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HIGH-RISE TIMBER ARCHITECTURE
AN OPPORTUNITY FOR THE SUSTAINABILITY OF THE BUILT ENVIRONMENT

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ABSTRACT

Bioeconomy, circular economy, land use reduction, sustainable use of natural resources, reduction of CO_2 *emissions in the atmosphere and recycling are the keywords which the building world must face in the near future, as the environmental emergency can no longer be postponed. In order to disseminate in the scientific community the different possibilities of timber as a sustainable building material throughout its whole life cycle and to provide the professionals with suitable decision-making tools for a conscious design, within the cultural and scientific scenario of the recent years, the paper serves as a moment of reflection highlighting how a closer integration between different sectors (forestry, building, energy, industrial and waste management) can find, in the use of timber, an opportunity to significantly reduce the overall impact of a built environment life cycle.*

KEYWORDS

timber buildings, vertical development, sustainability, biobased economy, environmental product declaration

Europe is directed towards a biobased circular economy (European Commission, 2015), and it promotes building development with the lowest land use; the interest in the use of recyclable, innovative and sustainable technologies is increasingly growing (Tebbatt Adams et alii, 2017), but the revival of an ancient building system, precisely timber, is also strengthening. The combination of 'tradition and innovation' perfectly describes this building material, one of the most widespread all over the world, also thanks to its recent technical rediscovery and engineering (Laminated Timber, Cross Laminated Timber, etc.). Timber was able to renew itself, become high-tech and contemporary architecture, slowly overcoming preconceptions and prejudices about its durability. Although in North America, Japan and Northern Europe it is normally used and often preferred when building residential and public premises even of great importance, in most of Europe, timber has yet to overcome a groundless cultural resistance, which has conditioned and limited its use. Therefore, timber artifacts, if properly designed and manufactured, and cyclically maintained, guarantee a much longer life cycle to the artifact than the one envisaged for reinforced concrete or steel build-

Fig. 1 - The Pagoda of the Temple of Hōryū-ji *(607 AD) in Nara, Japan (credit: www. italiajapan.net/horyuji/).*

Fig. 2 - The Cafi Holzofe *in Wollerau, Switzerland (credit: D. M. Weidmann, 2010).*

Fig. 3 - The Burmeister House *(1562) in Visby, Sweden.*

ing systems. Today, there are many examples: in Japan, hit by earthquakes, the Pagoda of the Temple of Hōryū-ji in Nara (Fig. 1), built in 607 AD with five floors and over thirty metres high; in the Old World, the two-storey house in Schwyz Canton (Fig. 2), in central Switzerland, built in 1257 and the medieval centre of Visby (Fig. 3), in Sweden, with its timber architecture of Scandinavian tradition mixed with the German culture of the Hanseatic era.

There are many reasons that justify a radical change from the building techniques of the 20th century which, for a long time, have led to prefer the use of industrial manufactured materials instead of natural-derived materials, for their supposed durability and safety. The main reason is that the recent literature reports tests showing that it is safe in case of fire (Barlett et alii, 2017) and earthquakes (Demirci, Málaga-Chuquitaype and Macorini, 2017). The first tests on the safety of multi-storey timber buildings were carried out in 2007 by the IVALSA Institute of Trento, in collaboration with the CNR, in order to describe the characteristics and potential of the X-Lam building system. Within the project called SOFIE, at the Building Research Institute laboratories of Tsukuba in Japan, a fire was simulated in a hotel room on the first floor of a three-storey timber building, using the double of the fire load provided for by European legislation. The results of the test have shown a fire-resistance of the load-bearing walls of one hour without changing its mechanical properties, without the flames spreading to the other rooms of the building and with a comparable performance to those of masonry or reinforced concrete buildings. In fact, in the event of a fire, the wood burns slowly and predictably – 42 mm per hour – without collapsing, thanks to the planned wear layer (Ceccotti et alii, 2013). In Japan in 2007, at the NIED laboratories (National Institute for Earth Science and Disaster Prevention) of Miki, a timber building of three floors and one of seven floors have admirably resisted to the same earthquake of 6.8 Magnitude of the Richter scale, the one that in 1995 destroyed the city of Kobe (IVALSA, 2011).

Other elements that have promoted the use of timber in buildings in recent years can be found in the scientific literature, which shows that not only is it a natural and renewable building material with a sustainable footprint (Gorvett, 2017) but, in a holistic 'cradle to cradle' point of view, is also capable of starting a virtuous environmental cycle (it is recyclable) and encouraging a new eco-sensitive lifestyle (Boarin, Calzolari and Davoli, 2018), which can be optimized through industrialization processes, and in particular through light, flexible and customizable prefabrication, which is characterized by a quick building, certainty of execution times and easy installation (Hurmekoski, Jonsson and Nord, 2015; Koppelhuber, 2017). However, there is still much work to be done. Therefore, in order to disseminate in the scientific community the different possibilities of timber as a sustainable building material throughout its whole life cycle, and to provide the professionals with suitable decision-making tools for a conscious design, within the cultural and scientific scenario described below, this paper serves as a moment of reflection highlighting how a closer integration between the forestry, building, energy, industrial and waste management sectors can find, in the use of timber, an opportunity to significantly reduce the overall impact of a built environment life cycle.

High-rise timber building – In Italy, until the late 20th century, the building sector has used timber mainly for some building components (beams, boards or cladding panels) and only in some geographical areas (favoured by the widespread availability of the raw material), producing only a few examples that did not favour its success and use, also because the building system was often concealed by 'traditional' claddings and finishes that did not enhance its building essence (Favole, 2017). The second report on Wood Homes and Buildings, instead, gives a very different overview of recent years: «Over 3,400 new houses built with timber in 2015, equal to 7% of the total building permits, one in fourteen houses made of timber, 696 million Euro is the value of built timber buildings, residential and non-residential» (Centro Studi Federlegno Arredo Eventi, 2017, p. 1). The reasons of this growth can be found in the combination of many positive factors. First of all, in 2008 the implementation of the Norme Tecniche di Costruzione (Technical Building Standards) for buildings with a timber building system with four or more above-ground floors: the recent update of the Standards in 2018 (Decreto del Ministero delle Infrastrutture e dei Trasporti, 2018) suggests a further important boost to the dissemination of this building system, since,


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for the first time, the ‘glued cross-laminated panels’ (CLT) are explicitly mentioned and the coefficients for the static verification report values very close to those foreseen by the Eurocode 5 ‘Design of Timber Structures’ (CEN, 2004). In addition to this regulatory aspect, the driving forces have also been: the footprint of sustainability and energy efficiency of the building system promoted by trade magazines (for example, we can mention the building with twelve social houses created in 2011 by Matteo Thun for the ATER of Motta di Livenza; Fig. 4) but also the speed of execution shown in the post-emergency reconstruction phase in the areas hit by the 2009 earthquake. There are two Italian examples of high-rise buildings that use load-bearing cross-laminated timber panels: the four towers with 9 floors of the well-known Social Housing Via Cenni in Milan (Fig. 5) designed in 2009 by Studio Rossi Prodi Associati and inaugurated in 2013, and the 12-storey Cross Lam Tower in Jesolo (Fig. 6) which is expected to be finished by the end of 2019.

The subject of the high-rise development of buildings with timber structural systems has, in recent decades, stimulated designers and companies, especially in the Old World, both as a technical challenge and as a sustainable model (Borup et alii, 2006; Toppinen et alii, 2018a) mainly for residential or office buildings (Hurmekoski, 2016). With the evolution of engineered timber technologies and with the research increasingly aimed at identifying new structural solutions – fire safety strategies and building methods – the design of timber towers will allow to reach increasingly greater heights (Dangel, 2016). Today the timber multi-storey buildings are a ‘niche’ type (Toppinen et alii, 2018c) as shown by the studies carried out by Hurmekoski et alii (2015). According to them, in Europe, the average market share is less than 1%, although in some Countries, such as Finland, the market share is 10%. The diffusion of this typology is due to the fact that Finland, on the one hand, started the ‘vertical’ experimentation already in the mid-1990s (Lazarevic, Kautto and Antikainen, 2019), and on the other, it carried out several studies on the use of this building system with regard to the perception/knowledge of performance, sustainable building scenarios, drivers of corporate innovation, sustainable production methods of raw materials (Tykkä et alii, 2010; Hurmekoski, Jonsson and Nord, 2015; Jarský, 2015; Hurmekoski, Pykäläinen and Hetemäki, 2018; Toppinen et alii, 2018b).

A recent study by Kuzmanovska et alii (2018) has presented the state of the art of contemporary buildings in engineered timber and with at least a real height of 25 metres or 8 floors (Wood Solutions, 2017), in order to define and understand emerging strategies within multiple frameworks, including design methods, materials, structural systems and building methods. The study, which has examined 46 buildings created

Fig. 4 - The ATER *of Motta di Livenza (2011) by Matteo Thun (credit: ilgiornaledellarchitettura.com, 2019).*

Fig. 5 - The Social Housing via Cenni *in Milan (2009) by Studio Rossi Prodi Associati (credit: www.promolegno.com).*

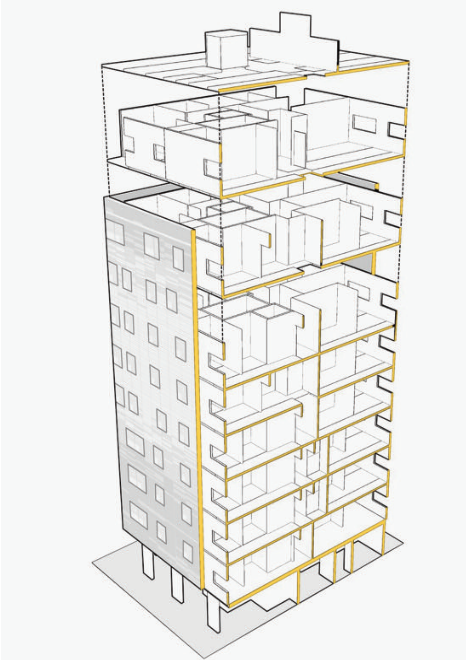

Fig. 6 - The Cross Lam Tower *in Jesolo which is expected to be finished by the end of 2019: rendering (credit: Urban-Bio).*

Figg. 7, 8 - The Murray Grove *in London, 2009 (credits: waughthistleton.com/murray-grove/; www.promolegno.com/materialegno/02/legno-in-the-city/).*

Fig. 9 - The Fortè Living *in Melbourne, 2013 (credit: www.victoriaharbour.com.au/news-and-events/news-and-events/news-forte-wins-2013-australian-timber-design-awards).*

from 2009 or that will be finished by 2020 in Europe, North America and Australia, integrates the knowledge acquired from the Survey of International Tall Buildings Report commissioned by Forestry Investment Innovations and BSLC on processes and challenges linked to the planning and building of 10 premises (Perkins+Will, 2014), and from the Solid Timber Construction Report on the economies caused by 18 buildings built with this building system (Smith, Griffin and Rice, 2015). In order to determine emerging trends on Structure, Envelope and Architectural Form parameters, the researchers of the University of Sydney have divided the buildings by date into four groups. The first group (G1) includes 8 projects going from the creation of the first building with timber panels in 2009 to the publication of the first American and Canadian handbooks in 2013 on Cross Laminated Timber (CLT): they are 'ground-breaking' buildings that have started the global dissemination of engineered timber structures and their construction techniques. The second group (G2) includes 11 projects carried out between 2014 and 2016; the third group includes 12 projects between 2017 and 2018; finally, the fourth group (G4) includes 14 projects under construction or which will be completed by 2020.

Regarding the Structural System, the study shows that while roofs and floor slabs (generally in CLT) are the most common in the first generation, the last generation mainly has linear vertical structural elements often combined with CLT floor slabs. The Cell Construction System constitute 75% of first-generation buildings and only 21% of fourth-generation buildings, while structures with linear elements have increased from 13% to 67% in the four generations. Since residential and mixed-use residential typologies are the most common in the four generations, this change in the structural typology can probably be attributed to the high-rise development of the building rather than to space and functional needs. The use of a cement core has increased throughout the generations (from 38% in G1 to 57% in G4) and it is the most common in 16-storey or more buildings. Conversely, the use of CLT cores has decreased over time (from 63% in G1 to 43% in G4). 9-storey buildings have an anomaly with a peak of CLT cores and a fall of concrete cores, while the G3 considers cases with a steel core. In general, there is a tendency to hybridization probably due to technological evolution. Other tendencies foresee the broadening the base (from 25% in G1 to 60% in G4), to keep the structural elements visible, or in the case of false ceilings, required by specific and stringent fire prevention regulations, to use slats elements that recall the natural structural material used.

The evolution of the Envelope in timber buildings follows the one of the first steel skyscrapers in Chicago, with a progressive abandonment of its load-bearing purpose (from 75% in G1 to 35% in G4) and timber cladding for other materials and technologies widely tested in steel and reinforced concrete skyscrapers, with a tendency to use fully glazed curtain walls (from 0% in G1 to 30% in G4). The use of sunshade panels changes between the different groups, even if with the increase in height there is a tendency to fragment the facades also with greeneries, probably determined by the desire

Fig. 10 - Previous page. *The* Treet *in Bergen, 2015 (credit: www.panelsfurnitureasia.com/en/news-archive/world-s-tallest-timber-building-officially-opens-in-bergen/17).*

Fig. 11 - *The* Brock Commons Tallwood House *in Vancouver, 2017 (credit: www.naturallywood.com/emerging-trends/tall-wood/brock-commons-tallwood-house).*

to communicate the reduced 'impact' of the building and make it perceptively more 'sustainable'. Regarding the Architectural Form, we can observe a prevalence of linear flat surfaces and regular extrusions (the use of protruding balconies is a declining trend among the four generations, especially when the timber is visible) referring the expressive values of the artifacts to the use of timber becomes an architectural and marketing feature in itself; the rare cases in which the volume is more complex depend mainly on the geometric and urban constraints of the settlement areas. Flexibility and adaptability to the space for different future uses characterize the design of some case studies, technological innovation and energy efficiency are distinctive elements of others in which natural ventilation, due to excessive air pressure on the upper floors, is replaced by the mechanical one.

The race to build the tallest timber building started in 2009, when the 9-storey (30 m) Murray Grove in London was built (Figg. 7, 8); many others followed, such as: Fortè Living (Fig. 9), inaugurated in Melbourne in 2013, with 10 floors (32 m), the Treet (Fig. 10), made in Bergen in 2015 with 14 floors (49 m), the Brock Commons Tallwood House in Vancouver (Fig. 11), finished in 2017 with 17 floors (53 m) and the HoHo (Fig. 12), finished in 2019 in Vienna with 24 floors (84 m). These projects

Fig. 12 - The HoHo *in Vienna, 2019 (credit: vaaju.com/austriaeng/final-track-at-the-wooden-hoho-height-in-vienna-seestadt-aspern/).*

Fig. 13 - Next page. *The* Mjøstårnet *in Brumunddal, 2019 (credit: buildingcue.it/mjostarnet-il-grattacielo-in-legno-piu-alto-del-mondo/12256/).*

are linked by the use of a hybrid structure with cross-laminated timber and reinforced concrete. Currently, according to the Council on Tall Buildings and Urban Habitat, record of the tallest building completely made in timber is set by the Mjøstårnet (Fig. 13), finished in March 2019 in Brumunddal. The building has 18 floors and is 85.4 metres tall. Someone might say that we are just getting started, since the research continues to investigate on this high-rise development reintroducing new standards to use timber as building system in skyscrapers capable of going way beyond the 115 metres of Hyperion, the world's tallest coast redwood.


Gjensidige
WOODCON
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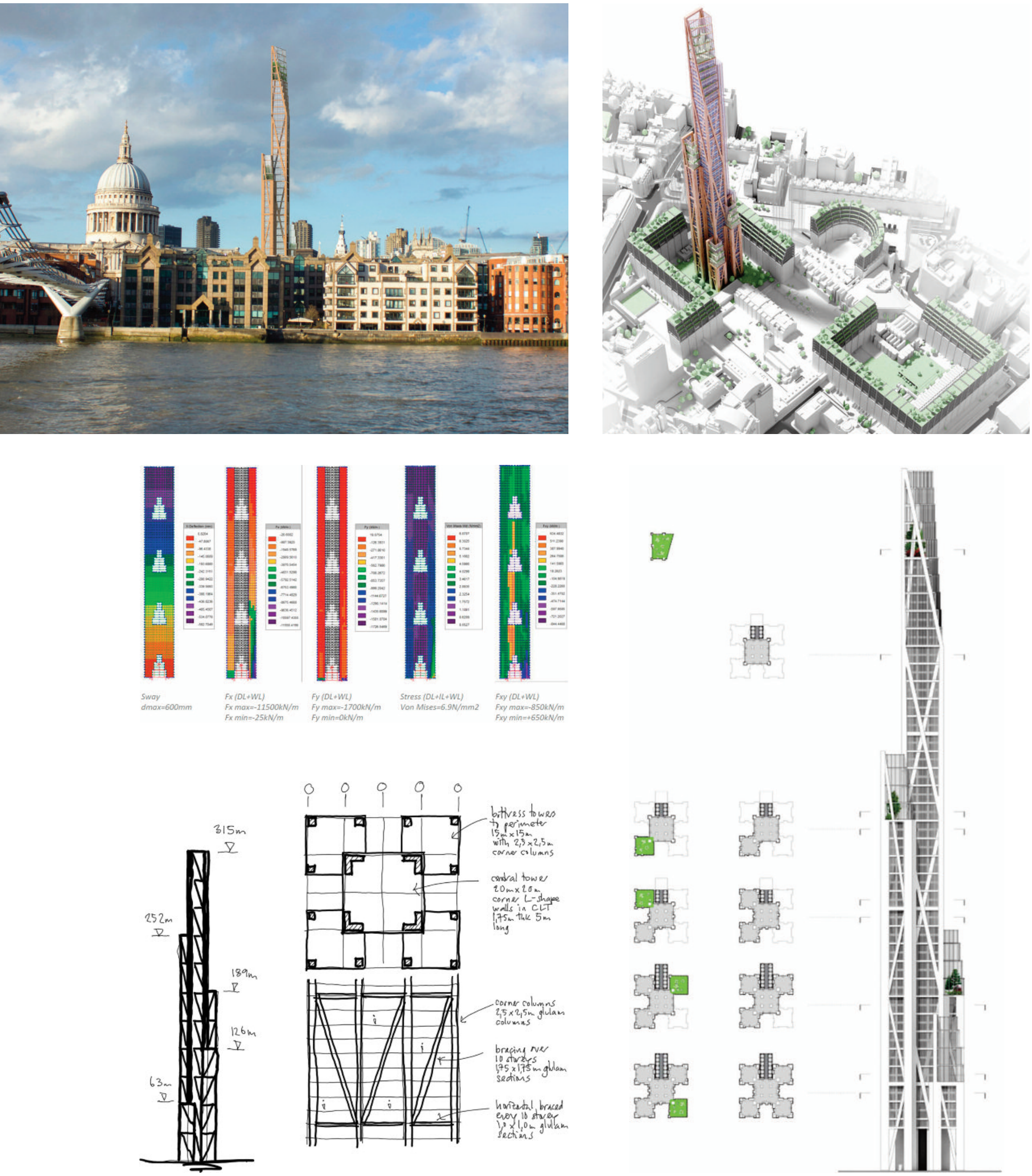
FRICH'S


Sway
dmax=600mm

Fx (DL+WL)
Fx max=-11500kN/m
Fx min=-25kN/m

Fy (DL+WL)
Fy max=-1700kN/m
Fy min=0kN/m

Stress (DL+IL+WL)
Von Mises=6.9N/mm2

Fxy (DL+WL)
Fxy max=-850kN/m
Fxy min=+650kN/m

Fig. 14 - The Oakwood Tower *in London (credit: www.dezeen.com/2016/04/08/plp-architecture-cambridge-university-london-first-wooden-skyscraper-barbican/); The notional site for the* Oakwood Tower*, London's Barbican (credit: PLP Architecture); 3D finite element model for the crossed I-beam structural solution (credit: Smith and Wallwork); Buttressed mega-truss (credit: Smith and Wallwork); Floor plans at various levels highlighting sky gardens and core (credit: PLP Architecture).*

In this regard, an interesting research program is Super Tall Timber. It was developed by the engineers of PLP Architecture together with Smith and Wallwork and the University of Cambridge at the Centre for Natural Material Innovation to create a skyscraper with a building system entirely made of engineered timber, the Oakwood Tower (Ramage et alii, 2017; Fig. 14). The choice of the place where to settle the new building has fallen upon London, a dynamic metropolis open to explore the potential of new materials and building techniques. A key objective of the research program was to explore new static layouts specific for timber buildings, instead of merely copy the conventional solutions used in the steel and cement buildings, since, at 300 metres of height, the reduced specific weight of the timber accentuates the problem of lateral stability to wind loads, which can be solved with adequate wind bracing and with optimized shape and orientation. Specifically, the designers of the Oakwood Tower used a static system mainly with linear elements (pillars, beams and trusses) to convey the loads along the perimeter of the building, which characterizes the architectural and structural expression of the building. The square central tower – each side is 20 metres long – is 300 metres high and is supported by four angular towers of different heights (65 m, 125 m, 190 m and 250 m) which, depending on the origin of the winds, act as a buttress, further simplifying its architectural configuration. The large-sized lattice elements (for example the pillars at the base of the building have a section of two square metres) also play a key role in the building's fire prevention strategy: thanks to the phenomenon of carbonatation, in fact, in the event of a fire, a protective layer is created on the external surface that isolates the underlying timber.

The research carried out by the European and North American team has interesting point of views on the architectural design of timber skyscrapers and can certainly be an inspiration for professionals, companies and the academic world in order to develop new and innovative approaches to use this natural material. Although it requires further study in relation to the production of structural elements of 'mega' size (up to 35 m in length and 100 tons of weight), to the study of special carpentry joints, to the integration between logistics and laying stages, to the dynamic behaviour of long-span timber flooring systems in response to vibrations induced by foot traffic, this study certainly provides an important contribution in the promotion of timber (specifically the C24 softwood), a natural building material – although it is engineered in laminated timber and CLT – chosen for its wide availability in the sustainable forests of central and northern Europe.

Sustainable Raw Materials and Forests – By defining the biobased economy, the European Commission (2012a) has promoted important challenges, such as the prevention of the natural resource depletion and the reduction of dependency on non-renewable resources; moreover, about climate emergency, most of the Countries that signed the Paris Climate Agreement recognized the need to take urgent action, giving to forests and their products a key role to mitigate CO_2 emissions in the atmosphere

Fig. 15 - A sustainable forest (credit: S. Black-Flickr).

(FAO, 2016). The building sector has a significant potential to effectively decrease the environmental impact of the world economy (Ruuska and Häakkinen, 2014), with a chance of influencing the 42% of the final energy consumption, 35% of GHG total emissions, 50% of extracted materials and 30% of water consumption in some regions (European Commission, 2011). The increasing environmental pressure faced by the building industry has, therefore, brought to coin the idea of a 'green building industry', about building methods aiming at answering the environmental, economic and social dimensions of sustainability (Zuo and Zhao, 2014).

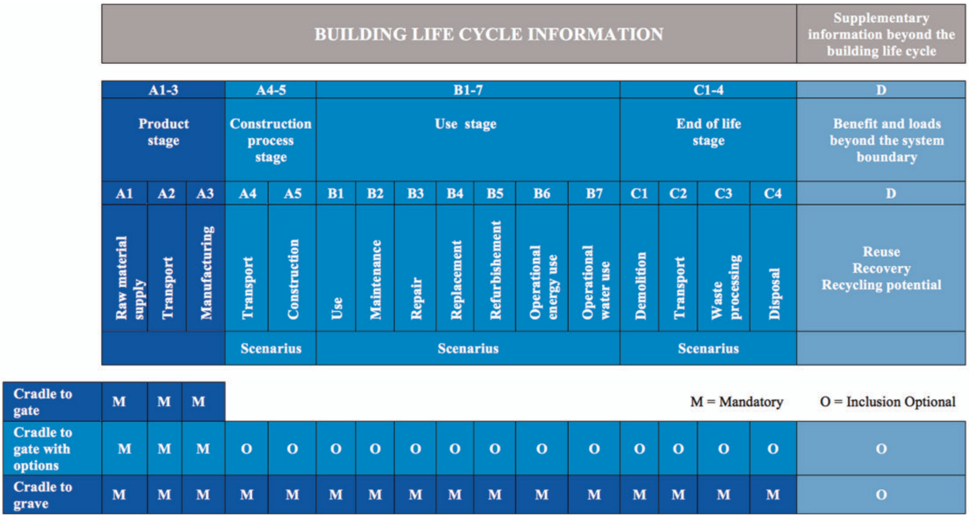
Many national policies promote biobased economy and green building. Worldwide, 45 Countries have a biobased economy strategy (Bioökonomierat, 2015) and 22 Countries of the European Union have a national action plan for green public procurement (Herczeg et alii, 2014). Moreover, the European Union has promoted green building through several strategies (European Commission, 2012b), roadmaps (European Commission, 2010, 2011), and flagship initiatives (European Commission, 2014), although the binding objectives concern only the energy efficiency and the recycling of the materials (Energy Performance of Buildings Directive 2010/31/EU; Energy Efficiency Directive 2012/27/EU; Waste Framework Directive 2008/98/EC). Over the last years, there has been a steady increase in the use of timber as building material in Europe, China and North America (Food and Agriculture Organization and UNECE, 2018; Howard, McKeever and Liang, 2017). However, while the green building strategies of the European Union do not promote specific materials, many studies and research on green building have underlined the role that forest-based industries and timber buildings can have (Wang, Toppinen and Juslin, 2014), the positive environmental impacts of wood products (Bösch et alii, 2015; González-García et alii, 2011b; Suter, Steubing and Hellweg, 2017), the value of forest ecosystem services, the future potentials and current risks to which they are subject (Ojea et alii, 2016; Ouyang et alii, 2016; Thom and Seidl, 2016). Research and studies are flourishing, especially in the Nordic countries where timber buildings are considered as one of the most important means to achieve growth based on circular biobased economy (Antikainen et alii, 2017), allowing benefits both in terms of CO_2 emission reduction (Oliver et alii, 2014) and of low-cost creation (Esala, Hietala and Huovari, 2012).

Therefore, forests can play a key role in the transition to low-carbon economies and in the building of a sustainable environment as they represent carbon accumulators and wood products have a lower embodied energy than other products, especially in the building sector that is responsible for 36% of global energy consumption and 39% of CO_2 emissions (UN Environment, 2018). But this role can be crucial only if timber comes from sustainable sources (Lucon et alii, 2014; Fig. 15). While growing, trees accumulate CO_2 and release oxygen into the environment; while aging, they absorb less and less CO_2, and if they are not cut down, they rot, releasing into the atmosphere the quantity of CO_2 stored during their life cycle. Sustainable forest management provides for cutting only adult plants and replace them with new trees; in wood products made from cut down trees the carbon stays stored, thus representing a carbon dioxide storage tank. At the end of their life cycle, the wood products can be reused for power, for example as biomass. In this case, it is released the same quantity of CO_2 that the tree had previously withdrawn from the atmosphere and the cycle is thus closed in balance, without damaging the environment. Many manufacturers of timber elements have adopted timber biomass thermal power plants that generate power from the waste of woodworking and its recovery at end-of-life. The power produced with this method is used in the production processes, triggering an eco-sustainable energy cycle capable of eliminating carbon emissions, which is not possible with other building materials (especially steel, aluminium and plastic), whose recycling and transformation process demand an enormous quantity of power and an enormous quantity of emissions into the atmosphere.

Life Cycle Assessment – There are many scientific evidences showing how the commonly used building materials (concrete, steel and aluminium) make a crucial contribution, during the production process, to CO_2 emissions into the atmosphere (Akbarnezhad and Xiao, 2017), therefore for a correct analysis of the overall energy balance, the embodied energy take into account the whole life cycle of the material, with an analysis ‘cradle-to-grave’ that includes the energy needed for the extraction of raw materials, processing and transport, periodic energy for maintenance and final energy for disposal (Hammond and Jones, 2008; Dixit et alii, 2010). An appropriate building materials choice can cause a 17% reduction of the energy used in the construction of a building (Thormark, 2006), and it can reduce the CO_2 emissions by 30% (Gonzalez and Navarro, 2006). In terms of environmental sustainability, it seems fundamental to focus on the use of ‘low-energy materials’, their production method and recycling possibilities.

A fundamental tool for assessing the environmental impacts of materials is the EPD (Environmental Product Declaration) or Type III Environmental Label (Minkov et alii, 2015), which provides quantified environmental data using predetermined parameters and, if necessary, additional environmental information based on the ISO 14025 standard (2006). The EPD is a technical document verified by a certification body that accompanies the marketing of a product and contains quantitative information based on the LCA method, as set by the ISO 14040 Standard (2006). The CEN TC350 committee – Sustainability of Construction Works has outlined the Product Category Rules (PCR) for EPD of building materials in compliance with the EN 15804:2012+A1:2013 standard. The PRC describes what life cycle stages – Product stage, Construction stage, Use stage, End of life stage, and an optional module Reuse-recovery (D) – have to be considered in the environmental product declaration and which processes should be included.

Table 1 lists the mandatory and optional stages, according to the system limit considered: the ‘cradle to gate’ analysis evaluates only the Product stage (A1-A3), which is



	BUILDING LIFE CYCLE INFORMATION																Supplementary information beyond the building life cycle
	A1-3			A4-5		B1-7							C1-4				D
	Product stage			Construction process stage		Use stage							End of life stage				Benefit and loads beyond the system boundary
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
	Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishement	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Reuse Recovery Recycling potential
				Scenarius		Scenarius							Scenarius				
Cradle to gate	M	M	M														
Cradle to gate with options	M	M	M	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Cradle to grave	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	O

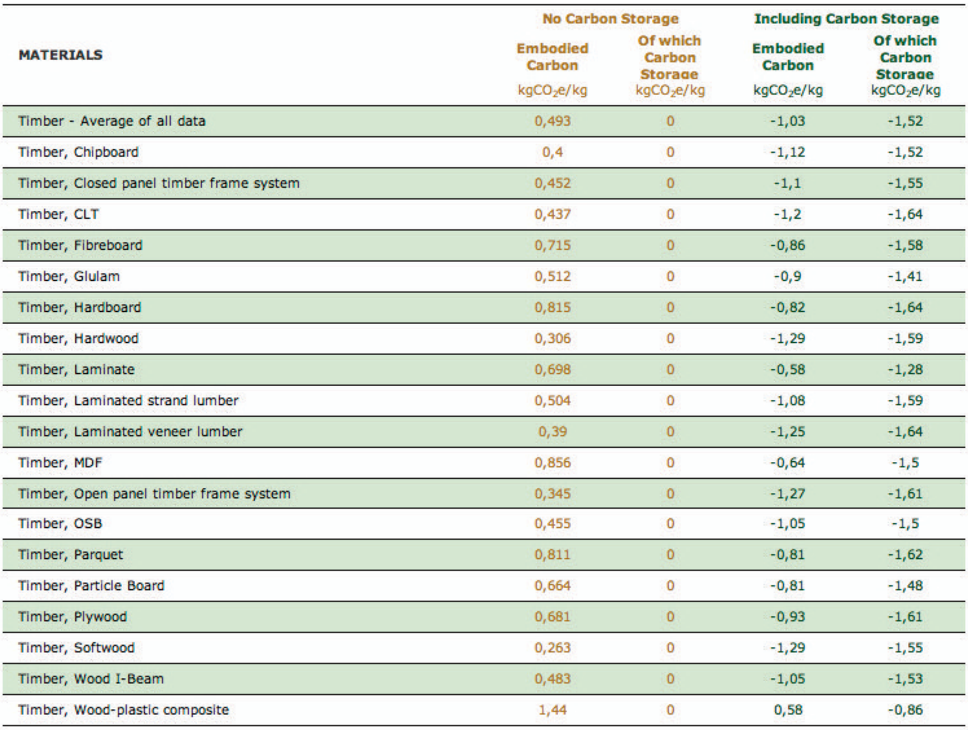
M = Mandatory O = Inclusion Optional

Table 1 - Information modules for construction products, adapted from EN 15804:2012.

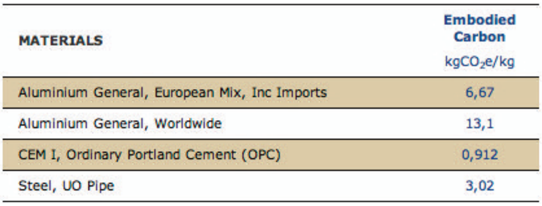
therefore mandatory; in the 'cradle to gate with options' analysis, the Product stage (A1-A3) is mandatory while all other phases are optional; in the 'cradle to grave' analysis all phases are mandatory except D) which is optional. However, it should be noted that, while, on the one hand, the TC 350 standards, through the harmonized methodology currently proposed, provide an important tool for assessing the environmental performance and costs of the life cycle of buildings, on the other they have many limits which research and the environmental policies of the different countries will have to face in the near future. In fact, the tool's voluntary nature, accuracy of the measurements and the discretion of the data of some stages, do not allow to supply the real energy consumption of the materials and building components during their entire life cycle and, therefore, do not allow to univocally evaluate their general energy balance.

The production of wood products requires, in general, less energy than the production of most materials, specifically cement and steel (Dodoo, Gustavsson and Sathre, 2009; Sathre and González-García, 2014; Guardigli, 2014). One of the best known and used databases that gives data on the embodied energy of materials is the Inventory of Carbon and Energy (ICE) created by Hammond and Jones from Bath University, whose latest version has been published in 2019 (Hammond and Jones, 2019). Table 2 shows the data on the wood products in the ICE. First, it is important to consider that these data concern only the 'cradle-to-gate' analysis, therefore only the Product stage (A1-A3) is considered. If the data are compared with other materials that are always in the ICE, the embodied carbon of most products is lower than that of materials as Aluminium, Ordinary Portland Cement (OPC) and Steel (Tab. 3).

Table 3 shows the data including the carbon stored in the timber and those that ex-



MATERIALS	No Carbon Storage		Including Carbon Storage	
	Embodied Carbon $kgCO_2e/kg$	Of which Carbon Storage $kgCO_2e/kg$	Embodied Carbon $kgCO_2e/kg$	Of which Carbon Storage $kgCO_2e/kg$
Timber - Average of all data	0,493	0	-1,03	-1,52
Timber, Chipboard	0,4	0	-1,12	-1,52
Timber, Closed panel timber frame system	0,452	0	-1,1	-1,55
Timber, CLT	0,437	0	-1,2	-1,64
Timber, Fibreboard	0,715	0	-0,86	-1,58
Timber, Glulam	0,512	0	-0,9	-1,41
Timber, Hardboard	0,815	0	-0,82	-1,64
Timber, Hardwood	0,306	0	-1,29	-1,59
Timber, Laminate	0,698	0	-0,58	-1,28
Timber, Laminated strand lumber	0,504	0	-1,08	-1,59
Timber, Laminated veneer lumber	0,39	0	-1,25	-1,64
Timber, MDF	0,856	0	-0,64	-1,5
Timber, Open panel timber frame system	0,345	0	-1,27	-1,61
Timber, OSB	0,455	0	-1,05	-1,5
Timber, Parquet	0,811	0	-0,81	-1,62
Timber, Particle Board	0,664	0	-0,81	-1,48
Timber, Plywood	0,681	0	-0,93	-1,61
Timber, Softwood	0,263	0	-1,29	-1,55
Timber, Wood I-Beam	0,483	0	-1,05	-1,53
Timber, Wood-plastic composite	1,44	0	0,58	-0,86



MATERIALS	Embodied Carbon $kgCO_2e/kg$
Aluminium General, European Mix, Inc Imports	6,67
Aluminium General, Worldwide	13,1
CEM I, Ordinary Portland Cement (OPC)	0,912
Steel, UO Pipe	3,02

Table 2 - Inventory of Carbon and Energy (ICE) related to wood products (data extracted from Hammond and Jones, 2019).

Table 3 - Inventory of Carbon and Energy (ICE) related to construction materials other than wood (data extracted from Hammond and Jones, 2019).

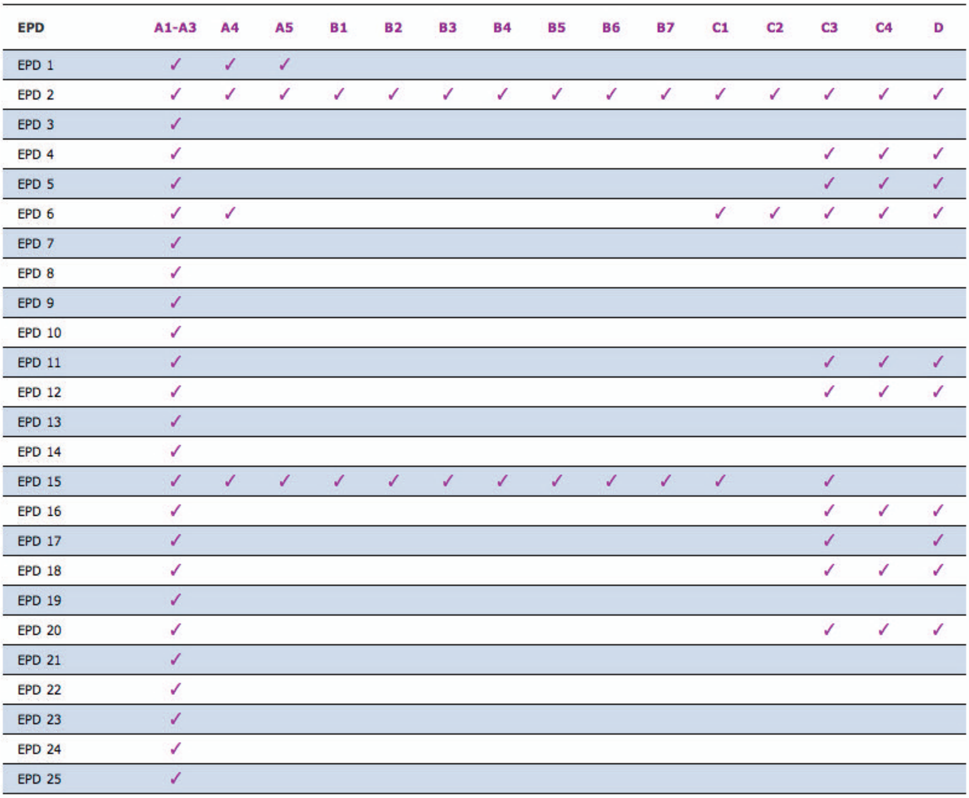
clude it; carbon storage can only be requested for timber coming from sustainable sources. This table also shows how carbon storage values are presented as negatives, because, as an example, if 1.5 kg of CO_2 per kilogram of timber is stored and 0.5 kg of CO_2 per kilogram is the carbon embodied to make a timber product (Mod A1-A3) without carbon storage, the embodied carbon with carbon deposit will be -1.0 kg CO_2 per kilogram of timber. The storage of carbon can be applied only to timber transformed in a product and not to the excess timber that will become waste material. Moreover, it is particularly important to consider the end-of-life stage for timber, since the quantity of stored carbon that will reenter the atmosphere depends on the methods used for its end-of-life: incineration, throwing in a landfill, recycling or reuse.

Despite the importance of the end-of-life stage, most of the EPDs are limited to the ‘cradle to gate’ or ‘cradle to gate with options’ analysis. A recently published research

(Scalisi and Sposito, 2019) examines 395 products available on the International EPD System website. The analysis of the 395 EPD files shows that, in most cases, the system limit is ‘cradle-to-gate with options’, precisely in 46% of the cases; in 29% of the cases the system limit is ‘cradle-to-gate’ and only in 25% of the cases the system limit is ‘cradle to grave’. Furthermore, the research highlights that in the files declaring ‘cradle to gate with options’ as system limit, besides the mandatory stages A1-A3, most cases show data related only to the A4 stage, among the optional ones, only a small percentage shows data related to A5 stages, among the optional ones, while a few cases show data for stages B1-B7 and C1-C4. The same happens for step D, that is rarely considered.

As listed in the EN 15804: 2012, the end-of-life stage of a building product begins when it is replaced, dismantled and does not have any purpose. Specifically, it includes: C1 (demolition of the building/construction product); C2 (transport of demolition waste including the end-of-life building product in the waste treatment plant); C3 (waste treatment operations for reuse, recovery or recycling); C4 (disposal and linked processes). During the end-of-life step, everything coming out from the system (that is the building) is considered waste until it gets the status of end-of-waste. The end-of-waste status is reached if one of these materials or products meet one of these requirements: it is commonly used for specific purposes; there is a market or a demand for it; it meets technical requirements for specific purposes; its use will not lead to negative effects. The module D refers to the possible reuse/restoration/recycling. About wood products, this paper has analysed the EPD files present not only in the International EPD® System but also in the IBU-EPD. Of 91 products analysed, 25 are in the International EPD® System (Tab. 4) and 66 in the IBU-EPD, 27 of which are of the structural wood product type (Tab. 5) and 39 of timber-based panels type (Tab. 6). The three tables confirm the results of the aforementioned research, since the life cycle analysis includes a ‘cradle to grave’ analysis only in few cases. About the end-of-life stage of wood products, from the 91 files analysed, it is clear that have been taken into account mostly the C3 module (73%) and the D module (77%), while the C1, C2 and C3 have been analysed only in 12%, 29% and 21% of cases respectively. These latter percentages show how, although EPDs give useful information for professionals to choose sustainable materials, they still have limits with respect to the whole analysis of the life cycle (in which all the phases should be taken into account), also in the case of the wood products we have dealt with.

Glues – It is known that wood products coming from sustainably managed forests can have a significantly lower environmental life cycle impact than other common building materials such as cement and steel (Werner and Richter, 2007; Sathre and O’Connor, 2010). But what limits the possibility of recycling them at their end-of-life is mainly the presence of petroleum-based glues such as urea and phenol-formaldehyde. The anisotropic nature of timber and the variability of its properties, which depend on



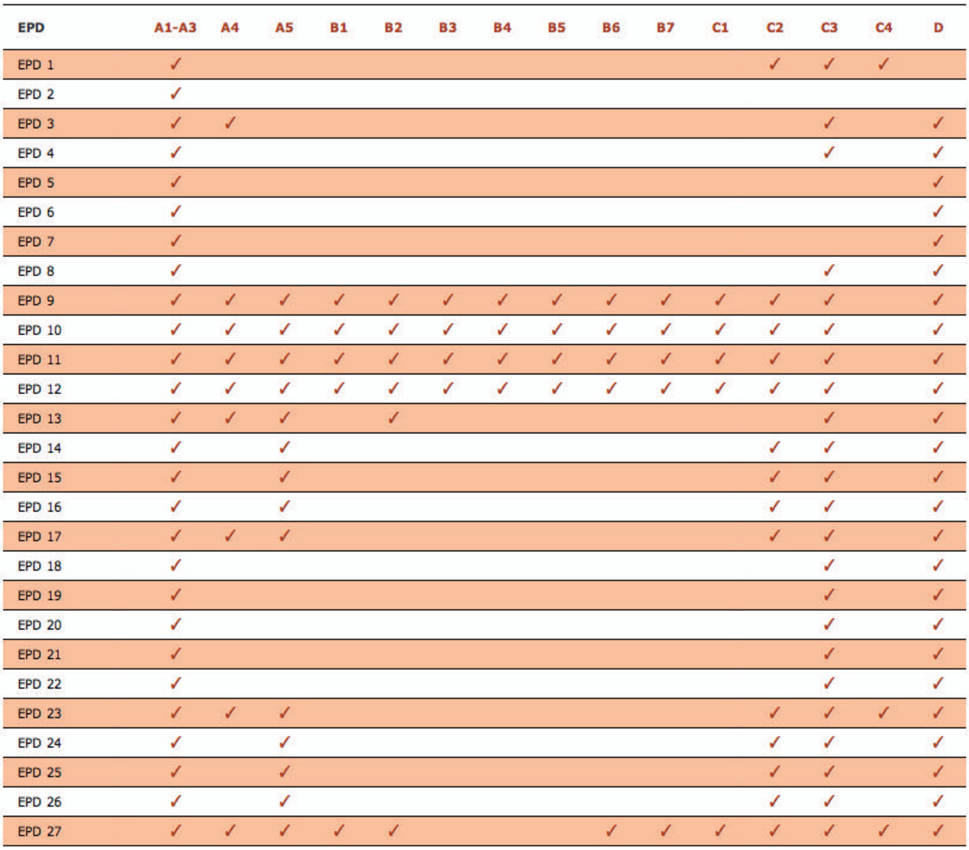
EPD	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
EPD 1	✓	✓	✓												
EPD 2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
EPD 3	✓														
EPD 4	✓												✓	✓	✓
EPD 5	✓												✓	✓	✓
EPD 6	✓	✓									✓	✓	✓	✓	✓
EPD 7	✓														
EPD 8	✓														
EPD 9	✓														
EPD 10	✓														
EPD 11	✓												✓	✓	✓
EPD 12	✓												✓	✓	✓
EPD 13	✓														
EPD 14	✓														
EPD 15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		
EPD 16	✓												✓	✓	✓
EPD 17	✓												✓		✓
EPD 18	✓												✓	✓	✓
EPD 19	✓														
EPD 20	✓												✓	✓	✓
EPD 21	✓														
EPD 22	✓														
EPD 23	✓														
EPD 24	✓														
EPD 25	✓														

Table 4 - Environmental Product Declaration of wood and wood-based products (source: International EPD® System; access 29th April 2019).

the tree species and climate zones of their origin, have been overcome by composite wood products, made by gluing together smaller pieces, which have created a more homogeneous material with significantly better performances. However, many studies (González-García et alii, 2009) show that the use of petroleum-based glues has a negative impact on the environment, being responsible for polluting emission favouring global warming, the formation of photochemical oxidants and acidification, eutrophication and toxicity phenomena.

The research of the last ten years has, therefore, focused on developing environmentally friendly glues. One of the first studies was carried out by Widsten and Kandelbauer (2008) who evaluated the production of timber fibre panels using a lignin-based glue with enzymes, with good results in the laboratory; Moubarik et alii (2009) proposed the use of resins obtained from corn starch and tannin from the quebracho tree (Schinopsis balansae) used as glue to partially replace the phenol-formaldehyde resin in plywood production, obtaining panels with better mechanical properties and water resistance; González-García et alii (2011a) studied the production of panels using a two-component double sided adhesive made of a timber-based phenolic material and a phenol-oxidizing enzyme. More recent studies are carried out by: Kaufmann, Kolbe and Vallée (2018) on gluten and casein-based glues that have similar performances to epoxy and 2K polyurethane glues, provided that they are used in dry conditions; Nairong et alii (2019) on bio-based glues derived from renewable defatted soy flour and epichlorohydrin, capable of giving to glued Pinus Massoniana plywood a wet shear strength of 0.93 MPa, a parameter in line with the Chinese national legislation. Finally, the experimentation carried out by Guo et alii (2019) on a bio-based polymer composed of a natural monoterpene (β-myrcene) and sulphur dioxide – which can be taken from industrial exhaust gases – whose adhesive properties have been tested on glass, timber, aluminium and copper with promising results.

The methods of connecting timber are also reviewed from a materials science point



EPD	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
EPD 1	✓											✓	✓	✓	
EPD 2	✓														
EPD 3	✓	✓											✓		✓
EPD 4	✓												✓		✓
EPD 5	✓														✓
EPD 6	✓														✓
EPD 7	✓														✓
EPD 8	✓												✓		✓
EPD 9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
EPD 10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
EPD 11	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
EPD 12	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
EPD 13	✓	✓	✓		✓								✓		✓
EPD 14	✓		✓									✓	✓		✓
EPD 15	✓		✓									✓	✓		✓
EPD 16	✓		✓									✓	✓		✓
EPD 17	✓	✓	✓									✓	✓		✓
EPD 18	✓												✓		✓
EPD 19	✓												✓		✓
EPD 20	✓												✓		✓
EPD 21	✓												✓		✓
EPD 22	✓												✓		✓
EPD 23	✓	✓	✓									✓	✓	✓	✓
EPD 24	✓		✓									✓	✓		✓
EPD 25	✓		✓									✓	✓		✓
EPD 26	✓		✓									✓	✓		✓
EPD 27	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	✓

Table 5 - Environmental Product Declaration of structural timber product (source: IBU-EPD; access 29th April 2019).

EPD	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
EPD 1	✓											✓	✓	✓	✓
EPD 2	✓											✓	✓	✓	✓
EPD 3	✓											✓	✓	✓	✓
EPD 4	✓														✓
EPD 5	✓												✓		✓
EPD 6	✓														✓
EPD 7	✓												✓		✓
EPD 8	✓		✓										✓		✓
EPD 9	✓		✓										✓		✓
EPD 10	✓														✓
EPD 11	✓												✓		✓
EPD 12	✓												✓		✓
EPD 13	✓												✓		✓
EPD 14	✓	✓			✓							✓	✓		✓
EPD 15	✓												✓		✓
EPD 16	✓		✓										✓		✓
EPD 17	✓		✓										✓		✓
EPD 18	✓											✓	✓		✓
EPD 19	✓		✓										✓		✓
EPD 20	✓		✓										✓		✓
EPD 21	✓												✓		✓
EPD 22	✓												✓		✓
EPD 23	✓												✓		✓
EPD 24	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
EPD 25	✓														✓
EPD 28	✓	✓			✓							✓	✓		✓
EPD 29	✓														
EPD 30	✓													✓	
EPD 31	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
EPD 32	✓	✓	✓									✓		✓	✓
EPD 33	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓		
EPD 34	✓												✓		✓
EPD 35	✓		✓										✓		✓
EPD 36	✓												✓		✓
EPD 37	✓		✓									✓	✓		✓
EPD 38	✓												✓		✓
EPD 39	✓		✓												✓

Table 6 - Environmental Product Declaration of wood based panels (source: IBU-EPD; access 29th April 2019).

of view (Bechthold and Weaver, 2017). Friction welding of timber (a process adapted from the metal industry) turns out to be more promising than the use of mechanical fasteners and glues, which limit the reuse of timber in an end-of-life scenario (Hahn et alii, 2014; Stamm, Natterer and Navi, 2005). In the friction welding, an oscillating movement under pressure produces heat at the interface of two timber elements so that pyrolysis occurs between organic materials; maintaining pressure during cooling allows the two layers to bond permanently when the softened material hardens. The technique is particularly interesting for the gluing of several layers of solid timber in the production of CLT panels but the complexity of welding timber in the current production system has prevented its widespread implementation so far. The ongoing project called Towards Adhesive Free Timber Buildings is following this principle. The project is funded by the European Community within the 2014-2020 INTERREG VB North West Europe program and coordinated by the Centre for Materials and Structures of the University of Liverpool. On a long run, the project aims to produce one million cubic metres of wood products without adhesives and 100% recyclable, removing 6,000 tons of toxic adhesives currently used in their production (Keep.eu, 2016).

Conclusions – Bioeconomy, circular economy, land use reduction, sustainable use of natural resources, reduction of CO_2 emissions in the atmosphere and recycling are the keywords which the building world must necessarily face in the near future, as the environmental emergency can no longer be postponed. In this light, the use of timber as building material can give an immediate solution to the problem. Timber is a renewable raw material if its production takes place in sustainable forests. Using timber has a twofold benefit for the environment because, when growing, the plants accumulate CO_2 and release oxygen into the environment, a regulated cutting down of adult trees allows to block the stored carbon dioxide which would be dispersed with their death. The possibilities of recycling the material range from the use as biomass for the production of energy (clean, also thanks to the natural and biodegradable adhesives which are being tested and have similar performances to petrol-based and more polluting adhesives) and its reuse, if originally used in dry building systems. It turns out that a closer integration between the forestry, building, energy, industrial and waste management sectors can find in the use of timber as building material an opportunity to significantly reduce the overall impact of the life cycle of a built environment, bringing great energy, environmental and economic benefits (Lucon et alii, 2014; Truong and Gustavsson, 2013).

Over the last two decades, the industrial research and the research promoted by the academic world have made an important contribution through the engineering of this natural material which has become more performing at combined compressive and bending loads, with greater durability and safety (to earthquakes and fires). Moreover, the study of new static configurations of the building system has favoured the achievement of greater quotas, challenging year by year the consolidated supremacy of similar skyscrapers in steel and reinforced concrete. The phenomenon of the verticalization of cities, which is scarcely present in Europe, except as a very unique situation, is still mainly linked to the desire to create a landmark or a symbolic element, a manifest of a specific company, technology or innovation but it can certainly favour, with its sustainable and smart skyscrapers, the return to a compact, high-density city, favouring better urban comfort and lower land use.

Technical-technological and planning aspects, but also functional, formal and aesthetic issues to be solved through flexibility in the organization of spaces and versatility in establishing intended uses, experimentation with new linguistic forms that in the case of timber will find expressive strength and formal identity through the attention to building details. In this framework, Building Technology can give its contribution through the organization of processes and the implementation of programs, strategies and projects aiming to favour the development of new and more current policies of territorial transformation into different realities for scale and context, investigating functional, social and morphological aspects, setting indicators, criteria and assessment methods for the urban and building project, experimenting type-technological solutions in synergy with industrial production and finally tracing those lines of innovation that will soon allow to build, only with timber, a skyscraper capable of going way beyond the 115 metres of Hyperion, the world's tallest coast redwood.

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