Life cycle analysis of cross laminated timber in buildings: a review

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Abstract: Greenhouse gas (GHG) emissions have increased for the last three consecutive years in Australia, and this directly threatens our ability to meet our 2030 GHG emission reduction target under the Paris Agreement. Despite progress in reducing building-related GHG emissions, little focus has been placed on the indirect GHG emissions associated with building material manufacture, and construction. Cross laminated timber (CLT) is an alternative construction material that has been subject to numerous comparison studies, including many life cycle assessments (LCA). The aim of this paper is to provide a review of the recent literature on the environmental performance of CLT construction for Medium Density Residential (MDR) buildings and to identify knowledge gaps that require further research. Studies reviewed were sourced from web-based research engine, direct searches on global wood promotion websites, and the review was limited to peer reviewed publications. This review provides a useful basis for informing the exploration of important gaps in the current knowledge of how CLT buildings perform from an environmental perspective. This will ensure a comprehensive understanding of the environmental benefits of CLT construction and inform decision-making relating to structural material selection for optimising the life cycle GHG emissions performance of buildings.

Keywords: Cross laminated timber; life cycle assessment; greenhouse gas emissions; construction.

1. INTRODUCTION

The latest quarterly update of the National Greenhouse Gas Inventory December 2017 reveals that Australian GHG emissions have increased by 1.5 percent compared to the previous year (Department of the Environment and Energy, 2018). Unfortunately, this increase in national GHG emissions has been consistent for the last three years, thus making it more difficult to achieve the 2030 target of reducing GHG emissions by 26-28 per cent from 2005 levels (Australian Government, 2015). Moreover, this 2030 target is conservative and will result in Australia emitting about 85% of its IPCC Carbon Budget in only 14 years. Accordingly, there will potentially remain only 15% of this budget for the following twenty years, until 2050, at which stage, the national population is projected to reach between 33 and 40 million (Krockenberger, 2015). It is therefore reasonable to express concerns regarding the ability for Australia to successfully meet the Paris Agreement, and it highlights the current emergency for the nation to rapidly reduce GHG emissions.

1.1 Carbon footprint of buildings

According to the Intergovernmental Panel on Climate Change (IPCC), buildings (residential and commercial) accounted for 19% of energy-related global GHG emissions in 2010 (IPCC, 2014). More recent studies estimate the global GHG emissions contribution from buildings at between 30-40% (Ilbn-Mohammed et al., 2013; GABC, 2017; Sandanayake et al., 2018). Recent studies, using life cycle assessment (LCA), have identified the source of those large GHG emissions and revealed that indirect emissions, in comparison to direct emissions occurring during the use stage of buildings, are responsible for a major and increasing proportion of the total GHG emissions. This share is found to range from 71% in Ireland (Acquaye and Duffy, 2010), to 89.5% in Australia (Yu et al., 2017), and even up to 96.6% in China (Chen et al., 2017).

Referring to the European Standard EN15978 (2011), Figure 1 shows that the building life cycle includes four distinct stages from which GHG emissions result. The use stage (B), relates to the time in which the building is occupied, and its operation produces direct GHG emissions from the energy it uses. In addition, indirect GHG emissions are produced by Stages A, C and D, relating to the ‘product’ and ‘construction’ stage, the ‘End of Life (EOL)’ stage and the ‘Benefits and loads beyond the system boundary’ stage, respectively.
For decades, construction regulations relating to the reduction of GHG emissions have focused on the building use stage and have largely disregarded potential GHG emission reductions in the three others stages, in particular Stage A. Indeed, the product and construction process stage not only represents a significant share of the indirect GHG emissions (Crawford and Stephen, 2013), it is also a stage where decisions regarding materials and construction processes can be most easily changed for better long-term GHG emissions outcomes. Thus, an increasing number of studies have promoted a more holistic approach to GHG emissions reduction, using LCA inter alia (Hafner, Winter, and Takano 2012; Crawford et al. 2016).

1.2 GHG emissions of conventional structural materials

The construction of conventional buildings in most parts of the world uses highly emissions intensive materials, such as concrete and steel for their main structural elements. In 2014, it was estimated that energy-related GHG emissions from iron, steel and cement manufacturing represented 9% of global GHG emissions (GABC, 2017). Concrete has benefited from considerable research aiming to reduce GHG emissions, particularly those related to producing Portland cement (Schneider et al., 2011; Gartner and Sui, 2017). Yet, it is estimated that by 2050 the global GHG emissions share associated with Portland cement will represent 26% if current manufacturing processes remain unchanged, or still 20% even if cutting-edge processes are implemented (Gunner, 2017).

Steel production has seen similar progress regards to GHG emissions reduction, through replacement of formulas (Van Wesenbeeck et al., 2016), or innovative processes, such as molten oxide electrolysis (Allanore et al., 2013). Yet severe technology hurdles have cut short implementation in industry, and iron and steel production are currently estimated to account for 6.7% of global GHG emissions. This is anticipated to rise if disruptive innovations and international collaboration aren’t implemented (Shatokha, 2016). Therefore, the global GHG emissions share associated with concrete and steel is projected to remain significant and a substantial barrier to achieving necessary GHG emissions reduction targets within the building industry. Furthermore, most conventional materials, including the two mentioned above are of mineral and non-renewable nature. When considering that the Australian building stock is predicted to double by 2050 (ASBEC, 2017), severe stress on raw mineral resources is highly likely.

1.3 Cross-laminated timber: an alternative structural material

In London, a breakthrough occurred when Waugh Thistleton Architects designed the Stadthaus, a nine storey tower in North London, UK (Thompson, 2009), using Cross Laminated Timber (CLT). CLT is an Engineered Wood Product (EWP) panel composed of layers of solid timber called lamellas, typically 12 to 45 mm thick and 40 to 300 mm wide, glued together. The novelty of CLT comes from the 90° orientation of each layer of lamellas to adjacent layers, thus achieving better structural rigidity and dimensional stability in both direction of the panel. CLT panels are typically 57 to 320 mm thick, ranging from 2.2 to 2.95 m wide and up to 11.9 m long depending on transport constraints (England and Iskra, 2016).

CLT is a bio-sourced, and thus renewable material. Therefore, it could potentially mitigate the risk of raw mineral resource
depletion related to the use of conventional structural materials, such as steel and concrete. Besides other advantages such as safety and construction time savings, previous studies have also demonstrated other potential environmental benefits. An Australian study published by Durlinger et al. (2013) with a case study of Melbourne’s Forté building, commonly accepted as the most significant CLT construction in Australia, confirmed these benefits with a Global Warming Potential (GWP) 13%-22% lower than a building of similar design using concrete.

Durlinger et al.'s study is one of several studies that have used LCA to assess the environmental performance of CLT construction and compare it with conventional construction, most often Reinforced Concrete (RC) construction. These studies vary widely in the LCA methodologies used and their complexity, but all try to answer the same question: What is the potential for CLT construction to reduce the GHG emissions associated with buildings?

2. CRITICAL REVIEW OF PREVIOUS STUDIES

While CLT brings clear benefits over steel and concrete in terms of minimising non-renewable material depletion, the extent of other environmental benefits is less certain. This certainty is needed to ensure it provides a viable solution to mitigate environmental issues, such as the release of GHG emissions, associated with the built environment. A critical review was conducted on selected previous international LCA studies comparing conventional and CLT construction.

2.1 Methodology

The review of LCAs of CLT construction was based on the systematic approach used by Booth et al., including two stages: scoping review and mapping review. First, the scoping review was used to assess the number and quality of publications on the relevant topic and reveal primary gaps within the literature. Secondly, the mapping review maps existing literature and identifies secondary gaps, which leads to a summary assessment and identification of areas for future research (Booth et al., 2016).

The search process included three main steps. First, an initial search using keywords, as listed in Table 1, in Google Scholar, Scopus and Web of Science databases. The first one hundred results from each search from each database were considered, resulting in an initial batch of nine international articles (including P1-3, P5-8, as per Table 2). Secondly, further research through Google Scholar alerts and the ResearchGate community resulted in four more relevant publications (including P4 and P9). Finally, meetings and discussions during conferences resulted in one more research report. Therefore, a total of 14 relevant studies were identified for further analysis.

<table>
<thead>
<tr>
<th>Comparative cross laminated timber life cycle assessment</th>
<th>Comparative CLT LCA buildings</th>
<th>Life cycle approach cross laminated timber CLT</th>
<th>Environmental impacts cross laminated timber CLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWP climate change mitigation</td>
<td>Cross laminated timber CLT</td>
<td>Cross laminates timber CLT passive house</td>
<td>Cross laminated timber CLT positive low energy building</td>
</tr>
<tr>
<td>MTC mass timber construction</td>
<td>zero energy</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2 Selection of studies for review

To guarantee the quality of this review, only peer reviewed studies were selected. This process removed two studies from the review selection, a Masters thesis from Canada and one industry report from Australia. As this study focusses on the use of CLT in the building context, only studies that considered entire buildings were analysed in further detail. This, excluded a US study from the review. Furthermore, the quality and consistency of this review is maintained by further limiting the scope to CLT construction and so excluding an Australian study that focuses on Laminated Veneer Lumber. A final study from Germany that treats about a single dwelling house has also been excluded as it represents a unique case compared to all other studies that assess multi-storey buildings ranging from 4 to 21 levels. The nine remaining studies have been reviewed, as detailed in Table 2.
Table 2: Nine published LCA studies of CLT construction selected for review.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Author(s) (Year)</th>
<th>Title</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Robertson et al. (2012)</td>
<td>A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office</td>
<td>Canada</td>
</tr>
<tr>
<td>P2</td>
<td>Darby et al. (2013)</td>
<td>A Case Study to Investigate the Life Cycle Carbon Emissions and Carbon Storage Capacity of a Cross Laminated Timber, Multi-Storey Residential Building</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>P3</td>
<td>Durlinger et al. (2013)</td>
<td>Life Cycle Assessment of a Cross Laminated Timber Building</td>
<td>Australia</td>
</tr>
<tr>
<td>P4</td>
<td>Grann (2013)</td>
<td>A Comparative Life Cycle Assessment of Two Multi-Story Residential</td>
<td>Canada</td>
</tr>
<tr>
<td>P6</td>
<td>Skullestad et al. (2016)</td>
<td>High-Rise timber Buildings as Climate Change Mitigation Measure - A Comparative LCA of Structural System Alternatives</td>
<td>Norway</td>
</tr>
<tr>
<td>P7</td>
<td>Guo et al. (2017)</td>
<td>A Comparison of the Energy Saving and Carbon Reduction Performance between Reinforced Concrete and Cross-Laminated Timber Structures in Residential Buildings in the Severe Cold Region of China</td>
<td>China</td>
</tr>
<tr>
<td>P9</td>
<td>Teh et al. (2017)</td>
<td>Replacement Scenarios for Construction Materials Based on Economy-Wide Hybrid LCA</td>
<td>Australia</td>
</tr>
</tbody>
</table>

3. LITERATURE REVIEW

Results of all previous studies, except for some scenarios of P2 and P9, show Global Warming Potential (GWP) benefits for CLT construction compared to conventional construction. However, a comparison of final results regarding GWP from these nine papers is extremely difficult. Indeed, the difference in GWP benefits of CLT ranges from +15%, meaning that CLT buildings result in more GHG emissions than RC ones, to -278%. This broad variation is a result of variations in study parameters such as local climate, building legislation, energy mix, but also assessment methods including system boundaries, carbon estimation, data quality and overall LCA approach.

3.1 Building characteristics

The wide range of buildings assessed, as shown in Table 3, is one source of variation in the results of the various studies. Two major variables are observed, first the presence or not of a RC basement that reduces the potential GWP reduction of CLT buildings that can be achieved through reduced footings. Second, the number of levels also increases the RC share in a CLT building, since footings are dimensioned according to building height and stress load. For example, hybrid structural systems with concrete cores are often used for taller CLT buildings. Table 3 shows the mix of structural materials (CLT, RC and steel) assumed for buildings modelled in each study.
Table 3: Building details, uses and construction status of the nine published studies selected for review.

<table>
<thead>
<tr>
<th>Building details</th>
<th>Use</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 1 CLT vs. 1 RC, 5 levels, RC basement</td>
<td>100% Commercial</td>
<td>RC built</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CLT hypothetical</td>
</tr>
<tr>
<td>P2 1 CLT vs. 1 RC, 5 &amp; 8 levels, no basement</td>
<td>100% Residential</td>
<td>CLT built</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RC hypothetical</td>
</tr>
<tr>
<td>P3 1 CLT vs. 1 RC, 10 levels, no basement</td>
<td>89% Residential and 11% Commercial</td>
<td>Both built</td>
</tr>
<tr>
<td>P4 1 CLT vs. 1 RC, 4 levels, RC basement</td>
<td>100% Residential</td>
<td>CLT built</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RC hypothetical</td>
</tr>
<tr>
<td>P5 1 CLT vs. 1 Timber post &amp; beam vs. 1 Timber modular, 4 levels, no basement</td>
<td>100% Residential</td>
<td>All hypothetical</td>
</tr>
<tr>
<td>P6 4 CLT vs. 4 RC, 3, 7,12 &amp; 21 levels, RC basement</td>
<td>100% Residential</td>
<td>All hypothetical</td>
</tr>
<tr>
<td>P7 4 CLT vs. 4 RC, 4,7,11 &amp; 17 levels, No basement</td>
<td>100% Residential</td>
<td>RC built</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CLT hypothetical</td>
</tr>
<tr>
<td>P8 1 CLT vs. 1 RC vs. 1 Steel frame, 9 levels, No basement</td>
<td>50% Residential and 50% Commercial</td>
<td>All hypothetical</td>
</tr>
<tr>
<td>P9 New building stock replaced by CLT, 10 levels, No basement</td>
<td>100% Residential and 100% Commercial</td>
<td>All hypothetical</td>
</tr>
</tbody>
</table>

3.2 Regional variation

When analysing CLT buildings from the most comparable papers P2, P3 and P7, since they are mostly residential, without a basement and of similar height, one can observe that their results regarding total GHG emissions fluctuate from 0.16 tCO$_2$/m$^2$ to 5.98 tCO$_2$/m$^2$. This large variation can be explained first by the difference of climate. Operational energy (OE) demand to reach comfort in severe cold Harbin, China (P7), far exceeds that in the more temperate London, UK (P2). In addition, variation of building codes and thermal stringencies potentially escalates this variation. For example, for an external CLT wall in a cold climate (P5), under Swedish conventional design a minimum of 245mm of rock wool, estimated at R5.4, is required. In comparison, under a Chinese improved design (P7), the building requires only 50 mm of EPS, estimated at R1.78.

Finally, the energy mix for each of the locations also plays a significant role in the resultant GHG emissions. While the CLT building in P3 located in Melbourne, Australia, should benefit from a milder climate than in P2 (UK), the carbon intensity of the Victorian energy mix, mostly generated from brown coal, dramatically increases GHG emissions compared to London where coal represents less than 40% of the total energy mix, with hydro and wind representing more than 20% (Department of Energy and Climate Change, 2013). When comparing results from international studies, these regional variations are critical to consider, and furthermore, they will evolve as construction standards change, the energy mix becomes cleaner, and climate changes.

3.3 System boundary

One of the main reasons for the variation in the GHG emissions of CLT construction amongst the nine selected studies is the system boundary considered. LCA enables a holistic approach when studying the life cycle of a product, however for many studies a streamlined approach is used, excluding many life cycle stages. Table 4 shows that only four studies out of nine consider the full life cycle of the buildings, from ‘cradle to grave’. While a cradle to gate system boundary can be justified to detect carbon ‘hotspots’ at Stage A (Figure 1), the major drawback is that this can potentially lead to conclusions about the GWP benefits that can be counterbalanced in later stages of the building’s life. For example, study P3 shows that CLT construction has 30% lower GWP than RC construction at Stage A (cradle to gate). However, when considering Stages A to D (full life cycle) and EOL scenario without carbon sequestration, CLT is shown to have a GWP 15% higher than RC. This is concerning given that this information can be used to inform material choices. It is therefore critical to analyse the full life cycle implications of the use of CLT in buildings to be able to more reliably draw conclusions on the net GWP benefits of CLT construction.
Table 4: System boundary and lifetime horizon for the nine published studies selected for review.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Lifetime horizon and comments</th>
<th>Publication</th>
<th>Lifetime horizon and comments</th>
<th>Publication</th>
<th>Lifetime horizon and comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>50 years, Stage A5 excluded</td>
<td>P2</td>
<td>50 years, Stage B excluded</td>
<td>P3</td>
<td>50 years</td>
</tr>
<tr>
<td>P6</td>
<td>60 years, Stages A4 &amp; A5 excluded</td>
<td>P4</td>
<td>60 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P9</td>
<td>Not applicable, Full Stages A1 to A5 included</td>
<td>P5</td>
<td>50 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P7</td>
<td>50 years</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Note: Publication P8 doesn’t mention system boundary and lifetime horizon.

### 3.4 Assessment of carbon cycle

Amongst the nine studies reviewed, there is a clear division regarding the method used in assessing life cycle GHG emissions. Five studies out of nine consider a percentage, ranging from 0% to 100%, for carbon sequestration. Carbon sequestration is the process performed by trees in removing atmospheric CO$_2$ and storing it as carbon in wood fibres. This carbon, called biogenic carbon, is removed from the atmosphere as long as the wood product is used. According the EOL scenario, all biogenic carbon is either returned to the atmosphere (0% sequestration), and this is the case for bioenergy, or is reused in another wood product (100% sequestration) for the life of the secondary wood product. Depending on the percentage of sequestration, GHG benefits fluctuate largely and have led to confusion on the GHG emissions balance of CLT construction.

Three other studies, did a full assessment of the life cycle of biogenic carbon, two of them followed the IPCC recommendations in considering biogenic carbon as neutral GWP. Alternatively, Grann (2013) (P4), hasn’t followed the IPCC recommendations and has included the change of forest albedo at harvest site, as well as considering concrete carbonation in their RC scenario. This study also explores various EOL scenarios, including landfill, bioenergy and reusing or recycling, resulting in a thorough assessment of the biogenic carbon life cycle, which differs from most of the other studies. Compared with a sequestration percentage, which can be confusing information for decision makers, Grann’s approach in assessing the full biogenic carbon life cycle results in more accurate, detailed and valuable outcomes regarding the GWP benefits of CLT construction.

### 3.5 LCA method and data

Out of the nine selected studies, eight studies apply an LCA approach and one, P8, uses a survey approach with its conclusion limited to identifying potential ‘hot spots’ associated with CLT construction. Seven studies out of the eight that use LCA, used a process-based approach, which is often considered acceptable for comparative studies, but ill equipped to provide a comprehensive estimation of GHG emissions associated with CLT construction.
Harvey (2012) stated that ‘to rely entirely on a process-based approach will underestimate the true embodied energy and subsequent environmental burdens, since interactions beyond some relatively low order [processes] will be omitted (that is, there is a truncation error)’. This finding has also been reinforced by Lenzen and Treloar (2002) who estimated, in a comparative study of a wood frame versus RC building, that a process-based approach underestimated the GHG emissions by a factor of two, compared with an economy-wide input-output (IO) approach.

This IO method has been further developed into hybrid methods that integrate both the precision of the process-based method and the comprehensiveness of the IO method, and this is the method used by Teh et al. (2017) (P9). Unfortunately, due to the limitation of this study’s scope, the system boundary has been restricted to cradle to gate and so missed the opportunity to reveal a broader economy-wide estimation of the GHG emissions from CLT buildings.

The quality and relevance of data regarding CLT products has been an ongoing challenge evidenced by these nine studies. Since CLT is a relatively new construction material, with only a limited, but growing, number of manufacturers, data regarding its environmental performance is rare, which has resulted in approximations or considerable limitations in assessment of its environmental performance.

4. CONCLUSION

This paper has provided a review of studies on the environmental performance of CLT building construction. The review of nine studies reveals that most conclude that CLT construction results in lower GHG emissions than conventional RC construction. However, there is a wide range of results due to the variety of buildings assessed, regional variations, the treatment of biogenic carbon, LCA approach used, and data source. Only one study uses a comprehensive hybrid LCA approach, but even this study suffers from limitations, i.e. a limited scope. This study has highlighted the need for further in-depth analysis of the environmental performance of CLT construction using a hybrid LCA approach, complimented with CLT production process data, comprehensive consideration of concrete carbonation and biogenic carbon. This would provide a more realistic estimation of the potential for CLT construction to reduce GHG emissions associated with buildings. The new knowledge generated would form an important element of the decision-making process for the selection of structural materials, potentially integrated with the framework for assessing the environmental benefits of mass timber construction proposed by Crawford and Cadorel (2017).

References


