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A review of the thermal and acoustic properties of materials for timber building construction

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ABSTRACT

Nowadays, there is a vast need to calculate performances of timber constructions. Usually, simulations are implemented to predict buildings elements final performances. Here, the thermal and acoustic parameters necessary to simulate the performances of timber buildings elements are investigated. These data are need as input information for simulations. Anyway, at present literature does not provide a unified view and it lacks an overall vision. Furthermore, in this paper the material properties used as starting points for simulation methods are collected, compared and catalogued in order to produce a complete dataset, useable for acoustic and thermal simulation in timber buildings.

1. Introduction

The environmental advantages of timber buildings and their construction processes are worldwide acknowledged [1–3]. Wood is one of the most eco-friendly raw resource, suitable for construction and characterized by (i) wide availability in nature and (ii) relative ease of handling [4]. It is a cutting-edge material thanks to environmental friendliness and with a broad scope of end-reuses. Moreover, wood can be used in several phases of the construction process [5]. It is bio-degradable [6], sustainable [7] and recyclable [8]. Wooden elements are an ecological resource compared to other similar products based on different materials [9]. These characteristics are the main reasons for its wide diffusion. Indeed, it can be used either directly in the building structure or as an element of other subsystems, such as floors, roofs and walls or façades [10].

The building sector is accountable for 42 % of final energy consumption, 35 % of total green gas (GHG) emissions, 50 % of the extracted materials utilization and 30 % of the water consumption in the European Union [11]. Environmental construction impacts are associated with material renewability and recyclability [12]. In the selection and evaluation process of alternative sustainable materials, several criteria have to be considered including stability, durability, environmental impact, speed of erection, cost, availability and delivery time [13]. Thus, timber buildings imply lower Global Warming Potential and consequential benefits on Life Cycle Assessment [14]. In addition, even if timber structures can respond to all open issues, worldwide the prejudices on Multi-Storey Wooden Buildings (MSWB) are still strong [15], even if in many countries of the Northern Hemisphere, wooden edifices are the most widely acknowledged constructions, due to their economical and practical qualities [16] and contribute to social well-being [17].

At present, a large number of studies has been focused on wood properties for construction purpose and various types of building solutions were engineered [18]. In order to understand the research topics trends, an investigation focused on understanding the most diffused timber construction techniques. In Fig. 1, it is possible to notice the results (using Scopus), presenting the most frequent keywords related to timber buildings used when searching for “timber construction elements”. In the centre, one can find the most used keyword (yellow background), where the other ones are presented far way, featuring a fading background when less used. Among all the results, it is possible to note that the only keywords related to wooden construction elements are “Cross Laminated” (top-left) and “timber frames” (bottom-left). Thus, these timber elements are not only more widely considered, but also used in the market. Furthermore, the “finite element method” is also present, highlighting the existence of numerical simulation related to this topic.

Nevertheless, when undergoing a literature review based on these latter topics, one can find a notable segmentation of research, focusing only on some of the potential timber constructions properties [19]. Special attention was paid to the issue of simulation, which permits to

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avoid construction accidents, limits the uncertainties and addresses issues before the construction site has even started, avoiding constant and time-consuming site visits [20]. This tool is now a common practice among engineers and architects [21].

Computational building performance modelling and simulation is a multidisciplinary, problem-oriented and wide-in-scope procedure [22]. Computational simulation is one of the most powerful analysis and avant-garde development tools for experts in our world [23]. Wang and Zhaib [24] provided an overview of Building Programs Simulation advancements and trends for development and application between 1987 and 2014. They focused on six different topics [25] finding that the trend of interest in coupled simulations has grown in the last years. Indeed, due to some common properties, studies on thermal and acoustic analyses [26,27] and simulations [28] are increasingly diffused, but not always converging. Thus, building simulation is an essential tool for trying out different solutions and interchanging insulation layers before construction. This step is crucial in the decision-making process of thermal and sound insulation, where the layers of the walls have to be carefully chosen not only to optimize the spaces but also to ensure a good quality of both thermal [29] and acoustic [30] comfort for users.

With attention to timber buildings, some authors simulated their efficiency to test the performance and the thermal insulation and comfort [31–35]. Furthermore, the application of building simulation on thermal insulation is widely used also to estimate the long terms effects of future solutions [36] or to test new potential insulations that may be improved. These procedures could be used also to understand the behaviour of a newly marketed product or material and assess its potential for inclusion in the project [37]. Moreover, in the thermal insulation evaluation and simulation, it is important to consider the influence of the materials location [38] to test the design and the used materials correctly.

Another well-suited topic is sound insulation and acoustic performance of walls. In this case, simulations are powerful tools useable to (i) perform and compare different numerical modelling of complex building elements [39], (ii) compare different approaches on evaluation methods [40] and (iii) test new materials and their future application in building sector [41]. As for the thermal, also in acoustic field simulations are used to test the performance of several multilayers options [42] or to perform timber construction in new perspectives [43].

It is also interesting to note that also several funded international projects dealt with these topics. This demonstrates how these issues are of interest to scientists, public and private institutions and practitioners. Accordingly, the European Union encourages sustainable building development [44,45]. As examples, some projects, focused on the thermal and acoustic performances of timber elements, are listed below:

- FormaWood [46] is an Interreg project based in the Wallonia region between France and Belgium which mainly aimed to highlight the difference between the thermal and acoustic standards in the two countries involved and to simulate passive and energy-efficient construction [47];
- NERO project [48] aims to show the cost reduction of nearly zero-energy wooden buildings through demonstration projects that include both residential and non-residential individual buildings with a focus on the LCA;
- Build in wood project [49] main aim is focused on thermal efficiency perspective and it develops a structural and customizable construction system platform and guidelines for incorporating ICT tools in the design process.

Simulation approaches need robust and reliable inputs [50], focusing on materials characterization [51]. Attention to this issue is crucial not also in structural [52], but also in thermal [53] and acoustic [54] applications. Timber elements thermal and acoustic simulations are present in literature, but not always focused on the same issues. They are often based on building components related to envelope, but a clear understanding of reliability and robustness of selected used data is still unclear.

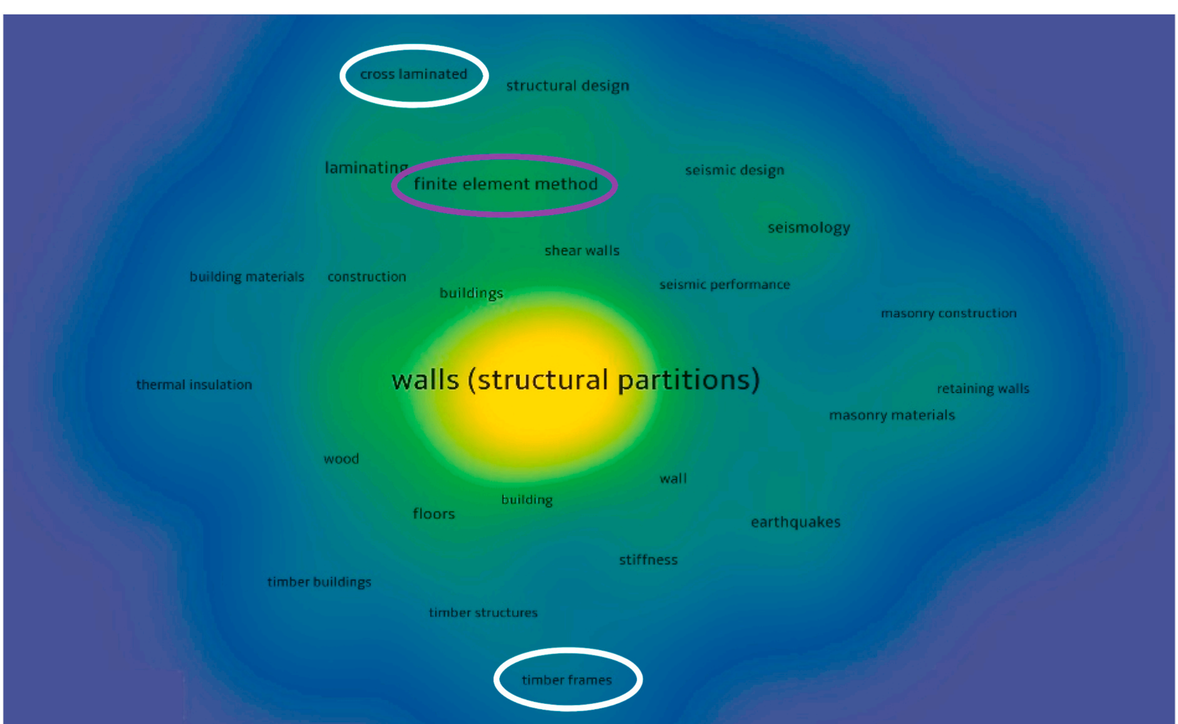

Fig. 1. Analysis of most used keywords in research papers dealing with timber construction elements. “Cross laminated” and “timber frame” are within white circles, whether “finite element method” is the purple one to highlight their positions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Conversely, numerical simulations focused on seismic issues present high reliability. The reliability of the seismic simulations is well known [55–60] and the results are based on parameters that have been validated by the technical and scientific community in years [61–64]. The same conclusion can be applied to fire-resistance simulations [65–69].

In this perspective, the aims of this paper are to:

- determine if there is a clear link between numerical simulation and materials characterization or, conversely, these two procedures are managed and developed separately in scientific papers;
- investigate if there is a variability of materials parameters, basing on the available data contained in past research;
- provide an overview of the main physical parameters used in numerical thermal and acoustic insulation simulations of timber elements;
- draw a critical analysis related to parameters detected by discussing the reliability of the data, the range of variability and the role in the simulation procedure.

Hence, it will be possible to understand the availability of these parameters and their variability in literature. The discussed issues will highlight the concentration of information availability. To this aim, the adopted procedure used to gain, collect and study all the physical parameters is shown. The needed elements for the simulation and computational phase of timber building elements are also depicted. A brief introduction of the more diffused computational methodologies from the thermal and acoustic insulation point of view is then provided, followed by an in-depth analysis of the research outputs.

2. Bibliometric research

2.1. Bibliometric networks

This section aims to collect papers and studies focused on the characterization of materials for future simulation phases and to understand if there is a strong connection between materials characterization and simulation.

Thus, VosViewer was used to build graphic schemes, including connections between keywords. The bubbles dimension indicates the most used keywords, the width of the lines expresses the number of co-citation and connection of a selected keyword. The topics are organized by cluster, each primary colour, based on the RGB model, identifies a specific cluster, identified by the software algorithm [70]. The investigation is repeated for four analyses, one for each typology of construction technique individuated in Fig. 1 (Cross Laminated Timber, CLT, or Timber Frame, TF) and one for each main topic (acoustic and thermal insulation).

2.1.1. Timber frame

In Fig. 2 the first investigation results are reported for the keywords “Timber frame thermal”. It is highlighted that mineral wool is the mostly cited insulation material. This could be justified by the great availability on the market and the wide use of this material from 2010 onwards for thermal, acoustic and mostly for fire resistance purposes [71]. When

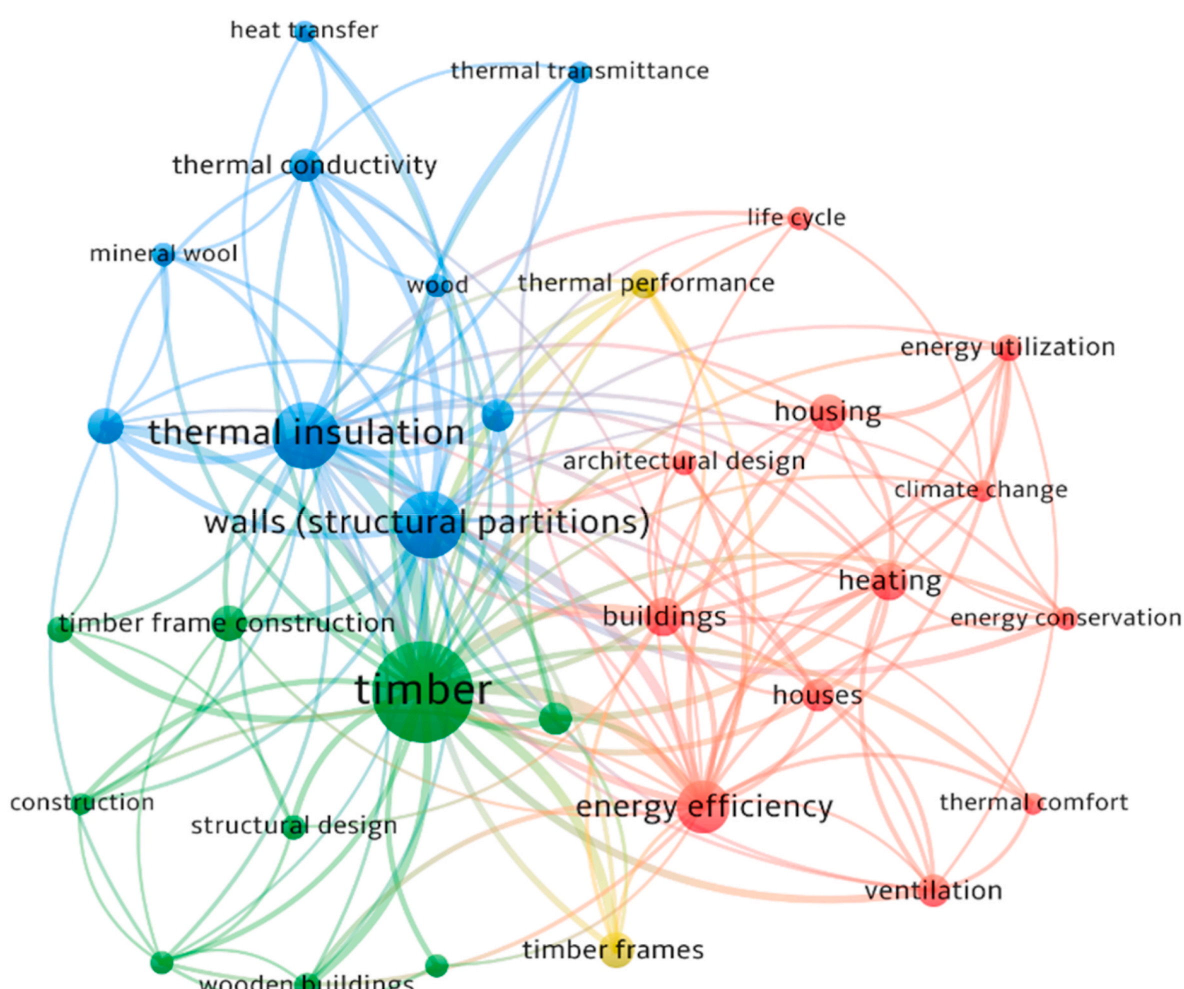

Fig. 2. Analysis of repetition of keywords and overlay of the association strengths of “Timber frame thermal”.

focusing on thermal properties, it appears that the analyses related to the thermal conductivity are the most commonly characterized. Nevertheless, the dimensions of the thermal conductivity bubble highlight that a relatively small number of works faces this topic. Finally, almost a third of the papers focuses on energy efficiency related to sustainability and environmental issues (red bubbles). A further one-third deals with building techniques (green bubbles) and only the remaining part focuses on the thermal issues.

On the other hand, when we investigate the acoustic topic, things change. Results are depicted in Fig. 3 for the keywords "Timber frame sound". It is possible to note that sporadically "acoustic" and "sound propagation" are related to "Finite Element Method". Moreover, focusing on green bubbles, it is possible to see that among the keywords used, there is also a connection with "thermal insulation". This means that these two topics sometimes are treated in the same papers, highlighting their interconnection related to timber frame construction technique. Another important issue is related to materials characterization: "acoustic variables control" appears as a frequently investigated topic mostly cross-linked with "timber", "architectural acoustics", "acoustic noise" and "laboratory measurements". This implies that materials take part usually when facing general topics, more rarely when facing sound insulation, which is more related to "acoustic waves". However, this latter topic intrinsically considers materials properties.

2.1.2. Cross laminated timber

In Fig. 4, the connection web of the keywords related to the "Cross Laminated Timber thermal" is shown. The most diffused keywords are related to CLT referring to the composition of the structural element, (e.g. "laminating", "cross-laminated", "CLT"), followed by the ones referred to fire resistance capacities and fire protection. As for Timber Frame, here again, the only thermo-physics characterization found among the keywords seems to be the thermal conductivity (blue), which also is included in "thermodynamic properties". Anyway, these two are not related to "thermal insulation", "energy efficiency", "thermal performances", etc. (red bubbles), meaning that studies focused on thermal characterization are separated from the ones managing the overall building thermal comfort and efficiency. This demonstrates how the studies on these topics are fragmented.

Fig. 5 shows the connection web related to the most used keywords in the acoustic field (Cross Laminated Timber sound). In the acoustic analysis, the most used are "Cross Laminated Timber", "laminating", "floors", "sound insulation" and then "acoustic variables control". "Sound insulating materials" is only related to "floors" as structure identification [72], even if "wall" does not appear. Other keywords like "acoustic wave transmission", "acoustic wave propagation", "sound transmission" intrinsically contain materials properties. Remarkably, no mention of numerical simulation is clearly presented, even if "acoustic variable control" could include this item.

2.2. Research databases

The results of the previous sections are used here as inputs for the

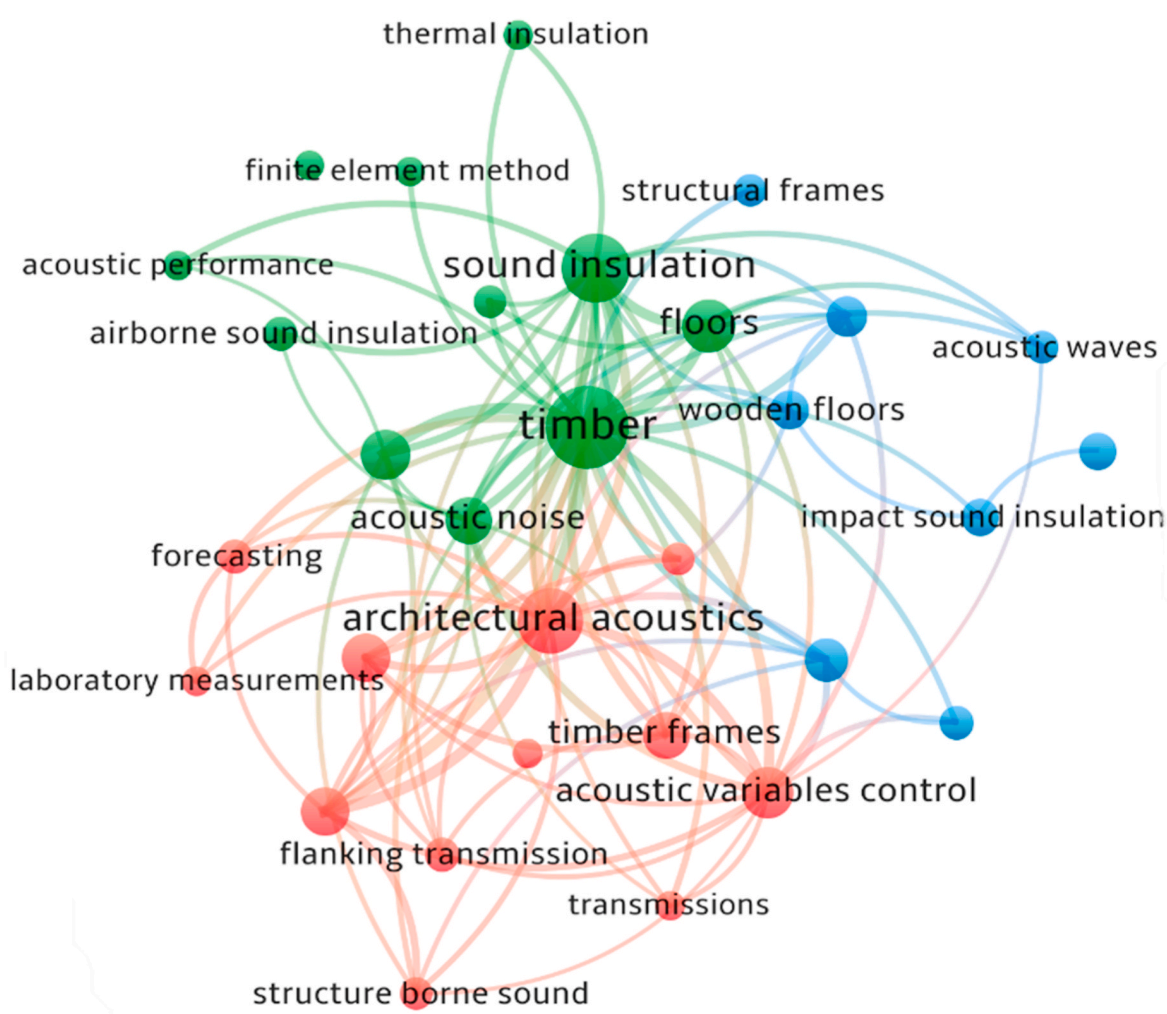

Fig. 3. Analysis of repetition of keywords and overlay of the association strengths of "Timber frame sound".

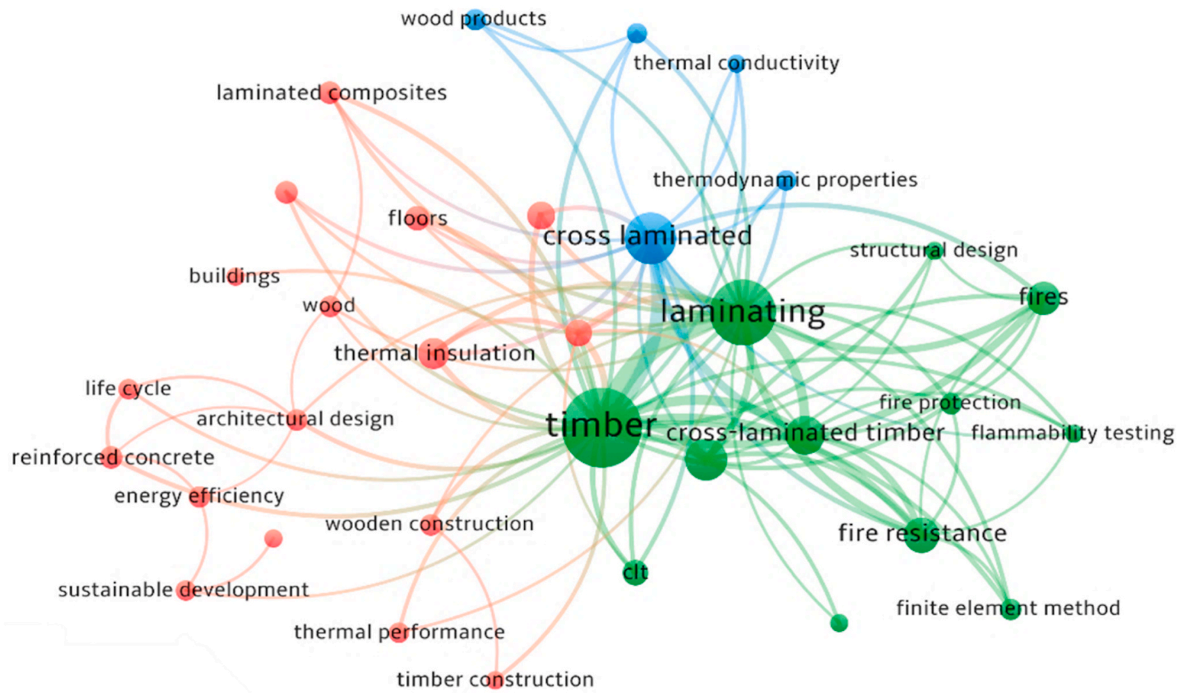

Fig. 4. Analysis of repetition of keywords and overlay of the association strengths of "Cross Laminated Timber thermal".

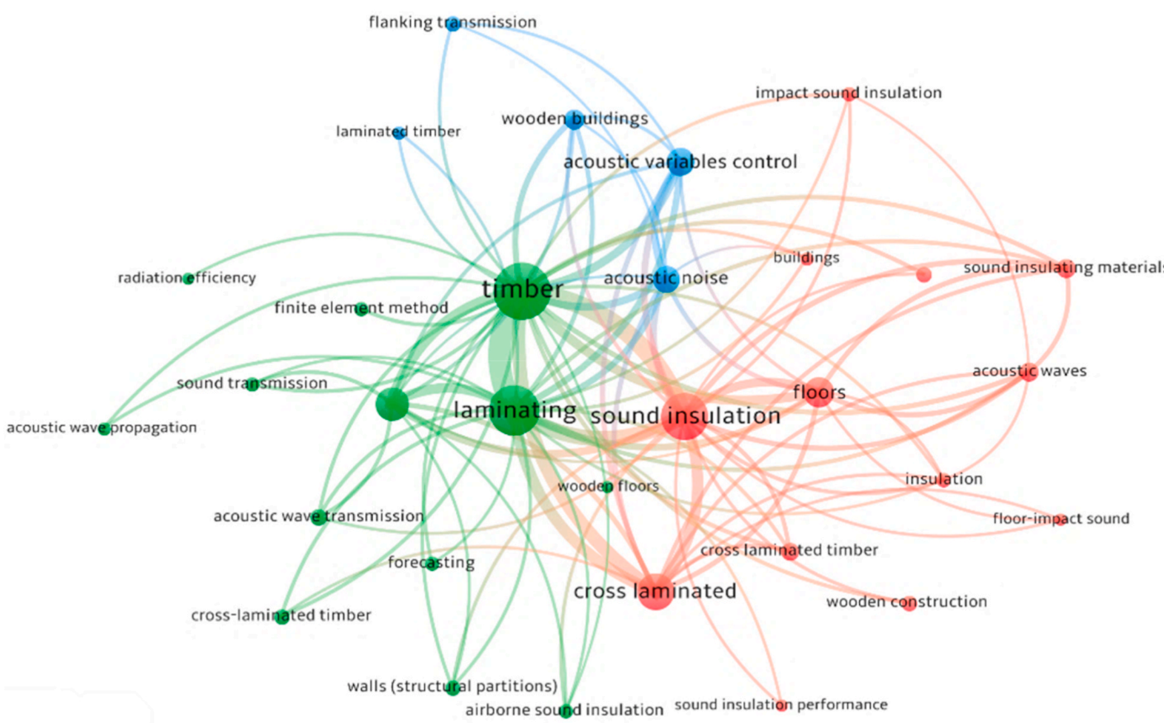

Fig. 5. Analysis of repetition of keywords and overlay of the association strengths of "Cross Laminated Timber sound".

research databases definition, namely Google Scholar and Scopus. Thus, the first keywords used are related to the construction elements most found in literature ("Timber Frame" or "Cross Laminated Timber") in combination with different physical characterization requirements, like "thermal performance/simulation", "sound performance/simulation", "noise performance/simulation" and also with the keyword "insulation" (i.e. "sound insulation performance"). The output of this phase is intended to highlight the differences in the number of papers and proceedings available in the two web search engines. The collection process of the different steps for the timber frame is depicted in Fig. 6. In this, it is possible to see how in Scholar only the 35,8 % describes timber performance, while the 7,4 % approaches to the simulation. Then, in Scopus higher percentages meet the keywords selected: the 68,3 % of papers describes the performance of TF, while the 8,5 % depicts the simulation approach. Then, when focusing on the thermal and acoustic topics, it is possible to see how for the adoption of "performance" and

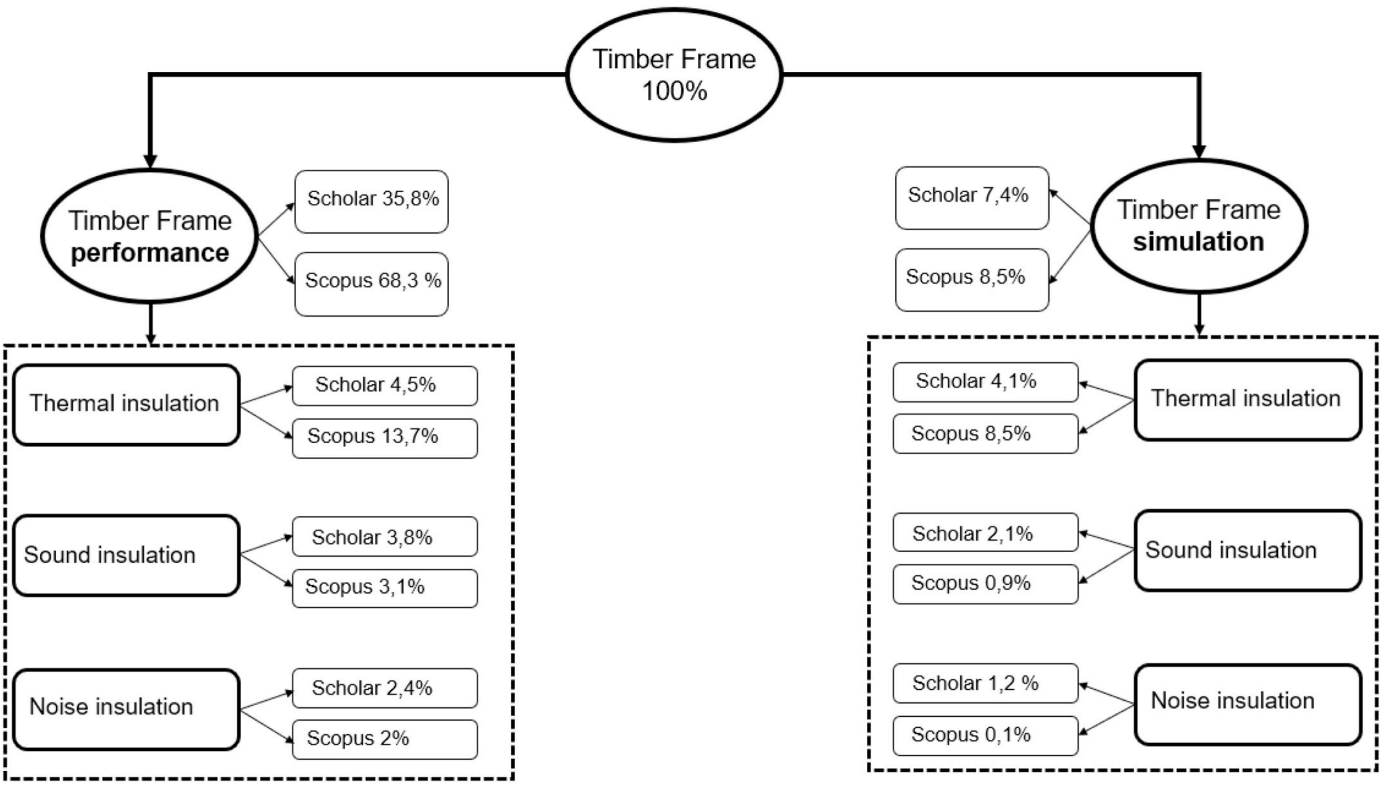

Fig. 6. Collection procedure's scheme for the "Timber Frame" keyword both for the "performance" side (left) and for the "simulation" side (right).

"simulation" keywords, the thermal topic is more treated in Scopus, conversely the acoustic topic (sound and noise) is slightly more treated in Scholar.

Fig. 7 presents the collection process related to CLT with the same process and same behaviour found for the Timber Frame. Indeed, also in this case the Scopus rates are significantly higher. In Scholar only the 22,3 % describes its performance, while the 5,8 % approaches to the simulation. Then, in Scopus the 35,2 % of papers reports the

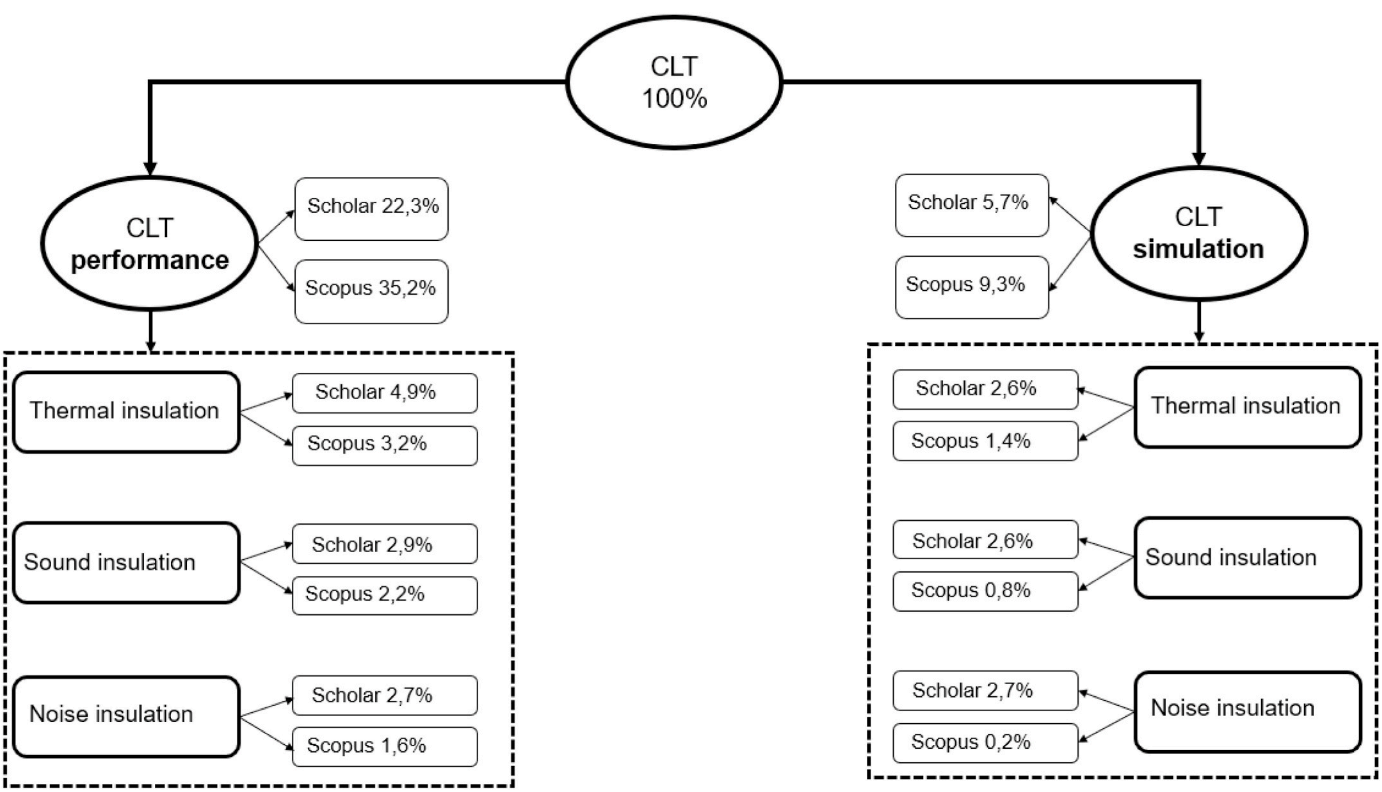

Fig. 7. Collection procedure's scheme for the Cross Laminated Timber both for the "performance" side (left) and for the "simulation" side (right).

performance of CLT, while the 9,3 % describe the simulation approach. Then, when focusing on the thermal and acoustic topics, it is possible to see how, both the thermal topic and the acoustic topics (sound and noise) are more present in Scholar, highlighting how the CLT characterization in these two fields is more diffused in the Scholar database with significantly higher percentages than in Scopus.

Furthermore, the papers were divided into chronological order, based on the publication year using both Scopus and Google Scholar databases. The chronological division is based on the decade of publishing. This procedure shows if these issues are of some interest in years and if the two databases agree.

The percentage ratings and the information acquired by the research will be depicted firstly for Timber frame and finally for Cross Laminated Timber. The results presentation will be focused firstly on thermal then on acoustic insulation. In the end, these two aspects will be merged for a complete database.

2.2.1. *Timber frame*

The chronological division is based on the decade of publishing. The results are depicted, for the Google Scholar, in Fig. 8 for the thermal and Fig. 10 for the acoustic approach. The Scopus sorting is shown in Fig. 9 for the thermal and Fig. 11 for the acoustic issue. Papers before the decade 1970–1980 were not included.

It is evident how the papers included in Google Scholar dealing with the thermal insulation are widely available. Particularly, it can be observed in both cases that an increasing trend of publications is present related to the two last decades, highlighting that there is a clear technical improvement of technologies, software and simulation's tools (Fig. 8).

From Fig. 9, it can be seen how the trends founded in Scopus are similar to the Google Scholars ones. Still, the numbers of papers available are noteworthy lower using both the keyword “performance” and “simulation”.

Fig. 10 shows the Google Scholar outcomes from the acoustic point of view. Firstly, it is remarkable to note that in the last two decades the topics related to the acoustic of the timber frame have significantly increased. Accordingly, these trends show a constant increase in the number of papers published and thus an interest in the subject.

As in the case of the thermal outcome from Scopus, as shown in Fig. 11, a lower amount of research is available in this online database. Anyway, the positive time trend is confirmed.

2.2.2. *Cross laminated timber*

The results are depicted for the Google Scholar outputs in Fig. 12 both for the thermal and the acoustic topics. The Scopus outputs are illustrated in Fig. 13. Papers before 1980 were not included.

How can be seen in Fig. 12, the interest in Cross Laminated Timber has clearly grown up in this last decade. Then, paying attention to the distinction between the two outputs related to the two keywords, it is noticeable that papers related to “simulation” are higher than the outcome related to “performance”. This could be related to the increasing of new simulation tools developed from 2000. Another interesting result is connected to the acoustic field. Indeed, the papers featuring “noise” as keyword in combination with “performance” are more available than the papers coming from the same research field but featuring the keyword “simulation”.

The Scopus results, depicted in Fig. 13, always show that the new interest in the topic is developed only in the last decade. Thus, all the papers before 2010 rarely deal with thermal and acoustic issues.

Therefore, it can be deduced that the two databases show large differences in the availability of academic articles in the case of CLT. Even if the results for individual searches contrast with each other in terms of the used keywords, it is still evident that Google Scholar shows more results for academic searches. This means that, in this field, researchers present their results mostly using conference proceedings, reports, projects deliverables, which are not often indexed in Scopus.

2.3. *Numerical approaches analysis*

Here, an investigation was conducted, in order to retrieve the most used numerical models in the fields of acoustic and thermal insulation related to timber performances. In Fig. 14, it is highlighted that the most diffused acoustic approaches are the Finite Element Method (top - centre and bottom - left), followed by the Transfer Matrix Method (down-right). For the thermal insulation, the Finite Elements Method appears to be always preferred (top – right). Conversely, neither of these appears to mention the Statistical Energy Analysis (SEA) or Boundary Element Method. However, there is evidence that in acoustics for the high frequencies SEA is often used [73]. Thus, it will be comprised in this research.

Despite this, in both acoustic and thermal insulation fields, as remarked by Fig. 14, the most used method for the thermal analysis is the Finite Elements Method [74–76], as well as for the acoustic insulation, [77–79]. However, if from one side in the thermal applications FEM requires only two parameters (c_p and λ) of inputs coupled with density and short computation times [80], on the other in acoustics a higher number of required input parameters are needed [81] and at least six elements per wavelength have to be considered for the mesh creation [82], implying longer computation times. For these reasons, despite the physical accuracy of FEM, often it is computationally expensive [83]. Conversely, Transfer Matrix Method (TMM) provides a fast and practical solution and, if compared to the FEM, the size of the system (the matrix) is smaller [84]. The TMM could be used in the determination both of thermal [85] and acoustic [86] performances. Recently, some studies approached the heat transfer problem using the Transfer Matrix Method [87], but at present, this methodology seems to be most appreciated and used in acoustics. In this latest field, TMM is applied to increase the simulation accuracy also in the low-frequency range using hybrid approaches that have been developed combing finite element method (FEM) or wave-based (WB) approaches with TMM model [86]. In the acoustic characterization, there are several models used for the description of sound wave propagation, which can be chosen basing on the morphology of the materials. For instance, in the case of woven fabrics it is possible to adopt the perfect plate [88] or the Attenborough

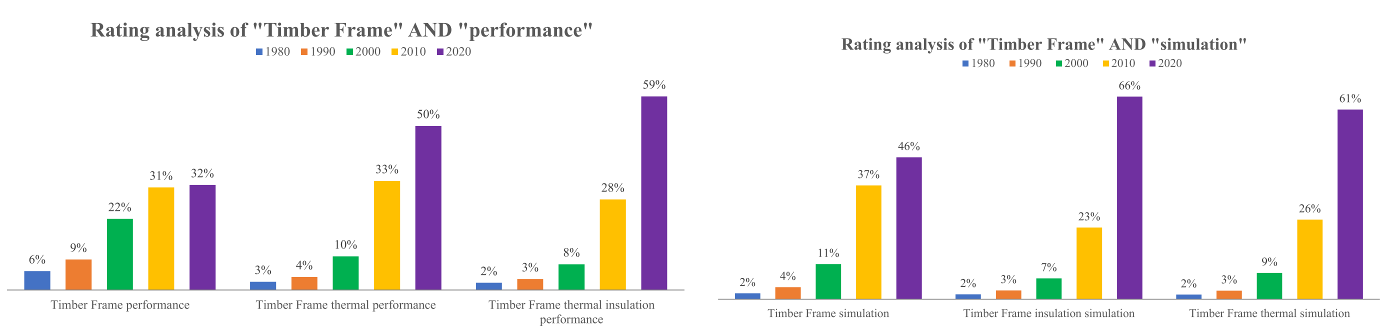

Fig. 8. Rating analysis of Timber Frame thermal performance/simulation/characterization from Google Scholar.

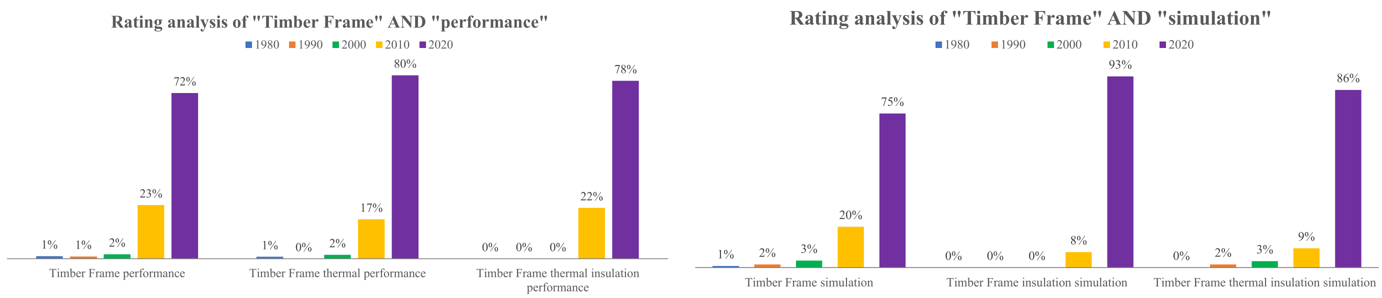

Fig. 9. Rating analysis of Timber Frame thermal performance/simulation/characterization from Scopus.

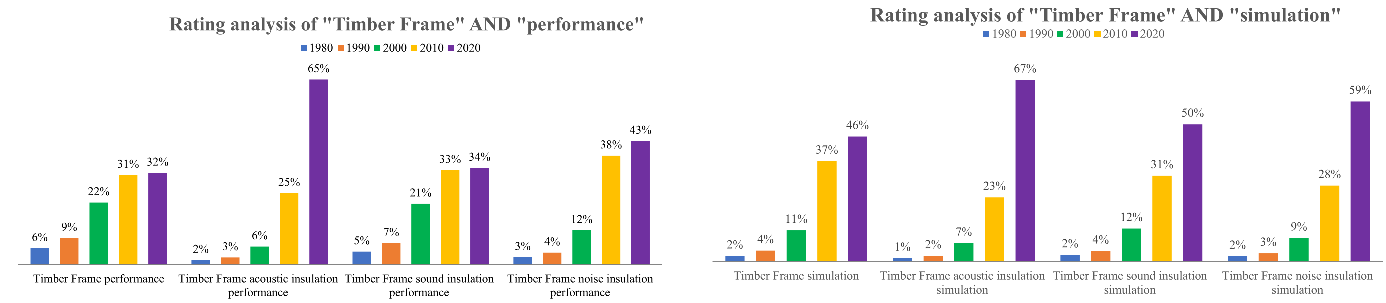

Fig. 10. Rating analysis of Timber Frame acoustic performance/simulation characterization from Google Scholar.

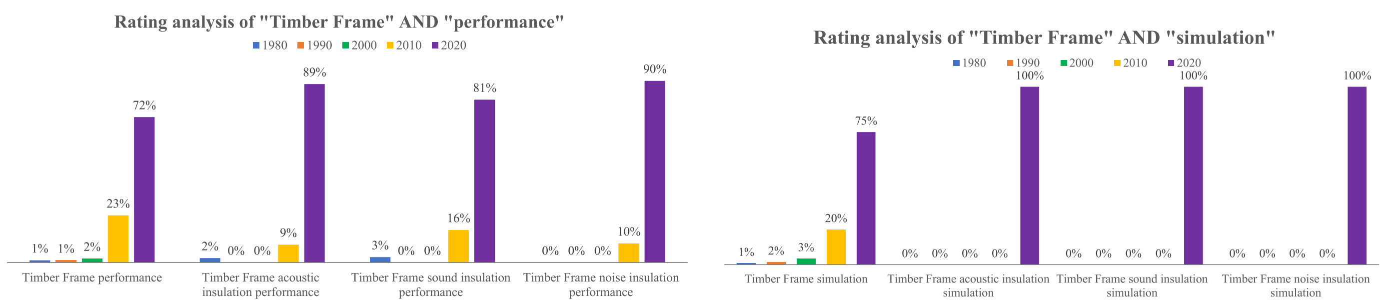

Fig. 11. Rating analysis of Timber Frame acoustic performances characterization from Scopus.

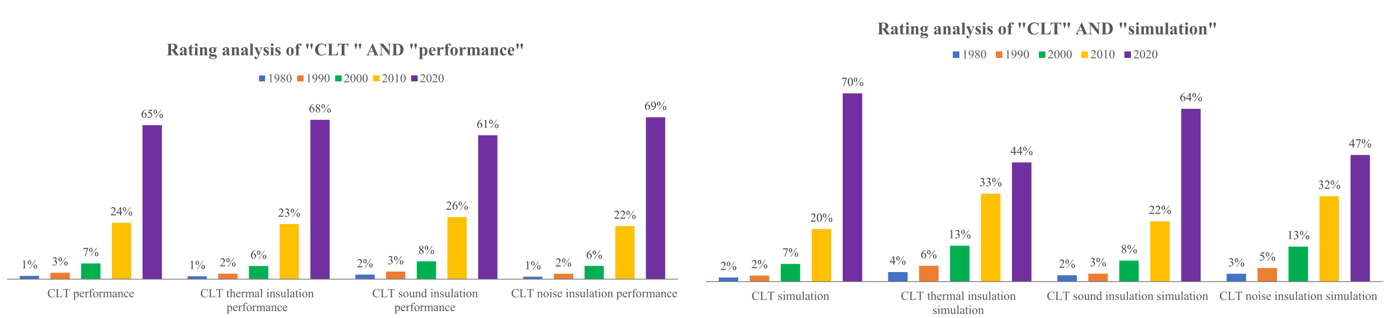

Fig. 12. Rating analysis of Cross Laminated Timber performance/simulation characterization from Google Scholar.

model for fibrous materials, cellular foams or granular materials [89] or Miki model for fibrous materials and felt [90]. Anyway, recently, the Johnson-Champoux-Allard using Biot's theory is the widely used procedure to describe the visco-inertial dissipative effects inside the porous media [91–93]. Accordingly, it was demonstrated that highlight how the Transfer Matrix Method is more and more a diffused acoustic approach to sound transmission [94].

Mechanical parameters	
density	ρ
Young's modulus	E
Poisson's ratio	ν
Thermal parameters	
coefficient of emissivity	ε
thermal conductivity	λ
specific heat at constant pressure	c_p

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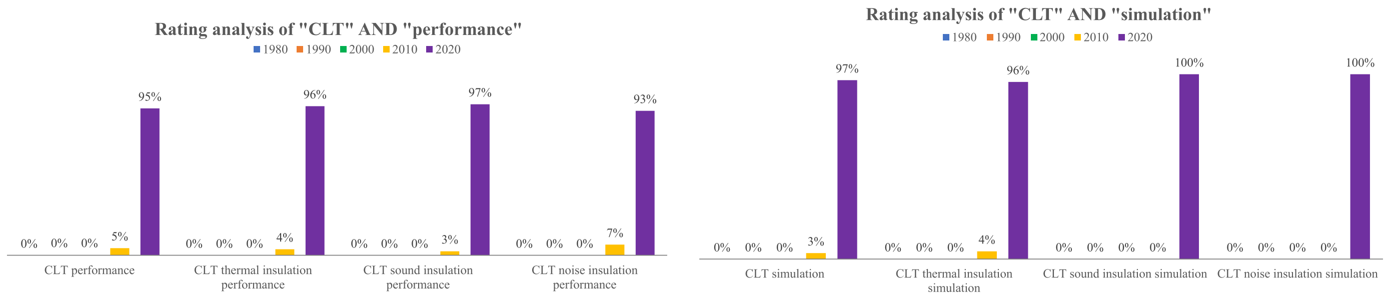

Fig. 13. Rating analysis of Cross Laminated Timber performances characterization from Scopus.

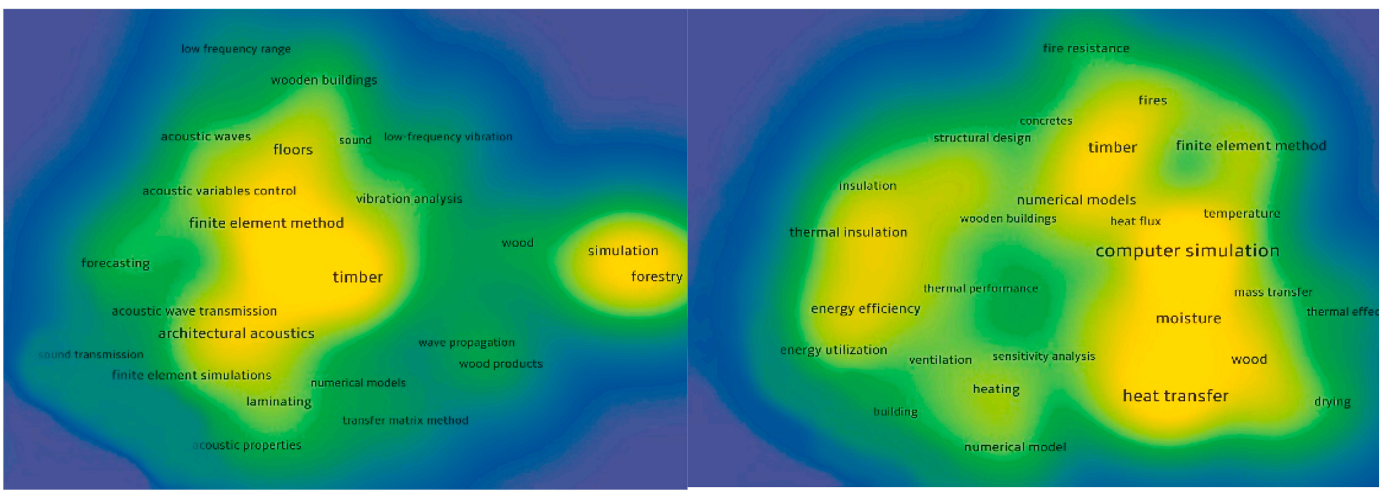

Fig. 14. Analysis of most used keywords in research papers for timber construction both for acoustic (left) and thermal insulation (right).

(*continued*)

Mechanical parameters	
Acoustic parameters	
flow resistivity	σ
porosity	φ
tortuosity	α_∞,
viscous length	Λ
thermal length	Λ'

3. Selection of inherent papers

The research methodology is structured using inclusion and exclusion criteria and requirements. Firstly, the construction techniques and the structural elements are selected, in order to better focus on dedicated timber components production methodologies. To this aim, after an in-depth literature study, it is determined that the most used ones [95] are Timber Frame (TF) and Cross Laminated Timber (CLT). Accordingly, these two methods are frequently presented, discussed and compared in literature both from thermal [96] and acoustic [97] point of views. Another inclusion criterion is to consider all the parameters needed to the simulation process.

In order to better focus on the needed input, the most used parameters on thermal and acoustic insulation simulation are introduced in the following. Accordingly, FEM, TMM and SEA often require the same input factors.

The thermal insulation model is mostly represented by the transmittance parameter, which is represented in eq. (1):

$$U = \frac{1}{\frac{1}{h_{cv,i}+h_{r,i}} + \frac{1}{h_{cv,e}+h_{r,e}} + \frac{t}{\lambda}} \tag{1}$$

where U is the thermal transmittance, $h_{cv,i}$ is the internal convective heat transfer coefficient, $h_{r,i}$ is the internal radiative heat transfer coefficient, $h_{cv,e}$ is the external convective heat transfer coefficient, $h_{r,e}$ is the external radiative heat transfer coefficient, λ is the material thermal conductivity and t is the thickness of the material. In case of more than one insulating layer, t/λ ratio has to be summed considering all the materials thicknesses and thermal conductivities.

The internal and external convective heat transfer coefficient depend on air movements around the vertical or horizontal walls. Usually, fix values are assumed for these parameters [98]. On the other hand, radiative heat transfer coefficient is proportional to the emissivity of the material surfaces as expressed in eq. (2)

$$h_r = 4\,\varepsilon\,\sigma\,T_m^3 \tag{2}$$

where ε is the surface hemispherical emissivity, σ is the Stefan-Boltzmann coefficient and T_m is the mean thermodynamic temperature between the wall surface and its surroundings.

When analysing an insulating material or layer, heat transfer is mostly regulated by conductivity. Fourier's Law (eq.(3) (3)) describes this phenomenon:

$$q = -\left(\lambda_{cond} + \lambda_{conv} + \lambda_{rad}\right) \nabla T \tag{3}$$

where λ_{cond} is the thermal conductivity caused by the conduction, λ_{conv} is the thermal conductivity caused by the convection and λ_{rad} is the thermal conductivity caused by the radiation, q is conduction heat flux and ∇T is the gradient of temperature. In a porous or fibrous material, the sum of these three conduction is named equivalent conduction (λ_e).

When a material is considered in a dry condition, the equivalent thermal conductivity can be described by a general equation (Eq. (4)):

$$\lambda_e = f(\varphi, \lambda_g, \lambda_f) \tag{4}$$

where λ_e is the material equivalent thermal conductivity, φ is the porosity, λ_g is the contained stagnant gas thermal conductivity, λ_f is the thermal conductivity of the pore solid phase. Actually, in buildings there will not be any gas motion inside thermal insulating layers. Thus, the stagnant air hypothesis is always considered valid. For this reason, the thermal conductivity value will be only described by a variation of porosity or tortuosity, using $\lambda_g = 0.02$ W/mK as a fixed value [99].

For the dynamic thermal performance of components, the periodic transmittance is considered. A Transfer Matrix has to be implemented to calculate this parameter, considering its main parameter, the periodic penetration depth δ, expressed by Eq. (5):

$$\delta = \sqrt{\frac{\lambda T}{\pi \rho c}} \tag{5}$$

where T is the periodic variation, ρ is the density of the material and c is the specific heat capacity.

From the acoustic insulation point of view, the issue has to be divided into two topics:

- airborne transmission,
- structure borne transmission.

For the first case, for a frequency domain investigation, the well-established Johnson et al. [92] approach, modified by Champoux and Allard [93], is most of the time used to model or minimize the five factors influencing this phenomenon, namely:

- flow resistivity σ [N s m^{-4}],
- porosity φ [−],
- tortuosity α∞ [−],
- viscous characteristic length Λ [μm]
- thermal characteristic length Λ' [μm]

For the solid-borne sound propagation, the Hook's law relates a proportional dependence between stresses and strains. For isotropic elastic solids, it can be written in matrix form as (Eq. (6)):

$$\sigma = C\varepsilon \tag{6}$$

where σ is the stress tensor applied to the elastic isotropic mean and ε is the obtained strain tensor. C is defined in Eq. (7) [100]:

$$C = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix} \tag{7}$$

where E is the Young's Modulus and ν is the Poisson's ratio.

For the viscous-elastic case, a different elastic modulus value per frequency is assumed as well as for the Poisson's ratio. At the same time, for the damping effect, a complex E number is considered.

Thus, the complete list of necessary parameters for thermal [101,102] and acoustic [103,104], insulation numerical simulations is resumed in Table 1.

Thus, the presence of listed parameters in Table 1 provides an additional inclusion criterion for the selection of papers.

In order to select the inherent works, the title, the results and the data mentioned have been screened and sorted. After this process, the literature has been catalogued. Consequently, only those papers have been considered for this literature analysis.

Table 1
List of the material properties necessary for the thermal and acoustic insulation simulations.

Mechanical parameters		
density	P	[kg/m3]
Young's modulus	E	[MPa]
Poisson's ratio	ν	[−]
Thermal parameters		
coefficient of emissivity	ε	[−]
thermal conductivity	λ	[W/(m K)]
specific heat at constant pressure	c_p	[J/(kg K)]
Acoustic parameters		
flow resistivity	σ	[(kPa s)/m2]
porosity	φ	[%]
tortuosity	α_∞,	[−]
viscous length	Λ	[μm]
thermal length	Λ'	[μm]

Conversely, excluding criteria were adopted, to better focus on the topics of this work. The excluding criteria are:

- the characterization of materials used in non-wooden building elements;
- the physical characterization of a material not belonging to neither of the two construction techniques above presented;
- the characterization of a physical parameter not included in the list defined in the previous section.

No excluding criteria have been adopted related to the year of publishing.

From the method depicted below, 42 papers were included to be discussed and compared.

4. Results and discussion

4.1. Georeferenced and topics distribution

Basing on the approach depicted in Section 3, only a limited number of papers were included. Among these, three main topics were found: mechanical, thermal and acoustic characterization of the physical parameters. The topics distribution percentage of the sample is shown in Fig. 15. Here, it is possible to understand that the mechanical and the thermal approach are the most diffused, while the acoustic characterization is the less discussed.

Geographical origin distribution is reported in Fig. 16, where on the left side, the continental division of the papers and research are depicted, while on the right side, the country sorting is displayed. It can be noticed that the higher percentage comes from Europe, followed by North America, Asia and finally South America. From country sorting it can be seen that the most contributing countries are Italy (14 %), China (10 %) and both Romania and the United States (7 %).

4.2. Discussion of the literature results

The collection is related to the parameters listed in Table 1. In order to better understand outcomes, this section will be divided in different units. The analysis was performed investigating the single layer composing timber frame elements, while Cross Laminated Timber was treated as a whole, as it is not a multi-layered element.

For each analysed material, a summary of the data found is depicted in a dedicated table by providing, if specified, the thickness of the material, the source providing the data and how the source determined the information depicted. For the wooden materials, when possible, the type

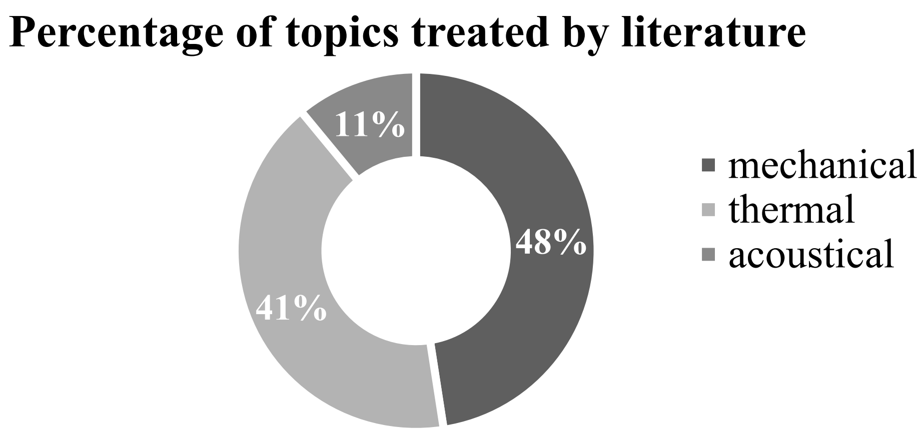

Fig. 15. Topics treated in the sample of papers collected.

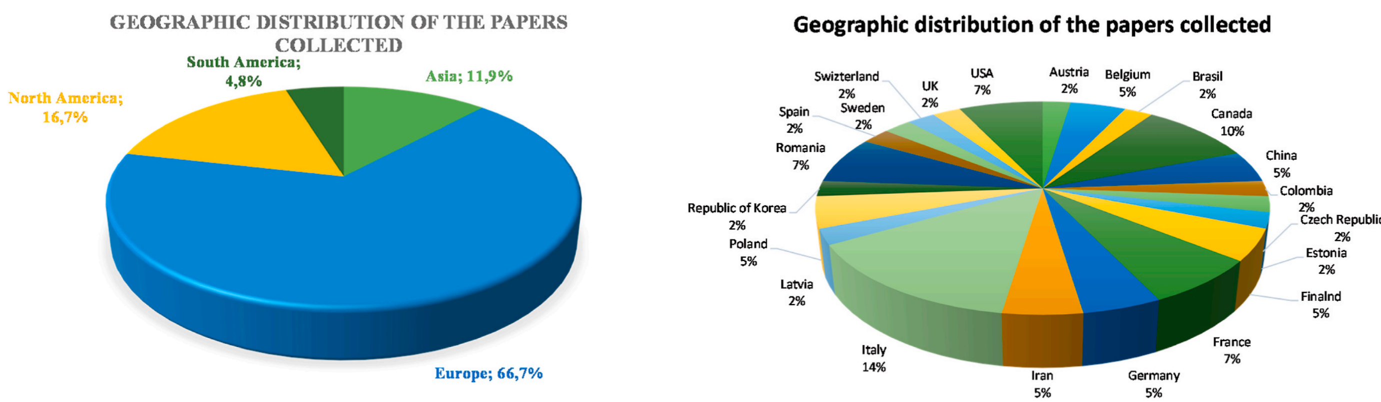

Fig. 16. Geographic distribution of the papers collected - continental division (left) and nationality division (right).

of wood was detailed.

4.2.1. *Timber frame*

The analysis here proposed will be discussed in relation to mechanical, thermal and acoustic properties of each Timber Frame element.

4.2.1.1. Timber stud. A synthetic summary about the timber stud physical characterization can be seen in Table 2. Many of the identified studies characterized timber stud mechanically with wide ranges of

Table 2
Summary of the parameters characterizing the Timber Stud.

source	source of data	type of wood/stud	Thickness	Mechanical parameters		Thermal parameters		
			d [mm]	ρ [kg/m^3]	E [MPa]	ε [−]	λ [W/(m K)]	c_p [J/(kg K)]
[105]	reports collected by the Authors	white oak	–		12270			
		red maple	–		11310			
		Douglas fir	–		13440			
		western white pine	–		10070			
		longleaf pine	–		13650			
		Laminated veneer lumber	–		8960–19240			
[106].	measured values	Pine wood	–	340	10000			
[107]	Delphin database + measured values	Pine stud	50	532			0.11–0.13	
[108]	ISO 10456	Pine wood					0.16	
[109]	WUFI database	-.	45	455			0.09	1500
[110]	ISO 10211	Spruce-pine-fir stud	–	455			0.1	1400
[111]	not specifies	–	15 28	450			0.12	1500
[112]	not specified	Oak wood	–	700			0.21	2090
		Spruce wood	–	500–600			0.14	
		Pine wood	–	500–600			0.14	
[113]	reports collected by the Authors	–	–	400–700			0.08–0.15	
[114]	not specified	–	–			0.85		
[115]	not specified	–	–			0.82		
[116]	ONORNM EN 12524 + ONORM B 8110-7	–	–	500			0.13	

variability in density and Young's Module. Conversely, no study, among those identified, dwells on the characterization of the Poisson's ratio. As far as the thermal characterization of the timber stud is concerned, there are numerous data concerning the thermal conductivity and the specific heat at constant pressure, but only two data concerning the emissivity. No study among those identified qualifies this material acoustically.

4.2.1.2. Oriented strand board (OSB). A summary of the values regarding the OSB physical characterization is depicted in Table 3. As found for the timber stud, also the OSB is the focus of numerous studies that provided values on density and thermal conductivity. Unlike the previous material, however, only a few provided data of Young's modulus and specific heat at constant pressure. Then, in this case, only two studies provided the Poisson's ratio, while from a thermal approach, data characterizing emissivity are missing. In this case too, no studies were found that offer an acoustic characterization of the Oriented Strand Board.

4.2.1.3. Insulation layer: rock wool. A recap of all the data for this insulation material is depicted in the following Table 4. In literature, rock wool is characterized both from a thermal and acoustic perspective. For this reason, two different tables are used to include studies characterizing thermal (Table 4), acoustic and mechanical aspects (Table 5).

It can be highlighted that a great bunch of data regarding the density of this material is available, whereas Poisson's ratio and Young's modulus are only provided by a study concerning acoustics. Then, focusing on the thermal characterization of the material (Table 4), there are many data provided for thermal conductivity, some for specific heat at constant pressure, but none for emissivity.

When talking about acoustics (Table 5), there is a lot of data regarding airflow resistivity, some values for porosity and tortuosity, but few results for thermal length and viscous length.

4.2.1.4. Insulation layer: glass wool. Glass wool is characterized in literature both from the acoustic and thermal point of view. For this reason, in Table 6 the thermal characterization and in Table 7 the acoustic one are reported.

It is clear that the thermal and mechanical studies lack in the investigation of Young's modulus and Poisson's ratio. On the other hand, the collected values provide several results for density and thermal conductivity but provide few results for specific heat at constant pressure and emissivity.

Table 4
Summary of the mechanical and thermal parameters characterizing the rock wool.

source	source of data	Thickness	Mechanical parameters	Thermal parameters	
		d [mm]	ρ [kg/m^3]	λ [W/(m K)]	c_p [J/(kg K)]
[107]	Delphin database + measured values	50		0.037	
[109]	WUFI database	160	60	0.04	850
[110]	ISO 10211	184	20	0.034	850
[112]	not specified	–	80–180	0.033–0.039	840
[114]	not specified	–	–	0.02–0.04	
[116]	ONORNM EN 12524 + ONORM B 8110-7	–	15	0.040	
	ONORNM EN 12524 + ONORM B 8110-7	–	30	0.042	
	reports collected by the Authors	–	20–150	0.035–0.05	840
[118]	not specified	–	–	0.041	
[124]	simulation software	–	23–45	0.033–0.040	
[126]	not specified	50	70		
[127]	not specified	–	70	0.035	
[128]	product supplier	–	32	0.037	
[129]	reports collected by the Authors	–	50–60	0.04	
[130]	reports collected by the Authors	–	50–60	0.04	
[131]	measured values	76	96	0.032	850
[132]	not specified	–	20	0.032–0.044	1030
[133]	not specified	–	–	0.033–0.040	
[134]	reports collected by the Authors	40	70		

Table 3
Summary of the parameters characterizing the OSB.

source	source of data	Thickness	Mechanical parameters			Thermal parameters	
		d [mm]	ρ [kg/m^3]	E [MPa]	ν [–]	λ [W/(m K)]	c_p [J/(kg K)]
[105]	reports collected by the Authors	–		4410–6280			
[106]	measured values	–	550				
[107]	Delphin database + measured values	50	646			0.11–0.13	
[108]	ISO 10456	–				0.13	
[109]	WUFI database	18	595			0.11	1700
[110]	ISO 10211	12	615			0.13	1400
[112]	not specified	–					
[117]	measured values	14 22	606	3200	0.3		
[118]	product supplier	–	600–620				
[119]	product supplier	8 12 25	520				
[120]	measured values	14 22	700	3800	0.2		
[121]	measured values	–	680			0.089	
[122]	measured values	18	662			0.0959	
[123]	product supplier	12	600			0.125	
[124]	not specified	9				0.13	
[125]	measured values	–					1552

Table 5
Summary of the mechanical and acoustic parameters characterizing the rock wool.

source	source of data	Thickness	Mechanical parameters			Acoustic parameters				
		d [mm]	ρ [kg/m^3]	E [MPa]	ν [−]	σ [(kPa s)/m^2]	φ [%]	α_∞ [−]	Λ [μm]	Λ' [μm]
[117]	product suppliers + measured values	160	40			15.4	0.98	1.04	56	
[120]	measured values	160	40	0.014	0	14.08	0.99	1	76	137
[135]	measured values	–	21			16.5	0.98	1.1		
[136]	measured values	–	183			51.2	0.97	1.06		
[137]	product supplier + measured values	140 (uc)				12 (uc)				
		100 (uc)				12 (uc)				
		100 (uc)				21 (uc)				
		100 (uc)				12 (uc)				
		100 (c)				18 (c)				
		75 (c)				21 (c)				
		75 (c)				30 (c)				
		75 (c)				20 (c)				

(uc) = data regarding the "uncompressed" sample.
(c) = data regarding the "compressed" sample.

Table 6
Summary of the mechanical and thermal parameters characterizing the glass wool.

source	source of data	Thickness	Mechanical parameters	Thermal parameters		
		d [mm]	ρ [kg/m^3]	ε [−]	λ [W/(m K)]	cp [J/(kg K)]
[114]	not specified	–			0.023–0.040	
[106]	measured values	–			0.05	
[112]	not specified	–	14–80		0.032–0.038	840
[116]	reports collected by the Authors	–	25–220		0.035–0.05	840
[124]	simulation software	–	(10–32)		0.033–0.040	
[129]	reports collected by the Authors	–	34		0.034	
[134]	reports collected by the Authors	–	30			
[138]	reports collected by the Authors	–	18–50		0.04–0.05	
[139]	not specified	–			0.032–0.040	
[140]	measured values	89–140			0.042	
[141]	not specified	–		0.075		

Table 7
Summary of the mechanical and acoustic parameters characterizing the glass wool.

source	source of data	Thickness	Mechanical parameters			Acoustic parameters				
		d [mm]	ρ [kg/m^3]	E [MPa]	ν [−]	σ [(kPa s)/m^2]	φ [%]	α_∞ [−]	Λ [μm]	Λ' [μm]
[117]	product suppliers + measured values	80	56	0.6	0	36.23	0.99	1	40	162
[136]	measured values	–	53			24.3	0.98	1.01	63	
[137]	product suppliers + measured values	50 (uc)				9 (uc)				
		32 (c)				12 (c)				
[142]	not specified	50	80			70				
[143]	analytical process	25	17			14.2	0.99	1	182	400
[144]	not specified	45	16	0.055	0	15	0.98	1	60	150

(uc) = data regarding the "uncompressed" sample.
(c) = data regarding the "compressed" sample.

We can also find some results from mechanical characterization, as shown in Table 7 (Young's modulus and Poisson's ratio). As far as the acoustic parameters are concerned, the airflow resistivity is treated extensively, providing many different results. Some authors also report the other parameters of the JCA model. For porosity and tortuosity, the variation between the various studies is not significant, while in the case of thermal length and viscous length the variations are more noteworthy.

4.2.1.5. Insulation layer: polystyrene. For the physical characterization of Extruded Polystyrene (XPS), as expected only thermal properties are provided by several authors, as depicted in Table 8. Although numerous values are given for the density and thermal conductivity, there is a lack of data and characterization regarding certain mechanical properties (E, ν) and an acoustic representation of the material. No thickness values were found.

Table 8
Summary of the parameters characterizing the XPS.

source	source of data	Mechanical parameters	Thermal parameters	
		ρ [kg/m^3]	λ [W/(m K)]	c_p [J/(kg K)]
[113]	reports collected by the Authors	20–40	0.033	
[116]	reports collected by the Authors	20–50	0.030–0.040	1500
[124]	simulation software	≤400	0.027–0.036	
[132]	not specified	20–40	0.035	

On the other hand, for the Expanded Polystyrene (EPS) an extensive thermal analysis is offered and reported in Table 9. This shows that the thermal conductivity of expanded polystyrene is almost always coupled

Table 9
Summary of the parameters characterizing the EPS.

source	source of data	Thickness	Mechanical parameters	Thermal parameters	
		d [mm]	ρ [kg/m^3]	λ [W/(m K)]	cp [J/(kg K)]
[110]	ISO 10211	151	25	0.034	1500
[111]	not specified	30 120	30	0.040	1500
[112]	not specified	–	20–60	0.03–0.04	900–1500
[116]	ONORNM EN 12524 + ONORM B 8110-7	–	15.8	0.040	
	reports collected by the Authors	–	15	0.035	1500
	reports collected by the Authors	–	20	0.035	
	reports collected by the Authors	–	30	0.040	
[129]	reports collected by the Authors	–	30	0.031	
[130]	reports collected by the Authors	–	30	0.031	
[133]	not specified	–	–	0.031–0.038	
[124]	simulation software	–		0.032–0.040	

with the density values. Few data are available on the specific heat at constant pressure, while data on Young's modulus and Poisson's ratio are missing, as well as emissivity. An acoustic material characterization is also missing.

Few authors also reported a thermal characterization of the glass foam (Table 10), providing some information on thermal conductivity, specific heat and density. Data on Young's modulus, Poisson's ratio, emissivity and acoustic characterization are missing.

4.2.1.6. Insulation layer: natural insulation materials. Some works characterized natural insulation materials. Particular attention was given to sheep wool, as shown in Table 11. Many works report the density. Some studies also provided thermal conductivity and only few papers include specific heat and airflow resistivity.

When talking about hemp characterization, few data have been collected, as depicted in Table 12. Many data are available regarding acoustic description and density, few regarding thermal conductivity, but there is a lack of specific heat, emissivity, Young's modulus and Poisson's ratio.

In the case of cellulose, numerous authors managed to characterize this natural material, as can be seen from Table 13. Although there are numerous data on density and thermal conductivity, few authors provided specific heat at constant pressure and acoustic characterization. Young's modulus, Poisson's ratio, thermal emissivity and thermal length are missing too.

Limited information was collected about the straw (Table 14). Among all data, only density, thermal conductivity and, in one case, airflow resistivity are reported. Information regarding its Young's modulus, Poisson's ratio, emissivity and all other parameters of the JCA acoustic model were not found.

Table 10
Summary of the parameters characterizing the foam glass.

source	source of data provided	Thickness	Mechanical parameters	Thermal parameters	
		d [mm]	ρ [kg/m3]	λ [W/(m K)]	cp [J/(kg K)]
[112]	not specified	–	140	0.06	1100
[116]	reports collected by the Authors	–	106–165	0.04–0.05	840
[124]	simulation software	–		0.042	

Table 11
Summary of the parameters characterizing the sheep wool.

source	source of data	Thickness	Mechanical parameters	Mechanical parameters		Acoustic parameters
		d [mm]	ρ [kg/m^3]	λ [W/(m K)]	c_p [J/(kg K)]	σ [(kPa s)/m^2]
[112]	not specified	–	20	0.04	900	
[129]	reports collected by the Authors	–	30	0.04		
[130]	reports collected by the Authors	–	30	0.04		
[134]	reports collected by the Authors	–	100			
[145]	not specified	–	40			2.1

Some authors have also approached wood fiber, as shown in Table 15. From the information collected, it is evident that most of the reported data concern the density and thermal aspects (thermal conductivity and specific heat), excluding the mechanical (E, ν) and the acoustic characterization.

Taban et al. [149] studied the sound absorption performance of date palm fibers and estimated some parameters varying thickness. The results are summarized in Table 16. To the authors' knowledge, no other work reported a further characterization of this material.

The cork has been characterized by Hairstans et al. [124] thermally and by Berardi and Iannace [145] acoustically. Details of their data are depicted in Table 17. Data regarding its Young's modulus, Poisson's ratio, emissivity and all other parameters of acoustic models were not found.

Some authors also reported data for the coconut fibres as depicted in Table 18. These studies report results mainly on density, Young's modulus, thermal conductivity, specific heat and acoustic parameters of the JCA model. However, no values were found on Poisson's ratio and thermal emissivity.

The jute has been characterized by Fabbri et al. [150] thermally and by Gle et al. [146] acoustically. Details are depicted in Table 19. However, values about the main mechanical properties (E, ν), emissivity and specific heat are missing.

Furthermore, Fabbri et al. [150] provided thermal characterization of kenaf, while Gle et al. [146] analysed its acoustic performances (Table 20).

Some investigations have also been made on the textile fibers. Firstly, the cotton was thermally characterized both from Asdrubali and Arenas [129] and Kymäläinen and Sjöberg [138], as shown in Table 21.

Secondly, also the flax was thermally characterized by some authors (Table 22).

It is possible to see that acoustic characterization and information about Young's modulus and Poisson's ratio are not provided.

4.2.1.7. Other insulation material. Other materials have been studied within the timber buildings framework. For example, the polyurethane foam has been characterized in some works (Table 23), especially from the acoustic point of view. Anyway, data about Young's Modulus, Poisson's ratio and thermal properties are not provided.

For the kraft, Pihelo and Kalamees [107] and Berardi and Iannace

Table 12
Summary of the parameters characterizing the hemp.

source	source of data	Thickness	Mechanical parameters	Thermal parameters	Acoustic parameters				
		d [mm]	ρ [kg/m^3]	λ [W/(m K)]	σ [(kPa s)/m^2]	φ [%]	α_∞ [−]	Λ [μm]	Λ' [μm]
[129]	reports collected by the authors	–		0.04					
[138]	reports collected by the authors	–	20–45	0.04–0.06					
[143]	analytical process	25	51		6.2	0.990	1.05		
[145]	not specified	–	50		1.4				
[146]	measured values	90	28.9		1.6	0.935	1	335	360
		90	24.1		3.3	0.976	1	359	453
		50	55..6		8.1	0.949	1.1	134	272
		8	91.8		11.0	0.936	1.4	58	122
		18	140.5		33.0	0.895	1.2	31	145
[147]	measured value + analytical process	40	88		5.5	0.930	1.05	109	160

Table 13
Summary of the parameters characterizing the cellulose.

source	source of data	Thickness	Mechanical parameters	Thermal parameters		Acoustical parameters			
		d [mm]	**ρ [kg/m^3]**	**λ [W/(m K)]**	**c_p [J/(kg K)]**	**σ [(kPa s)/ m^2]**	**φ [%]**	**α_∞ [−]**	**Λ [μm]**
[107]	Delphin database + measured values	50	37 (dry cellulose)	0.048–0.049					
		50	60 (wet cellulose)	0.041–0.0043					
[109]	WUFI database	160	70	0.04	2500				
[112]	not specified	–	65,00	0.04	1800				
[114]	not specified	–		0.022–0.035					
[124]	simulation software	–		0.038–0.044					
[129]	reports collected by the Authors	–	35–70	0.037					
[138]	reports collected by the Authors	–	30-45 (cellulose from recycled paper)	0.041					
		–	30-60 (cellulose from wood fibre)	0.050					
[148]	not specified	–	37.3			6	0.984	1.08	157.4

Table 14
Summary of the parameters characterizing the straw.

source	source of data	Thickness	Mechanical parameters	Thermal parameters	Acoustic parameters
		d [mm]	ρ [kg/m3]	λ [W/(m K)]	σ [(kPa s)/m2]
[108]	ISO 10456	–		0.073	
[123]	product suppliers	50	79.43	0.054	
[139]	not specified	–		0.037	
[145]	not specified	–	50		1.4

Table 15
Summary of the parameters characterizing the wood fibre.

source	source of data	Thickness	Mechanical parameters	Thermal parameters	
		d [mm]	ρ [kg/m^3]	λ [W/(m K)]	c_p [J/(kg K)]
[107]	Delphin database + measured values	50		0.048–0.050	
[109]	WUFI database	8; 15	300	0.05	1500
[129]	reports collected by the authors	–		0.065	

[145] provided some thermal data, especially thermal conductivity but, with the exception of density, mechanical and acoustical parameters are not reported in other studies (Table 24).

4.2.2. *Cross laminated timber*

Contrary to the Timber Frame structure, the CLT is made of the same wooden component layered in different directions. Here, only a few papers among the ones selected concern the characterization of CLT. The summary of these data is included in Table 25. It can be highlighted that there is a lack of acoustic characterization and of values about some mechanical properties (E, ν) and thermal emissivity.

5. Conclusions

This research aims to provide a complete overview of the input parameters useable to simulate the performances of timber buildings elements. In order to pursue this aim, some issues have to be solved in relation to construction methodologies, simulation approaches, materials characterizations and a consequent variability of the results. Thus, an in-depth literature review is developed and results are discussed in terms of distribution in time, bibliometric data cross-correlation, link between different research, simulation methodologies and analytic parameters involved in the calculations.

Many useful results can be here highlighted:

✓ the investigated topic is of great interest for the scientific community. Data show that in last one or two decades, we can find a rapidly increasing trend related to studies dealing with this thermal and acoustic insulation issues related to timber buildings;
✓ scientists do prefer conference proceedings instead of journal papers to disseminate their results. This is probably due to the fact that many funded projects do not pay for high open access fees, so it is simpler to present them within international congresses;
✓ the most studied construction methodologies are Cross Laminated Timber and Timber Frame, even if a notable segmentation of research is found;

Table 16
Summary of the parameters characterizing the date palm fibre.

source	source of data	Thickness	Mechanical parameters	Acoustic parameters				
		d [mm]	**ρ [kg/m^3]**	**σ [(kPa s)/m^2]**	**φ [%]**	**α_∞ [−]**	**Λ [μm]**	**Λ' [μm]**
[149].	not specified	20	65	1.07	0.9276	2.95	250	422
		30		0.956	0.9278	2.90	247	430
		40		0.879	0.9280	2.90	245	418

Table 17
Summary of the parameters characterizing the cork.

source	source of data	Thickness	Mechanical parameters	Thermal parameters	Acoustic parameters
		d [mm]	ρ [kg/m3]	λ [W/(m K)]	σ [(kPa s)/m2]
[124]	simulation software	–	120	0.04–0.05	
[145]	not specified	–	100		1000

✓ nowadays, computer simulations are not the most used methodology to study and predict timber buildings elements performances, probably because this approach need very robust and reliable materials characterization; a lack of this latter topic in literature was also found;

✓ the most used simulation approaches are Finite Element Methods and Transfer Matrix Method, even if for acoustics also SEA is used.

From the point of view of parameters availability, all simulation methods are based on common factors. These were analysed, sorted and collected for all elements layers such as timber studs, oriented strand board, insulation elements (such as rock, glass and sheep wool, hemp,

Table 21
Summary of the parameters characterizing the cotton.

source	source of data	Thickness	Mechanical parameters	Thermal parameters
		d [mm]	ρ [kg/m3]	λ [W/(m K)]
[129]	reports collected by the Authors	–	25	0.04
[138]	reports collected by the Authors	–	5–100	0.035–0.075

Table 22
Summary of the parameters characterizing the flax.

source	source of data	Thickness	Mechanical parameters	Thermal parameters	
		d [mm]	ρ [kg/m3]	λ [W/(m K)]	cp [J/(kg K)]
[112]	not specified	–	20	0.04	840
[134]	reports collected by the Authors	–	40		

Table 18
Summary of the parameters characterizing the coconut fibre.

source	source of data	Thickness	Mechanical parameters		Thermal parameters		Acoustical parameters				
		d [mm]	ρ [kg/m^3]	E [MPa]	λ [W/(m K)]	c_p [J/(kg K)]	σ [(kPa s)/m^2]	φ [%]	α_∞ [−]	Λ [μm]	Λ' [μm]
[106]	measured values	–	1150–1460	4000–6000	0.04						
[112]	data source not specified	–	100		0.045	1600					
[129]	reports collected by the Authors	–			0.043						
[145]	not specified	–	60				1.5				
[146]	measured values	105	101				11.581	0.945	1	68	339
[150].	reports collected by the Authors	–	75–125		0.040–0.045						

Table 19
Summary of the parameters characterizing the jute.

source	source of data	Thickness	Mechanical parameters	Thermal parameters	Acoustical parameters				
		d [mm]	ρ [kg/m3]	λ [W/(m K)]	σ [(kPa s)/m2]	φ [%]	α_∞ [−]	Λ [μm]	Λ' [μm]
[146]	measured values	11	137.3		4.027	0.907	1	34	
[150]	reports collected by the Authors	–	35–100	0.038–0.055					

Table 20
Summary of the parameters characterizing the kenaf.

source	source of data	Thickness	Mechanical parameters	Thermal parameters	Acoustic parameters				
		d [mm]	ρ [kg/m3]	λ [W/(m K)]	σ [(kPa s)/m2]	φ [%]	α_∞ [−]	Λ [μm]	Λ' [μm]
[146]	measured values	11	137.3		4.027	0.907	1	34	
[150].	reports collected by the Authors	–	35–100	0.038–0.055					

Table 23
Summary of the parameters characterizing the polyurethane foam.

source	source of data	Thickness	Mechanical parameters	Acoustical parameters			
		d [mm]	ρ [kg/m^3]	σ [(kPa s)/m^2]	φ [%]	α_∞ [−]	Λ [μm]
[136]	reports collected by the Authors	–	60	2.3	0.96	1.28	202
[142]	not specified	–	48				
[143]	analytical process	–	25–55	5.4–12.9	0.97–1	1.08–1.41	

Table 24
Summary of the parameters characterizing the kraft.

source	source of data	Thickness	Mechanical parameters	Thermal properties
		d [mm]	ρ [kg/m3]	λ [W/(m K)]
[107]	Delphin database + measured values	–	756–900	0.11–0.12
[145]	not specified	–	400–470	0.85–1

Table 25
Summary of the parameters characterizing the CLT.

source	source of data	type of wood	Thickness	Mechanical parameters	Thermal parameters	
			d [mm]	ρ [kg/m3]	λ [W/(m K)]	cp [J/(kg K)]
[110]	ISO 10211	spruce-pine-fir	–	600	0.104	960
[111]	not specified		120; 140	410	0.10	1300
[116]	ONORNM EN 12524 + ONORM B 8110-7		–	500	0.13	
[118]	product suppliers		–	450		
[131]	measured values	Quebec black spruce	102	536	0.12	2500
[151]	product suppliers	spruce	–	500	0.13	1600
[152]	not specified		–	470		
[153]	product suppliers		25	400		

cellulose, cork, cotton palm fibre, flax, kenaf, etc.) cross laminated timber. The results are resumed in tables, where values of 11 parameters are reported and discussed for each considered material. This constitutes the very first database containing input data for thermal and acoustic simulations of timber building elements. It has to be clearly specified that often studies report different values for similar materials, while sometimes it can be found that for very different materials very similar values are described. As a conclusion, we can clearly state that databases have to be considered only if real measurements are not available, nor possible. Accordingly, basing numerical simulation on literature values can be misleading, due to the wide presented ranges.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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