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A comparative life cycle study of alternative materials for Australian multi-storey apartment building frame constructions: Environmental and economic perspective

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ABSTRACT

The building construction sector contributes to a quarter of the total Australian Greenhouse gas emissions. These emissions are mainly attributed to the use of energy intensive materials. To achieve better environmental benefits and cost saving, the utilisation of wood-based construction materials is currently attracting attention. However, the manufacturing of engineered wood products consumes large quantities of chemicals and energy, which may have adverse environmental impacts. Therefore, a life cycle study was conducted to compare various materials for constructing the structural frame of a 4-storey apartment building compliant with the Australian building codes. Five alternatives were assessed: Laminated Veneer Lumber (LVL) manufactured from early to mid-rotation hardwood plantation logs (LVL_m), LVL manufactured from mature hardwood plantations (LVL_h), LVL manufactured from mature softwood plantations (LVL_s), concrete and steel. The functional unit was defined as the whole building structural frame. Global Warming Potential (GWP), Acidification, Eutrophication, Fossil Depletion, Human-toxicity Potential (HTP) and Life Cycle Cost (LCC) were evaluated. The LVL generally performed better than concrete and steel structural products. Particularly, LVL_m had the lowest GWP (2.84E4$\pm$233 kg-$CO_{2\text{-eq}}$) and LCC (\$128,855 $\pm$ 2797), which were less than a quarter of the concrete option. However, the usage of chemical preservatives and phenol-formaldehyde adhesive during the LVL production and treatment caused the HTP impact to be higher than the steel option. Monte Carlo Analysis showed that while the LVL options presented a higher sensitivity to the combined uncertainties, the overall ranking of the five options remained the same. Therefore, the inclusion of wood-based material in structural elements may significantly contribute to reduce the environmental impacts and the LCC of the construction sector.

1. Introduction

The Australian housing market, in particular, the mid-rise apartment buildings, is witnessing a boom due to a sustained population growth and overseas investments combined with historically low-interest rates (Australian Construction Industry Forum (ACIF), 2014). A recent research pointed out that the annual growth rate in the market of multi-level apartment buildings reached 14.5% in 2015 and further increased by 4.1% in 2016 (Australian Construction Industry Forum (ACIF), 2014). This dramatic growth is associated with a proportional increase in the environmental impacts of the sector, with the majority of emissions being attributed to the use of energy intensive materials such as concrete and steel (Cabeza et al., 2014). On the other hand, wood and wood-based structural products are promoted as sustainable and renewable building construction materials (Bribián et al., 2011) and their use has been increasing steadily over the past few decades (Wang et al., 2014). This trend is now further supported by the new Australian building code (National Construction Code Series 2016) which allows timber buildings of up to 25 m high to be designed under the 'Deemed to satisfy' provisions (Australian Building Codes Board (ABCB), 2016). With this drastic change, the

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use of wood or wood-based materials in mid-rise constructions is expected to significantly increase in the near future. However, an increase in wood uses can only be justified if there is a corresponding increase in the availability of long term sustainably managed forests (Buchanan and Levine, 1999).

Excessive logging and unsustainable forestry practices may lead to deforestation, which is a major contributor to climate change (Chakravarty et al., 2012). More than 40% of the Australian native forests were lost since the last century due to excessive timber harvesting (Bradshaw, 2012). In response to growing environmental concerns about the sustainability of forestry practices, timber plantations are currently being promoted as a long-term wood supply strategy in Australia (Bradshaw, 2012). Generally, only high-quality timber from plantations can be used to produce sawn timber for structural purposes. The low-quality logs are usually excluded due to their high proportion of natural defects (e.g. knots, grain deviation, gum veins, etc.) and reduced mechanical properties (McGavin et al., 2006). Additionally, the use of sawn timber usually has limitations, such as the unavailability of large timber sections that meet the spans required for modern building components (McGavin et al., 2006). Nevertheless, researchers such as McGavin et al. (2013), Gilbert et al. (2014, 2017) have shown that the aforementioned low-quality logs can be converted to high performing engineered wood structural sections. Engineered wood products are manufactured by bonding together wood boards, veneers, strands or flakes using adhesives to form panels or other shaped structural products (Lam, 2001; Barbu et al., 2017). By randomising wood defects, engineered wood structural products have less variability in their mechanical properties and usually higher strength than sawn timber (Barbu et al., 2017). Today, engineered wood products such as Laminated Veneer Lumber (LVL), Oriented Strand Lumber (OSL) and Cross-Laminated Timber (CLT) have gained popularity in the construction sector and are increasingly accepted as cost-competitive building materials (Mallo and Espinoza, 2015).

Wood or engineered-wood products are generally identified as the most sustainable structural materials and strongly recommended for substituting high energy intensive products in building constructions (Knowles et al., 2011; Wang et al., 2014). Increasing use of wood-based materials could reduce the net Greenhouse gas (GHG) emissions from the building and construction sector because of their relatively low energy requirement during the manufacturing stage as opposed to other building materials, such as concrete and steel (Gustavsson et al., 2006). In addition, wood substitution in long-life-span products results in accumulated carbon storage (Sathre and Gustavsson, 2009), which is seen as a potential climate mitigation strategy (Cabeza et al., 2014). An early study conducted by Buchanan and Levine (1999) indicated that for typical forms of building construction, wood buildings require significantly lower process energy and released less GHG emissions than buildings constructed from other materials such as brick, steel, and concrete. They estimated that a 17% increase in wood usage in the New Zealand building industry could result in 1.5% reduction in the national total GHG emissions. Goverse et al. (2001) claimed that 50% reduction in CO_2 emissions could be achieved technically by utilising timber as a substitute to concrete in the main and secondary structural elements in houses.

Life Cycle Assessment (LCA) is commonly used to gain a better understanding of the environmental impacts of wood-based materials, when compared to other materials, in the construction industry. Börjesson and Gustavsson (2000) conducted a comparative LCA of both wood and concrete frames in a built multi-storey building and found that the primary energy used during the production of the concrete building was 60–80% higher than the wooden one. The better performance of the wood building was attributed to the use of forestry residues in the production, as well as using the wood waste for energy recovery at the end of life. Furthermore, Börjesson and Gustavsson (2000) claimed that the environmental impact of the wood frame building strongly depended on wood handling options during the final disposal stage. Perez et al. (2009) calculated the embodied energy and Global Warming Potential (GWP) of four alternative theoretical office building designs and found that engineered wood design had the best performance compared to concrete and steel buildings. Nevertheless, only looking at a single environmental indicator, such as GWP, is not sufficient (Robertson et al., 2012). Particularly, some researchers are concerned that chemical consumption (e.g. preservative and resin) in the manufacturing phase of engineered wood products may lead to various environmental impacts related to human health or ecological concerns (Nebel et al., 2006; Rivela et al., 2007; González-García et al., 2009). The use of multiple indicators is then required to better inform the environmental decision-making process. Hence, Robertson et al. (2012) conducted an LCA study of a typical mid-rise office building in North America by including 11 environmental impact indicators such as GWP, Ozone depletion, human health, ecological toxicity, and acidification. Results showed that the laminated timber building had the lowest environmental impact in 10 out of the 11 impact categories. However, the embodied energy was almost identical to that of the concrete option, mainly due to a heavy timber-frame design and associated use of adhesive resins during the manufacture frame elements. However, Perez-Garcia et al. (2007) argued that the substitution of sawn wood joists by engineered I-joists in residential homes has very little effect on the environmental performance indices as the use of resins and energy in the latter product was offset by its greater material efficiency. Their results also showed that wooden houses have outstanding performances when compared to concrete and steel houses on embodied energy, GWP, air emission index and water emission index. More recently, Bolin and Smith (2011) also indicated that although borate-treated lumber structural frame consumed chemical preservatives, the cradle-to-grave life cycle impacts of borate-treated lumber frames were still less than that of galvanised steel frames. Their results also indicated that the lumber production and preservative treatment were not the main impactors. Similar to the findings in Börjesson and Gustavsson (2000), Bolin and Smith (2011) found that the disposal stage significantly contributed to the environmental impact in the borate-treated lumber structural frame option, particularly on GHG emission, fossil fuel use, acid rain potential and ecological impact. These impacts are attributed to the landfill construction, carbon release during wood decomposition and associated transportation process.

The economic performance of building constructions from different materials also received considerable attention (Dakwale et al., 2011). Life Cycle Costing (LCC) analysis is usually integrated with an LCA to evaluate the overall performance of the building sector. For instance, Islam et al. (2014) combined LCA and LCC analyses to evaluate the influence of alternative wall assemblages in a typical Australian double-storey townhouse. The system boundaries included the building construction, maintenance and replacement operations, and final disposal stages. However, the forestry phase was excluded in the study. In the waste disposal stage, the aged timber materials were assumed to be landfilled, without considering alternative options such as energy recovery and recycling. Nässén et al. (2012) compared the net present cost of concrete and wood buildings on the total material, energy, and carbon dioxide costs. Their results showed that the difference in material costs between the two options was small; hence it was unclear whether wood buildings would be a more cost-effective