CROSS LAMINATED TIMBER APPLIED TO THE BUILDING: A REVIEW ACCORDING TO LIFE CYCLE ASSESSMENT CRITERION

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ABSTRACT

The building sector is one of the largest consumers of natural resources and energy in the world. Designing buildings that emit less carbon dioxide or promote a smaller use of energy along its life cycle is an important strategy to improve the environmental performance of the building sector. The CLT, Cross Laminated Timber, is an innovative building material that consist in layer of timber glued and pressed 90 degrees from one layer to another, forming panels with an incredible resistance and performing as a sealing and structural material. Its capacity as an industrial building system allows the CLT to be used in many different constructions, from small to high-rise buildings. The use of timber as a building material is becoming more studied over the past years, as it appears as an alternative to the concrete building since its positive points related to installation, energy saving and cost. The aim of this research is to analyze the environmental performance of CLT as a building material, reviewing articles that compare buildings constructed with different materials according to different impact criteria. This review focuses on finding common elements between the studied articles and analyzing if the CLT, as a material applied to building, performs better than other materials. Hence, as could be seen from the analyzed papers, the CLT applied as a building material can reduce the embodied energy in the construction, GHG and CO_2 emission. However, the adoption of CLT has some barriers as a construction material, like the lack of information and cost concerns, so it remains a frontier of knowledge for engineers, architects and the hole public.

Keywords: *Cross Laminated Timber, Comparative Case Study, Life Cycle Assessment, Timber Building*

1. INTRODUCTION

In the last decades, the climate is passing though drastically changes. The Intergovernmental Panel on Climate Changes (IPCC) [1] describes that the probability of human influence causing the climate changes is from 95% and to prevent more impacts, it is necessary to drastically reduce the global temperatures [1]. One of the strategies is to reduce the anthropogenic greenhouse gases (GHG) emissions. However, to put it in action, all the human activities must reduce and make changes in terms of production and consumption.

In the building sector the discussion about the emission at the building life cycle are important factors to be treated as a measure to reduce men-made impacts, since the construction industry is responsible for around a third of the global greenhouse gas emissions (GHGE) and 10% percent less than a half of the global energy use [1-2]. In that sense, many efforts had been made to reduce the environmental impacts during the operation phase of the buildings. This way, after reducing the emission of gases and the energy consumption associated with the operational phase, the focus on material and the construction process of the building sector receive more attention [3-4].

According to the UN-HABITAT [5], The Quito Declaration on Sustainable Cities and Human Settlements for All estimates that by the year 2050 the population will double, making urbanization one of the 21st century most transformative trends. The declaration also concludes that in 2050, 7 in each 10 people will be living in cities. If business as usual grow in the same proportion as the population, the human emissions may double or triple in 30 years [5]. Consequently, the IPCC see the reduction of the energy use by the buildings sector as a critical climate change measure [1].

Since Life Cycle Assessment covers information about the entire life cycle of the building, it is an interesting tool for assessing the environmental impacts of it. LCA supports industries and policymakers in taking decisions about its production processes, strategies and final products [6]. This is, in fact, an important tool to understand the real impacts for each choice that is made during the building life cycle, assisting architects and engineers on choosing the best construction options.

At the building life cycle, the operational phase is the biggest responsible for emission [2], thus, for decades regulations applied to building have focused more on reducing these operational associated impacts. However, with the building energy efficiency being achieved at the operational phase, the researchers and the industry are getting more interested on reducing the second biggest cause of gas emission in building, the construction phase [7]. This way, the focus is to analyze mainly the emissions associated with the materials origin, fabrication process and construction [8].

The CLT is a material derived directly from the forestry, so it is often referred as a carbon neutral material, due to its carbon storage on its biomass. Because of this characteristic, not only the construction industry, but several other industries are increasingly considering the wood from the forest as a source, since the use of bio-based materials can contributes to mitigate climate impacts [9], this way, the wood building could be considered more sustainable than building that use mineral resources [10].

From another perspective, the discussion about medium and high-rise buildings pass by the investigation of structural systems that support the efforts required for the building. Tall buildings have been made in steel and concrete, since these mineral materials responded well to the required efforts along building history. However, the extraction and the fabrication of these materials are very aggressive and contributes with environmental pollution caused by the building sector [11], thus, if mineral materials were compared with bio-based materials, like timber, many studies report that they are responsible for more impact in the planet [12-17]. Consequently, timber tall buildings studies have grown and many systems that use timber as the main building materials have being developed, such as the CLT [18-20].

This way, the main goal of this research is to compare different building LCAs studies according to its materials, focusing on articles that analyses CLT building material, this way, the use of CLT is a selection criterion. Thus, the aim is to compare the wood-based buildings with other building materials, analyzing its performance according to the materials choice.

2. METHODS

This research is classified as a critical review. The stages of analyzes start from the selection of articles according to the subject till the critical analyzes of the results obtained in each article. The articles were obtained from some research databases, like “Science direct”, “Research gate” and “Portal Capes”. The keywords picked as selection criterions are “CLT building” and “LCA”, using the filters “years” and “article type” as selection criteria. The filter “years” was selected to show results from 2014 to 2018 and the filter “article type” was used to select only the review articles and the research articles.

After this first selection of articles, the resultant articles will be classified according to the title relation with the subject, if there was any doubt, the article was speared to be analyzed by the next criterion. The next criterion was the content of the abstract, according to this criterion was possible to verify if the hole building was analyzed, what building materials were analyzed in the LCA simulation and if the CLT is included. Fifteen articles were in accordance with the section criterions and they will be analyzed by this review study.

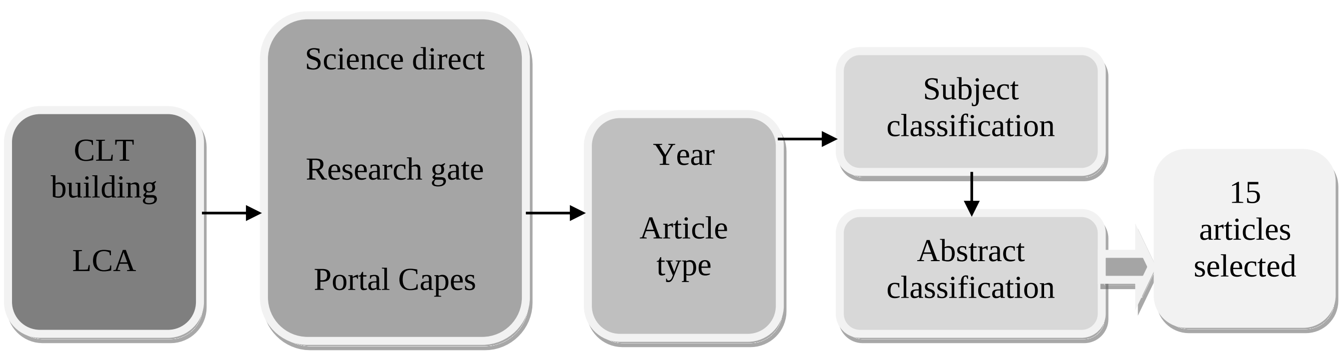

Figure 1. Selection of articles method

3. CLT

The CLT, a composed of massive timber panels, glued and pressed in layers with different directions applied as a building material, and it usually has an impar number of layers, commonly composed by 3, 5, 7 or 8 layers pressed and glued in different directions [21]. The CLT panels were developed in Germany and Austria in the 90`s beginning and increased the use at the beginning of twenty-first century, being used in the construction of different building typology, including high-rise buildings [22]. The CLT panels have good structural performance, rigidity, strength and stability if compared to natural wood.

The CLT could be used for many parts of the construction, like columns, beams, slabs, walls and others, as freestanding system. Its fabrication is developed by specialized industries in an automatized process, using computational technology to make the panels according to the project and with a small margin of error. During the panel fabrication it is possible to include also the clipping of frames and additional installation holes. After the fabrication, the panel is transported to the construction site and is installed, being necessary only to make the junctions with metallic fittings. The work at the construction site is fast, clear, and includes the assembly of parts and after that the finishes of the building [23].
The discussion about the use of CLT in building construction show up some barriers on its use, the main barrier pointed is the lack of information about the benefits of CLT by the construction sector professionals, like building system design and limitations. The conservative views by construction industry professional on the wood products about the structural, fire protection and operational performance preconception [24].

4. ANALIZES

From the first analyzes of the articles, it is interesting to highlight that the first point discussed in many of the analyzed articles is the GHG emission caused by the materials production. According to Giesekam *et al.* [24] it is recommended to use timber in the construction of buildings as a low embodied energy construction material. This way, according to the Table 1, the analyzed articles that include the GHG emissions as an environmental criterion [25 - 27] point that the GHG emissions are reduced first because of the carbon absorption during the tree growth. The second cause of reduction in GHG emissions are the industrial production and the reduction of waste in the CLT and engineered timber products production. Takano *et al.* in 2014 [26] analyzed the influences of databases in GHG emissions. In this study they concluded that even with database differences, the fact that influences the most GHG emission is the wood production energy consumption.
From all the analyzed articles, only three were not made in Europe, as showed in Table 1. Between them two were made in Australia, and the other one in North America, a constructed building in Canada. It shows that the discussion of the CLT is still more advanced in Europe. Justified by the fact that the CLT was created and developed in Switzerland, Germany and Austria [21], and the biggest part of the factories of CLT are concentrated there and the continent have a legislation about massive timber buildings [28], while in other continents, the panels are being developed only a few years ago and the legislation about it is still being developed, like the Canadian case [29].

4.1. Building typology, building materials and life span

The CLT applied to the building is a material developed to be used as a freestanding system, performing as structure and as a seal at the same time. It is a revolutionary building material, applied to tall building [21]. In that context, tall building could be highlighted as a building possibility analyzed in many cases by the selected researches. The tallest building analyzed is a hypothetical building with 21-storeys [11], while the tallest building in the selected articles that was built has 18-storeys [39]. In the other hand, also small buildings were analyzed and compared in the case studies [10, 26, 27, 33, 34, 35, 36, 37, 38], as could be seeing in Figure 2, representing also an important context to be analyzed, since the CLT applied to building represents not only an advance in height of wood-based building, but also an advance in relation to applied technology, allowing also small buildings. The smallest building founded in the analyzed articles was a small box-shaped building (10,14m²) [26], assessed to compare only the impact caused by the materials 'cradle-to-gate' stages [40].
Also, in a few studies, not only on building typology was used as a case study, but a few possibilities, discussing and comparing the CLT performance applied to different buildings contexts, like in the case of Skullestad *et al.* [11], made in Norway. This article compares low-energy family residences according to the higher of the building, from 3, 7, 12 and 21-storeys, making an analogy from higher and environmental performance according to the material use. This way, still Takano *et al.* [38] studies the differences of housing typologies applied to different materials, the study compares the performance from a detached house, a row house, a townhouse and an apartment block.
As could be seen from the Table 1, residential buildings are the most common typology in the analyzes, from isolated houses [37], townhouses [38], multi-family social [32], student residence [34, 39] to apartment buildings [10, 38]. Only in a few cases the object study of the article was a non-residential building [25, 30], in some cases also analyzes as a comparative case study to a residential one [25].
It was also interesting to observe how the building analyzes was made. In a few cases the analyzes of the CLT applied to the building represents only the use of it as structure [27, 30, 33, 34, 37, 38]. In these cases, the comparison is only made to choose the lower impact structure for the building, thus the structure for significant environmental impacts at the LCA pre-operational stage. In the model case study of Azzouz *et al.* [30] the structure represents 10% for GWP emission of carbon and 7% for fossil fuel emission of carbon, while all the rest of the envelope and perimeter of the construction represents 3 and 2%, respectively. In that sense, the structure emits more CO_2 than the hole envelope, if the product and construction stage were analyzed. Showing the importance of

studying the structure in the initial stages of the building design [40]. Yet, knowing that the CLT is a self-supporting system, in some cases the comparison between the CLT structure and other structures seems incompatible, such as comparing CLT structure and steel structure, since the CLT panels are used as structure and sealing, while the steel is used in a pillar beam system.

Table 1. Building analyzes.

Author	Country	Functional Unit	Building Tipology	Life Span (years)	Data Base	Environmental Criteria
Azzouz *et al.* [30]	United Kingdom	Complete building/ structure	office building	60	BRE- GreenGuide Book (2015)	Global Warming Potential (CO_2-eq.), Fossil Fuel Depletion (MJ)
Hafner & Schafër [10]	Germany and Austria	1 m²	1 m² GEA of product system building-residential building	50	Database in line with EN 15978:2012	Global Warming Potential (CO_2-eq.)
Huey Teh *et al.* [31]	Australia	Complete building	residential and non-residential	no inform.	Eora	carbon footprint (Mt CO_2 eq.)
Invidiata *et al.* [32]	Italy	Complete building	multi-family social	100	ICE database [42], Ecoinvent 3 and the EPD certifications, Milan Chamber of Commerce	Confort Hours (h), Primary Energy Demand (LCEA) in MWh, Carbon Dioxide Emission ($LCCO_2A$) in TCO_2E, Cost (LCCA), Multi-Criteria Decision Making (MCDM)
Kumar Pal *et al.* [33]	Finland	Complete building/ structure	townhouse	50	Ecoinvent, Statistics Finland, REVER ISSO	Life Cycle Energy, Life Cycle Cost
Moncaster *et al.* [34]	United Kingdom	Complete building/ structure	student residential	no info.	Bath/BSRIA Inventory of Carbon and Energy	Global Warming Potential (CO_2-eq.)
Peñaloza *et al.* [35]	Sweden	Complete building	low-energy apartment block family residential building	50 and 70	Ecoinvent with adjustments to the datasets for material manufacturing and their background processes to make them more representative of the Swedish industry.	GWP100 (kg CO_2 eq/m² living area)
Sandanayake *et al.* [29]	Australia	Complete building, m2	residential and comercial	no info.	Alcorn (2003) and AGGA (2013) ***	GHG emissions

Skullestad *et al*. [11]	Norway	Structure 1 m²	structure	60	Ecoinvent v.3.2 , EPDs, information from manufacturers and other studies	Climate Change Impact (CC)
Stazi *et al.* [36]	Italy	Complete building	low-energy family residential	75	Ecoinvent, transport distances, EnergyPlus simulation for heating and cooling	Environmental Impacts; Energy Demand; Environmental Costs; CO_2 Emissions
Takano *et al.* [26]	Finland	Complete building	small box-shaped buildings (10,14m²)	only materials life cycle	Gabi 6, Ecoinvent V3.0, IBO (Australia), CFP (Japan), Synergia (Finland)	GHG emissions
Takano *et al.* [27]	Finland	Complete building/ structure	townhouse	no info.	Ecoinvent and Finnish literature	Resource Use (RU), Embodied Energy (EE), Energy Content (EC), Embodied Greenhouse Gas Emissions (GHG), Carbon Storage (CS), Material Cost (cost)
Takano *et al.* [37]	Finland	Complete building/ structure	isolated house	50	Ecoinvent, IDA ICE	MJ/kg of product or MJ/MJ of final energy
Takano e*t al*. [38]	Finland	Complete building/ structure	detached house (DH), row house (RH), townhouse (TH) and apartment block (AB)	50	Ecoinvent, IDA ICE	MJ/kg of product or MJ/MJ of final energy
Teshnizi *et al*. [39]	Canada	1 m²	student residential	100	Athena	Global Warming Potential (kg CO_2 eq./m²), Ozone Depelation (kg CFC eq./m²), Acidification Potential (kg SO_4 eq./m²), Eutrophication Potential (kg N eq./m²), Smog Potential (kg O_3 eq./m²), Fossil Fuel Depletion Potential (MJ surplus/m²), LCC (Life Cost Cycle)

In fact, the choice of materials to be compared by the articles represent for each author the most relevant ones on each case study context, however, a common justification for their building materials chose was founded. Yet, the hypothesis of using the regional or national more applied materials for buildings is not discarded. In all the selected researches, the CLT is applied as a building material, but in some cases the CLT is applied only with other materials in a hybrid structure [11, 39] as could be seen from the Figure 3. This way, in a few of the studies the CLT is analyzed only as a structural system, in others also as a sealing material, according to the functional unit of analyzes, that could be inferred from the Table 1.

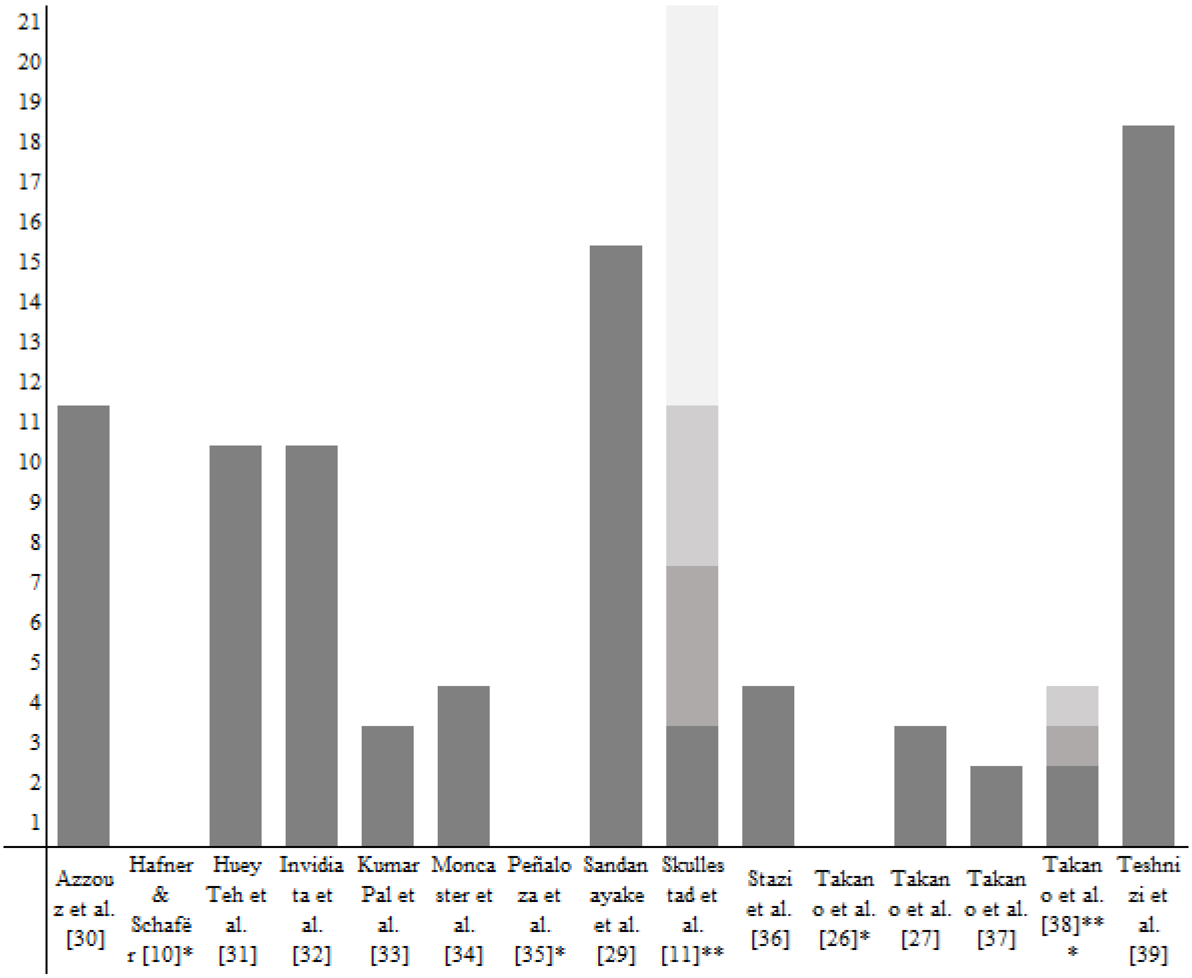

Figure 2. Buildng higher.
**Different unit base (as could be seen in Table 1: functional unit)*
***Skullestad et al. [11] analyzed 4 building typologies (3,7,12 and 21-storeys)*
****Takano et al. [38] analyzed 4 building typologies (as could be seen in Table 1: functional unit)*

The way the analyzes were made and what they considered or not in the studies also vary according to the propose of the researchers, but in most of the cases the foundation is not analyzed, assuming to be the same for all studied materials. In other cases, the use of CLT is pointed to reduce the foundation demand, since the CLT has less weight then other mass structures. Another part of the building that was not analyzed, in the cases where a mid-rise or a high-rise building is the case study, is the base, or the floor plan, like in the study of Stazi *et al*. [36], that consider the floor plan to be the same in all cases. It occurs because the CLT, as a timber-based material, is not recommended to be in touch with the land, avoiding problems with humidity, being made in these cases in concrete.

Timber applied to building is becoming more used in researches over the past years. It appears as an alternative to the concrete building because of its advantages during the construction stage, costs along the life cycle and because of its carbon sequestration capacity. Not only the academia, but also the architects, engineering and constructors concern that timber building, especially in mid-rise buildings, is a viable alternative [41, 42, 43, 25].

It is also important to say that the CLT appears in some studies complemented with other construction materials, not as the only system, such as X-lam and CLT [11, 39] and lightweight CLT as the main structure and steel frame for sealing [27]. It shows that the CLT system could be complemented with other construction systems, reinforcing its capacity as an integratory building system.

At the category of wood-based materials compared to CLT appear glulam [32], wood-cement [36], light-weight timber (LVL) [26], and curiously timber frame, wood frame or light weight timber (LWT) don't appear with a big frequency at the selected studies. Only four studies have timber frame systems compared as one of the case study scenarios [10, 27, 37, 38]. It could be justified because this system is considered a light structure system, in the way that the CLT is a massive construction system, more comparable with other massive materials, such as concrete or masonry.

Thus, the concrete appears in the biggest part of the cases selected for this review to be compared to CLT, in most of the cases described as reinforced concrete of just as concrete [25, 31, 32, 34, 35, 39]. In some cases, also alternative concrete composition appears, such as concrete panels [26, 27, 33, 36, 38], porous concrete [10], lighter concrete [30], geopolymer concrete [31], cellular concrete blocks [32] and autoclaved aerated concrete [27, 37, 38]. In short, the concrete appears as a comparative material in all the studies.

Brick and masonry also appear, but in a small proportion of cases [10, 34, 36]. And steel structure and steel frame system, also lighter weight system, are more common than wood frame as a comparable material in the analyzed studies, the steel buildings were found in six studies [11, 27, 30, 33, 34, 37, 38], while the wood frame was found in only 1 case study [10].

The life span of the buildings analyzed vary according to the country where the building was simulated, usually respecting country legislation. The life span analyzed goes from 50 to 100 years. Although, in a few cases, the life span of the building was not analyzed, mainly because these studies do not assess the operational stage of the building. It was observed that in most of the cases the analyzed buildings are not yet built, most of them are still in the design phase, representing the concern to analyze and select the best materials for the building according to the LCA and, consequentially, to the environmental impact.

	Azzouz et al. [30]	Hafner & Schafër [10]	Huey Teh et al. [31]	Invidiata et al. [32]	Kumar Pal et al. [33]	Moncaster et al. [34]	Peñaloza et al. [35]	Sandanayake et al. [29]	Skullestad et al. [11]	Stazi et al. [36]	Takano et al. [26]	Takano et al. [27]	Takano et al. [37]	Takano et al. [38]	Teshnizi et al. [39]
LWT (1)											x	x	x	x	
Increased Bio (2)							x								
Masonry or Brick		x				x				x					
Wood Frame		x													
Steel					x				x						
Steel Frame	x					x						x	x	x	
Concrete panel and others	x	x	x		x						x	x	x	x	
Reinforced concrete	x	x	x	x		x	x	x	x						x
Hybrid wood-steel	x														
Hybrid wood-cement										x					
Timber Hybrid		x							x						x
CLT (4)		x	x	x	x	x	x	x		x	x	x	x	x	

Figure 3. Compared building materials.

(1) Light Weight Timber.

(2) Mineralbased insulation and cladding have been replaced with biobased products, and a sprinkler system is included in order to comply with fire protection regulations.

(3) Timber Frame, Prefabricated Timber, Glulam and CLT combined, Mass-Timber Hybrid Structure.

(4) Cross Laminated Timber

4.2. Environmental criteria

As said before, from the Table 1 could be inferred that most of the analyses were made with the environmental criteria of GHG emission or an environmental process that includes the carbon emissions [10, 25, 26, 27, 30, 31, 32, 34, 35, 36, 39], appearing sometimes in different ways, like carbon footprint [31]. From that, it is possible to conclude that this criterion is an important one in environmental analyses, and a relevant criterion to compare timber and mineral products in the building sector.

The construction in timber has a carbon offset because of the stock of carbon and is compensated for the area that is used to provide wood to the construction, if this area will go through a management of reforestation and will absorb more carbon during the growth of new trees.

As the operational energy is reduced, so the importance of the pre-operational energy consumption increases, thus, the building embodied energy related to the material source have to be taken in the beginning of the design stages of the building [44]. This way, this stage is often critical for designers, in a way that its determinates if the building follows sustainable practices [45].

In cases studies where the energy demand is analyzed as an environmental criterion, the conclusion is that even with all the advance in low-energy emission building, it is important to study the operational stage, since the reduction of the energy consumed during this phase must be proved. Although with the reduction of the energy demand during the operational phase, the study of the material transformation by the industry and at the construction site becomes more important as an environmental criterion.

Therefore, for Stazi *et al.* [36], the construction stage seems to have the more weight than any other stage on global LCA. As an example, in this comparative case study of CLT system, wood-cement compose and masonry, the main contributions to the global LCA are given by the impacts resulting from the concrete used for wood-cement compose and masonry. Also, for the CLT system, the construction phase is a very impacting one because of the raw material demand. This affirmation is justified by the high land use necessary for trees planting in this case, since more trees will be used in the construction. This study also points the worst performance of CLT in thermal operational phase, yet, because of the smaller energy demand of the product in other phases, the CLT system, if compared with the other materials is said as an important material to be used to reduce the building energy demand.

Other criterion that appear frequently in the analyzed studies is the cost [27, 32, 33, 39], but always as a complement criterion. The necessity of comparing the CLT cost is justified because of the lack of knowledge about the material. The biggest price comes from its innovation capacity, the small demand of market and the reduced number of factories that produce this high technology material. The article [39] made an LCC (Life Cost Cycle) comparing a CLT 18-storeys building with an 18-storeys traditional building made with concrete structure, both with the same finality, a student residence in Vancouver-Canada. The conclusion is that the Brock Commons, made with a hybrid CLT structure, costs only 11% more than the building made with traditional materials. If the caveat that this is a pioneering building in CLT in Canada is applied, this cost become insignificant near the proposed potential of innovation.

However, the CLT application in building should be made not only based on environmental criteria, but from a deepest reflection about the benefits and limitations of the CLT system. So, the material properties and influences on functionality and operability should be made. This way, timber-based materials could perform similarly or even better than equivalent mineral material applied to building, not only in terms of environmental performance, but also in constructability, fire resistance, acoustic performance or thermal capability [46].

4.3. Database and LCA stages

The database used for the LCA is extremely important to determinate the LCA method and the study results, since each database is based on different criteria and data collection [40]. The LCA calculation is also a variable to be analyzed. To Takano *et al.* [26] the databases comparison has to be discussed, since the calculation is based on different LCA purpose and each database collect data from different places and contexts.

The very first resemblance is that all the selected articles analyze CLT buildings comparing the life cycle assessment of them to similar buildings made with other materials. Although, the differences between them are various, from the country, building typology, building materials, life span, environmental criteria to the LCA phase and database. The last item, the database used for the LCA is a determinant criterion when analyzing the results obtained from the different stages of an LCA.

This way, it is difficult to compare the case studies assessed on each LCA research of this review paper. The first point that difficulties the comparison is the difference between the building typologies, also elaborated with different material and in different locations. The second difficulty is to analyze them according to the same criteria, since each article have its own environmental criteria and uses different LCA database.

There is no consensus about a specific database used for the assessment, even if in some studies the LCA database coincides, like the cases that had used the Ecoinvent as database. It occurs because of the LCA stages that each study chose to assess, as could be seen from the Figure 4. As discussed by Wittstock *et al.* [47], buildings are composed by many different and complex materials, resulting in difficult to compare LCA results and the necessity to choose the best database for each case study. From the analyzed studies, the Ecoinvent database is the most used database [26, 48, 49], as could be inferred from Table 1.

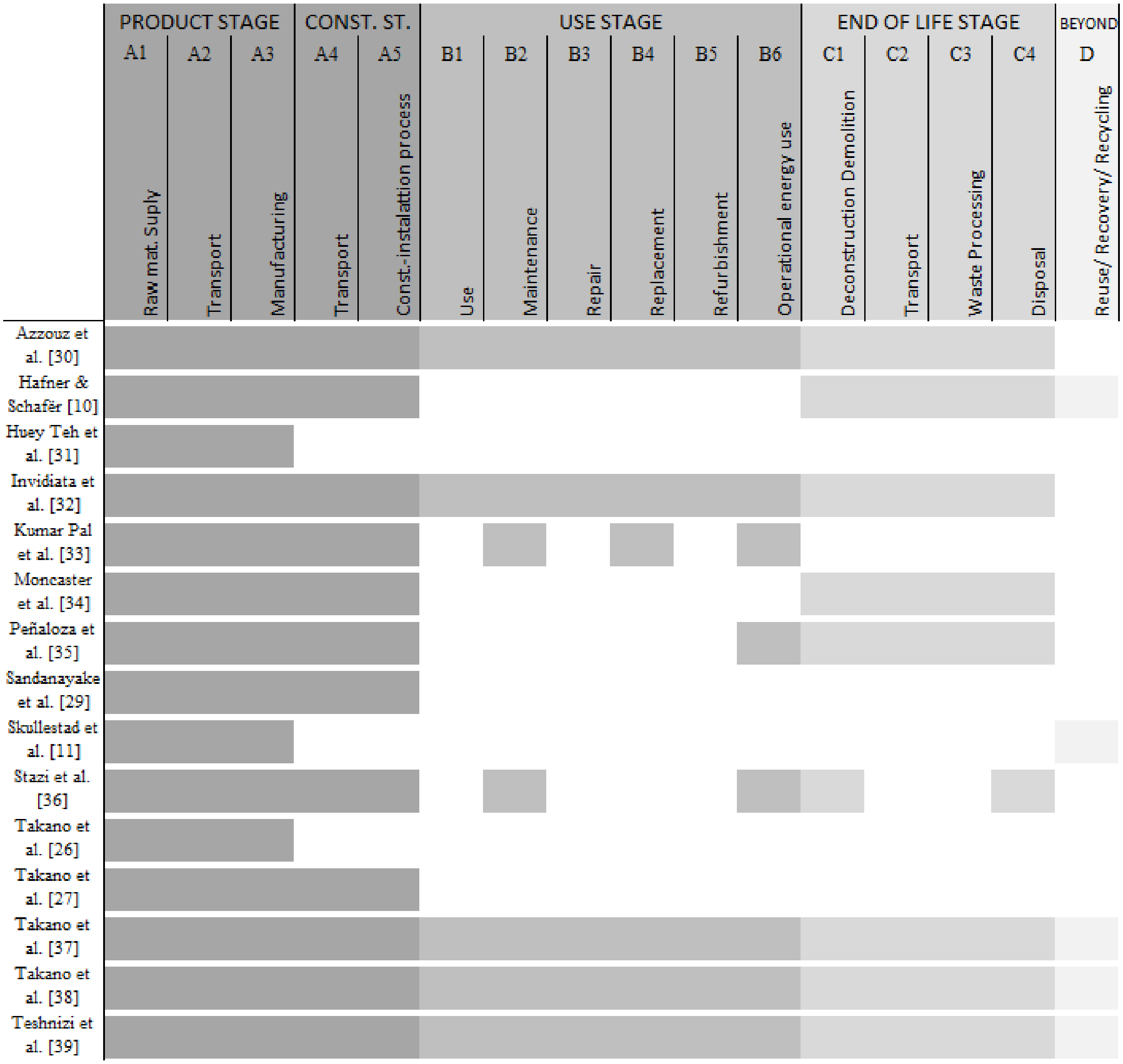

Figure 4. Life cycles stages of the analyzed building studied.

Not only the differences in LCA database are determinant to the results, but also the stages assessed in the analyze. Moncaster *et al.* [34] made a review from papers that analyze the LCA from buildings. The article concludes that the 'cradle to first gate' stages of the building are the most calculated stages. 'Transport to site' and 'construction' stages occupies second place in the most studied stages, followed by the 'end-of-life' stage and then 'beyond end of life' stages. Already the use stage is most often omitted.

According to the Table 1 the life span used for the LCA is an important point to be analyzed as it determinates the material environmental performance applied to building. In the review, according to the Figure 4, the first stages of the life cycle were analyzed by all the articles, the 'cradle-to-gate' phase (A1 to A3). Only three of the articles does not include the construction process stage: transportation (A4) and construction (A5) [11,26,31].

The second stages in an LCA, the use stage, that is verified by Moncaster *et al.* [34] as the less analyzed phase for the building researches. As could be inferred from the Figure 4, in this current CLT buildings review paper the use stage [40], is not the less analyzed phase in the LCA. However, in only a few reviewed papers the hole use stage is evaluated [30, 32, 37, 38, 39], never comprising the operational water use (B7). The most common is to analyze in the use stage the operational energy use (B6), because this stage is determinant to analyses the heating and cooling necessity of the building.

The end-of-life stage (C) is the second stage more assessed. From that, it is possible to conclude that the concern about the end of the life cycle is a determinant action in the LCA and in the design of the building, mainly when you must compare different materials and analyses energy used at their destination. However, the beyond stage should appear as an important stage when comparing different materials, since the reuse, recovery or recycling processes determinate the impact of the product in the nature and if it is possible to this material get in a new process, making possible to have a circular economy.

4.4. Comparing the LCAs

Despite the differences between databases, LCA stages and the differences between the case studies, the presented results are similar in most of the studies when assessing the carbon emission of the building. Already for the other criteria, the results differ from each other. However, a very impacting criterion is the consideration about bio-based materials carbon sequestration, since there is no consensus about its performance according to its carbon or climate neutrality [50-51].

According to the discussion of the carbon sequestration is the study of Peñaloza *et al.* [35] buildings that uses bio-based materials tend to cause less impact though the building life cycle. But it just occurs if the carbon dioxide sequestration and emissions are accounted. If forest carbon sequestration is not accounted in the LCA calculation, the results can be substantially different. At the end-of-life scenario, the results of bio-based materials also differ from non-bio-based materials, and it includes the final destination and the timing between the carbon sequestration and emission.

For Invidiata *et al.* [32], the CLT, if compared with other materials, performs better according to carbon dioxide emissions, however, if the cost was considered, this design performs worst than concrete. This article concludes that different databases impact the results by 30%.

Azzouz *et al.* [30] on the LCA calculation conclude that the CLT-steel system adds 0.6% on life cycle energy, but reduces the carbon emission in 3.1%, once again because of the carbon sequestration properties of the timber. However, this carbon sequestration serves only to compensate the embodied energy spent on the fabrication and the use of glue during the panel’s fabrication.

Moreover, Stazi *et al*. [36] conclude that the operational stage in CLT buildings consume more energy than building made with other materials, because of the material characteristics applied to the building sealing. Already, the aim of Hafner & Schafër [10] study is to investigate if it is possible to calculate a substitution factors for timber building when substituting a mineral building. The article shows that the results vary according to the building typology and size. For small residential buildings the potential of GHG reduction is from 35% up to 56%. Already, caused by the fire safety and sound insulation legislation, for multi-story buildings the reduction of GHG goes from 9% to 48%. During the end-of-life stage, more benefits are predicted when more timber-based materials are used, since the wood is thermally recovered. It is also important to point that this article [10] asses many timber-based building typologies compared with mineral-based building, so the presented results are not only from the CLT compared to mineral buildings, but from other timber-based buildings.

Still Skullestad *et al.* [11] made an LCA applied to different building typologies, like building from 3 to 21-storeys substituting timber instead of steel and concrete building structure, and concluded that the higher the building, the less it reduces absolutely climate change impact, if the assumption of sustainable harvest was made, like other studies pointed [27, 31], it happens from 3 to 12-storeys. Already from 12 to 21-storeys the reduction of climate change impact increase.

Analyzing the end-of-life scenario, Skullestad *et al.* [11] pointed that incinerated with heat recovery 90% of timber material waste and timber production residues, the structure can cause from -140 to -235 kg CO_2-eq/m², depending on the higher, consequently causing a negative climate change impact from timber structure.

At the study of Teshnizi *et al.* [39], even though the 11% higher cost of the CLT based building compared with concrete structure building, for other analyzed categories the CLT building is less impacting. The Fossil Fuel Depletion Potential in around 18% smaller ass well as the Global Warming Potential (GWP), reduced in 25%, excluding the operational impacts. Although, if the whole cycle was analyzed, CLT building does not necessarily performs better, but the materials are not the primary contributors for that.

In an optimistic scenario made in Australia, Huey Teh *et al.* [31] concludes that if all the new building structures used as residence in the country were constructed in engineered wood products instead of reinforced concrete, 26 Mt CO_2e can be achieved in around 40 years, and if the forest sequestration is take into account, 119 Mt CO_2e will be reduced. For commercial building the results are very similar, but in a smaller proportion, because of the reduced representativeness of commercial building if compared to residential building.

Hence, according to the analyzed articles it is possible to highlight that the use of CLT can reduce the embodied energy of the building, GHG and CO_2 emission as affirmed from Huey Teh *et al.* [31], Otherwise, many criteria have to be analyzed before making a global conclusion, this way, it was necessary to take more attention and to propose more comparative case studies to be analyzed by an LCA. Even with all the recent studies, the adoption of CLT has some barriers as a construction material, that are linked with the lack of information and cost concerns [52] then with the environmental performance of it.

5. CONCLUSIONS

Studying the CLT compared to other common building materials is important so it helps the consolidation of the CLT as an option in the construction sector, mainly as a structural and sealing system that can be applied tom id-rise and high-rise building.

Even with the differences in Life Cycle Assessment, different database analyses, life span and LCA stages, the CLT performance is good if compared to other materials. It occurs mainly for the fact that the CLT is a bio-based material that could be reset in nature, with the growth of the tree. Its fabrication and installation processes also contribute for that, reducing the waste and increasing the speed of construction. During the use stage CLT does not perform as well as other materials in a few cases, because of it smaller mass. At the final stages it shows a good performance, because of its ability to be completely used to other finalities, like a biomass or as a recyclable material.

According to the studied articles, the CLT has a good performance in many of the analyses of environmental performance. Mainly caused because of the material capability of CO_2 reduction, GHG emission and energy demand. However, it is also possible to conclude that the CLT is a material that still have to be more explored in academic researches and also more explained to the main public, even in countries that still do not have a significant CLT production or buildings made in this timber-based material, like South American countries, since the globalization and the building process of CLT production could be reproduced in many places in the globe, and the most determinant criterion for its implantation is the existence of management forests with a quality wood for its production.

The CLT is being more used as a construction system in the past 30 years, most impulse by the mid-rise and high-rise building constructions [43], but even with all the researches developed of the cross laminated timber (CLT), it remains a frontier of knowledge for engineers and for the architects, because of the cultural point of view that the wood is not good for building, that it requires a lot of maintenance and because of the massive timber techniques are still not very developed in many countries. In that sense, it is interesting to highlight the importance of future studies on developing conclusive researches about the CLT characteristics, process of fabrication, assembly, use and the main advantages and limitations on this building technology so the building designing professional could better understand the technique and propose on their projects.

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