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Review

Acoustic Characteristics of Cross-Laminated Timber Systems

Antonino Di Bella * and Milica Mitrovic

Department of Industrial Engineering, University of Padova, Via Venezia, 1, 35131 Padova, Italy; milica.mitrovic@unipd.it

* Correspondence: antonino.dibella@unipd.it; Tel.: +39-049-827-6867

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Abstract: The growing diffusion of cross-laminated timber structures (CLT) has been accompanied by extensive research on the peculiar characteristics of this construction system, mainly concerning its economic and environmental benefits, lifecycle, structural design, resistance to seismic actions, fire protection, and energy efficiency. Nevertheless, some aspects have not yet been fully analysed. These include both the knowledge of noise protection that CLT systems are able to offer in relation to the possible applications and combinations of building elements, and the definition of calculation methods necessary to support the acoustic design. This review focuses on the main acoustic features of CLT systems and investigate on the results of the most relevant research aimed to provide key information on the application of acoustic modelling in CLT buildings. The vibro-acoustic behaviour of the basic component of this system and their interaction through the joints has been addressed, as well as the possible ways to manage acoustic information for calculation accuracy improvement by calibration with data from on-site measurements during the construction phase. This study further suggests the opportunity to improve measurement standards with specific reference curves for the bare CLT building elements, in order to compare different acoustic linings and assemblies on the same base. In addition, this study allows to identify some topics in the literature that are not yet fully clarified, providing some insights on possible future developments in research and for the optimization of these products.

Keywords: cross-laminated timber; wooden building technology; building acoustics; noise control in buildings; flanking transmission; energy efficiency; sustainability

1. Introduction

Cross-laminated timber (CLT) is an engineered timber product at the basis of an articulated construction system that is rapidly establishing itself for the construction of wooden buildings designed to achieve particular structural performance, allowing the rationalization of site management and reduction of construction time [1–3].

Among the wooden construction systems, CLT represents one of the most interesting and innovative material. Its introduction into the world of construction has given a significant boost to the use of wood as an alternative to heavy construction systems, offering new possibilities to reduce the environmental impact of the building industry.

The construction sector, as a whole, is responsible for about 42% of European energy consumption and 35% of CO_2 emissions [4,5]. The reduction of energy consumption is currently one of the main priorities at international level and the building industry represents one of the sectors that can make an important contribution to saving energy and achieving the objectives of energy efficiency [6–9]. Taking into account these evaluations, the European Union is moving the construction market in a more ecological direction with the aim of achieving a 20% reduction in global energy consumption by 2020; in fact, many designers are taking into consideration new sustainable technological solutions [10].

For several decades, concrete has proven to be the most widely used construction material for elements with structural capabilities. The ease in finding the materials that compose it, the simplicity of processing and transport, as well as the possibility of being produced on-site or used for the construction of prefabricated elements, has decreed its success. Leaving aside the environmental aspects related to the procurement of raw materials and the need for water required for the production of concrete, the real ecological problem derives from its CO_2 emissions; in fact, concrete is responsible for 5% of global annual carbon dioxide emissions [11–14].

For this reason, the building industry is investing in the search for new and more environmentally efficient solutions [15]. For the first time, after a massive production of concrete in the 20th century, this material has begun to be considered obsolete for some types of construction. Thanks to numerous studies on alternative technological solutions, timber seems to be one the most valid option [16,17]. Recently, research conducted on sustainable forest management, the lifecycle of wood products, and the use of timber in infill construction, has attracted the construction industry's interest especially in regards to various international climate change countermeasures [18].

Wood is known as a renewable material because of the possibility to store carbon that has been extracted from carbon dioxide in the atmosphere, with the ability to re-grow rapidly, to provide excellent opportunities for re-use, and to serve as a carbon-neutral source of energy for construction materials, especially when harvested from certified sustainable forestry and properly recycled [19].

One of the most important things is that the material comes from the forest and this is a decisive climate factor particularly if wood is sourced in a sustainable way from well-managed forests. Timber construction is an efficient method of CO_2 storage, as long as the material is obtained using responsible methods of forest cultivation (plantations) and from a certified source that is not too far away (to avoid transport-generated greenhouse gases) [19].

Timber construction systems are very widespread, not only in Europe [20,21] but also in all those countries where wood suitable for this type of application and the technologies for its transformation into industrialized building products are available, such as in North America [2].

CLT was first developed in Europe in the mid-1990s. Initially, this product was designed to reduce processing waste from sawmills and to use log parts considered less valuable [22]. This system then quickly evolved so as to constitute an efficient industrialized construction technology, particularly suitable for the production of massive prefabricated elements with mechanical performance. In many cases, the structural capabilities are superior to those obtainable with other wooden construction systems [23].

Although it has appeared on the market only recently, CLT (cross-laminated timber), also known by other trade names such as X-Lam or CrossLam, composite plywood, cross-laminated wood, BBS (Binder BrettSperrholz), or MM-BSP (Mayr–Melnhof–Brett Sperrholz Platten), has attracted considerable interest in the field of technological innovation and eco-sustainable construction materials [24,25]. CLT structures are becoming a reference model in Europe, especially in the field of multi-storey wooden constructions [26–31] and not only for residential use [32,33]. The use of the CLT is very adaptable and it allows constructing walls, floors, and roofs in various types of buildings: Multi-storey residential buildings, schools, auditoria, exhibition places, worship places, sports halls, theatres, and commercial buildings. As was the case with other construction systems, the introduction of CLT to meet specific needs of the supply chain of wood products and construction products took place without being preceded by a systematic performance analysis. In spite of the fact that many aspects of the design and construction with CLT structures are now consolidated and that the environmental advantages are clear, both in terms of sustainability and energy savings, investigations on the acoustic aspects of this construction system have only begun recently [34].

The purpose of this paper is to provide an overview of the characteristics of this construction system through a literature review and to focus on specific acoustic properties by comparing recent acoustic researches. This allows for highlighting how the CLT construction system is particularly interesting, especially thanks to the considerable development potential still unexpressed, mainly in the field of noise protection in buildings. The aim is to provide useful information and knowledge for manufacturers, construction operators, and designers to reduce the risk of evaluation errors or overestimation of the acoustic requirements necessary to achieve the required comfort goals. Due to the still incomplete knowledge of some aspects of the acoustic behaviour of the CLT systems and the reduced accuracy of the prediction models in the case of complex architectural layouts, the uncertainty of the results is commonly compensated by over sizing the acoustic linings of the CLT panels. This approach is twice as disadvantageous: On one hand, the economic and environmental advantage in the use of this technology is reduced, and on the other, the users' expectations for the failure to achieve cost-related comfort conditions are disappointed.

The structure of the review is organized around the analysis of four main clusters of topics related to the specific acoustic performance of CLT systems.

Since CLT is a relatively new material in the panorama of wooden construction systems, the analysis of the literature has tried to organize, in a timeline, the subdivision of the research themes that have accompanied the development and diffusion of this product. The characteristics of practicality, economy, and sustainability have determined a rapid affirmation of the CLT systems. However, unlike other aspects relating to the internal quality of buildings built with this technology, the approach to noise protection problems materialized relatively late. Because of this, the researchers have addressed issues that start from the basic knowledge of the vibro-acoustic properties of this industrialized wood product to arrive at the formulation of hypotheses for the inclusion of this particular system within the existing standardized prediction models.

Following this distinction, the review aims to give answers to four main questions:

1. How does an orthotropic laminated wood panel "work", from a vibro-acoustic point of view, in the frequency range of interest of building acoustics?
2. What are the noise protection performances that can be expected from a bare CLT panel, in itself, and covered to form a complete building element?
3. What role do the fixing systems between CLT panels play in the flanking transmission of sound?
4. How reliable is the estimation of acoustic performance of a wooden building from the performance of CLT elements and its junctions?

The discussion will attempt to address and relate these issues to each other, taking into account that the research has not yet provided an exhaustive answer on all the elements. Despite these knowledge gaps, acoustic designers are called upon to make important decisions in the initial stages of the architectural project about the best way to reach acoustic requirements. In the presence of significant unknowns, there is a risk of choices that can invalidate some of the sustainability aspects of this construction system. It is therefore in the interest of manufacturers and economic operators in the building sector to promote the research and the optimization of the acoustic design of CLT buildings.

2. Materials and Methods

The review focused mainly on the evolution of acoustic research on CLT, which has seen a particular development in recent years. However, to understand the extraordinary success of this product and how it has established itself as a reference for many types of wooden constructions, it is also necessary to summarize the main features from various points of view: From economic and environmental advantages to those of design and construction.

2.1. Research Criteria and Selection of Studies on the Characterization of CLT Systems

The literature search and the grouping of reference results and performances of CLT systems was carried out in order to point out the evolution of the research on this topic. The review was originally restricted to English language full-text articles, published in academic and scholarly peer-reviewed journals, publication date ranging from 1990s. It is interesting to observe how the trend of research in these three decades can be generally grouped as follows:

- 1990s: Basic research on the building and architectural aspects of this building system, presented as a quick and cheap alternative to traditional wooden building systems; during this period, studies on production and methods, mechanical, structural, seismic, and fire reaction behaviour are concentrated.
- 2000s: The increase in the spread of CLT as a construction system capable of competing with other prefabrication systems has mainly stimulated research on environmental and energy aspects, together with economic and sustainability analyses.
- 2010s: With the achievement of a level of consolidated basic knowledge and the inclusion of CLT within regulatory references for structural design, the most recent developments have focused on aspects previously not sufficiently investigated; if on one hand, the need to study the aspects related to living comfort (acoustic and thermo-hygrometric well-being) emerges, on the other the first problems of maintaining performance over time (maintenance, renovation and reuse) begin to arise.

The topics that have characterized CLT research over the past decade are still evolving. For this reason, it was preferred to draw information from other sources, such as conference proceedings, reports of research projects, and technical documentation of the manufacturers.

2.2. Overview on Basic Research on CLT Systems

Many studies were carried out in the last 30 years in order to define the behavior of CLT from a structural, seismic, firefighting, thermal, and acoustic point of view.

Since the 1990s, the University of Graz has been one of the first institutions to undertake numerous international CLT research activities. Further, more complete and elaborated studies were carried out in the 2000s, on dimensional stability and stiffness [35] and the adequate connections for a high dissipation capacity: Ceccotti et al. proposed a simplified method for the determination of the seismic behavior factor "q" of timber buildings [26], that measures a relative energy loss per oscillation cycle; Sustersic et al. investigated the seismic analysis of multi-story cross-laminated timber buildings [29]; Gavric et al. proposed an extended experimental program on typical cross-laminated panels connections [36]; Demirci et al. investigated the scaling of seismic shear and acceleration demands in multi-story cross-laminated timber buildings and its dependency on various structural properties [37]; Sustersic et al. worked with the issue of seismic retrofit and thermal insulation improvement of existing buildings with CLT technology [38].

However, the most comprehensive experimental research on seismic behavior of CLT systems and connections was carried out by CNR– IVALSA (Italy) under the SOFIE Project [39–42].

The standardization activities on CLT in Europe began at the beginning of the 2000s: Common rules buildings and design of timber structure have been included in 2004 in the European Timber Code Eurocode 5 [43,44], while the first European product standard for CLT is EN 16351:2015 [45].

From the thermal insulation and energy saving point of view, many studies investigated the indoor thermal conditions and overheating risks in prefabricated timber buildings: Chang et al. analyzed the thermal properties and heat transfer performance of ply-lam CLT [46]; Wang and Ge looked into the evaluation of the hygro-thermal performance of CLT wall assemblies through simulations, using a stochastic approach to account for the uncertainty of material properties, boundary conditions, and environmental loads [47]; Hallik et al. analyzed the air leakage of joints filled with polyurethane foam and its influencing factors [48].

Also, the fire safety was analyzed in the last decade: Lineham et al. presented a series of new fire tests on CLT beams subjected to sustained flexural loading, coincident with non-standard heating using an incident heat flux sufficient to cause continuous flaming combustion [49]; Östman et al. provided some experiments about both reaction to fire and fire resistance of CLT [50].

Systematic research on the acoustic behavior of building systems in CLT was the last to start and is concentrated mainly in the last decade. Early studies include those of Kouyoumji et al. [51] for predicting the acoustic insulation performance of CLT buildings using a Statistical Energy Analysis based model. Subsequent attempts to evaluate possible relationships between the acoustic quality perceived by users and the on-site determination of the actual performance to be achieved are due to Ljunggren et al. [52,53] and Caniato et al. [54]. These studies revealed, on the one hand, the complexity in defining acoustic calculation models and, on the other, the problems connected with the effective achievement of the expected sound insulation. Several parallel lines of research have therefore developed: Laboratory and on-site characterization of the properties of sound insulation and impact noise level of CLT elements with the creation of the first repertoires for the use of acoustic performance data in calculation models by Hoeller et al. [55], Homb et al. [56], Schoenewadl et al. [57], and Zeitler et al. [58]; the study of the vibro-acoustic behavior of CLT panels and their radiation efficiency by Santoni et al. [59,60] with the effects on the modelling of the acoustic behavior of the panels developed by Morandi et al. [61] and validated through comparisons between laboratory measurements and models; the study on the influence of the joints between CLT panels on the on-site acoustic performance by Guigou-Carter et al. [62] and Morandi et al. [63], which led to the inclusion of specific relationships for CLT in the standardized prediction methods. Di Bella et al. [64,65] proposed parametric reference curves of acoustic insulation and the impact noise level for bare CLT structures in order to use the data available from laboratory measurements of the performance improvement provided by acoustic linings, in the absence of laboratory-measured data on complete structures. Validation methods of the acoustic models through specific comparison protocols with on-site measurements during the different construction phases of a CLT building have been proposed by Di Bella et al. [66]. The analysis of the main results of the basic research allowed to collect the pros and cons of using the CLT and the opportunities offered by this construction system, as summarized in the strengths, weaknesses, opportunities and threats analysis in Figure 1.

Figure 1. Strengths, weaknesses, opportunities and threats analysis of cross-laminated timber (CLT) building systems.

2.3. State-of-the-Art of the Acoustic Research on Building Acoustic Modelling and Design with CLT Systems

Focusing on the most recent research aimed at creating consolidated knowledge to support acoustic design with the CLT, it is possible to observe how the central theme developed around the prediction models introduced with the ISO 12354 series standards [67–69].

The first edition of these standards, published in 2000 and elaborated within CEN/TC 126, quickly established itself as a reference for the estimation of acoustic performance in buildings from the performance of elements. However, many aspects of the proposed calculation methods remained not sufficiently detailed and the limitations appeared immediately. The main ones were related to the modelling of non-homogeneous building elements or with complex joints.

The research developed in the first 10 years of this series of standards was mainly oriented on five topics:

- The definition of a complete database of building elements performance, measured in the laboratory, to provide accurate and updated input data.
- The experimental determination of the vibration reduction index on a number as large and representative as possible of actual junctions between building elements.
- The deepening of the vibro-acoustic characteristics of new materials and the comparison with those already known and widely used.
- The validation of prediction models by comparing the estimated acoustic performance with those actually measured on-site.
- The development of new parametric relationship to improve the reliability of the models and extend the frequency range that can be analyzed.

The outcome of these researches has made it possible to update the calculation methods, making them more flexible and reliable. The current edition, prepared by the ISO/TC 43 in collaboration with CEN/TC 126 and published in 2017, contains empirical data for junctions of lightweight buildings which can also be referred to the CLT systems.

As a matter of fact, the increase in the diffusion of wooden buildings, and CLT systems in particular, has favored the development of research at the same time as updating and revising of the ISO 12354 series standards. Many studies have therefore focused on aspects related to the development of these forecasting methods for wooden buildings.

After the first studies and comparisons to adapt vibro-acoustic parameters measurement and prediction methods for lightweight wood-framed structures to the standardized prediction model by Villot et al. [70] and Guigou-Carter et al. [71], the main research in this field has flowed into European Cooperation in Science and Technology (COST) Action FP0702 [72], supported by 12 European countries and with the contribution of New Zealand and Australia. The research activities coordinated under this action were focused mainly on the acoustics and low frequency vibration of timber based lightweight buildings and building elements. One of the common themes for the various participants was to focus the attention of the acoustic analysis of wooden buildings also below 100 Hz. This was necessary as lightweight buildings are likely to have performances at low frequency, lower than in heavy buildings. In the case of the subjective perception of impact noises radiated by wooden floors, the analyses were also extended in the field of low frequency vibrations, below 25 Hz.

During the period of activity of this research group, from 2008 to 2012, numerous contributions were produced for the characterization of wooden buildings in general. Among the main contributions that specifically concerned the CLT system, there are: the measurement uncertainty by Öqvist et al. [73,74]; the performance rating of generic floor assemblies used in Europe and North America by Kouyoumji et al. [75]; the use of Statistical Energy Analysis acoustic models for the characterization of lightweight CLT floors and the validation of calculations through on-site measurements by Kouyoumji et al. [51].

Many of these works and others that followed this research experience were the basis of the revision of ISO 12345 series in its current edition, such as the comparison and validation of airborne prediction models for wooden structures by Schoenwald [76] and the characterization of junctions between lightweight timber elements, based on empirical data from vibration level difference measurements, by Guigou-Carter et al. [62].

This research is currently focusing on a deepening of the knowledge on the CLT panels vibro-acoustic behavior [59–61] and on the implications that building design and the available fixing techniques can have on the correct modelling of the joints between the panels [63].

3. Results

3.1. Characteristic Properties of CLT Systems

Cross-laminated timber is a structural element made of wooden planks glued transversely, to create a monolithic panel (Figure 2). CLT is characterized by high rigidity combined with low weight. These characteristics, together with the advantages in terms of affordability and modularity, speed, and simplification of transport and installation, have made it a successful product in the field of wooden buildings [34]. Nowadays, this system is presented as an innovative solution designed to develop large prefabricated wood panels and reduce thickness with good mechanical properties both as walls and as floors [77–83].

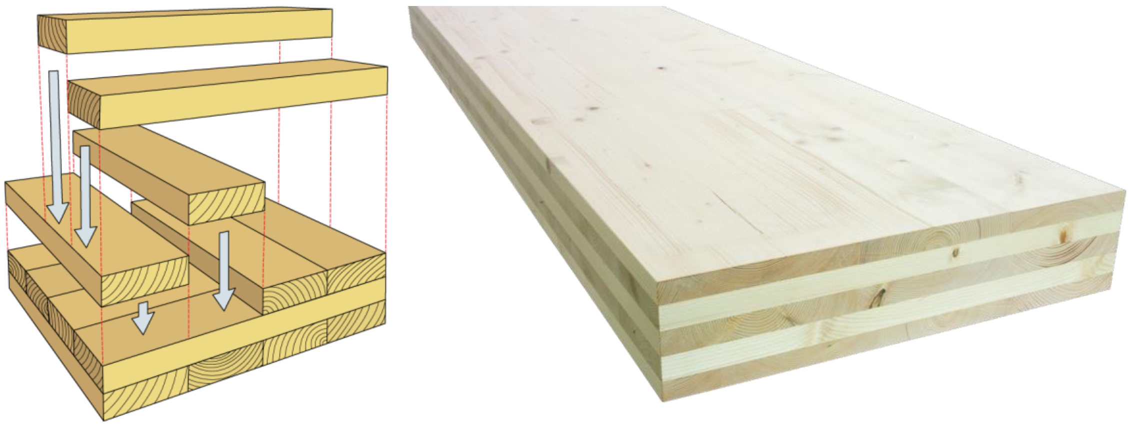


Figure 2. Composition of CLT panels.

The production process of these panels begins with the collection of raw materials from local forests, 55% of which are presently managed in a sustainable way [84]. As with many other products in the wood sector, CLT panels also play a potentially important role in the circular economy. This concerns the possibility of increasing the availability of timber by promoting recovery at source in the construction and demolition sectors—by encouraging disposal—to increase the recovery targets for wood-based waste, to remove legal barriers to the use of timber in urban areas and to restrict and subsequently prohibit the sending of timber to landfills.

Generally, timber buildings require less primary energy consumption and have a lower global warming potential (GWP) than concrete or steel buildings; indeed, the difference can be 25% or more. Not coincidentally, some researches on life cycle analysis (LCA) reveal that during raw material extraction, transportation, and the manufacture process, CLT may store more carbon, emit less GHG, and use less fossil energy than steel, concrete, and brick [19,85–93].

In these terms, there are some specific analyses about the performances of CLT: Research that discussed the influence of the building shape on the building's environmental performance [94]; a study of the primary energy consumption of the life cycle of CLT buildings in Sweden [95]; the evaluation of the energy consumption in the life cycle of hypothetical CLT building models in Finland [96]; and a study that confirms that the impact of carbon extraction on CLT buildings is significant in the total GHG emissions during the life cycle [97].

In this way, the construction system adapts also to the principles of sustainability, ensuring the use of a renewable resource. Once transported to the factory, the timber is sawn, trimmed, and seasoned to the air and dried [25,45]. Like most wooden elements for structural use, CLT panels are also derived from coniferous wood, normally spruce wood [98].

The structural element with crossed wooden layers consists of large panels, formed by several layers superimposed and glued on each other, so that the grain of each single layer is 90° compared to the adjacent one. The number of layers and their thickness vary according to the type of panel and the reference manufacturer (there are usually at least three layers). Bonding is based on polyurethane or melamine mixtures and the joints between the panels are made through metal connections or wooden dowels [24,25,99], as shown in Figure 3. The different connection methods between CLT panels, even with the same mechanical characteristics of the joint, play a particularly important role in achieving noise protection performance. As it will be detailed later, the possibility of reducing the vibrations transmitted through the joints by suitable fixing devices, allows to control the flanking transmissions and, consequently, to avoid significant losses of acoustic insulation.

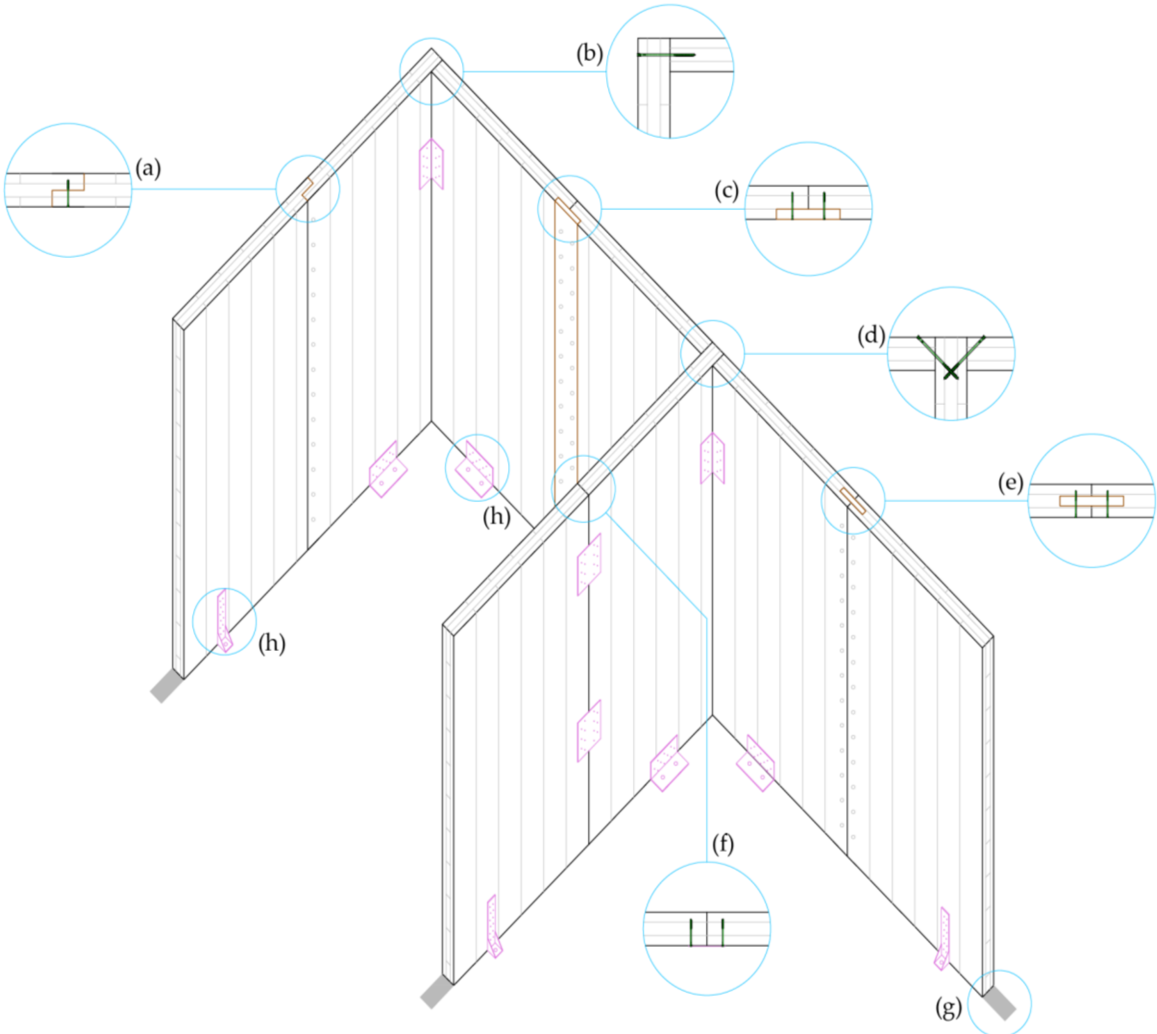


Figure 3. Examples of connections for CLT shear walls: (**a**) Coupled wall with lap joint; (**b**) corner/"L-shaped" joint; (**c**) coupled wall with external spline joint; (**d**) intersection/"T- shaped" joint; (**e**) coupled wall with internal spline joint; (**f**) single wall joined with steel plates; (**g**) optional decoupling strip; (**h**) connectors and fasteners (hold-down and steel brackets with self-tapping screws, spiral, or ring nails) [100].

Some of the biggest advantages that come from using this type of system are the dimensional stability and stiffness, which make the panels suitable for earthquake-resistant construction [35].

The particular composition of the panels gives them excellent dimensional stability and the same structural performance in both directions of the stratigraphic composition (Figure 4). Moreover, the use of adequate connections allows to create light and ductile structures with high dissipation capacity [2,24,29,36,39].

It is also possible to build multi-story buildings, making the construction system in CLT attractive from the economic point of view and from the environmental perspective thanks to a reduced exploitation of the soil [26,37,101,102].

According to several laboratory experiments, CLT constructions have high in-plane and out-of-plane strength and stiffness in both directions, showing a two-way action capability [2]. Therefore, CLT panels can be used as walls, floors, roofs, or even stairs in a three-dimensional structural system. Other laboratory tests reveal that the panels behave as almost completely rigid plate elements, with negligible shear deformation while all the energy dissipation is required by the connections, where local failure phenomena occur. Moreover, the hysteresis loops show a great equivalent viscous damping of 14% as average, demonstrating good ductile and dissipating performances of the CLT system and so highlighting its suitability for seismic purposes [39]. The CLT panels also have an excellent functioning as plugs anchored to reinforced concrete structures; in fact, it was possible to see an increase in the permissible ground acceleration up to almost 90% [103]. In addition, in masonry constructions, the presence of an outer shell of CLT panels brings a 40% increase in strength and a 100% increase in ductility. Furthermore, it was demonstrated that in a building already severely damaged by an earthquake, the application of CLT panels brings its stiffness back to an almost undamaged state level. The CLT panels result to be particularly suitable also for energy upgrading of existing older buildings if combined with an effective insulation [38].

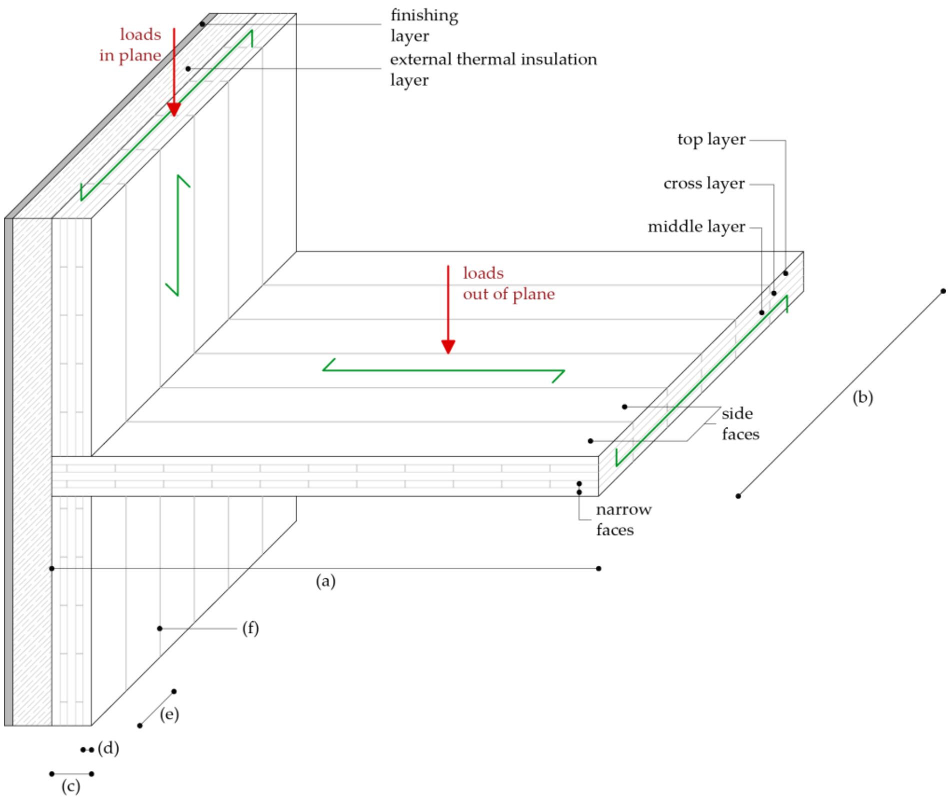


Figure 4. Geometrical properties of CLT elements for loads out-of-plane and in-plane. Typical dimension: (**a**) Maximum length, l_{CLT} = 18,000 mm; (**b**) maximum width, W_{CLT} = 4000 mm; (**c**) maximum thickness, t_{CLT} = 300 mm; (**d**) ply thickness, 6 mm ≤ t_i ≤ 45 mm (standard values 20, 30, and 40 mm); (**e**) plank width, 40 mm ≤ W_i ≤ 300 mm (recommended width $W_i \geq 4\, t_i$); (**f**) plank spacing, w_{gap} ≤ 6 mm; number of ply 3, 5, 7, or 9 (up to 11 for beams) [104].

According to a study on prefabrication methods, the dry building system (with a metal or wood bearing structure) is the most functional design solution. It has emerged that the gap between the construction sector and the mass production industries can be compensated by the adoption of an off-site construction process [101,105]. The construction system in CLT perfectly meets these requirements. The use of prefabricated panels for walls, ceilings, and roofs also facilitates the reduction of construction times [16] and the possibility to use the building in a short period; in fact, after that it is sufficient to intervene with insulation layers and finishes [24].

If we consider the 2D panel construction method, the construction times are 20% shorter than the traditional concrete construction technique. Moreover, if the factory prefabrication also includes the installation of some components such as windows and doors and some layers of the casing, the working time on the construction site could be reduced by about 30% [106].

In addition, the installation of the plant system (electrical, heating, and hydraulic system) is also made adaptable and flexible despite possible inaccuracies in the pre-assembly [107].

Comparing concrete with the CLT construction system, the latter turns out to be more expensive in terms of the initial investment, but thanks to reduced construction times, it proves to be highly competitive. In these terms, the guarantee of an adequate management of construction details, and therefore of the construction site, is given by an integrated approach between the architectural, structural, and plant design from the early planning phases. Working within BIM platforms, thanks to a holistic vision of the design choices, allows to realize that integrated approach [108,109].

Moreover, the prefabricated construction system in CLT guarantees greater safety on-site, considering that most of the work is carried out in the factory, and therefore in a safe and controlled environment, only few tasks of completion are realized on the site. This ensures that few people work and interact on the construction site, reducing the probability of accidents at work.

In this type of construction, the problems associated with thermal and acoustic insulation are particularly important, given the low density of the material. Stratifications of different materials are needed to ensure that the building envelope has adequate performance in order to guarantee the right degree of thermo-hygrometric and acoustic comfort.

With regards to thermal conductivity λ, the CLT wooden element has a good value in itself, compared to other building materials [34,46], as shown in Table 1.

Table 1. Comparison between the typical heat conduction properties of common building materials and CLT panels made of spruce.

Material	Thermal conductivity λ [W/mK]	Density ρ [kg/m^3]
Concrete	1.51	2000
Brick	0.56	1500
Wood [1]	0.110 ± 0.028	500 ± 140
OSB [110]	0.097	~580
CLT [111]	0.104	~450

[1] Average value for different wood essences (Spruce, Red Fir, Pitch Pine) with similar density.

However, the conductivity of a material, and consequently the thermal transmittance of a perimeter wall, is not exhaustive for the determination of environmental comfort in summer. In this case, the ability of the building component as a whole to absorb and release heat, plays a decisive role. It is therefore necessary to evaluate quantities such as specific heat, periodic thermal transmittance, and phase shift. An important information in the case of a CLT building comes from the determination of the time constant τ, which allows to evaluate the walls' ability to dampen and delay the external temperature variation.

A building with low mass, therefore, usually has greater thermal oscillations than one with a greater mass. This means that there will be higher maximum temperatures inside the building in summer. From the analysis of the time constant, however, it can be deduced that with wooden walls and layers of insulation it is possible to obtain conditions of comfort equally positive, if not even better.

Wood has a higher specific heat value and a high thermal resistance, which compensates for the reduced mass. Ultimately, the greater the time constant, the less the internal thermal oscillations are, and this improves the thermal behavior in summer of the building envelope. In short, the use of a building element composed of lined CLT panel produces good damping effects, despite having a total surface mass of less than 230 kg/m^2 [47,112].

An essential aspect of the buildings is the air tightness, which allows for avoiding thermal dispersions, formation of condensation located in the casing, presence of draughts, and possible acoustic bridges. In the case of CLT constructions, panels are necessarily watertight and can therefore be considered as an airtight layer with the interposition of a vapor barrier on the hot side of the insulating layer. Particular attention should be paid to the joints among the elements, where the airtightness is guaranteed by a sealing joint cover [48].

The windproof capacity is ensured by the skim coat in case of plaster finish or, for dry-coated walls, by the use of a transparent UV-resistant cloth, to be placed with special jointing strips on the external side of walls and roofs.

A thermal bridge is determined when there is no material continuity in the building envelope or there is a sudden change in geometry. In the envelope of wooden building, the material continuity between the insulating elements cannot always be guaranteed, but must be sought as much as possible [48], mainly at the joints of the panels for CLT structures.

Considering that wood is a combustible material, one of the greatest challenges facing the construction industry is fire safety. CLT panels show great potential for fire resistance because the carbonization takes place in a slow and controlled way allowing the panels to maintain a good structural behavior for a long time. Furthermore, the use of solid wood panels reduces the risk of fire propagation through empty cavities, as usually happens in lightweight constructions. The burning rate of a CLT panel, made for example of coniferous wood, is equal to 0.7 mm per minute [43]. A further extension of the resistance time is possible by increasing the thickness of the panel as well as by using suitable construction solutions that have, for example, the addition of non-combustible insulating materials.

Depending on the reaction to fire characteristics, CLT panels can be classified in Euroclass D-s2, d0, with a low smoke output and no dripping or falling of burning materials.

With regards to the structural fire-fighting design of wooden elements, it is an established practice to refer to the EN 1995-1-2 standard [44]. The calculation procedure also follows the method used for the beams because the CLT construction technique is not explicitly covered in the EN 1995-1-1 standard [43]. In this sense, several experiments have been carried out [49,50] demonstrating the need to review the regulatory provisions regarding CLT behavior [113].

Finally, another advantage of the CLT system is the possibility to reuse the material at the end of its life cycle, especially for the construction of second-order structures [23,114–116].

3.2. *Specific Acoustic Properties of CLT Building Elements*

As highlighted above, the quick development of construction technologies based on wooden elements took place at the same time as a growing focus on environmental and energy issues. However, while for the design aspects strictly related to structural behavior, reduction of energy needs, and the environmental management of the production chain, the research immediately had a strong boost, and the acoustic aspects were initially neglected.

One of the consequences of this asymmetrical development of the most recent wooden-based construction techniques is that for users, as well as for designers, wooden buildings seem to show a very high level of expectation in terms of both thermal and acoustic comfort [54]. The failure to achieve the expected acoustic protection performance for these construction technologies is particularly relevant for the low-frequency airborne sound insulation and for the containment of the structure-borne noise [52,53,117]. If, on one hand, the use of acoustic performance rating methods designed for heavy structures can penalize the classification of wooden elements, in particular light ones, on the other hand, the peculiar sound insulation weakness at low frequency of wooden building elements cannot be overlooked [118].

Apparently, the introduction of prefabricated wooden elements characterized by high surface mass, as in the case of CLT panels, should have allowed an increase in low frequency acoustic performance. However, the CLT construction system was initially used as a sort of wooden substitute for massive monolithic building elements made with materials that allow a continuous joint between them. The connection systems of CLT panels, as well as for the majority of wooden building elements, is typically based on "force-transmitting" dry connections (nails, screws, dowels and other metal anchors combined with brackets, hold-downs, and plates) [2]. This type of point connections does not allow the effective application of many of the soundproofing systems based on the decoupling of the components that make up the building elements, mainly for structurally transmitted noises.

The evidence of these limitations in acoustic performance has therefore developed research relating to the vibro-acoustic properties of the panels, the interaction with the fixing systems, and the optimization of soundproofing techniques, to then converge towards the integration of the CLT construction system in the acoustic models.

The first systematic approaches to the study of the acoustic behavior of wooden structures, for sound and vibration analysis and for building acoustic design, are due to the activities of the COST Action FP0702. These research network mainly focused on developing an overview of existing knowledge of timber-based lightweight buildings and elements [72]. After the national Swedish project *AkuLite* and the European Wood Wisdom Net project *AcuWood* [119], a further development of specific prediction models and techniques for the improvement of acoustic design of wooden buildings is due to the *Silent Timber Build* project [120]. These research projects stimulated the advance of new insights, parametric analyses, and comparisons to highlight the specific acoustic characteristics of the CLT construction elements. Three research areas are emerging: The study of the mechanical characteristics of CLT panels relevant in the acoustic field; the evaluation of acoustics insulation properties of the complete CLT building element; and the analysis of the acoustically relevant interactions between the elements that make up a CLT building.

3.2.1. Vibro-Acoustic Properties of CLT Panels

CLT panels can be considered orthotropic elements, like the wood of which they are made, with material properties that differ along three mutually orthogonal twofold axes of rotational symmetry at a particular point. If compared with other massive and continuous heavy elements, like concrete, they have a low density combined with a relatively high stiffness [59].

These properties, particularly appreciated from a structural point of view, make the interpretation of the acoustic behavior of CLT elements complex as the transition frequencies from modal to diffuse vibrational field can fall within the typical range of soundproofing performance classification methods. In fact, the acoustic modelling of walls at low frequency is usually carried out using the statistical energy analysis (SEA), assuming that the vibrational field is diffused in the panel [121–123]. When this occurs, the reflections have random phase in any point and there is an equal probability of sound waves coming from any direction. However, these conditions, certainly verified for isotropic elements, characterize orthotropic materials only beyond frequency values that must be carefully evaluated [61], also according to stiffness, boundary conditions, and dimensions of the elements. Although many aspects related to the radiation efficiency of CLT elements have been extensively investigated [60,124,125], the request to have even lighter and stiffer CLT panels for structural requirements makes further investigations, on the orthotropic behavior of laminated panels with internal ply made of chipboard or oriented strand board (OSB), necessary.

3.2.2. Airborne and Impact Insulation Properties of Bare and Lined CLT Building Elements

The CLT, like other modular and prefabricated construction systems, needs to be completed with layers of thermal insulation, air tightness, and sound insulation, as well as a finishing coating.

One of the biggest difficulties related to predicting the airborne and structure borne sound in wooden constructions is the lack of laboratory data for the entire building element, including the additional layers. In most cases, CLT manufacturers only supply the panels as a basic or semi-finished product. The system is then completed on the basis of the structural, thermal, and acoustic needs defined in the building project. The manufacturers of coating and finishing systems, in general, also offer the same products for other construction technology. It follows that, due to the high number of possible combinations between CLT panels and linings or finishing systems, it is difficult to find data for a specific building element based on CLT.

Although extensive laboratory tests have been carried out for the evaluation of the sound reduction and impact noise level index on several types of CLT building elements [55–58,126–129], the database available for the standardized prediction models is not sufficiently large if compared to other construction systems, both light and heavy.

According to the result of the main laboratory measurement campaigns of sound reduction and impact level, the reference values of these parameters are listed in Table 2.

Table 2. Average airborne sound insulation and normalized impact sound pressure level data for bare CLT assemblies.

Material	Thickness Range [mm]	Surface Mass Range [kg/m^2]	Average R_w [dB]	Average $L_{n,w}$ [dB]
Bare CLT 3-ply	80–90	38–42	32	-
Bare CLT 5-ply	100–175	45–92	40	86
Bare CLT 7-ply	200–245	95–130	45	80

For wall assemblies with lined CLT panels, the laboratory performances of airborne sound insulation can reach remarkable levels: Up to 60 dB for single-side linings and up to 70 dB for double-sided linings. However, it is a matter of complex structures of considerable thickness, typically on the order of 250–350 mm thick or more, with several layers of fibrous sound absorbing panels, resilient studs and at least two layers of plasterboards as finishing surface. For floor assemblies, similar values can be easily reached. In this case, a positive contribution is offered by the greater thickness and surface mass of the CLT load-bearing structures, compared to that of the vertical partitions, and the typical presence of suspended ceilings.

It is more complex to provide reference values for the impact noise level of CLT floors. The large variability of technical solutions for floor coverings (light and heavy floating floors, resilient coverings, raised floors, radiant heating/cooling floors, etc.) makes comparison difficult. In any case, the values obtainable in the laboratory for the impact sound pressure level can drop to 46-48 dB in the presence of floating floors.

For many types of building elements, it may be sufficient to use the laboratory data of wall linings and floor coverings, to be combined according to the characteristics of the basic structures, to obtain reliable data for the prediction models. The actual behavior of the entire CLT wall can be significantly affected by the performance of the base structure. Unfortunately, the standardized procedures for determining the improvement of airborne sound insulation by linings, or impact sound insulation by toppings or floating floors, refer to structures with characteristics very different from those of CLT panels (e.g., calcium-silicate blocks or concrete slabs). Recent studies proposed empirical formulas for single-number airborne sound insulation (Equation (1)) and normalized impact sound pressure level (Equation (2)), based on the "mass-law" and generally valid for bare CLT panels with mass per unit area (m′) between 35 kg/m^2 and 130 kg/m^2.

$$R_{w,eq} = 20.3\ \lg(m') \tag{1}$$

$$L_{n,w,eq} = 128 - 22\ \lg(m') \tag{2}$$

Moreover, applying an analytical method borrowed from the single-number rating standard procedures [130,131], reference curves for bare CLT structures can be defined [58,64,65]. In this way, it is possible to adapt data of sound reduction or impact noise level improvement, obtained according to the procedure of ISO 10140 standards [132–136], also on CLT panels in order to acquire sufficiently reliable input data for prediction models. This aspect is of particular importance also for an effective comparison among different coating solutions, as well as to evaluate the effects induced by the fixing systems of the linings.

3.2.3. Flanking Transmission through the Joints of CLT Building Elements

The flanking transmission of sound describes the amount of acoustic energy transferred trough a building element to the adjacent ones, and then to the surroundings. It represents the sound that is transmitted between spaces indirectly, going over or around, rather than directly through the main separating element between rooms. All the possible flanking transmissions add up to the direct sound transmission and return to a lower value of the characteristic sound insulation of the separating element between rooms, as measured in laboratory with suppressed flanking transmission.

The most critical parameter to estimate is the vibration reduction index K_{ij}, defined as the quantity related to the vibrational power transmission over a junction between structural elements, normalized in order to make it an invariant quantity. It is determined by normalizing the direction-averaged velocity level difference over the junction, to the junction length and the equivalent sound absorption length, if relevant, of both elements. It is measured according to ISO 10848-1 standard for specific configurations of building elements layout and connection [137].

This quantity represents the vibration energy dissipating into the junction and is associated with the structural coupling of the elements. High values of K_{ij} generate the best junction performance and a reduced relevance on a specific flanking path.

In the recent update of the ISO 12354-1 standard [67], empirical data have been introduced for the joints characterized predominantly by the vibration reduction index more than the internal damping (Figure 5). These relations derive from theoretical and experimental analyses on buildings made with CLT panels, for which the structural reverberation time is often determined mainly by the connection methods between the panels and adjacent structures [62]. However, at the moment, only data for the junctions between mass elements per unit of area $0.5 < m_1/m_2 < 2$ are available and further studies are underway to increase the number of cases.

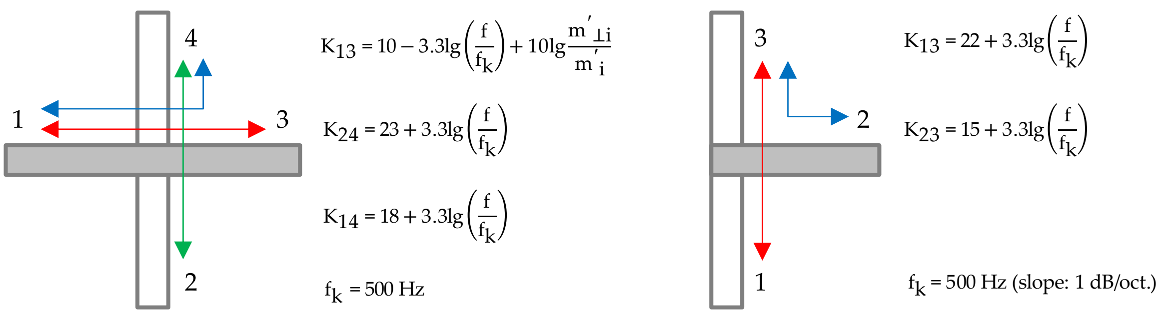


Figure 5. Parametric relations for the determination of the vibration reduction index K_{ij} for T- or X-shaped joints between CLT panels according to the direction of propagation of the vibrations and in relation to the frequency, f, of the sound considered and of the surface mass of each pair of intersecting elements.

These aspects, of fundamental importance for the understanding of the mechanisms of interaction between CLT panels, and between these and the fixing systems that connect them, have been deepened within the *Flanksound* project [63,138,139]. This study concerned the effects of the different types of metal connections used to fix the CLT panels together and the improvements obtainable with the interposition of elastic elements between the connections and the panels. The results showed that the transmission of vibration through vertical CLT junctions is mainly due to the metallic connectors rather than to the actual transmission of vibration at the panel-panel interface.

By increasing the cases relating to panel fastening technologies and the characteristics of the joining systems, considerable discrepancies emerged with the values of vibration reduction index at high and low frequencies proposed by ISO 12354-1. This highlights the importance of the correct definition of the installation procedures to allow an improvement of the prediction methods and reduce the difference between the values estimated in the project phase and those actually achieved on-site.

Other studies have analyzed different characteristics of CLT joints, through an experimental approach, taking into account several aspects of performance improvement [140,141], assembly optimization [75,142], and limitation due to restrictions by the seismic and fire prevention design requirements [143].

3.2.4. Prediction Models for Building Acoustic Design with CLT Systems

The calculation model proposed in the ISO 12354 standards constitutes a consolidated reference for a reliable prediction of the protection level from intruding noise that a building element can provide on-site. The model allows to combine the characteristics of a separating building element to reduce the transmission of sound (airborne or structural, depending on which type of source is considered) with the effects of flanking transmissions that depend on the features of the adjacent elements and the interaction between their connections.

With regards to the possible modes of transmission of noise and the types of sources in relation to the sound field, the main standards of the series concern the evaluation of the apparent sound insulation offered by internal partitions [67], both vertical and horizontal, the level of impact noise radiated by the floors [68], and the façade sound insulation [69].

These standards provide both a detailed method, which can be used if data are available in frequency, and a simplified one in the case of calculation based on single-number performance indices [130,131].

In general, the input data needed to perform the calculation can be divided into three groups:

1. The direct transmission index of sound (R_w and $L_{n,w}$), measured in the laboratory on the building elements according to the standards of the ISO 10140 series [132–136], including additional linings for sound insulation on a reference structure (ΔR_w and $\Delta L_{n,w}$) or airborne sound insulation of small technical elements ($D_{n,e,w}$);
2. The vibration reduction index K_{ij}, measured according to ISO 10848-1 [137] and referred to the specific shape of the joint (L-, T, or X-, both vertical and horizontal) and mass of the elements that compose it;
3. The dimensional characteristics (separation surface, length of the sides) of the building elements considered.

The apparent airborne sound reduction index, R'_w, can be calculated as the logarithmic composition of the direct transmission component, $R_{Dd,w}$, and all the flanking transmission components, $R_{ij,w}$, also considering the normalized level difference of small building elements, if present (Equation (3)).

$$R'_w = -10\lg\left[10^{-\frac{R_{Dd,w}}{10}} + \sum_{i,j=1}^{n} 10^{-\frac{R_{ij,w}}{10}} + \frac{A_0}{S_S}\sum_{j=1}^{n} 10^{-\frac{D_{n,j,w}}{10}}\right] \quad (3)$$

The sound reduction index for flanking transmission paths $R_{ij,w}$ can be estimated according to Equation (4), considering the average of the soundproofing power of each element, the possible presence along the propagation path of sound reduction index improvement by additional layers,

$\Delta R_{ij,w}$, the vibration reduction index characteristic for the type of joint, K_{ij}, and the surface of the element, S, in relation to the length of the joint l_{ij} and the reference coupling length, l_0, of 1 m.

$$R_{ij,w} = \frac{R_{i,w}+R_{j,w}}{2} + \Delta R_{ij,w}+K_{ij}+10\lg\frac{S}{l_0 l_{ij}} \quad (4)$$

Similarly, the impact sound pressure level corresponding to the reference equivalent absorption area in the receiving room, can be evaluated from Equation (5) by logarithmically composing the contribution directly radiated from the floor, $L_{n,d,w}$, with all the flanking paths, $L_{n,ij,w}$.

$$L'_{n,w}= 10\lg\left[10^{\frac{L_{n,d,w}}{10}} + \sum_{i,j=1}^{n} 10^{\frac{L_{n,ij,w}}{10}}\right] \quad (5)$$

The impact flanking transmission is typically obtained, according to Equation (6), taking into account the effect of reduction of the impact sound pressure level of the floor covering, ΔL_w, on the equivalent weighted normalized impact sound pressure level of the bare floor, $L_{n,eq,0,w}$, the vibration reduction index, K_{ij}, and also considering the weighted sound reduction index of the floor and the adjacent elements on the basis of the same principles expressed for airborne transmission.

$$L_{n,ij,w}= L_{n,eq,0,w} - \Delta L_w + \frac{R_{i,w} - R_{j,w}}{2} - \Delta R_{j,w} - K_{ij} - 10\lg\frac{S}{l_0 l_{ij}} \quad (6)$$

If laboratory data of a complete horizontal structure, including the flooring and finishing surface, are available, these can replace the difference between the equivalent weighted normalized impact sound pressure level of the bare floor and the reduction of the impact sound pressure level of the floor covering.

Although it is relatively easy to find the data for the direct transmission of elements in CLT, the cases relating to the vibration reduction index are still limited, despite the numerous researches already carried out focusing the attention on several issues related to the improvement of prediction models and simulation accuracy [51,139,143–148].

The problem of correctly estimating the uncertainty of these prediction models and its possible improvement, remains one of the most critical topics, especially in the case of the emergence of new construction technologies such as CLT [66,73]. The knowledge of the weight that the various variables relating to design, materials, and workmanship can have on acoustic performance, is not yet consolidated.

One of the most effective approaches for validating the path from design to testing, also considering the effect on acoustic performance due to the presence of specific fixing systems for CLT panels, is based on advanced step-by-step modelling and verification through intermediate field measures [66], schematized as a workflow in Figure 6.

The acoustic model of the building made with the CLT construction systems can be implemented from the architectural design, according to ISO 12345 series [67–69], considering at first only the load-bearing structures and the external closures without linings. In this way, the bare structure model can be evaluated considering that flanking transmissions are negligible. This step requires the availability of laboratory data for bare structures (both for sound insulation and impact noise) from measurement carried out according to ISO 10140 series [132–136] or calculated from reference spectrum [64,65]. Subsequently, specific field measurements on bare structures, according to ISO 16283 series [149–151], are required to calibrate the model. This condition is often not readily obtainable. However, on timber building working sites it can be quite simple to find suitable conditions to carry out intermediate measures, due to envelope elements (CLT panels and windows) installed at the same time [73,141].

The next step is to consider flanking transmissions due to the type of fixing used to connect the CLT panels to each other. In the case of CLT, fixing techniques can significantly affect the extent of flanking transmissions. Measured data according to ISO 10848-1 [137] on actual joints are preferable to parametric data that can be calculated from ISO12345-1 [67], based essentially on the ratio between the masses of the contiguous elements. This aspect has to be carefully evaluated, mainly when the connection modes occur between offset elements or when they are not completely related to typical L-, T-, or X-joint situations.

The first step is therefore repeated, starting from the calibrated model, replacing the bare structures with the complete building elements, or applying the necessary wall linings and floor covering data. The results can be compared to the measures on-site to determine the accuracy of the acoustic model. The reverse process also allows for refining the evaluations of the actual extent of the flanking transmission or to consider the significance of the wall linings and floor covering data.

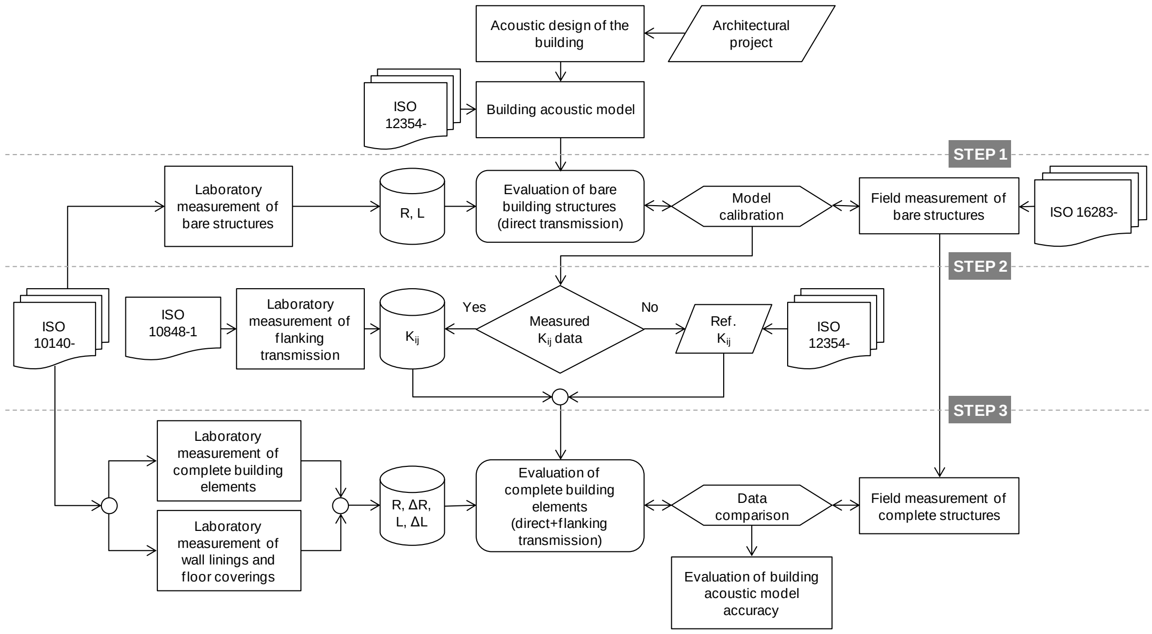


Figure 6. Workflow for comparison and evaluation of acoustic performance of building acoustic model [66] and improvement of prediction accuracy.

The application of the workflow illustrated in Figure 6 to different case studies [66] has highlighted the possibility of containing the difference between the acoustic performances calculated with the simplified methods of the ISO 12354 series standards and those measured on-site in the same order as expected for continuous and homogeneous structures, avoiding relevant bias due to the uncertainty of vibration reduction index input data. However, it is necessary to be very careful in the modelling phase because, for structural design and laying technique reasons, a symmetrical configuration of the panels does not correspond to a symmetrical connection of the screws or angles (as with the "T-shaped" joint shown in the Figure 3d), causing a difference up to 10 dB in lateral transmission than the expected theoretical values [66].

4. Discussion

From the analysis of the results of recent studies on the acoustic characteristics of cross-laminated timber systems, it is clear that this technology is able to offer numerous advantages, also taking into account all the other technical, economic, and environmental aspects that make it very competitive. However, it is also evident that there is the need to continue and expand experimental research on CLT building elements.

CLT panels constitute the load-bearing and continuity structure of complex building elements. The need to join the panels together with effective and stress-resistant connection systems has consolidated the use of metal elements and fastening components. In this way, punctual connections are created, assuming a considerable influence on the effective acoustic behavior of the panels.

Although the development of fastening products is moving towards components capable of reducing the relevance of the sound energy transmitted through flanking paths, there are still some more general issues deriving from the way in which CLT buildings are designed. Restrictions imposed by fire or seismic regulations can often play an important role in architectural choices, moving forward to acoustic requirements during the early stages of design. Other problems may then arise from the insertion of service equipment into wooden building, such as piping, service and waste systems, electrical wiring network, HVAC systems, elevators, etc. As a consequence of this, the need for correct acoustic design is even more necessary as the margins of uncertainty deriving from architectural choices not previously validated can be very wide.

4.1. Improvement of the Acoustic Design of CLT Buildings

Thanks to the remarkable acoustic performance achievable with CLT elements, especially for the protection from airborne noise, to date, the effects induced by some of these problems of acoustic bridges or loss of acoustic performance are usually solved improving the completion elements (air-leakages sealing, multilayer linings with sound-absorbing materials, floating floors with high mass and damping, etc.). Although this approach is not economically efficient due to the higher costs necessary to compensate for the loss of acoustic performance, it is commonly accepted as it can also lead to an improvement in the thermal performance of the building elements, even when it is not strictly functional to energy saving strategies [152].

A more rational and efficient approach requires the possibility of selecting specific and optimized coatings according to the CLT frequency response to airborne and impact noise.

The ISO 10140-5 standard proposes a laboratory method designed to evaluate the reliability of acoustic improvement data of wall linings on reference walls and floors. Several reference bare building elements are described for carrying out this type of test in laboratory, distinguished according to the characteristic range in which the critical frequency falls. The constructions described can be used as standard basic elements of linings, installed in a consistent way with the actual use. In this way, it is possible to directly compare, on the same bases, different types of coating techniques for increasing soundproofing capacity or reducing impact noise. Furthermore, it is possible to evaluate how the same lining interacts with different base structures of different surface mass and, therefore, according to the resulting dominant critical frequency. However, among these structures, there is no bare CLT wall or floor.

Considering airborne sound insulation, the standardized building element closest to the characteristics of a bare CLT wall, for thickness and surface mass, is the one with medium critical frequency (“lightweight wall”).

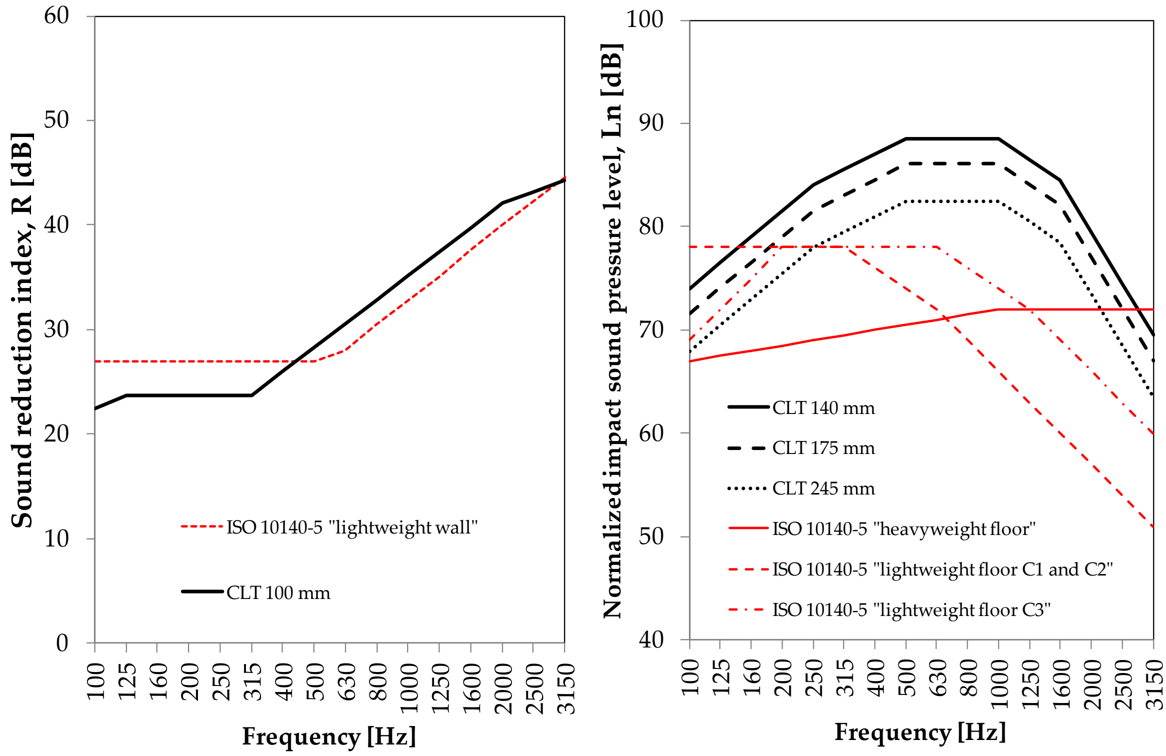
The reference “lightweight wall”, according to annex B of the ISO 10140-5, is a 100 mm thick wall of aerated concrete blocks, density 600 ± 50 kg/m^3, with 10 mm gypsum plaster on the side facing the lining. This wall should have a mass per unit area of about 70 kg/m^2 and a critical frequency within the 500 Hz octave band. A comparison between the reference curve of the standardized “lightweight wall” and a possible reference curve for bare CLT with the same surface mass (70 kg/m^2), obtained by the analytical method proposed by Di Bella et al. [65], is shown in Figure 7a.

From the comparison, it can be seen that, with the same surface mass, the CLT wall behaves quite similar to the reference “lightweight wall” up to 315 Hz. However, starting from 400 Hz, there are considerable differences, in particular about 6 dB between 630 Hz and 1600 Hz. These differences significantly affect the single-number airborne sound insulation value, that rise from R_w = 33 dB for the standardized “lightweight wall” to R_w = 37 dB for the bare CLT wall.

The different behavior between the standardized “lightweight wall” of ISO 10140-5 and a bare CLT wall, with the same mass per unit area, implies that it is not possible to use ΔR data obtained with this standardized method on bare CLT walls.

A similar approach can be taken for the evaluation of impact noise reduction techniques of floors. However, the annex C of the ISO 10140-5 does not have any type of floor that is comparable with one in CLT. The standardized heavyweight floor consists of a reinforced concrete slab of 140 mm ($L_{n,w}$ = 78 dB). The reference lightweight floors type C1, C2 ($L_{n,w}$ = 72 dB) and C3 ($L_{n,w}$ = 75 dB) are essentially variants of the wooden floor made of beams and planking, with or without a plasterboard ceiling.

Different studies have proposed reference curves for bare CLT floors [58,64]. A comparison between the reference curve of the standardized floors and possible reference curves for bare CLT of different thickness is shown in Figure 7b. The comparison highlights the characteristic trend of the normalized impact sound pressure level of the CLT floors ($L_{n,w}$ = 81–87 dB, according to the thickness). Therefore, for the same reasons illustrated above, the use of ΔL data obtained with these reference floors are not directly applicable on the CLT. However, it is possible to obtain a correlation that allow for applying ΔL data from a heavy concrete slab to a CLT structure of defined surface mass, taking into account the different frequency trend of the two building elements [64].



(**a**) (**b**)

Figure 7. Reference spectra proposed for the evaluation of the effect on CLT of acoustic linings and floating floors measured in laboratory according to the standards of the ISO 10140 series: (**a**) Comparison between sound reduction index of reference "lightweight" wall (ISO 10140-5) and an equivalent CLT wall (same surface mass of the reference "lightweight" wall), calculated according to a mass-law dependent reference curve (from [65] and Equation (1)); (**b**) comparison between normalized impact sound pressure levels for bare CLT floors of different thickness, calculated according to a mass-law dependent reference curve (from [64] and Equation (2)). Reference curves of ISO 10140-5 standardized floors are also reported.

It is therefore necessary to deepen the relationships that link the constructive aspects of the CLT building with the acoustic performance. CLT panels are considered homogeneous and orthotropic with relatively low mass per unit area, therefore it is necessary to know the radiation efficiency to properly estimate their acoustic behavior, both in terms of single panel vibration and lateral transmission effects, especially in complex building systems in which it is important to clearly identify resonant or non-resonant transmission to optimize soundproofing techniques. These techniques are based on the application of additional layers to the CLT panels but optimized in frequency response to maximize the level of noise protection achievable. As mentioned above, an important aspect to analyze is related to the actual insulation improvement achievable with linings, in order to define a reliable collection of laboratory values of ΔL and ΔR specifically designed for CLT. As a matter of fact, the effect of acoustic linings on a basic structure depends on the combination of the vibro-acoustic behaviors of the elements that are coupled. The same lining gives different results if used on one side or on both sides of a CLT wall. As the CLT base structure changes, the coupling leads to significant changes and, in some cases, even to a significant deterioration in performance [55].

Considering the support of acoustic modelling for building design, an important aspect that affects the accuracy of calculation is the application of K_{ij} measured values instead of empirical relationships provided by ISO 12354-1. In CLT structures, not only the shape of the junction and the mass per unit area of the involved elements are relevant, but also the actual connection between them is particularly important. Therefore, it is useful to carry out validation measures of the vibration reduction index on the joints actually used in the construction, which can have a much greater complexity and articulation than outlined through the available parametric formulas.

To summarize the aspects relating to the knowledge of the characteristics of the materials and the modelling techniques in a single theme, it can be considered that a substantial improvement in the acoustic design of CLT buildings can contribute to an increase in overall sustainability in the use of this construction system. For example, carrying out on-site tests for the calibration of the acoustic model and the compensation of transmission factors that cannot be controlled only on the basis of the available parametric relationships allows for avoiding more expensive refurbishments once the works are finished or to avoid using materials that are not consistent with the aim of achieving circular economy goals for these products. In fact, the main acoustic correction solutions currently proposed for CLT systems are borrowed from other construction systems, similar in terms of prefabrication, application, and management on the construction site but less environmentally sustainable.

4.2. State-of-the-Art Gaps and Future Works

This analysis of the recent literature, concerning the development of research on the acoustic aspects of CLT compared to other topics on the building environment field, showed the presence of some important gaps in the state-of-the-art of this construction system.

- Literature gaps (lack of holistic approach).
- High concentration of studies in a few countries.
- Regionalization of needs and requirements (methodological discrepancies deriving from specific technical frameworks).
- Lack of suitable parametric calculation models.
- Acoustic data repositories not sufficiently extensive to meet all project needs.
- Lack of laboratory studies on the interaction between the structural elements in CLT and building service equipment (structure borne noise and possible acoustic leakages).
- Lack of on-site data for the validation of calculation models.

The goal of improvement and optimization in the acoustic design of CLT buildings essentially requires the development of further research, which can be grouped into three distinct topics.

- Increase of the database of laboratory measurements of airborne sound insulation and impact noise pressure levels of complete CLT construction elements, which use coating materials optimized for the overall sustainability of this product.
- Consolidation of a reference curve for bare CLT elements to allow the conversion of the data of acoustic performance improvements already available but obtained from standardized elements with different vibro-acoustic characteristics.

- Development of a specific set of parametric formulas for the joints between the CLT panels, taking into account the variability induced by the different fixing systems of the elements with the same shape of the joint.

In addition to these purely acoustic aspects, future research might explore the placement of the CLT and products necessary for its correct use in construction in the context of circular economy and environmental sustainability, in order to effectively support some selection criteria for the definition of construction solutions for reference.

5. Conclusions

This systematic review of the acoustic characteristics of cross-laminated timber systems was not limited to an analysis exclusively based on the evaluation of the progression of knowledge on this topic, but also tried to frame the problem of noise protection in the broader context of the definition of the main aspects necessary for an overall characterization of a relatively new building product.

It has highlighted that the acoustic aspects have been the subject of interest in a systematic way only after 20 years of use of this construction system. This delay is not unusual in the scientific approach to the parameters that make up the indoor environmental quality (IEQ), that refers to the quality of a building's environment in relation to the health and wellbeing of those who occupy space within it. Among the criteria that define the quality of the indoor environments, there are some that are directly related to energy and therefore economic aspects, such as thermal comfort, air quality and lighting, and others that can only be parameterized in an economic sense indirectly. The acoustic comfort in buildings can be characterized firstly as the level of protection from intrusive noise, therefore not in an absolute way but considering the boundary conditions. Unlike the energy needs of a building, relatively simple to evaluate in the design phase but that require very long and elaborate analyses for a complete verification of the achievement of the project goals, the acoustic parameters are not easy to evaluate. This is mainly due to the uncertainty inherent to standardized calculation models and input data. Nevertheless, they can be easily measured on-site once the building is completed. These difficulties generally lead to considering the acoustic problems as secondary in the design phase. Consequently, the attention is focused on the issues that have an immediate relevance on the energy aspects. The common practice of considering the trend of the increase in acoustic insulation performances as that of thermal insulation (more is better) is not justifiable. The tendency to consider the problem of energy saving as a priority can more easily lead to inadequate acoustic comfort, due to the lack of a holistic and integrated approach. Despite this, it is not unusual to find the oversizing of the acoustic linings of the CLT elements as an acceptable solution, if economically feasible, to compensate for the calculation uncertainty. Moreover, it must be considered that it may not be practically convenient to push the acoustic insulation performance of a single separating element too high since, beyond a certain limit given by the coupling characteristics of all the other elements that make up a building environment, lateral transmissions prevail over direct ones through a separating element, limiting the possible benefits.

A limit to the development of an organic approach to this problem derives partly from the organization of the production of this building element and its methods of use. CLT manufacturers are mainly operators in the wood sector and rely on other specialized industries for the development of fastening systems and for linings with thermal and acoustic insulation functions. Unlike other construction systems, an integrated approach to defining robust and standardized acoustic solutions has not yet been fully reached. Market needs, linked to the ever-increasing diffusion of CLT, lead companies to differentiate the offer through the customization of complete building systems and assemblies. However, judging by the availability of laboratory data actually carried out for the determination of the parameters useful for acoustic modelling (airborne sound insulation, impact sound pressure level, vibration reduction index, etc.), only a limited selection of complete CLT systems (intended as a set of structure, connections, and linings) can be used with sufficient reliability. For this reason, it is important to emphasize the need for an implementation of laboratory measurement standards to include specific reference curves for the bare CLT building elements. The benefit of having a specific reference bare structure, or a set of reference curves for a building product, is twofold. A reference structure in the laboratory makes it possible to compare different linings or finishing elements of a CLT assembly on the same base. It also allows for proceeding successfully with the optimization of the systems by experimentally comparing the effectiveness of the sound-absorbing or anti-vibration products used, for example, in acoustic coatings or floating floors. A set of parametric reference curves based on laboratory data of bare structures, on the other hand, allows for developing correlations with other reference structures already present in the standards. This offers the advantage, also economic, of being able to reuse, in preliminary assessments, data deriving from measurements carried out in previous studies but on different reference structures. In this way, it would be possible to carry out extensive preparatory analyses and then focus on the current laboratory measurements only on the selection of materials that offer the best combination of acoustic performance, ease of installation, sustainability, and economy.

Another important aspect that can certainly contribute to making the acoustic design of CLT buildings more effective and accurate is linked to the availability of a wider range of joints in the series of ISO 12354 standards. The schemes and the parametric relations currently available are not sufficient to model many of the architectural choices commonly adopted to make the best use of the structural characteristics of CLT panels.

An improvement and optimization of the acoustic design of CLT buildings, together with an upgrade of prediction models, is necessary to create the conditions for an even more effective use of this product, which already has undoubted advantages over other wooden construction systems. Thus, the outcome of this review can be useful to point out research and standardization aspects not yet fully analyzed.

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References

1. Brandner, R.; Flatscher, G.; Ringhofer, A.; Schickhofer, G.; Thiel, A. Cross laminated timber (CLT): Overview and development. *Eur. J. Wood Wood Prod.* **2016**, *74*, 331–351. [CrossRef]
2. Mohammad, M.; Gagnon, S.; Douglas, B.; Podesto, L. Introduction to Cross Laminated Timber. *J. Contempary Wood Eng.* **2012**, *22*, 3–12.
3. Jones, K.; Stegemann, J.; Sykes, J.; Winslow, P. Adoption of unconventional approaches in construction: The case of cross-laminated timber. *Constr. Build. Mater.* **2016**, *125*, 690–702. [CrossRef]
4. Zhang, L.; Liu, B.; Du, J.; Liu, C.; Wang, S. CO_2 emission linkage analysis in global construction sectors: Alarming trends from 1995 to 2009 and possible repercussions. *J. Clean. Prod.* **2019**, *221*, 863–877. [CrossRef]
5. Zhang, X.; Wang, F. Hybrid input-output analysis for life-cycle energy consumption and carbon emissions of China's building sector. *Build. Environ.* **2016**, *104*, 188–197. [CrossRef]
6. Ahmad, M.; Zhao, Z.-Y.; Li, H. Revealing stylized empirical interactions among construction sector, urbanization, energy consumption, economic growth and CO_2 emissions in China. *Sci. Total Environ.* **2019**, *657*, 1085–1098. [CrossRef]
7. Hung, C.C.-W.; Hsu, S.-C.; Cheng, K.-L. Quantifying city-scale carbon emissions of the construction sector based on multi-regional input-output analysis. *Resour. Conserv. Recycl.* **2019**, *149*, 75–85. [CrossRef]
8. Foxell, S.; Cooper, I. Closing the policy gaps. *Build. Res. Inf.* **2015**, *43*, 399–406. [CrossRef]
9. Chou, J.-S.; Yeh, K.-C. Life cycle carbon dioxide emissions simulation and environmental cost analysis for building construction. *J. Clean. Prod.* **2015**, *101*, 137–147. [CrossRef]
10. Rogge, N. EU countries' progress towards 'Europe 2020 strategy targets'. *J. Policy Model.* **2019**, *41*, 255–272. [CrossRef]

11. Choi, S.W.; Oh, B.K.; Park, J.S.; Park, H.S. Sustainable design model to reduce environmental impact of building construction with composite structures. *J. Clean. Prod.* **2016**, *137*, 823–832. [CrossRef]
12. Gaidučis, S.; Mačiulaitis, R.; Kaminskas, A. Eco-balance features and significance of hemihydrate phosphogypsum reprocessing into gypsum binding materials. *J. Civ. Eng. Manag.* **2009**, *15*, 205–213. [CrossRef]
13. Ghayeb, H.H.; Razak, H.A.; Sulong, N.H.R. Evaluation of the CO_2 emissions of an innovative composite precast concrete structure building frame. *J. Clean. Prod.* **2020**, *242*, 118567. [CrossRef]
14. Di Filippo, J.; Karpman, J.; DeShazo, J. The impacts of policies to reduce CO_2 emissions within the concrete supply chain. *Cem. Concr. Compos.* **2019**, *101*, 67–82. [CrossRef]
15. Oh, B.K.; Choi, S.W.; Park, H.S. Influence of variations in CO_2 emission data upon environmental impact of building construction. *J. Clean. Prod.* **2017**, *140*, 1194–1203. [CrossRef]
16. Lehmann, S. Low carbon construction systems using prefabricated engineered solid wood panels for urban infill to significantly reduce greenhouse gas emissions. *Sustain. Cities Soc.* **2013**, *6*, 57–67. [CrossRef]
17. Lyons, A. *Materials for Architects and Builders*, 4th ed.; ButterWorth Heinemann: Oxford, UK, 2010; ISBN 9780080949598.
18. Intergovernmental Panel on Climate Change. Climate Change 2014 Mitigation of Climate Change; 2014. Available online: https://www.ipcc.ch/report/ar5/wg3/ (accessed on 30 June 2020).
19. Lehmann, S. Sustainable Construction for Urban Infill Development using Engineered Massive Wood Panel Systems. *Sustainability* **2012**, *4*, 2707–2742. [CrossRef]
20. Hurmekoski, E.; Jonsson, K.H.R.; Nord, T. Context, drivers, and future potential for wood-frame multi-story construction in Europe. *Technol. Forecast. Soc. Chang.* **2015**, *99*, 181–196. [CrossRef]
21. Ramage, M.H.; Burridge, H.C.; Busse-Wicher, M.; Fereday, G.; Reynolds, T.P.S.; Shah, D.; Wu, G.; Yu, L.; Fleming, P.; Densley-Tingley, D.; et al. The wood from the trees: The use of timber in construction. *Renew. Sustain. Energy Rev.* **2017**, *68*, 333–359. [CrossRef]
22. Harris, R. Cross Laminated Timber. In *Wood Composites*; Woodhead Publishing: Cambridge, UK, 2015; pp. 141–167. ISBN 9781782424772.
23. Risse, M.; Weber-Blaschke, G.; Richter, K. Eco-efficiency analysis of recycling recovered solid wood from construction into laminated timber products. *Sci. Total Environ.* **2019**, *661*, 107–119. [CrossRef]
24. Callegari, G.; Cremonini, C.; Rocco, V.M.; Spinelli, A.; Zanuttini, R. The production of hardwood X-Lam panels to valorise the forest-wood chain in piemonte (Italy). In Proceedings of the 11th World Conference on Timber Engineering WCTE, Riva del Garda, Italy, 20–24 June 2010; Volume 2, pp. 1617–1622.
25. Brandner, R. Production and Technology of Cross Laminated Timber (CLT): A state-of-the-art Report. In Proceedings of the Focus Solid Timber Solutions—European Conference on Cross Laminated Timber (CLT), Graz, Austria, 21–22 May 2013; pp. 3–36.
26. Ceccotti, A.; Sandhaas, C. A proposal for a standard procedure to establish the seismic behaviour factor q of timber buildings. In Proceedings of the 11th World Conference on Timber Engineering WCTE, Riva del Garda, Italy, 20–24 June 2010; Volume 4, pp. 3604–3614.
27. Van De Kuilen, J.W.G.; Ceccotti, A.; Xia, Z.; He, M. Very tall wooden buildings with Cross Laminated Timber. *Procedia Eng.* **2011**, *14*, 1621–1628. [CrossRef]
28. Wells, M. Stadthaus, London: Raising the bar for timber buildings. *Proc. Inst. Civ. Eng. Civ. Eng.* **2011**, *164*, 122–128. [CrossRef]
29. Sustersic, I.; Fragiacomo, M.; Dujic, B. Seismic Analysis of Cross-Laminated Multistory Timber Buildings Using Code-Prescribed Methods: Influence of Panel Size, Connection Ductility, and Schematization. *J. Struct. Eng.* **2016**, *142*, 1–14. [CrossRef]
30. Reynolds, T.P.S.; Casagrande, D.; Tomasi, R. Comparison of multi-storey cross-laminated timber and timber frame buildings by in situ modal analysis. *Constr. Build. Mater.* **2016**, *102*, 1009–1017. [CrossRef]
31. Mugabo, I.; Barbosa, A.R.; Riggio, M. Dynamic Characterization and Vibration Analysis of a Four-Story Mass Timber Building. *Front. Built Environ.* **2019**, *5*. [CrossRef]
32. Stenson, J.; Ishaq, S.L.; Laguerre, A.; Loia, A.; MacCrone, G.; Mugabo, I.; Northcutt, D.; Riggio, M.; Barbosa, A.; Gall, E.; et al. Monitored Indoor Environmental Quality of a Mass Timber Office Building: A Case Study. *Buildings* **2019**, *9*, 142. [CrossRef]
33. Fratoni, G.; D'Orazio, D.; Barbaresi, L. Acoustic comfort in a worship space made of cross-laminated timber. *Build. Acoust.* **2019**, *26*, 121–138. [CrossRef]

34. Asdrubali, F.; Ferracuti, B.; Lombardi, L.; Guattari, C.; Evangelisti, L.; Grazieschi, G. A review of structural, thermo-physical, acoustical, and environmental properties of wooden materials for building applications. *Build. Environ.* **2017**, *114*, 307–332. [CrossRef]
35. Seim, W.; Hummel, J.; Vogt, T. Earthquake design of timber structures—Remarks on force-based design procedures for different wall systems. *Eng. Struct.* **2014**, *76*, 124–137. [CrossRef]
36. Gavric, I.; Fragiacomo, M.; Ceccotti, A. Cyclic behaviour of typical metal connectors for cross-laminated (CLT) structures. *Mater. Struct.* **2014**, *48*, 1841–1857. [CrossRef]
37. Demirci, C.; Málaga-Chuquitaype, C.; Macorini, L. Seismic shear and acceleration demands in multi-storey cross-laminated timber buildings. *Eng. Struct.* **2019**, *198*, 109467. [CrossRef]
38. Sustersic, I.; Dujic, B. Seismic strengthening of existing buildings with cross laminated timber panels. In Proceedings of the World Conference on Timber Engineering WCTE, Auckland, New Zealand, 15–19 July 2012; Volume 4, pp. 122–129.
39. Ceccotti, A.; Follesa, M.; Lauriola, M.P.; Sandhaas, C. Sofie Project–Test Results on the Lateral Resistance of Cross-Laminated Wooden Panels. In Proceedings of the Proceedings of the First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, 3–8 September 2006.
40. Ceccotti, A.; Lauriola, M.P.; Pinna, M.; Sandhaas, C. SOFIE project—Cyclic tests on cross-laminated wooden panels. In Proceedings of the 9th World Conference on Timber Engineering WCTE, Portland, OR, USA, 6–10 August 2006.
41. Sandhaas, C.; van de Kuilen, J.W.; Boukes, J.; Ceccotti, A. Analysis of X-lam panel-to-panel connections under monotonic and cyclic loading. In Proceedings of the International Council for Research and Innovation in Building and Construction, Karlsruhe, Germany, 24 August 2009; pp. 1–11.
42. Ceccotti, A.; Sandhaas, C.; Okabe, M.; Yasumura, M.; Minowa, C.; Kawai, N. SOFIE project—3D shaking table test on a seven-storey full-scale cross-laminated timber building. *Earthq. Eng. Struct. Dyn.* **2013**, *42*, 2003–2021. [CrossRef]
43. *Comité Européen de Normalisation EN 1995-1-1:2004, Eurocode 5: Design of Timber Structures—Part 1–1: General—Common Rules and Rules for Buildings*; European Union: Brussels, Belgium, 2004.
44. *Comité Européen de Normalisation EN 1995-1-2:2004, Eurocode 5: Design of Timber Structures—Part 1–2: General—Structural Fire Design*; European Union: Brussels, Belgium, 2004.
45. *Comité Européen de Normalisation EN 16351:2015, Timber Structures—Cross Laminated Timber—Requirements*; European Union: Brussels, Belgium, 2015.
46. Chang, S.J.; Wi, S.; Kim, S. Thermal bridging analysis of connections in cross-laminated timber buildings based on ISO 10211. *Constr. Build. Mater.* **2019**, *213*, 709–722. [CrossRef]
47. Wang, L.; Ge, H. Hygrothermal performance of cross-laminated timber wall assemblies: A stochastic approach. *Build. Environ.* **2016**, *97*, 11–25. [CrossRef]
48. Hallik, J.; Gustavson, H.; Kalamees, T. Air Leakage of Joints Filled with Polyurethane Foam. *Buildings* **2019**, *9*, 172. [CrossRef]
49. Lineham, S.A.; Thomson, D.; Bartlett, A.I.; Bisby, L.A.; Hadden, R.M. Structural response of fire-exposed cross-laminated timber beams under sustained loads. *Fire Saf. J.* **2016**, *85*, 23–34. [CrossRef]
50. Östman, B.A.-L.; Schmid, J.; Klippel, M.; Just, A.; Werther, N.; Brandon, D. Fire design of clt in europe. *Wood Fiber Sci.* **2018**, *50*, 68–82. [CrossRef]
51. Kouyoumji, J.L.; Boulet, S.; Gagnon, S. Sound transmission loss of Cross Laminated Timber 'CLT' floors, measurements and modelling using SEA. In Proceedings of the 38th International Congress and Exposition on Noise Control Engineering INTER-NOISE 2009, Ottawa, ON, Canada, 23–26 August 2009; Volume 1, pp. 258–265.
52. Ljunggren, F.; Simmons, C.; Hagberg, K. Correlation between sound insulation and occupants' perception—Proposal of alternative single number rating of impact sound. *Appl. Acoust.* **2014**, *85*, 57–68. [CrossRef]
53. Ljunggren, F.; Simmons, C.; Öqvist, R. Correlation between sound insulation and occupants' perception—Proposal of alternative single number rating of impact sound, part II. *Appl. Acoust.* **2017**, *123*, 143–151. [CrossRef]
54. Caniato, M.; Bettarello, F.; Ferluga, A.; Marsich, L.; Schmid, C.; Fausti, P. Thermal and acoustic performance expectations on timber buildings. *Build. Acoust.* **2017**, *24*, 219–237. [CrossRef]

55. Höller, C.; Mahn, J.; Quirt, D. Apparent sound insulation in cross-laminated timber buildings. *J. Acoust. Soc. Am.* **2017**, *141*, 3479. [CrossRef]
56. Homb, A.; Hagberg, K.; Schmid, H.; Guigou-Carter, C. Impact sound insulation of wooden joist constructions: Collection of laboratory measurements and trend analysis. *Build. Acoust.* **2016**, *23*, 73–91. [CrossRef]
57. Schoenwald, S.; Zeitler, B.; Sabourin, I.; King, F. Sound insulation performance of cross laminated timber building systems. In Proceedings of the 42nd International Congress and Exposition on Noise Control Engineering INTER-NOISE 2013: Noise Control for Quality of Life, Innsbruk, Austria, 15–18 September 2013; Volume 3, pp. 1864–1873.
58. Zeitler, B.; Schoenwald, S.; Sabourin, I. Direct impact sound insulation of cross laminate timber floors with and without toppings. In Proceedings of the 43rd International Congress on Noise Control Engineering INTER-NOISE 2014: Improving the World Through Noise Control, Melbourne Australia, 16–19 November 2014.
59. Santoni, A.; Schoenwald, S.; Van Damme, B.; Fausti, P. Determination of the elastic and stiffness characteristics of cross-laminated timber plates from flexural wave velocity measurements. *J. Sound Vib.* **2017**, *400*, 387–401. [CrossRef]
60. Santoni, A.; Schoenwald, S.; Fausti, P.; Tröbs, H.-M. Modelling the radiation efficiency of orthotropic cross-laminated timber plates with simply-supported boundaries. *Appl. Acoust.* **2019**, *143*, 112–124. [CrossRef]
61. Morandi, F.; Prato, A.; Barbaresi, L.; Schiavi, A. On the diffuseness of the vibrational field of a cross-laminated timber plate: Comparison between theoretical and experimental methods. *Appl. Acoust.* **2020**, *159*, 107104. [CrossRef]
62. Guigou-Carter, C.; Villot, M. Junction characteristics for predicting acoustic performance of lightweight wood-based buildings. In Proceedings of the 44th International Congress and Exposition on Noise Control Engineering INTER-NOISE 2015, San Francisco, CA, USA, 9–12 August 2015.
63. Morandi, F.; De Cesaris, S.; Garai, M.; Barbaresi, L. Measurement of flanking transmission for the characterisation and classification of cross laminated timber junctions. *Appl. Acoust.* **2018**, *141*, 213–222. [CrossRef]
64. Di Bella, A.; Granzotto, N.; Barbaresi, L. Analysis of acoustic behavior of bare CLT floors for the evaluation of impact sound insulation improvement. *Proc. Mtgs. Acoust.* **2016**, *28*, 015016. [CrossRef]
65. Di Bella, A.; Granzotto, N.; Quartaruolo, G.; Speranza, A.; Morandi, F. Analysis of airborne sound reduction index of bare CLT walls. In Proceedings of the WCTE 2018—World Conference on Timber Engineering; World Conference on Timber Engineering (WCTE), Seoul, Korea, 20–24 August 2018.
66. Di Bella, A.; Mastino, C.C.; Barbaresi, L.; Granzotto, N.; Baccoli, R.; Morandi, F. Comparative study of prediction methods and field measurements of the acoustic performances of buildings made with CLT elements. In Proceedings of the 46th International Congress and Exposition on Noise Control Engineering INTER-NOISE 2017: Taming Noise and Moving Quiet, Hong Kong, China, 27–30 August 2017.
67. International Organization for Standardization ISO 12354-1:2017, Building Acoustics—Estimation of Acoustic Performance of Buildings from the Performance of Elements—Part 1: Airborne Sound Insulation Between Rooms 2017. Available online: https://www.iso.org/standard/70242.html (accessed on 3 July 2020).
68. International Organization for Standardization ISO 12354-2:2017, Building Acoustics—Estimation of Acoustic Performance of Buildings from the Performance of Elements—Part 2: Impact Sound Insulation Between Rooms 2017. Available online: https://www.iso.org/standard/70243.html (accessed on 3 July 2020).
69. International Organization for Standardization ISO 12354-3:2017, Building Acoustics—Estimation of Acoustic Performance of Buildings from the Performance of Elements—Part 3: Airborne Sound Insulation Against Outdoor Sound 2017. Available online: https://www.iso.org/standard/70244.html (accessed on 3 July 2020).
70. Villot, M.; Guigou-Carter, C. Measurement Methods Adapted to Wood Frame Lightweight Constructions. *Build. Acoust.* **2006**, *13*, 189–198. [CrossRef]
71. Guigou-Carter, C.; Villot, M.; Wetta, R. Prediction Method Adapted to Wood Frame Lightweight Constructions. *Build. Acoust.* **2006**, *13*, 173–188. [CrossRef]
72. European COST Action FP0702. Available online: http://extranet.cstb.fr/sites/cost/default.aspx (accessed on 23 April 2020).

73. Öqvist, R.; Ljunggren, F.; Ågren, A. Variations in sound insulation in cross laminated timber housing construction. In Proceedings of the Forum Acusticum 2011, Aalborg, Denmark, 27 June–1 July 2011; pp. 1649–1654.
74. Öqvist, R.; Ljunggren, F.; Ågren, A. On the uncertainty of building acoustic measurements – Case study of a cross-laminated timber construction. *Appl. Acoust.* **2012**, *73*, 904–912. [CrossRef]
75. Kouyoumji, J.L.; Gagnon, S. Experimental approach on sound transmission loss of Cross Laminated Timber floors for building. In Proceedings of the 39th International Congress on Noise Control Engineering INTER-NOISE 2010, Lisbon, Portugal, 13–16 June 2010; Volume 1, pp. 347–356.
76. Schoenwald, S. Comparison of proposed methods to include lightweight framed structures in EN 12354 prediction model. In Proceedings of the European Conference on Noise Control, Prague, Czech Republic, 10–13 June 2012; pp. 174–179.
77. Cross-Laminated Timber (CLT) Stora Enso. Available online: https://www.clt.info/en/product/clt-massive-wood-system/ (accessed on 27 April 2020).
78. Cross-Laminated Timber (CLT) KLH Massivholz GmbH. Available online: https://www.klh.at/en/cross-laminated-timber/ (accessed on 27 April 2020).
79. Cross-Laminated Timber (CLT) BBS Binderholz. Available online: https://www.binderholz.com/en-us/products/clt-bbs/ (accessed on 27 April 2020).
80. Mayr-Melnhof Holz MM Crosslam. Available online: http://www.mm-holz.com/en/products/further-processing/mm-crosslam/ (accessed on 27 April 2020).
81. Cross-Laminated Timber (CLT) Hasslacher. Available online: https://www.hasslacher.com/cross-laminated-timber (accessed on 27 April 2020).
82. Cross-Laminated Timber (CLT)—The Canadian Wood Council. Available online: https://cwc.ca/how-to-build-with-wood/wood-products/mass-timber/cross-laminated-timber-clt/ (accessed on 27 April 2020).
83. Cross-Laminated Timber (CLT)—Structurlam. Available online: https://www.structurlam.com/construction/products/d/cross-laminated-timber-clt/ (accessed on 27 April 2020).
84. I Nuovi Orizzonti dell'LCA: Verso un Approccio Sistemico e Integrato alla Progettazione di Prodotti, Processi e Servizi. Available online: https://www.enea.it/it/seguici/pubblicazioni/edizioni-enea/2014/atti-lca-2014 (accessed on 9 June 2020).
85. Liu, Y.; Guo, H.; Sun, C.; Chang, W.-S. Assessing Cross Laminated Timber (CLT) as an Alternative Material for Mid-Rise Residential Buildings in Cold Regions in China—A Life-Cycle Assessment Approach. *Sustainability* **2016**, *8*, 1047. [CrossRef]
86. Bergman, R.D.; Bowe, S.A. Environmental impact of manufacturing softwood lumber in northeastern and north central United States. *Wood Fiber Sci.* **2010**, *42*, 67–78.
87. Puettmann, M.E.; Bergman, R.; Hubbard, S.; Johnson, L.; Lippke, B.; Oneil, E.; Wagner, F.G. Cradle-to-gate life-cycle inventory of US wood products production: Corrim phase I and phase II products. *Wood Fiber Sci.* **2010**, *42*, 15–28.
88. Malmsheimer, R.W.; Heffernan, P.; Brink, S.; Crandall, D.; Deneke, F.; Galik, C.; Gee, E.A.; Helms, J.A.; McClure, N.; Mortimer, M.; et al. Forest management solutions for mitigating climate change in the United States. *J. For.* **2008**, *106*, 115–171. [CrossRef]
89. Piccardo, C.; Magliocco, A. The Environmental Profile of Wood in the Building Industry Today: Comments on the Results of Some LCA Studies. *Am. J. Civ. Eng. Arch.* **2013**, *1*, 122–128. [CrossRef]
90. Izzi, M.; Flatscher, G.; Fragiacomo, M.; Schickhofer, G. Experimental investigations and design provisions of steel-to-timber joints with annular-ringed shank nails for Cross-Laminated Timber structures. *Constr. Build. Mater.* **2016**, *122*, 446–457. [CrossRef]
91. Sathre, R.; O'Connor, J. Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environ. Sci. Policy* **2010**, *13*, 104–114. [CrossRef]
92. Gustavsson, L.; Pingoud, K.; Sathre, R. Carbon Dioxide Balance of Wood Substitution: Comparing Concrete- and Wood-Framed Buildings. *Mitig. Adapt. Strat. Glob. Chang.* **2006**, *11*, 667–691. [CrossRef]
93. Jungmeier, G.; Werner, F.; Jarnehammar, A.; Hohenthal, C.; Richter, K. Allocation in LCA of wood-based products—Experiences of cost action E9: Part II. Examples. *Int. J. Life Cycle Assess.* **2002**, *7*, 369–375. [CrossRef]
94. Žegarac, V.Z.; Žigart, M.; Premrov, M.; Lukman, R.K. Comparative assessment of shape related cross-laminated timber building typologies focusing on environmental performance. *J. Clean. Prod.* **2019**, *216*, 482–494. [CrossRef]

95. Dodoo, A.; Gustavsson, L.; Sathre, R. Lifecycle primary energy analysis of low-energy timber building systems for multi-storey residential buildings. *Energy Build.* **2014**, *81*, 84–97. [CrossRef]
96. Takano, A.; Pal, S.K.; Kuittinen, M.; Alanne, K. Life cycle energy balance of residential buildings: A case study on hypothetical building models in Finland. *Energy Build.* **2015**, *105*, 154–164. [CrossRef]
97. Hafner, A.; Schäfer, S. Comparative LCA study of different timber and mineral buildings and calculation method for substitution factors on building level. *J. Clean. Prod.* **2017**, *167*, 630–642. [CrossRef]
98. Franke, S. Mechanical properties of beech CLT. In Proceedings of the WCTE 2016—World Conference on Timber Engineering, Vienna, Austria, 22–25 August 2016.
99. Sanborn, K.; Gentry, T.; Koch, Z.; Valkenburg, A.; Conley, C.; Stewart, L. Ballistic performance of Cross-laminated Timber (CLT). *Int. J. Impact Eng.* **2019**, *128*, 11–23. [CrossRef]
100. Shahnewaz, M.; Alam, S.; Tannert, T. In-Plane Strength and Stiffness of Cross-Laminated Timber Shear Walls. *Buildings* **2018**, *8*, 100. [CrossRef]
101. Dujic, B.; Strus, K.; Zarnic, R.; Ceccotti, A. Prediction of dynamic response of a 7-storey massive XLam wooden building tested on a shaking table. In Proceedings of the 11th World Conference on Timber Engineering WCTE, Riva del Garda, Italy, 20–24 June 2010; Volume 4, pp. 3450–3457.
102. Hummel, J.; Seim, W. Displacement-based design approach to evaluate the behaviour factor for multi-storey CLT buildings. *Eng. Struct.* **2019**, *201*, 109711. [CrossRef]
103. Sustersic, I.; Dujic, B. Seismic shaking table testing of a reinforced concrete frame with masonry infill strengthened with cross laminated timber panels. In Proceedings of the WCTE 2014—World Conference on Timber Engineering, Quebec City, QC, Canada, 10–14 August 2014.
104. Jeleč, M.; Varevac, D.; Rajčić, V. Križno lamelirano drvo (CLT)—Pregled stanja područja. *Gradjevinar* **2018**, *70*, 75–95.
105. Sicignano, E.; Di Ruocco, G.; Melella, R. Mitigation Strategies for Reduction of Embodied Energy and Carbon, in the Construction Systems of Contemporary Quality Architecture. *Sustainability* **2019**, *11*, 3806. [CrossRef]
106. XLAM Technical Data and Documentation. Available online: https://www.xlamdolomiti.it/en/xlam-technical-data-documentation (accessed on 29 April 2020).
107. Belpoliti, V.; Calzolari, M.; Davoli, P.; Guerzoni, G. The construction project for the exportability and assembly of the building system on/off-site. *J. Technol. Archit. Environ.* **2019**, *18*, 309–320. [CrossRef]
108. Tolszczuk-Leclerc, Z.; Bernier-Lavigne, S.; Salenikovich, A.; Potvin, A. Design process of a free-form structure using CLT panels—Analysis of an architectural large scale structure. In Proceedings of the WCTE—World Conference on Timber Engineering, Vienna, Austria, 22–25 August 2016.
109. Mastino, C.C.; Di Bella, A.; Semprini, G.; Frattolillo, A.; Marini, M.; Da Pos, V. BIM application in design and evaluation acoustic performances of buildings. In Proceedings of the 25th International Congress on Sound and Vibration ICSV 2018: Hiroshima Calling, Hiroshima, Japan, 8–12 July 2018; Volume 7, pp. 4241–4248.
110. Vololonirina, O.; Coutand, M.; Perrin, B. Characterization of hygrothermal properties of wood-based products—Impact of moisture content and temperature. *Constr. Build. Mater.* **2014**, *63*, 223–233. [CrossRef]
111. Di Bella, A. *ALPS Project Final Report*; University of Padova: Padova PD, Italy, 2017.
112. Adekunle, T.O.; Nikolopoulou, M. Thermal comfort, summertime temperatures and overheating in prefabricated timber housing. *Build. Environ.* **2016**, *103*, 21–35. [CrossRef]
113. Franzoni, L.; Dhima, D.; Lyon, F.; Lebée, A.; Foret, G. A Stiffness-based Approach to Analyze the Fire Behaviour of Cross-Laminated Timber Floors. *Struct. Eng. Int.* **2017**, *27*, 238–245. [CrossRef]
114. Hossain, U.; Poon, C.S. Comparative LCA of wood waste management strategies generated from building construction activities. *J. Clean. Prod.* **2018**, *177*, 387–397. [CrossRef]
115. Höglmeier, K.; Weber-Blaschke, G.; Richter, K. Erratum: Potentials for cascading of recovered wood from building deconstruction—A case study for south-east Germany. *Resour. Conserv. Recycl.* **2017**, *117*, 304–314. [CrossRef]
116. Risse, M.; Weber-Blaschke, G.; Richter, K. Resource efficiency of multifunctional wood cascade chains using LCA and exergy analysis, exemplified by a case study for Germany. *Resour. Conserv. Recycl.* **2017**, *126*, 141–152. [CrossRef]
117. Ljunggren, F.; Simmons, C.; Hagberg, K. Findings from the AkuLite project: Correlation between measured vibro- Acoustic parameters and subjective perception in lightweight buildings. In Proceedings of the 42nd International Congress and Exposition on Noise Control Engineering INTER-NOISE 2013: Noise Control for Quality of Life, Innsbruk, Austria, 15–18 September 2013; Volume 2, pp. 1578–1585.

118. Caniato, M.; Bettarello, F.; Ferluga, A.; Marsich, L.; Schmid, C.; Fausti, P. Acoustic of lightweight timber buildings: A review. *Renew. Sustain. Energy Rev.* **2017**, *80*, 585–596. [CrossRef]
119. WoodWisdom-Net+ Newsletter September. 2011. Available online: https://www.fcba.fr/sites/default/files/woodwisdom_newsletter_092011.pdf (accessed on 8 June 2020).
120. Silent Timber Build Project. Available online: https://silent-timber-build.com/ (accessed on 23 April 2020).
121. Kouyoumji, J.L. Vibro-acoustics characterization of timber constructions: Measurements and modeling using Statistical Energy Analysis (SEA). In Proceedings of the 36th International Congress and Exhibition on Noise Control Engineering INTER-NOISE 2007, Istanbul, Turkey, 28–31 August 2007; Volume 3, pp. 2138–2147.
122. Kouyoumji, J.L. Predicting sound transmission loss on of lightweight timber framed construction using SEA. In Proceedings of the 42nd International Congress and Exposition on Noise Control Engineering INTER-NOISE 2013: Noise Control for Quality of Life, Innsbruck, Austria, 15–18 September 2013; Volume 3, pp. 1909–1915.
123. Kouyoumji, J.L.; Guigou, C. Predicting sound transmission loss of timber framed walls and floors using sea, in "acoubois" project of the French wood industry. In Proceedings of the 44th International Congress and Exposition on Noise Control Engineering INTER-NOISE 2015, San Francisco, CA, USA, 9–12 August 2015.
124. Santoni, A.; Bonfiglio, P.; Fausti, P.; Schoenwald, S.; Tröbs, H.M. Sound radiation efficiency measurements on cross-laminated timber plates. In Proceedings of the 45th International Congress and Exposition on Noise Control Engineering:INTER-NOISE 2016: Towards a Quieter Future, Hamburg, Germany, 21–24 August 2016; pp. 3697–3707.
125. Santoni, A.; Bonfiglio, P.; Fausti, P.; Schoenwald, S. Predicting sound radiation efficiency and sound transmission loss of orthotropic cross-laminated timber panels. *Proc. Mtgs. Acoust.* **2017**, *30*, 015013.
126. Byrick, W. Laboratory data examining impact and airborne sound attenuation in cross-laminated timber panel construction. In Proceedings of the 44th International Congress and Exposition on Noise Control Engineering INTER-NOISE 2015, San Francisco, CA, USA, 9–12 August 2015.
127. Golden, M.; Byrick, W. Laboratory data examining impact and airborne sound attenuation in cross- laminated timber panel construction—Part 2. In Proceedings of the 45th International Congress and Exposition on Noise Control Engineering INTER-NOISE 2016: Towards a Quieter Future, Hamburg, Germany, 21–24 August 2016; pp. 3782–3791.
128. Tanaka, M.; Kasai, Y.; Murakami, T.; Kawatani, S. Experimental study on airborne sound insulation of cross laminated timber panel walls. *J. Environ. Eng.* **2016**, *81*, 1075–1084. [CrossRef]
129. Zhang, X.; Hu, X.; Gong, H.; Zhang, J.; Lv, Z.; Hong, W. Experimental study on the impact sound insulation of cross laminated timber and timber-concrete composite floors. *Appl. Acoust.* **2020**, *161*, 107173. [CrossRef]
130. International Organization for Standardization ISO 717-1:2013, Acoustics—Rating of Sound Insulation in Buildings and of Building Elements—Part 1: Airborne Sound Insulation 2013. Available online: https://www.iso.org/standard/51968.html (accessed on 3 July 2020).
131. International Organization for Standardization ISO 717-2:2013, Acoustics—Rating of Sound Insulation in Buildings and of Building Elements—Part 2: Impact Sound Insulation 2013. Available online: https://www.iso.org/standard/51969.html (accessed on 3 July 2020).
132. International Organization for Standardization ISO 10140-1:2016, Acoustics—Laboratory Measurement of Sound Insulation of Building Elements—Part 1: Application Rules for Specific Products 2016. Available online: https://www.iso.org/standard/67232.html (accessed on 3 July 2020).
133. International Organization for Standardization ISO 10140-2:2010, Acoustics—Laboratory Measurement of Sound Insulation of Building Elements—Part 2: Measurement of Airborne Sound Insulation 2010. Available online: https://www.iso.org/standard/42088.html (accessed on 3 July 2020).
134. International Organization for Standardization ISO 10140-3:2010, Acoustics—Laboratory Measurement of Sound Insulation of Building Elements—Part 3: Measurement of Impact Sound Insulation 2010. Available online: https://www.iso.org/standard/42089.html (accessed on 3 July 2020).
135. International Organization for Standardization ISO 10140-4:2010, Acoustics—Laboratory Measurement of Sound Insulation of Building Elements—Part 4: Measurement Procedures and Requirements 2010. Available online: https://www.iso.org/standard/42090.html (accessed on 3 July 2020).
136. International Organization for Standardization ISO 10140-5:2010, Acoustics—Laboratory Measurement of Sound Insulation of Building Elements—Part 5: Requirements for Test Facilities and Equipment 2010. Available online: https://www.iso.org/standard/42087.html (accessed on 3 July 2020).

137. International Organization for Standardization ISO 10848-1:2017, Acoustics—Laboratory and Field Measurement of Flanking Transmission for Airborne, Impact and Building Service Equipment Sound between Adjoining Rooms—Part 1: Frame Document 2017. Available online: https://www.iso.org/standard/67226.html (accessed on 3 July 2020).
138. Speranza, A.; Barbaresi, L.; Morandi, F. Experimental analysis of flanking transmission of different connection systems for CLT panels. In Proceedings of the WCTE 2016—World Conference on Timber Engineering, Vienna, Austria, 22–25 August 2016.
139. Barbaresi, L.; Morandi, F.; Garai, M.; Speranza, A. Experimental measurements of flanking transmission in CLT structures. *Proc. Mtgs. Acoust.* **2016**, *28*, 015015. [CrossRef]
140. Hiramitsu, A.; Otsuru, T.; Tomiku, R.; Harada, K. Flanking floor impact sound insulation in cross laminated timber model building for experiment. *J. Phys. Conf. Ser.* **2018**, *1075*, 012023. [CrossRef]
141. Hiramitsu, A.; Hirota, T.; Miyauchi, J.; Uematsu, T.; Nabeta, Y. Experimental study on floor impact sound insulation and vibration characteristics in cross laminated timber building. In Proceedings of the 46th International Congress and Exposition on Noise Control Engineering INTER-NOISE 2017: Taming Noise and Moving Quiet, Hong Kong, China, 27–30 August 2017.
142. Homb, A. Flanking transmission measurements in a cross laminated timber element building. In Proceedings of the European Conference on Noise Control, Prague, Czech Republic, 10–14 June 2012.
143. Di Bella, A.; Dall'Acqua d'Industria, L.; Valluzzi, M.R.; Pengo, A.; Barbaresi, L.; Di Nocco, F.; Morandi, F. Flanking transmission in CLT buildings: Comparison between vibration reduction index measurements for different mounting conditions. In Proceedings of the 48th International Congress and Exhibition on Noise Control Engineering INTER-NOISE 2019, Madrid, Spain, 16–19 June 2019.
144. Semprini, G.; Barbaresi, L. In situ acoustic performances of wood structural panels and evaluation of flanking transmission. In Proceedings of the 41st International Congress and Exhibition on Noise Control Engineering INTER-NOISE 2012, New York, NY, USA, 19–22 August 2012; Volume 3, pp. 2359–2366.
145. Kouyoumji, J.L.; Fuente, M.; Patissier, R.B. Measurement and prediction of flanking transmissions in wooden CLT constructions using Reverse-SEA. In Proceedings of the 47th International Congress and Exposition on Noise Control Engineering INTER-NOISE 2018: Impact of Noise Control Engineering, Chicago, IL, USA, 26–29 August 2018.
146. Mecking, S.; Scheibengraber, M.; Kruse, T.; Schanda, U.; Wellisch, U. Experimentally based statistical analysis of the vibrational energy of CLT building elements. In Proceedings of the 24th International Congress on Sound and Vibration ICSV 2017, London, UK, 23–27 July 2017.
147. Santoni, A.; Caniato, M.; Gasparella, A.; Fausti, P. Acoustic simulation of timber floors performance using numerical models. In Proceedings of the 26th International Congress on Sound and Vibration, ICSV 2019, Montreal, QC, Canada, 7–11 July 2019.
148. Speranza, A.; Di Nocco, F.; Morandi, F.; Barbaresi, L.; Kumer, N. Direct and flanking transmission in CLT buildings: On site measurements, laboratory measurements and standards. In Proceedings of the WCTE 2018—World Conference on Timber Engineering, Seoul, Korea, 20–24 August 2018.
149. International organization for standardization ISO 16283-1:2014, Acoustics—Field Measurement of Sound Insulation in Buildings and of Building Elements—Part 1: Airborne Sound Insulation 2014. Available online: https://www.iso.org/standard/55997.html (accessed on 3 July 2020).
150. International organization for Standardization ISO 16283-2:2018, Acoustics—Field Measurement of Sound Insulation in Buildings and of Building Elements—Part 2: Impact Sound Insulation 2018. Available online: https://www.iso.org/standard/73929.html (accessed on 3 July 2020).
151. International organization for standardization ISO 16283-3:2016, Acoustics—Field Measurement of Sound Insulation in Buildings and of Building Elements—Part 3: Façade Sound Insulation 2016. Available online: https://www.iso.org/standard/59748.html (accessed on 3 July 2020).
152. Di Bella, A.; Granzotto, N.; Pavarin, C. Comparative Analysis of Thermal and Acoustic Performance of Building Elements. In Proceedings of the Forum Acusticum, Krakow, Poland, 7–12 September 2014.