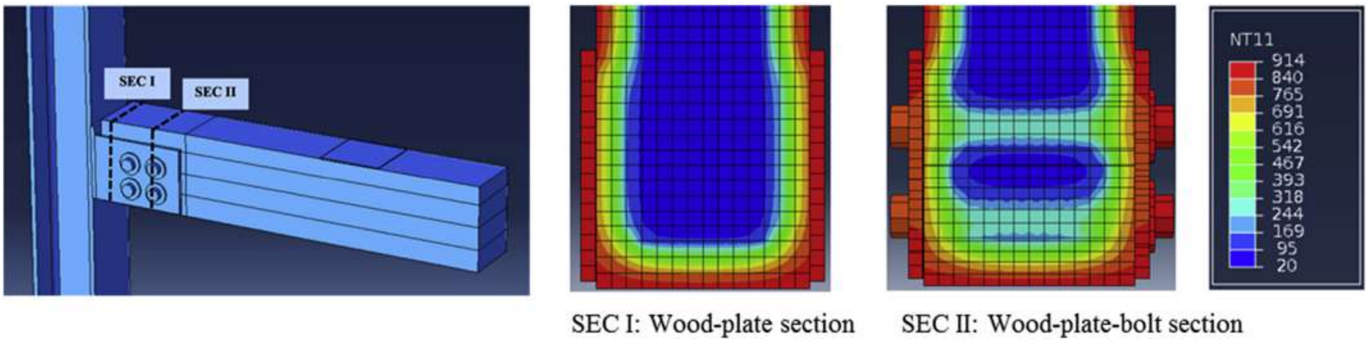

Fig. 9. Effect of steel connections in wood section inner temperature distribution [50].

Table 3
Mean service life of timber structural elements and possibility of easy painting.

Wood type	Service Life [years]	Painting
Beech	0–5	Easy
Fir	5–15	Not easy
Larch	15–25	Very difficult
Quercus	35–50	Very difficult
Chestnut	50–100	Very difficult

recycled plastic [56].

4. Thermo-physical properties

As regards thermal performances of a material the main parameters are: mass density, specific heat capacity, thermal conductivity, thermal diffusivity and relative humidity. The density of a material (ρ) is defined as the ratio between its mass and its volume. The specific heat capacity (c) is the amount of heat, measured in Joules, required to raise the temperature of 1 kg of a substance by one Celsius degree.

The thermal conductivity λ [W/mK] defines the steady state heat flux passing through a unit of a homogeneous material of 1 m of thickness, induced by a temperature difference of 1 K on its faces. The thermal transmittance, known as U-value [W/m^{2}K], is the steady state heat flux passing through a unit of a surface area induced by a temperature difference of 1 K that takes into account also convective and radiative heat transfer. Thermal resistance R [m^{2}K/W] is the inverse value of thermal transmittance.

Thermal diffusivity D [m^2/s] is defined as the ratio of thermal conductivity and the product of specific heat and density. Materials with high specific heat, over 1.4 kJ/kgK, have low diffusivity values even with low density and are very performing in unsteady conditions.

The Relative humidity (RH) is the percentage of water referred to the dry weight of the wooden material.

The resistance to vapor diffusion (μ-value, dimensionless) expresses the ability of a material to be not permeable to water vapor. The lower the value the higher the material vapor permeability. A μ-value of 1 is assigned to air. EPS building insulators have μ-values between 20 and 70, mineral wool insulators are characterized by lower values (under 5) whereas vapor barriers can reach values over 100,000.

$$g_v = -\frac{\delta_0}{\mu}\frac{dp}{dx} \tag{1}$$

where g_v is the water vapor flux density, p is the water vapor partial pressure, δ_0 is the water vapor diffusion coefficient in air and μ is the water vapor diffusion resistance factor of the material.

Due to the significant presence of wood elements in buildings, the wood energy performance evaluation strongly depends on thermal properties of wood products. Physical properties of wood also vary considerably due to material variability, even within one wood species [57]. Moreover wood has an anisotropic behavior also in thermal field: in the direction of the grain, for example, the wood thermal conductivity is about twice compared to the perpendicular one while similar values can be obtained for tangential and radial directions [58]. The thermal conductivity strongly depends, on moisture content and density of the wood material considered with a linear relation [57]:

$$\lambda = d(a_0 + a_1 M) + k_0 \tag{2}$$

where d is the dry density, a_0 and a_1 are two constants, M is the moisture content (percent of dry weight) and k_0 is a constant.

The heat storing capacity of wood depends on moisture content, temperature, direction of grains and not very much on its density [57]. A moisture increase improves the wood specific heat capacity, because the specific heat of the water is greater than that of the wood. Similarly, a temperature increase causes an increase in wood specific heat. Eq. (3) expresses the specific heat and moisture relationship [57]:

$$C = \frac{c_0 + 0.01 M c_w}{1 + 0.01 M} + A \tag{3}$$

where c_0 is the specific heat of dry wood, c_w is the specific heat of water, M is the moisture content (percent of dry weight) and A is a correction term.

As the temperature of wood decreases, its strength usually increases. The thermal expansion of wood in the direction of the grain is very little while in the radial and tangential directions, temperature movements are much greater [59]. The relationship between the thermal expansion coefficients and moisture contraction coefficients of wood in different directions relative to the grain is in the same class in terms of size. With low temperatures (less than 0 °C) wood may start to crack as water in the cell lumens expands as it freezes.

In wooden structures thermal insulation is applied in the external surface. In case of platform frames the composition of the wall consists of an indoor panel like a gypsum board with plaster in the inner side and a vapor barrier in the side at contact with insulation. Insulation is placed between the studs and the nailed particleboard on the outside (acting as wind bracing material) covered with a wind barrier. It is possible to have an air gap before the wooden external cladding. In X-LAM constructions the insulation layer is applied in the external part of the structural panel and the internal side is completed with a gypsum board to permit the creation of an air gap where tubes are installed. The wall is also protected by vapor barriers and vapor permeable membranes (see Fig. 10).

Wood has a low thermal conductivity and can be used for insulation panels. Kosny e al [60]. analyzed different types of wall frame assemblies with low thermal resistance. Instead of the use of classical brick materials, the use of wood, coupled with traditional and innovative thermal insulating materials, increases the thermal resistance of the wall. It is possible to reach high values of thermal resistance, higher than R = 3.5 m^2K/W (U-value lower than 0,29 W/m^2K) and with not big thicknesses. In case of truss walls and double walls a value of resistance R of about 5.3 m^2K/W can be easily exceeded with thicknesses of 216–254 mm; if Vacuum Insulation Panels are employed as insulating materials, the R value can reach 9 m^2K/W with a thickness of 254 mm. Wood structures also show lower thermal dispersions connected to thermal bridges.

Table 4 lists the thermal properties of different types of wood. It is possible to assert that the thermal properties of wood based materials strongly depend on dry bulb density [57]: the thermal conductivity increases with bulk density while the resistance to vapor diffusion decreases in case the wooden material is denser. Resistance to the diffusion water vapor is higher for dry materials than wet ones. An experimental study of various thermal properties of solid Aleppo wood, laminated timber wood and black cork was run by Limam et al. [61]. The thermal parameters studied are thermal conductivity, thermal resistance, specific heat and thermal diffusivity. It is possible to notice the strong influence of moisture content in wood on these parameters. With an increase of water content, the thermal conductivity and thermal diffusivity increase while thermal resistance decreases. The specific heat depends on temperature and cork has higher values than the other types of wooden materials.

In cold climates the attention to hygrothermal conditions of timber frames is very important because of the risk of mould growth. The interstitial condensation is otherwise a problem connected to the durability of wood frames and walls. To avoid hygrothermal problems in wood frames, wind and vapor barriers are used in wall assemblies. Pihelo et al. [62] show that risk of mould growth and longer dry out periods are higher when the thermal transmittance of the wall is lower (high thicknesses of insulation). The low transmittances in fact minimize the heat flow through the wall and it slows the dry out period of moisture that is present inside them. From a condensation perspective the most critical point is the interface between the insulating material and the wind barrier. The applications of wind barriers, i.e. insulating materials with high thermal resistance and vapor permeability, tend to reduce the mold risk even if the transmittance of the wood wall is increased. The effect of a wind barrier is to introduce an external layer with high vapor permeability in order to permit to the vapor to be dried out and to increase the temperature of the internal insulating materials in order to decrease their relative humidity. Another way to reduce the relative humidity of wood frames is to introduce a vapor barrier in the internal side of the wall next to the plaster. Furthermore, Raji et al. [63] in their experimental study demonstrated that wood thermal properties strongly depend on humidity and also the adhesive seal has a fundamental role for air flow and water vapor diffusion along the wall. Moreover, the authors assessed the important role of a felt packing characterized by a high permeability.

It is well known that wood fiber panels and cellulose have high moisture capacity and it can be a positive characteristic for moisture conditions in wood frames. An experimental study of moisture

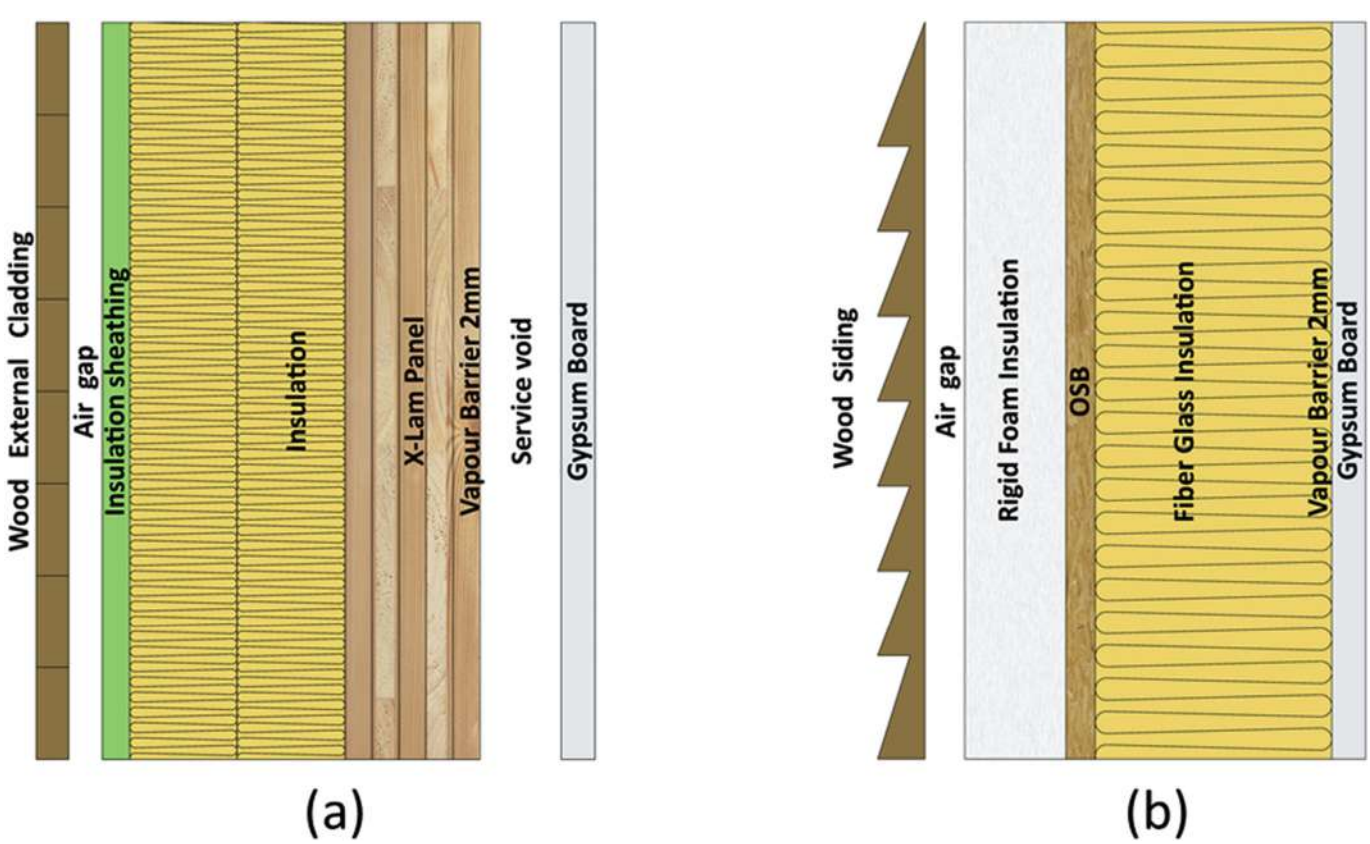

Fig. 10. Typical composition of X-LAM (a) and platform frame (b) walls.

Table 4
Thermal properties of different types of dry wood; the values in parenthesis are in perpendicular direction of fibers.

	Oven Dry Density [kg/m^3]	Specific Heat [J/kgK]	Thermal Conductivity - dry bulb, 25 °C [W/mK]
Aleppo pine solid wood [61]	580	1550	0,18 ± 0,11 (0,281 ± 0,13)
Aleppo laminated wood [61]	360	1500	0,14 ± 0,09 (0,203 ± 0,01)
Cork [61]	65	1900	0,036 ± 0015
Palm wood [66]	254 ± 1 (276 ± 2)	–	0,084 ± 0003 (0,083 ± 0003)
Date palm fibre panel [67]	187–389	–	0,072–0085
Durian Particleboard [67]	428	–	0,064
Oil palm fibre [67]	100	–	0,055
Wood Fiber [68]	149 ± 3	–	0,042 ± 0002
OSB [68]	582 ± 20	–	0,097 ± 0003
OSB [69]	619	1552 ± 25	–
Oak [58]	753,16 ± 4,52	1214 ± 29	0,58 ± 0,028 (0,22 ± 0,007)
Oak [70]	700	2390	0,23 (0,19)
Spruce [58]	334,63 ± 9,37	1251 ± 58	0,27 ± 0,027 (0,12 ± 0,011)
Spruce [70]	370	530	0,12
Spruce narrow rings [68]	393 ± 25	–	0,084 ± 0001 (0,080 ± 0004)
Spruce wide rings [68]	368 ± 14	–	0,095 ± 0006 (0,081 ± 0005)
Larch [58]	499,56 ± 4,50	1246 ± 30	0,44 ± 0,039 (0,14 ± 0,008)
Red Fir [70]	520	2280	0,14
Fir, Pine [70]	510	1380	0,12
Pitch Pine [70]	650	2120	0,17
Fibreboard [69]	256	1420 ± 52	–
Plywood [70]	540	1210	0,12
Plywood [70]	700	1420	0,15
Hardboard [70]	600	2000	0,08
Hardboard [70]	880	1340	0,12
Hardboard [70]	1000	1680	0,29
Particleboard [70]	800	1300	0,12
Particleboard [70]	750	1300	0,098
Particleboard [69]	634	1441 ± 27	–
Particleboard [69]	754	1423 ± 24	–
Particleboard [70]	1000	1300	0,17
Particleboard [69]	973	1450 ± 20	–
Cellulosic insulation [70]	43	1380	0,042

conditions of wooden walls composed by a wind barrier, an insulation layer with wood fiber or glass wool, a vapor barrier and a gypsum board was performed by Geving et al [64]. The results show that the insulation with wood fibers performs very similarly to the glass wool one and the effect of moisture capacity of wood fiber is perceivable only if there is a high initial moisture content, condition that can be real only after the construction of the building. A better value of relative humidity at the contact between the wind barrier and the insulation can be reached in case of loose fiber utilization instead of batts.

The radiative part of thermal transmittance of wood fiber insulation materials was studied by Kaemmerlen et al. [65]. The work asserts that a purely conductive model gives very similar results to experimental data. It means that it is not necessary to consider a coupled radiative-conductive modeling because radiative part is negligible respect to conductive and convective part in wood fiber materials.

In the field of the research of new sustainable materials, various studies are addressed to characterize innovative materials with presumed good thermal properties. There are lots of works with this aim: Agoudjil et al. [66] characterized palm wood and found a thermal transmittance similar to common insulating materials. Asdrubali et al. [67] present a review of thermal properties (thermal conductivity, specific heat and density) of unconventional and sustainable materials finding in natural wood based materials competitive properties in comparison with conventional commercialized insulation materials (e.g. Date palm, Durian peel, Oil palm fiber).

Taking into account the hygrometric properties, the coefficient of vapor diffusion resistance (μ-value) can be determined through the cup test method [71] in two different conditions of relative humidity: the dry cup test is characterized by UR from 9 to 50% while wet cup test is run with a UR value ranging from 50 to 97%. There is a large dispersion in the results obtained from the tests already done by different authors [68,72]. The cup tests already done for wooden materials show that the denser the tested material, the higher is resistance to vapor diffusion. Low density wood fiber materials have a high vapor permeability if compared with the other wood based materials. Table 5 lists the coefficient of diffusion resistance after air gap correction on dry specimen.

5. Acoustic properties

There are various parameters to characterize the acoustical properties of a material. The most common are Airborne Sound Insulation (R_w), Impact Sound Insulation (L_n) and the Sound Absorption coefficient (α). The Airborne Sound Insulation [73] is defined as the difference, in decibel, between the sound pressure level in the emitting room and the sound pressure level in the receiving room plus a term depending on the equivalent absorption area in the receiving room. The Impact Sound Insulation Level [74] is a decibel measure of the impact source pressure level in the receiving room minus a term depending on the equivalent absorption area in the receiving room. Finally, the Sound Absorption Coefficient [75] is defined as the ratio between the sound power absorbed and the incident sound power on a surface.

Wood is a light material, so its sound insulation performance is not particularly good. Wood conducts sound better in the longitudinal direction of the grain than in the perpendicular one. A dense wooden structure reflects sound, and can easily be made into surfaces that channel sound reflections. This property is exploited, for example, in musical instruments and concert halls.

A sufficient level of sound insulation in wooden buildings can usually be achieved structurally by using multi-layered

Table 5
Coefficient of diffusion resistance μ after air gap correction on dry specimen.

	Density	Coefficient of diffusion resistance (μ)	
		Dry Cup	Wet Cup
Spruce wide-ring wood radial [68]	367 ± 13	47	18
Spruce wide-ring wood transversal [68]	368 ± 14	34	15
Spruce narrow-ring wood radial [68]	383 ± 35	56	17
Spruce narrow-ring wood transversal [68]	393 ± 25	42	17
Plywood (beech) [72]	738	97,8	44,1
Plywood (beech) [72]	778	100,8	66
Plywood (beech) [72]	756	97,2	48,8
OSB [68]	582 ± 20	46	2
OSB [72]	659	100,5	42,8
OSB [72]	638	116,8	47,3
OSB [72]	618	112,6	47,6
OSB [72]	644	98,8	75,3
OSB [72]	629	139,1	93,3
Particleboard [72]	654	29,7	16,8
Particleboard [72]	636	35,1	18,5
Particleboard [72]	626	27,8	26,4
Particleboard [72]	776	65,1	27,1
Medium Density Fibreboard [72]	810	33,4	22,9
Medium Density Fibreboard [72]	749	20,4	15,4
Medium Density Fibreboard [72]	811	39	24,8
Medium Density Fibreboard [72]	856	58,9	31,1
Wood fibre [68]	149 ± 3	6	2

constructions. By positioning porous absorption material behind the board or paneling in addition to an air gap, for example a layer of thermal insulation, a so-called board resonator is formed which, when it vibrates, effectively dampens low sounds that are problematic for light structures (Fig. 11a). Furthermore, by making wooden battening or by making holes in wooden surfaces, a perforated resonator can be created that also efficiently dampens medium-to-high-pitched sounds. In multi-story wooden buildings, the means of controlling sound insulation (separate frames, sound breaks) are challenging, because they are contrary to how structural rigidity is achieved (reinforcement, joints, continuous structures). The footstep insulation of wooden floors can be improved by increasing the mass of the floor, for example using a concrete cast on the surface or so-called floating surface tiles on top of a flexible layer on the upper surface of the floor (see Fig. 11b).

When high sound-insulation performance is required, it is necessary to consider flanking transmission phenomenon, especially in multifamily houses and in houses built with lightweight building elements. It was demonstrated that in two coupled wooden floors the attenuation was found to be very directional and its rate is high along the whole structure perpendicularly to the beams. When the wavelengths exceeded half the distance between the beams there was only attenuation in the direction across the beams. The high attenuation is a consequence of the beams in the floor [76]. In order to achieve the wooden product improvement in this field, the development of prediction tools that could accurately predict impact sound transmission is needed. In this framework the Finite Element simulation could be a strong potential tool to face low frequency vibroacoustic issues. In Ref. [77] the authors investigated the influence of glue on the low frequency vibroacoustic performance of two types of wooden T-junctions, representing cutouts of actual full size floor assemblies, by means of measurements. Moreover, the authors carried out FE prediction tools by using measurements as calibration input, so as to study modeling issues related to the connections.

Timber floors have not good acoustic performances in term of impact sound insulation and airborne sound insulation. With an experimental campaign Martins et al. [78] analyze different solutions for timber floors: classical solutions with a timber deck, the timber deck solution composed with concrete or lightweight concrete with cork aggregates, and a solution that includes a suspending ceiling. Considering the two parameters of airborne and impact sound insulation the worst performances are obtained for the classical timber floors while better results are obtained for concrete composite floors without significant differences between concrete and lightweight concrete application. The best performances of composed floor cannot still fulfill the normative restrictions and a suspending ceiling can be necessary.

The acoustical properties of wall panels made of betung bamboo were measured by Karlinasari et al. [79]. The panels tested have medium density (0,8 g/cm^3) or low density (0,5 g/cm^3), and the bamboo particles vary the dimensions from whole/excelsior to medium and fine. From airborne sound insulation point of view, the composition with whole-excelsior dimensions of particles gives better sound insulations values. On the contrary a low density and fine-medium particles give worst insulating results but better absorbing performances. Porous materials can be useful for high frequency sound absorption while perforated wood panels are useful to obtain good absorption values at medium frequencies. In order to evaluate the transmission and reflection of the acoustical

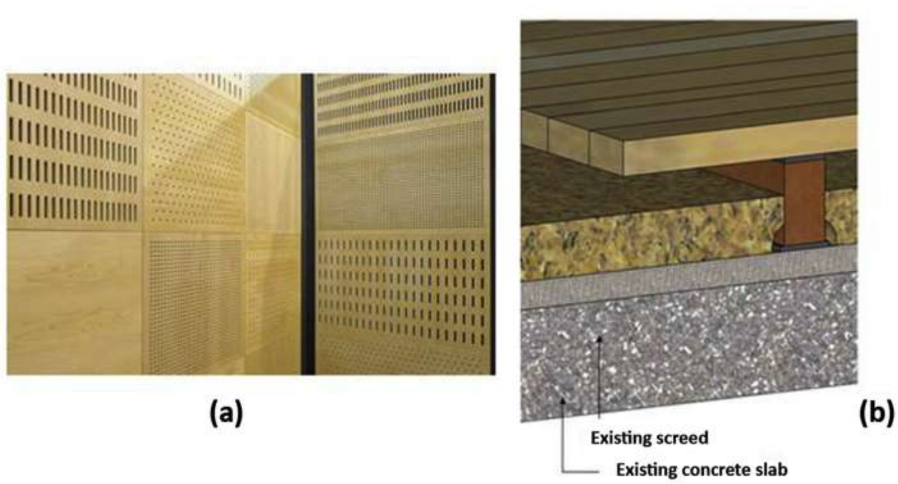

Fig. 11. (**a**) Wooden board resonator; (**b**) Wooden floating surface.

waves caused by wooden boards the most important parameter is the speed of sound into the panel. The values of speed of sound velocities vary in function of the species of wood employed and for the anisotropic behavior of the material as shown in Table 6.

Recently, new techniques were developed and new products are available to solve the building acoustic problems. One of these innovations is represented by a new sound absorbing panel made of wood and concrete (see Fig. 12): wood fiber gives to the panels a thermal insulating capacity, maintaining a sound-absorbing structure. On the other hand, concrete, a well-known and popular building material, is the binder to provide strength, moisture resistance and fire protection.

Windows are the weakest part of building envelope in term of acoustic performances. The transmission of the sound through wooden frame windows is a complex phenomenon and it is influenced by a lot of parameters. Buratti et al. [82] indicate only five parameters that most influence the sound insulation index of wooden windows: windows typology (window or French window), frame and shutters thickness, number of gaskets, index of sound insulation of glazing. The windows airborne sound insulation is very similar to the same parameter of the glass that is their component [83] with a reasonable reduction of about 2 dB. The most common way to increase the sound insulating performances is to insert one or more layers of PVB (polyvinyl butyral) between two sheets of glass. In the example of the work the improvement is of 2 dB.

6. Sustainability aspects

6.1. Properties included in Life Cycle Assessment studies

It is widely demonstrated that Life Cycle Assessment (LCA) is a very useful tool to evaluate the environmental performances of products and services bringing powerful insights about all the life cycle steps, from cradle to grave, measuring environmental, energy and resource sustainability. The application of LCA to wooden materials and elements in building sector can be roughly divided into studied related to the analysis of single materials or elements and studies related to the entire building where wood is used for different purposes. Several impact assessment methods have been proposed among which: IMPACT 2002+ [84], Eco-Indicator 99 [85], CML 92 [86], ReCiPe 2008 [87]. They provide a large variety of impacts as outputs and the categories of impact can sometimes be different from one to another. The attempt to provide an internationally harmonized methodology to measure the environmental burdens of products has brought to the definition of standard categories. In Europe the Product Environmental Footprint (PEF) [88] gives 14 categories while the Environmental Product Declaration (EPD) [89] includes information about product impacts on:

Table 6
Speed of sound in different wood species boards [80].

Species	Along Fiber [m/s]	Across Rings [m/s]	Along Rings [m/s]
Acacia	4714	1475	1352
Fir	4638	1336	784
Beech	3342	1837	1415
Oak	3859	1535	1289
Pine	3322	1405	794
Elm	4462	1498	1136
Sycamore	4668	1392	1262
Ash	5083	1615	910
Elder	4665	1369	1043
Aspen	5083	1615	910
Maple	4411	1538	1037
Poplar	4283	1402	1050

Fig. 12. New sound absorbing panel made of wood and concrete [81].

- Global Warming Potential (GWP);
- Ozone depletion;
- Acidification of land and water;
- Eutrophication;
- Photochemical ozone creation;
- Depletion of abiotic resources (elements);
- Depletion of abiotic resources (fossil).

A more harmonized methodology to calculate environmental burdens of buildings should however be established.

Generally, LCA is used to compare different alternative building materials and elements or entire buildings. In order to make an equitable comparison, the compared options should be functionally equivalent. Buildings are complex systems and their components usually have different functions (e.g. structural and fire proofing, structural and acoustical); therefore, in order to guarantee the same function, it is sometimes necessary to employ a combination of materials or building systems. These complex interactions are accounted considering as functional unit entire buildings with the same usable areas and function. In this case the above indicators are referred to the typical functional unit defined as the living surface unit of the building because it guarantees more homogenous basis in the indoor comfort conditions. When structural materials are analyzed instead, the functional unit is typically the mass unit of the material (Table 7).

When considering the entire building both the direct energy and the indirect energy used during its life cycle should be considered: the direct energy used in a building is the operational energy needed for heating, cooling or lighting while the indirect energy is the energy incorporated in the materials or components of the construction. In many cases a higher embodied energy level can contribute to lower operating energy. The Cumulative Energy Demand (CED) [90] is the right indicator to describe the amount of operating and embodied energy of a building because it is defined as the sum of direct energy, indirect energy and energy feedstock contained in potentially flammable materials. Usually the boundary of the CED is the entire life cycle of a building (from cradle to grave) and also the energy requirements for demolition, disassembly, disposal and maintenance, substitution and repair of parts are taken into account.

Most of LCA studies of buildings consider three main life cycle phases: construction, use and maintenance, end-of-life and dismantling. A lot of LCA analyses demonstrate that the use phase is responsible for the mayor contribution to the total impacts both in term of energy input, CO_2 emissions and for other environmental impacts [91]. According to Asdrubali et al. [92] the incidence of the

Table 7
LCA indicators referred to the entire building.

Ozone depletion	kg CFC-11/m^3 - kg CFC-11/m^2 living area
Acidification of land and water	kg SO_2-Eq/m^3 - kg SO_2-Eq/m^2 living area
Eutrophication	kg PO_4 Eq/m^3 - kg PO_4 Eq/m^2 living area
Photochemical ozone creation	kg Ethylene-eq/m^3 - kg Ethylene-eq/m^2 living area
Depletion of abiotic resources (elements)	kg Sb-eq/m^3 - kg Sb-eq/m^2 living area
Depletion of abiotic resources (fossil)	MJ/m^3 - MJ/m^2 living area
CED in Buildings	MJ/m^2 living area
GWP in Buildings	kg CO_2 eq/m^2 living area

use phase, as measured by the CED, is 77% for a detached house and 85% for an office building, while construction phase weights respectively 21% and 14%. Cuéllar-Franca and Azapagic [93] calculate the GWP contribution of use phase equal to 90% for a semi-detached or terraced house located in the UK; Chau et al. [94] evaluate a percentage of total energy consumption during use phase of 80–90% for high rise office buildings; for Scheuer et al. [95] the use phase accounts for 93,4% of global warming potential of a residential dwelling. Ortiz et al. [96] confirm that the use phase is the most critical in term of environmental impacts accounting approximately for the 80–90% of the total life cycle impacts of residential dwellings located in Catalonia; the study includes six category of impact: acidification potential, human toxicity, depletion of abiotic resources, climate change, terrestrial eco toxicity and ozone depletion. These values decrease when a low energy building is considered and, at the same time, the Embodied Energy phase acquires more importance accounting for about the 50% of the total CO_2 emissions [97,98]. Thus, if the focus is on low energy consumption buildings, the attention should be moved towards the construction and dismantling phases, in order to support proper design for selecting sustainable materials and to promote the reuse and recycling at the end of life of the building. If the focus is on Embodied Energy, we should consider that the structural materials contribute heavily to the total Embodied Energy (35–57% [94]) [93]. In this case wooden frames can be competitive because of the lower impacts generated compared with other structural materials like concrete and steel. The end of life phase instead contributes to the total impacts of the life cycle with very low values: 1% of the GWP for a semidetached house [93].

Using the eco-indicator Impact 2002+, a comparison of four single-family residential buildings [99] with the same usable areas and different types of construction systems, masonry and wood based, shows that traditional non passive wood houses guarantee the smallest environmental impacts (values of Impact 2002 + categories) and wooden buildings generate lower environmental impacts in comparison with their masonry equivalent types. Similarly, Peuportier [100] employs CML method to compare three reference house types including a reference wood frame one. All environmental impacts of the wooden frame house, considering energy, acidification, eutrophication, global warming, human and eco-toxicity, ozone and resources depletion, are about a half of the value obtained for the French reference type. Other studies on the environmental impacts of wooden and non-wooden constructions have been recently done by Dovetail Partners [101] considering three hypothetical buildings (wood, steel, and concrete) of identical size and configuration. In all outputs, covering fossil energy consumption, weighted resource usage, global warming potential, and measures of potential for acidification, eutrophication, ozone depletion, and smog formation, impacts of the wood design are lower (see Fig. 13). Guardigli et al. [102] confirm that wood structures are less impactful than reinforced concrete ones comparing the two different structural solution for a mid-sized green building and using Ecoindicator 99.

Considering only the global warming and EE of entire buildings, Buchanan and Levine [103] show that wooden buildings have lower EE and lower resulting emissions and that an increase of 17% of wooden materials application in buildings produces a reduction of 20% of the CO_2 emissions connected to the building materials manufacture sector and a reduction of 1,5% in the national fuel consumption of New Zealand. Similarly, Nassen et al. [10] compare buildings with concrete and wood frames and find lower carbon emissions for the second types.

LCA analyses of tall buildings are not very common in literature and few studies on wooden tall buildings can be found [104]. However, Folkhem [105] has recently proposed an EPD for a concept multi-dwelling residential wood building of 10 floors located in Stockholm. The building has a concrete foundation and first floor and CLT is employed as structural system for the other levels. The functional unit adopted is the living area and the boundaries considered are cradle to grave. The impacts reported in Table 8 can be used for a comparison with equivalent buildings.

Even if a lot of papers demonstrate the good environmental performances of wooden constructions, some authors warn about the contradictory results that emerge during the analysis in different categories of impact. LCA studies give very scattered results and sometimes they are in contradiction so it is important to explain the boundaries of the analysis in a very clear way and consider the life expectation of the building. By comparing wood with another common construction material, such as concrete, it is worthy to notice that it might have some drawbacks, and hence lower environmental performances, with respect to concrete for example considering the increase of the need of imported wood, while concrete production is generally localized in the developed countries near the construction site, and also taking into account that concrete guarantees a longer life expectancy of a house [106]. The cultural background of a region has a strong influence on the choice of the construction materials and of their sustainability because the local already developed economy guarantees approximately on site production and low transportation impacts.

6.2. Main properties

6.2.1. Renewability

Wood is usually considered a sustainable material. One important sustainability issue is related to the right management of the forests regarding the balance between the removed and the grown wood. Globally, the 31% of the land is covered by forests [107] but this percentage is decreasing because of heavy deforestation in tropical regions of Africa and South America. On the contrary, in Europe forests are growing as the result of afforestation projects (Fig. 14).

International organizations, such as Forestry Stewardship Council (FSC) [109] and the Program for the Endorsement of Forest Certification (PEFC) [110], release labels and certifications to encourage the sustainable exploitation of forests goods from an ecosystem conservation point of view, with particular attention to the rights of workers and local communities and economical value for local regions. Furthermore, PEFC endorses the Canadian

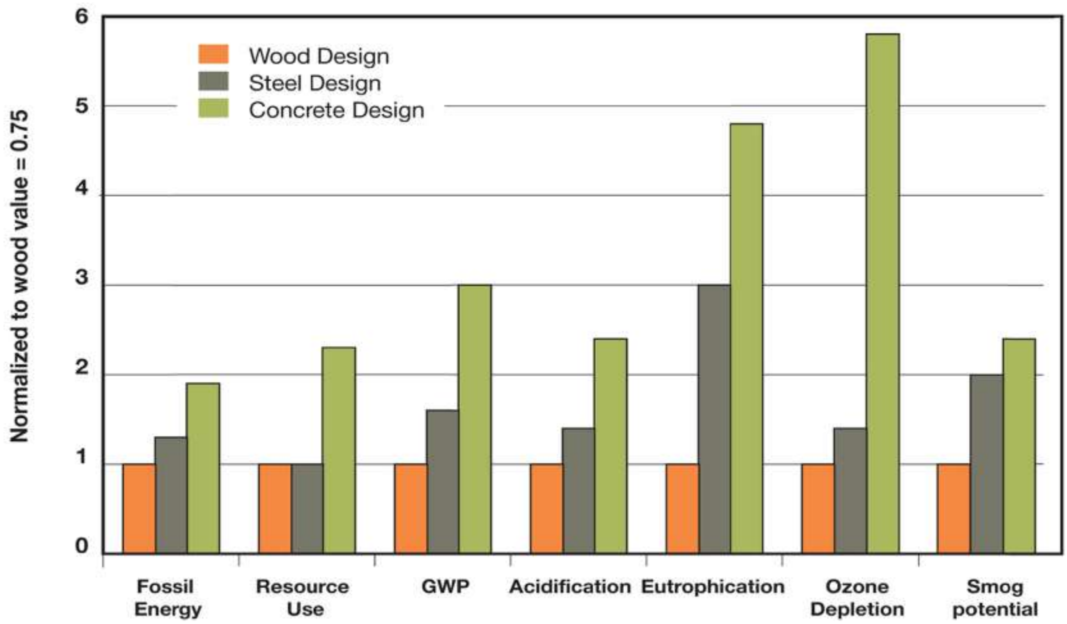

Fig. 13. Athena Eco-Calculator impacts of three hypothetical buildings normalized to wood value [101].

Table 8
EPD of Folkhem's multi-dwelling building, cradle-to-grave impacts [105].

	Functional unit	Folkhem's concept building
Global Warming Potential (GWP)	kg CO_2 equiv/m^2 living area	5,81E+02
Ozone depletion	kg CFC-11/m^2 living area	4,77E-04
Acidification of land and water	kg SO_2-Eq//m^2 living area	4,54E+00
Eutrophication	kg PO_4 Eq//m^2 living area	2,02E+00
Photochemical ozone creation	kg Ethylene-eq//m^2 living area	3,68E-01
Depletion of abiotic resources (elements)	kg Sb-eq//m^2 living area	2,20E-01
Depletion of abiotic resources (fossil)	MJ//m^2 living area	1,18E+04

Standards Association [111], the Sustainable Forestry Initiative [112] and the American Tree Farm System [113], three standards operating in North America in addition to FSC. Sustainable forest management certification complements the information in an environmental product declaration, including parameters such as biodiversity conservation, soil and water quality, and the protection of wildlife habitat. The principles are the respect of rights to land use, the respect of people's rights, the respect of communities and workers' rights and safety, the conservation of biological diversity, landscapes and water resources, the respect of natural cycles of productivity, the control in use of chemical substances, the implementation and monitoring of a long term management plan. Today 56% of the total forest lands in Western Europe and 28% in North America are certified (see Fig. 15), while in Eastern Europe and in emerging countries the certification is not very well established [114]. Cuadrado et al. [115] estimate a loss of 30% of wood sustainability index in absence of a forestry certification standard.

6.2.2. Embodied energy and embodied carbon

The Embodied Energy is defined as the sum of all the energy required to produce goods or services and includes the energy necessary for the mining and processing of natural resources to manufacturing, transport and product delivery. The Embodied Energy refers to the energy incorporated in materials or building components and it is the 'upstream' component of the life cycle impact of a building. The Embodied Carbon is linked to the Embodied Energy and represents the greenhouse emissions that happen, from cradle to gate, during the manufacturing and transport of construction materials or components.

When analyzing the Embodied energy and Embodied carbon of wood-based building materials and components it appears that the drying process is the most energy consuming of the entire manufacturing phase accounting for over the 92% of the total energy consumed [117] and for the 75% according to Lawson [118]. In general, hardwood drying process requires more energy consumes than softwood one. On the contrary, the harvesting shows a much lower incidence of 5% in the total energy [117]. Thus, one important factor influencing the grade of sustainability of wood as building material is the distance between the forest, the factory and the site of installation. The lower the distance is, the lower the environmental impacts generated for the transport of the material are. Cuadrado et al. [115] estimate a 10% reduction of the sustainability index if the transportation of the material is increased from 300 km to 1900 km. The weight of the material has a sensible effect on energy consumption and impacts caused by transport and a reduction of water content in green timber would be desirable.

Even if LCA indicators for wooden building products are generally very dispersed because of the different incidence of transportation, national energy mix or different impregnating substances, it is possible to notice that the increment of processing of raw wood generally causes a higher Embodied Energy [119]: fiberboard or particle board show a higher Embodied Energy than sawn wood as shown in Fig. 16.

When comparing wooden materials with other construction

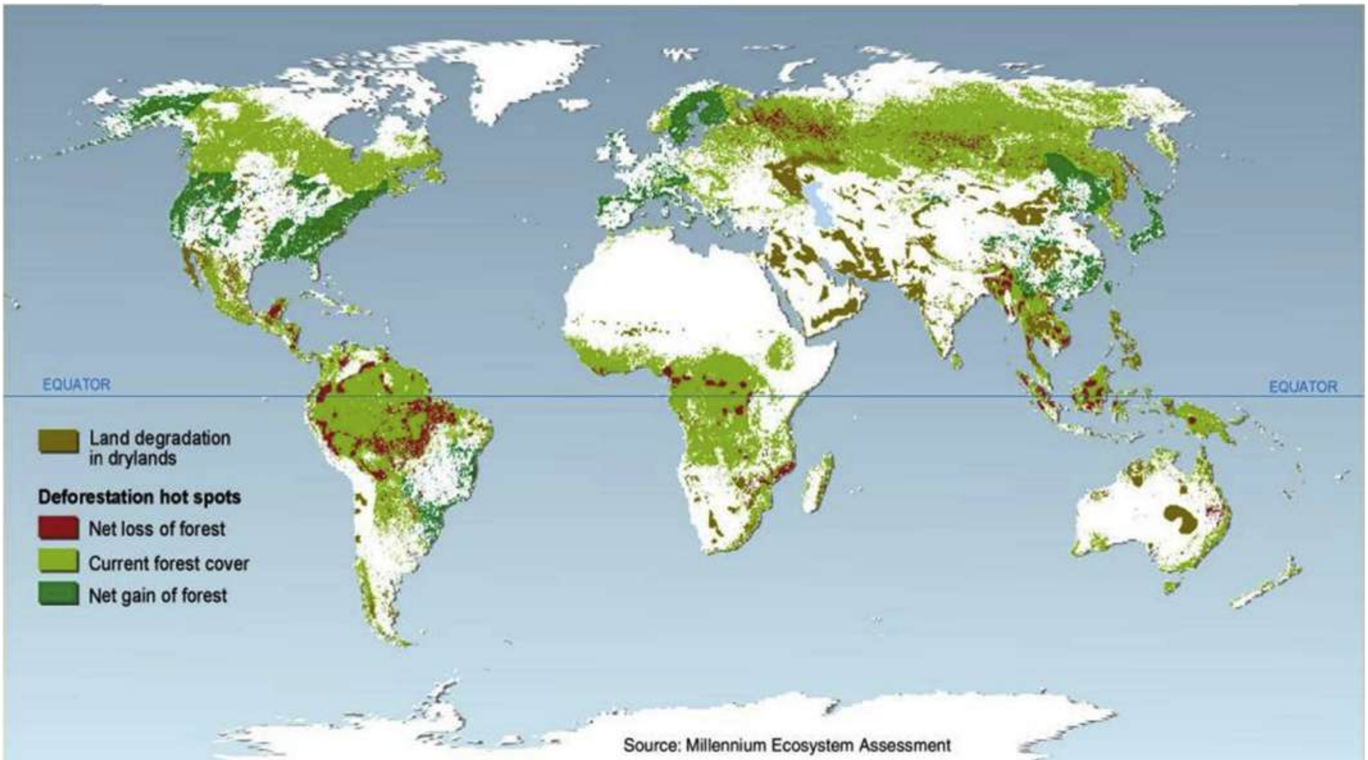

Fig. 14. Global forest cover and deforestation hotspots [108].

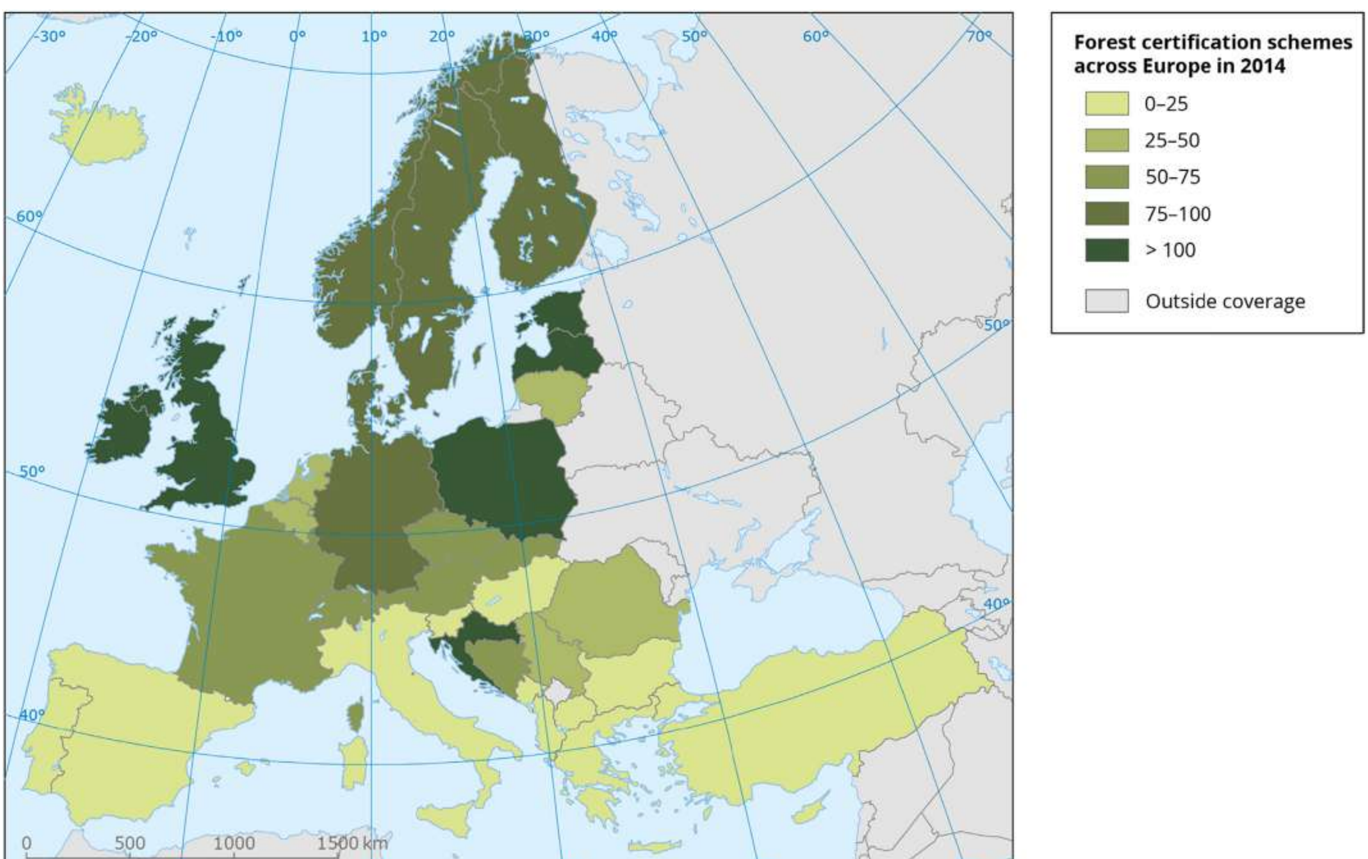

Fig. 15. Certified forests in Europe [116].

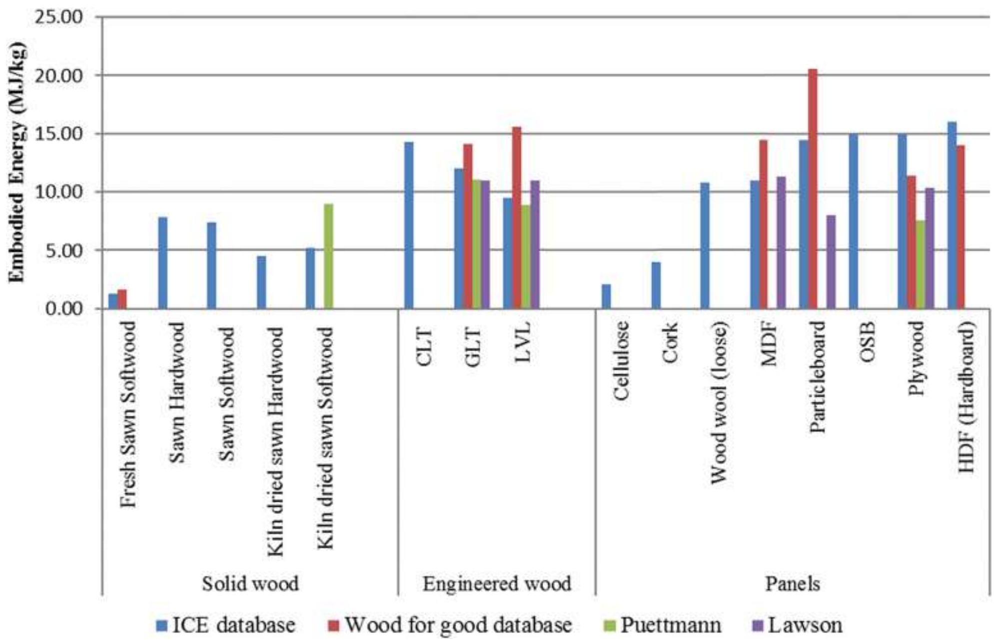

Fig. 16. Value of Embodied Energy for different wooden species [117,118,120,121].

materials it is worth to notice that the Embodied Energy of wooden materials is lower than other construction materials like concrete and steel. The average data given by ICE [121] show an Embodied Energy of timber of 10,00 MJ/kg and 20,10 MJ/kg for steel. Similarly, when considering the Embodied Carbon, wooden products show lower values in comparison with other building materials as reported in Fig. 17. A detailed estimation of the embodied carbon of a material is very complex and sometimes the values that can be found in literature are very dispersed because of the presence of a wide range of different approaches that set a different system boundary, include just carbon dioxide or all GHGs, include/exclude transport or end of life scenarios or service life or maintenance. Greater differences might be seen if the carbon sequestration or recycling are considered. The values shown in Fig. 17 are cradle to gate, exclude transport and consider only carbon dioxide emissions excluding GHGs.

Considering wood as insulating material, Richter and al [122]. elaborated one of the first comparisons between eight insulating materials considering as functional unit 1 m^3 of insulating material. In our view, this type of functional unit appears not appropriate, since different thickness of insulating materials (i.e. different volumes) generally provide a different effect of insulation (different function). In a more recent version Motzl et al. [123] consider, as the functional unit, the amount of material per m^2 necessary to obtain a thermal transmittance of 1 W/m^2K, providing in this case a more straight comparison. Asdrubali [124] considers the same functional unit. The most diffused functional units are listed in Table 9.

Asdrubali [124] demonstrates that there are also some wood based materials (like mineralized wood fibers) whose Embodied Energy per functional unit is as high as the one of synthesized materials like EPS or glass wool (see Fig. 18). Moreover, it is worth to notice that wood fibers show a very low value of Embodied Energy [125] compared to other common insulating materials, such as expanded polyethylene or expanded polyurethane that exhibit the highest values.

6.2.3. Carbon sequestration capacity

The Global Warming Potential (GWP) [126], measured in kilograms of equivalent CO_2 per functional unit on three time horizons (20, 50 and 100 years), evaluates all the greenhouse gas emissions during the life cycle. When trees grow they take carbon from the atmosphere and incorporate it in molecules and this “sequestered” carbon removes carbon dioxide from the atmosphere and it has benefits, particularly for long life products such as construction materials, as the carbon stays “stored” in the product until disposal. The amount of carbon stored in wood can be considered in the GWP and embodied carbon: from a photosynthesis point of view it is possible to calculate an approximate value of 1,83 kg of CO_2 for every kg of wood. The EN 16449 [127] gives a methodology to evaluate the “sequestered” carbon in wood products. Some authors however consider a negative GWP incorrect because at the end of life wood will be incinerated or land-filled and the total balance will be neutral or positive [100,128].

Meanwhile if GWP per functional unit of wooden building materials is compared with the same indicator for traditional building materials like concrete, steel or bricks, the advantages are clear when the CO_2 sequestrated during the life cycle is considered (see Fig. 19). Considering as functional unit the structural system of buildings up to 21 storeys, Skullestad et al. [128] show that timber load bearing structures cause lower climate change impacts than reinforced concrete ones. Given the short life of wood products, the amount of carbon stored in wooden products can be considered constant in a long period while the total emissions from manufacturing continue to increase over time [103]; it is also possible to notice that most of the total carbon storage is in solid wood products and that the major part of the total emissions over time are caused by panels and paper manufacture.

6.3. Other properties

Among the environmental properties it is worthy to take into account also the aspects related to:

- reusability and recyclability;
- additives content.

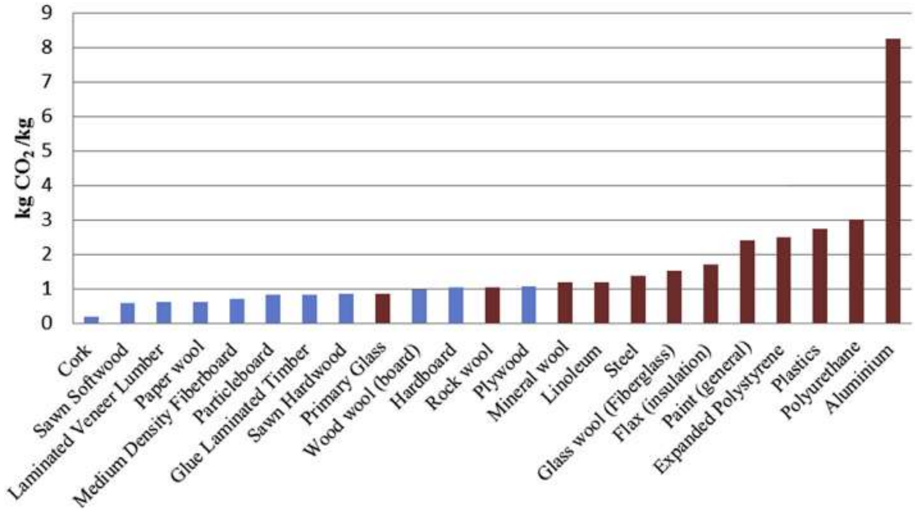

Fig. 17. Embodied Carbon Dioxide Emissions for wood based products (blue) and other products (red) [121]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 9
Indicators referred to typical functional units.

	Functional Units
EE of a building material or component	MJ/kg - MJ/m^3
EC of a building material or component	kg CO_2 eq/kg - kg CO_2 eq/m^3
EE of Insulating materials	MJ/kg to obtain a transmittance of 1 W/m^2K for m^2 of surface
EC of Insulating materials	kg CO_2 eq/kg to obtain a transmittance of 1 W/m^2K for m^2 of surface

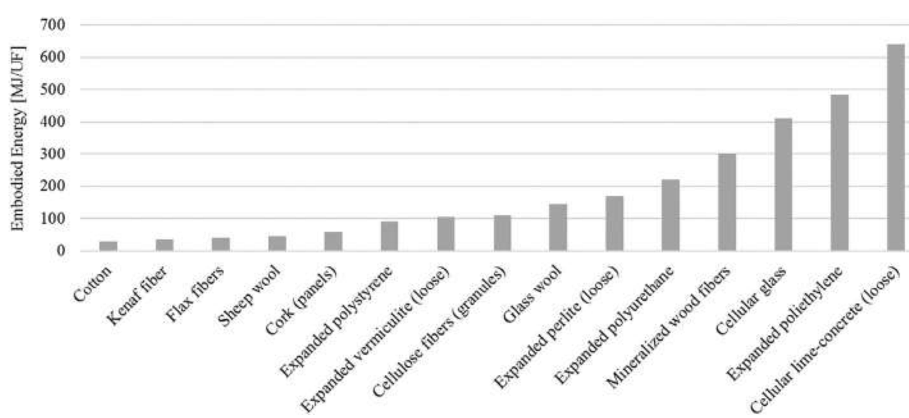

Fig. 18. Embodied Energy comparison among wooden and other thermal insulating materials per Function Unit [MJ/UF]. The Functional Unit is the amount of material per m^2 necessary to obtain a thermal transmittance of 1 W/m^2K [124].

The end of life can contribute to an environmental credit if the materials of the building are reused in another construction: the possibility of reusing a significant proportion of the structure, for example, may result in a reduction of waste and above all in a reduction of requirements of energy for the manufacture of additional new materials. The reuse for new buildings is not very common for wooden and concrete materials while it can be a significant environmental friendly operation for steel buildings as Aye et al. [129] shown. Investigating a multi-residential prefabricated eight-storey building, the solution with a steel structure resulted in an increase of EE of about 50% compared to the same building with a concrete structure but, the potential of reusing steel materials has been estimated as a saving of 81% in the initial embodied energy. Wooden building materials can be reused in different ways such as in furniture or as combustible materials in place of fossil fuels. Skullestad et al. [128] hypothesize the 90% of the structural wooden material to be incinerated with heat recovery to replace natural gas. If the benefits of recycle and reuse of the wooden material are taken into account, the climate change impact is negative due to the avoided emissions obtained by replacing fossil fuels with the incineration of wooden materials. This leads global warming savings greater than 100% compared to reinforced concrete structures; furthermore, the higher is the height of the building, the higher the CO_2 emissions avoided with the substitution of natural gas with biofuel from material reuse. When considering the reuse of building materials at their end-of-life it should be noted that the effective possibility of reuse depends on the possibility of their separation during the dismantling phase and so a strong attention

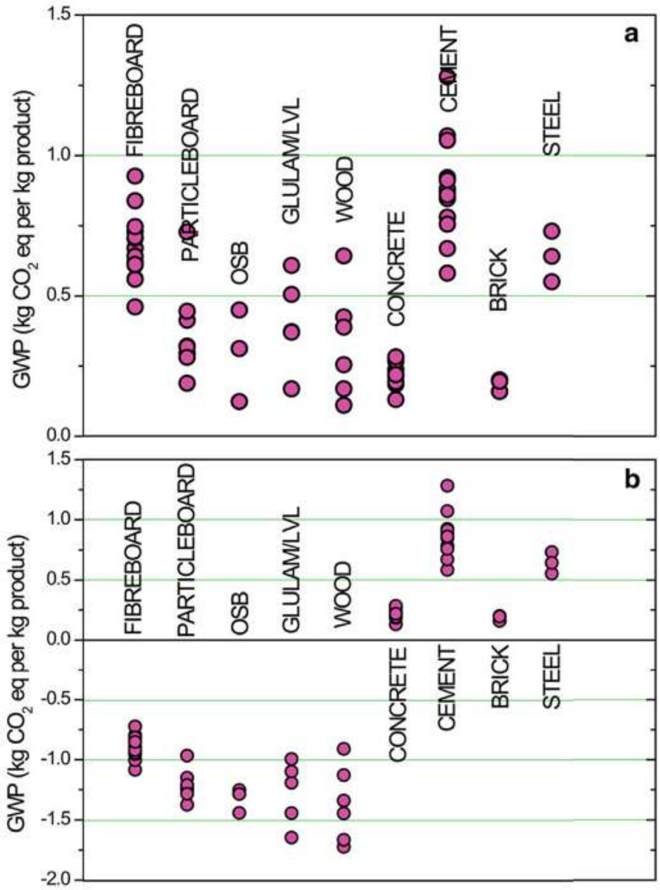

Fig. 19. Comparison of embodied GWP data for wood products with some common building materials first (a) excluding and then including (b) the sequestered atmospheric carbon in the wooden products [119].

at this issue should be given during the design phase.

Another factor having a significant influence on the grade of sustainability of wooden building materials is the use of impregnating substances, glues and adhesives [130]. Such compounds increase the environmental impacts related to global warming, acidification, photochemical oxidant formation, eutrophication and toxicological effects (see Fig. 20); the spread of new metal free and non-petroleum-based substances can reduce this kind of impacts [130,131]. Moreover, resin production consumes 8, 16, and 19% of the total energy employed for glulam, LVL and plywood, respectively [117].

7. Case studies

Over the past years, a number of tall wood building projects have been completed around the World, demonstrating successful applications of new wood and mass timber technologies. Learning from the experiences of early adopters is essential for establishing opportunities for tall wood buildings in North America and other countries, such as Austria and Germany in the 1990s. The use of wood as a structural material in tall buildings is an area of emerging interest for its potential benefits.

In the last five years, 17 buildings over seven-stories tall have been constructed using wood. An example of this kind of structures is represented by *Treet*, a wooden high-rise building in Bergen (Norway), 49 m high (see Fig. 21a). The employed technique led to achieve a new height plateau. It consists of glulam load-bearing structure and prefabricated modular flats, made from engineered timber. The idea involves the modules being stacked four stories high, with two platforms being anchored to the glulam frame. These platforms are supported and reinforced by 3 m glulam lattice beams. After that, other four stories are stacked on top of each platform [133].

Another example is represented by the *Haut* project, a 73 m high residential tower located in the Amstelkwartier (Netherlands) with 55 apartments, public plinth Hortus bicycles and an underground car park (see Fig. 21b). It is characterized by a total gross floor area of about 14,500 m^2 and is to receive the BREEAM Outstanding label, the highest possible sustainability score [134].

Moreover, also *Forté* was built with Cross Laminated Timber (CLT) in 2012, in Melbourne (Australia). The structure is characterized by a height of 32 m and over 10 storeys (see Fig. 21c). The building is composed of 23 residential apartments with ground floor retail. *Forté*, reduces CO_2 equivalent emissions by more than 1400 tonnes when compared to concrete and steel: this is the equivalent of removing 345 cars from the roads. In addition to the environmental benefits of using wood, this building combines other sustainable initiatives, such as LED lighting and smart metering. By using rainwater tanks, *Forté* collects rainwater from the roof and uses it to supplement toilet flushing and supply the fire system [135].

Another tall wooden building, expected to be completed in September 2017, is the Brock Commons at the University of British Columbia in Vancouver [136], a 18-story student residence tower of 53 m of height (see Fig. 22). The structure is composed by two concrete cores, CLT floors slabs, and an external frame composed of glulam elements and steel beams and connections. The project demonstrates the benefits of the hybrid design that combines wood with traditional construction materials. In order to meet fire safety in an easier way the cores and the first floor are constructed with concrete and the mass wood structures are encapsulated with gypsum board layers. Moreover, the building is strongly compartmentalized and provided with an automatic sprinkler system. The building has been designed to meet LEED gold certification and it has been connected to the district energy network that supplies hot water for space heating and domestic hot water.

Worldwide, many buildings were developed using wood and wooden structural elements. Some interesting case studies, presenting innovative approaches, are discussed in the following.

Roma TRE University and Rubner Haus took part to Solar Decathlon Europe 2014 competition through the RhOME for denCity Team [137]. The technical characteristics of wood were employed by the Team in order to obtain a competitive house prototype under a technological and constructive point of view. The structure is made of light wood and it was realized by using the platform frame technique (Fig. 23). The choice of this technique is related to sustainability, light weight and easy installation concepts. In fact, the Platform frame system allows the building to respond appropriately to the vertical and horizontal loads, but this system can be adopted only for low-rice buildings. To overcome these limits, additional structural elements were added as reinforcement system.

The Algonquin College Perth Campus building (placed in the Town of Perth, near Ottawa) is characterized by local materials and wood-frame construction [138]. It is composed of two different parts: The Academic Hall and the Construction Wing (Fig. 24a and b). These two structures are connected by a passageway. The Academic Hall is a single-storey, wood-framed structure with a concrete slab on grade for the ground floor. The Academic Hall external walls are made of wood-frame with plywood covering. The external shell is characterized by wood siding with sections of masonry veneer. The external and internal walls of the wood-frame play a

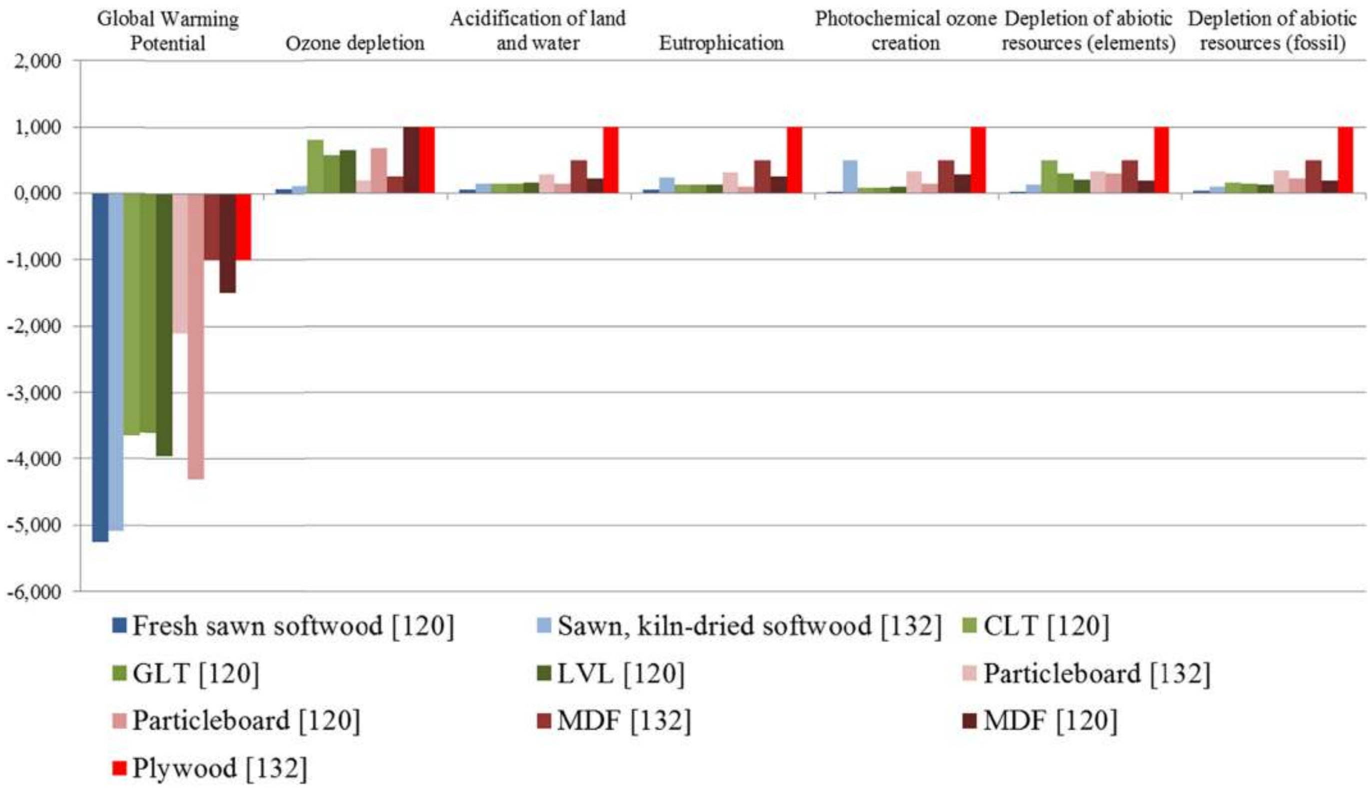

Fig. 20. EPD impacts of different wood building products normalized by the maximum value for every category; the functional unit is 1 m^3 of material [120,132].

Fig. 21. **(a)** Treet, wooden high-rise building in Bergen (Norway) [133]; **(b)** Haut, a 73 m high residential tower located in the Amstelkwartier (Netherlands) [134]; **(c)** Fortè, cross laminated timber structure in Melburne (Australia) [135].

key role against lateral forces caused by wind and earthquake. In order to offer an integrated appearance, the wood cladding was employed on the Construction Wing. Moreover, on the top of the Academic Wing classroom part, a system of engineered wood trusses was employed and it was reinforced by load-bearing wood-stud walls along the corridors and exterior walls.

The Metropol Parasol [139] is a particular structure placed in La Encarnacion Square, Seville (Spain). It can be considered as very innovative structure for the largest wooden construction currently diffused in the World. This structure was designed aiming at looking like a group of trees, in particular it consists of six mushroom-shapes parasols (see Fig. 25).

Another famous example, shown in Fig. 26, is The Superior Dome [140]. It opened as the biggest wooden dome in the 1991. It is a hemispherical stadium on the campus of Northern Michigan University (Michigan), in the United States. The dome is 44 m tall, has a diameter of 163 m and it covers an area equal to 21,000 m^2. It is a geodesic dome constructed with 781 Douglas Fir beams and 174 km of fir decking. The dome is designed to support snow taking into account high pressure level and winds characterized by velocities up to 130 km/h. The 2010 edition of Guinness World Records listed it as the fifth-largest dome and largest wooden dome in

Fig. 22. North west view of the Brock Commons Student Residence at University of British Colombia in Vancouver, Canada [136].

Fig. 23. RhOME for denCity House (Solar Decathlon Europe 2014) [137].

the world.

8. Conclusions

In Europe, as well as in many industrial countries, buildings are responsible for about 50% of the total energy consumption and for 50% of the total CO_2 emissions [141]. Wooden buildings help to

Fig. 25. The metropol parasol (la encarnacion square, Seville - Spain) [139].

meet the needs of sustainable and affordable constructions in many countries due to their good structural and environmental properties and low cost; furthermore, taking into account a correct design and maintenance, wood structures can maintain long service life.

Studying the evolution of the constructions sector, wood was the first building material and for a long time it was considered the most functional for load-bearing structures. In the last years, there was an evolution and improvement among the products and systems tailored to wooden construction. At the beginning, the use of wood was mainly due to its availability and lightness characteristics, despite the evident dimensional limitations and uncertainties in mechanical properties due to the wood nature. Nowadays the limits are overcome thanks to the technological advancement in the timber industry and the production of engineered wood and panels (Cross Laminated Timber, reconstructed panels, etc); moreover, the wood certification systems ensure the reliability of material properties. Therefore, these materials are currently employed for their significant structural, thermal, acoustical and environmental properties and, last but not least, for their aesthetic and formal features.

As far as structural properties, wood microstructure ensures a reduced own weight in front of an excellent load capacity. Wood shows similar properties for both compression and traction compared to concrete. Moreover, wooden elements have also the same volume of the concrete ones, with the advantage of 1/5 of the weight. Under a seismic and foundation point of view, the lightness is a very crucial issue. Although wood is a flammable material, it

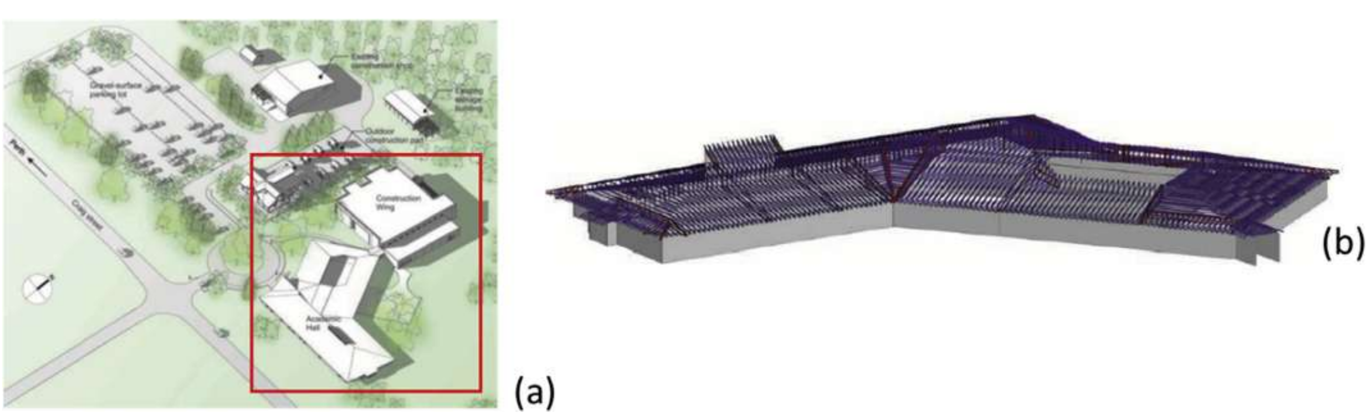

Fig. 24. **(a)** Site plan perspective; **(b)** Academic Hall truss arrangement [138].

Fig. 26. Superior dome in michigan (USA) [140].

shows very bad conduction under fire conditions and it does not lose its mechanical characteristics during the exposure to high temperature.

Wooden materials have low thermal conductivity, which ranges from 0,042 to 0,18 W/m^2K, this allows creating wall structures with significant thermal resistance with low thicknesses. These characteristics allow heat storing and releasing; this leads to an energy saving which can range from 15% to 40% compared to a masonry building. Consequently, thanks to its particular porous structure, it is possible to realize structures with reduced thickness and low power consumption.

Taking into account the acoustical behavior of wooden structures, the most critical phenomenon is the transmission of impact noise through the horizontal surfaces, because wood does not show good performance in terms of acoustics insulation, while perforated wood panels can be good sound absorbers.

Wood is an environmentally friendly and natural material, especially if a forest certification standard is adopted. These standards, which are more and more widespread in Western Europe and North America, allow a sustainable management of forests. Among the various environmental properties of wooden materials, embodied energy is the most important. Even if LCA indicators for wooden building products are generally very dispersed because of the different incidence of transportation, national energy mix or different impregnating substances, most studies confirm that wooden materials generally have a lower Embodied Energy compared to the materials traditionally employed for buildings construction (steel, concrete, bricks), especially if sequestrated CO_2 during growth is considered. It is also evident that the increase of processing of raw wood, in order to produce engineered wood or panels, generally causes higher values of Embodied Energy and of other environmental indicators, also due to the use of glues and other chemicals. Some authors also put in evidence there are some wood based insulating materials (like mineralized wood fibers) whose Embodied Energy per functional unit is as high as the one of conventional materials like EPS or glass wool.

Considering entire buildings, various LCA studies show that generally wooden buildings cause lower environmental impacts in comparison with conventional, masonry buildings. The main advantages are due to the construction phase, which may result in lower embodied energy if a wooden design is adopted. Wooden structures are also fully recyclable at the end of life, causing a very limited impact connected to this life cycle stage.

For the above mentioned properties, engineered wood is one of the most interesting and innovative materials for buildings construction. From the 70-s, the renewable, sustainable and environmental properties of wood increased its importance and employment, starting a new era for wooden buildings. This is also proved by several innovative wooden buildings raised recently all over the world – the paper provides some relevant case studies - and by the significant improvement in this scientific research field, which is testified by the long list of references included in the paper.

The technology development of the wood construction sector will presumably lead to an increasing spread of wooden buildings in the next years, also in the light of low energy and passive buildings.

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