Carbon Cequestering and Structural Abilities of Eucalyptus Cloeziana

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ABSTRACT: *In our time of urgency of climate action in the architecture/engineering/construction industry, new low-carbon building materials can very well be part of the solution, especially when these materials exhibit superior performance compared to existing materials. Low-carbon Eucalyptus Cloeziana (kloh-zee-ah-nuh), commonly known as Gympie Messmate, is a fast-growing hardwood native to Australia. Its quick growth makes it advantageous for carbon sequestering while its strength class lends itself to structural applications. Market research in the US shows a trend of growing demand for timber, especially mass timber. This is in line with SE 2050 Challenge which states that "All structural engineers shall understand, reduce, and ultimately eliminate embodied carbon in their projects by 2050". This research paper reports on applied research in which the first author, with the help of two faculty, experimented with the use of Eucalyptus to replace Douglas Fir in roof structures. A life cycle carbon analysis was conducted and resulted in defining the measurable performance of Eucalyptus Cloeziana.*

This paper investigates market potential as well as the environmental benefits and challenges to using Eucalyptus Cloeziana as a structural material for buildings. Although it may grow in the North American climate, Eucalyptus is currently not commonly found in the US. It grows and is commonly used in Australia, where its manufacturers provide the necessary environmental impact information in the standard format of an Environmental Product Declaration (EPD). An EPD follows a product throughout its life cycle, including values for global warming potential, ozone depletion potential, acidification potential, eutrophication potential, photochemical ozone creation potential, and abiotic depletion potential. The author used the material's EPD to conduct a comparative study, in which the performance of Eucalyptus was compared to the structural use of steel and Douglas Fir, using data of the same geographical region. The case study demonstrates the comparative properties and performance of Steel, Douglas Fir, and Eucalyptus in terms of embodied carbon and structural weight within a single structural bay. Although Eucalyptus has higher carbon content (negative carbon) than Douglas Fir per weight, the study showed that because the softwood system requires larger volume of wood than the hardwood system, the Eucalyptus structure weighs less than Douglas Fir. Because softwood sequesters more carbon due to its slow growth, Douglas Fir sequesters more carbon per structural bay. Eucalyptus sequesters less carbon (per structural bay) but since it grows twice as fast compared to Douglas Fir, it has market advantages that are not measured by the simple metric of embodied carbon.

KEYWORDS: decarbonization, sustainability, structural systems, eucalyptus cloeziana, life cycle analysis.

INTRODUCTION

Carbon dioxide is one of the major emissions causing global warming, and it is estimated that the built environment accounts for approximately 39% of global carbon emissions, with approximately 28% coming from building operations and 11% from the building materials and construction (Architecture 2030 2021). Lowering the embodied carbon in building materials is essential to reaching zero-carbon by 2050. This paper addresses embodied carbon in the structural system and tests the hypothesis that the use of E. Cloeziana in timber construction will reduce the total embodied carbon of the structural system. According to market survey conducted by the American Institute of Steel Construction (AISC), the use of timber is on the rise, which is now approximately at 10% of market share, up from around 7% in 2009. The use of concrete is also on the rise, while structural steel and masonry are on the decline (AISC 2020). This transformation in the market is partially due to the 2021 International Building Code (IBC) update, the rise of biophilic design, and the climate crisis as a threat to future generations. In the latest update of the IBC (2021 Edition), mass timber buildings are now allowed to reach up to 18 stories (ICC 2021). Wood is also a commonly utilized strategy of biophilic design which improves the quality of a space. Incentive programs such as WELL and LEED rating systems reward healthier and more sustainable projects, providing a metric for designers to aim for. It is worth noting that architects are not the only professional group promoting zero carbon. Structural engineers set up their own initiative, the SE2050 Challenge, which states "All structural engineers shall understand, reduce, and ultimately eliminate embodied carbon in their projects by 2050" (Simonen, 2021). Structure accounts for up to 80% of the embodied carbon in the building envelope (ULI 2020) and if it is built using low embodied carbon materials, the result will be a significant reduction in the building's overall embodied carbon. While foundation systems are primarily concrete, a material with a large amount of embodied carbon, the rest of the systems can be offset with low-carbon materials.

1. TIMBER CONSTRUCTION

The construction industry is always evolving and accepting new materials. Now, we have engineered wood products (EWPs) that can rival the strength of steel. Cross-laminated timber (CLT) offers increased strength, longer spans, and shallow depths, benefits which were previously only attributed to steel. CLT can even be more sustainable when made of lower grade wood that is not normally used in construction, as CLT assemblies can be made of any of the softwood species recognized by the American Lumber Standards Committee where it conforms to ANSI/APA PRG 320 (APA 2019). Other EWP products are available, such as, but not limited to, nail-laminated timber, dowel-laminated timber, glulam, and parallel strand lumber. However, a barrier to increasing timber market share is the concern over life safety and fire protection. Heavy and mass timber construction both have a natural defense against fire due to the volume of the wood itself, forming a protective char barrier on the outside while the interior is preserved, maintaining some structural capacity. For example, some CLT wall assemblies can achieve a fire rating of three hours (McLain 2021). Another concern over the use of wood is the cost, when compared to low budget construction types such as masonry, prefabricated metal buildings, and concrete. On the other hand, wood is still an attractive material for construction because it is lightweight, adjustable, and available almost anywhere in North America.

2. EUCALYPTUS CLOEZIANA

2.1 History of use

Eucalyptus Cloeziana, commonly called Gympie Messmate, has been grown in Australia for construction purposes for many years. It is currently used in home framing, flooring, exterior cladding, and furniture. As the timber is naturally resistant to decay, it lends itself to exterior construction such as wharf and bridge construction, railway sleepers, mining timbers, transmission poles, landscaping, and retaining walls (DOA 2013).

2.2 Present day use

Eucalyptus Cloeziana is suitable for many product types, as sawn lumber, veneer-based panels, and round poles (DOA 2013). Today, it is grown around the world and has plantations in China, Sri Lanka, Brazil, and several African countries such as Congo, Kenya, Malawi, Nigeria, Zimbabwe, Uganda, and Zambia (Harding et al 2012) and (Atyeo et al 2008). A Netherland-based company, Gessel Senel Timbers (GS Timbers) has been providing E. Cloeziana across Europe, claiming to have discovered a method of sawing the material into dimension lumber. Their catalogue explains the forestry operations of harvesting, sawmilling, and processing, and their plantations are certified by the Forest Stewardship Council (FSC) under a larger group of companies, Phylum B. V. The company discovered that E. Cloeziana is a fast-growing timber, providing an alternative to endangered hardwood species. Where it is one of the heavier and stronger species of Eucalyptus, it performs well in heavy construction. They offer it in both poles and sawn lumber dimensions (GS Timbers 2019), with poles being most efficient use of the lumber, where the only machining applied is debarking (TU Delft 2009). E. Cloeziana is also readily adjustable in the field, it saws, machines, dresses, and dries easily (DOA 2013) and (Atyeo et al 2008). This, along with its potential in engineered wood products, shows potential for construction.

3. ENVIRONMENTAL PERFORMANCE

3.1 Environmental product declaration comparison

An Environmental Product Declaration (EPD) is a tool to compare the environmental impact of a product throughout its entire life. The main categories for comparison are global warming potential, ozone depletion potential, acidification potential, eutrophication potential, photochemical ozone creation potential, and abiotic depletion potential. Global warming potential refers to the total carbon and greenhouse gas emitted from the creation and use of the product. Ozone depletion measures the ozone layer damaging gases while acidification measures acidic gases. Eutrophication measures the nitrates and phosphates that would be released into the water in a system. Photochemical ozone creation refers to nitrogen oxides and VOCs that cause smog, and abiotic depletion refers to the use of non-renewable resources (Rockpanel 2021). For the case study that follows, Eucalyptus, an Australian hardwood, is compared with softwood and steel declarations in the same region. Both wood EPD's are based on an industry standard across multiple companies instead of a specific product while the steel EPD is based on all hot-rolled products within a single company. Of the nine hardwood companies that provided measured data for the EPD, all of them produced Gympie Messmate (Wood-Solutions 2017). All three of the declarations focused only on the production and end of life stages of the material, as use of the product wouldn't affect any of the above categories, and the impact of transporting material depends on the location of the project.

The global warming potential for producing one kilogram of sawn hardwood and softwood is negative because the trees absorb carbon over their lifetime, offsetting the carbon created during production. Thereby creating a total of -1.1 kg of carbon dioxide for the hardwood and -1.4 kg for the softwood (Wood-Solutions 2017). Conversely, steel has a much higher value because producing an equivalent amount of steel produces 3.3 kg of carbon with no offsetting (Fig. 1) (Liberty GFG 2016). The energy required to produce the kilogram is lowest in hardwood at 20 MJ, surpassed by softwood with 25.3 MJ, and topped by steel at 37.5 MJ (Fig. 1). The water used in production follows the same pattern as the energy required, hardwood needing 1.5 kg of water, softwood needing 1.8 kg, and steel requiring 9.4 kg (Fig. 2). The water for producing the wood does not account for the water used in growing the timber, which is known as green water consumption, in the forest/plantation hardwood requires much more than the softwood, 1155.3 kg compared to 547.4 kg (Fig. 2).

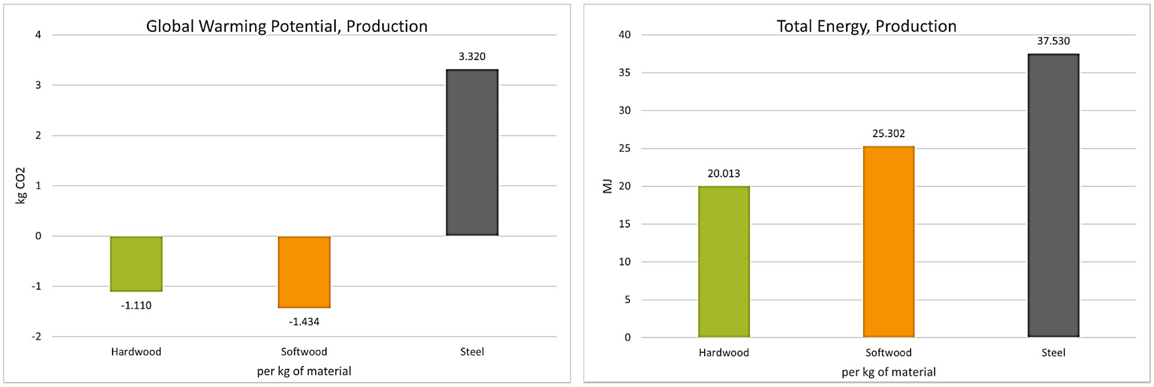


Figure 1: Global warming potential (left) and total energy in production (right) per kg of the material.

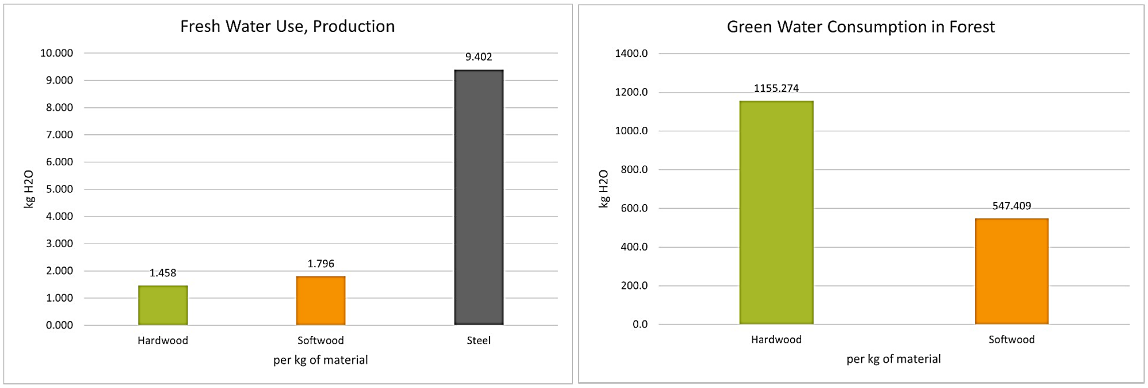


Figure 2: Fresh water use in production (left) and green water consumption in forest before production (right) per kg of the material.

At the other end of the life cycle analysis, the products are given an assortment of options as to their end-of-life stage. In Australia, hardwood has five options: energy recovery, recycling, reuse, landfill (typical), and landfill (NGA). Energy recovery is described as shredding and combusting the wood, replacing coal in the power grid. Recycling is the process of turning old wood into woodchips. Reuse is taking the material and directly reusing it without further processing. The two landfill options are based on bioreactor lab research, accounting for a certain amount of the carbon being degradable. The NGA value comes from Australia's National Greenhouse Accounts and is associated with the degradation of lumber in anaerobic conditions (Wood Solutions 2017). The softwood shared the same end-of-life options as the hardwood, excluding reuse. Steel had two options: disposal and recycling; recycling accounts for the scrapping and repurposing of steel while disposal refers to steel that ends up in the landfill (Liberty GFG 2016) Only the recycling and reuse modules have been compared in the end-of-life scenarios, as they were the common options. The global warming potential is least in recycled softwood and highest in recycled steel. The recycled softwood produced .1 kg of CO2, reused hardwood produces 0.2 kg, recycled hardwood 0.4 kg, and 1.2 kg were produced with recycled steel (Fig. 3). As for energy used in the end of life, reused hardwood is the least with -1.2 MJ, recycled softwood is next at -0.1, then recycled hardwood with 0.5 MJ, and steel uses the most with 15.3 MJ (Fig. 3). Freshwater use is the least in reused hardwood and the most in recycled steel. The reused hardwood uses -0.9 kg of water, recycled hardwood uses 0.7 kg, recycled softwood uses 0.8 kg, and steel uses 7 kg (Fig. 4).

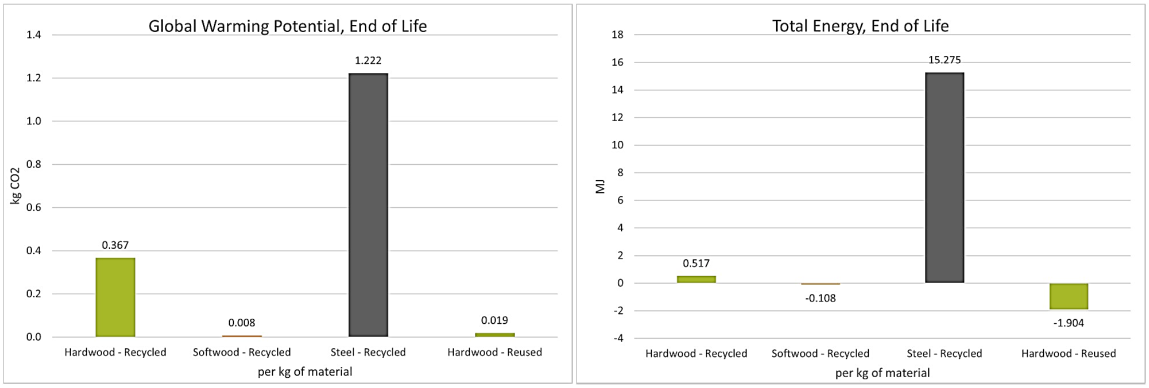


Figure 3: Global warming potential (left) and total energy (right) at end of life per kg of the material.

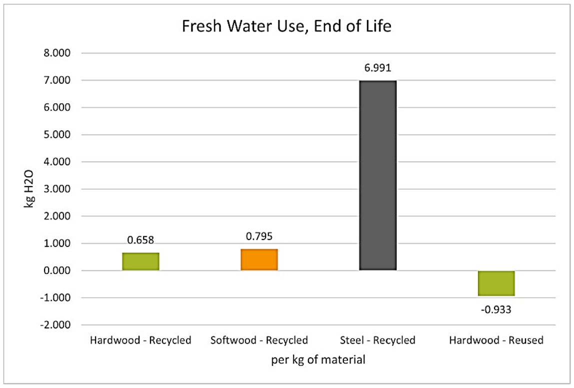


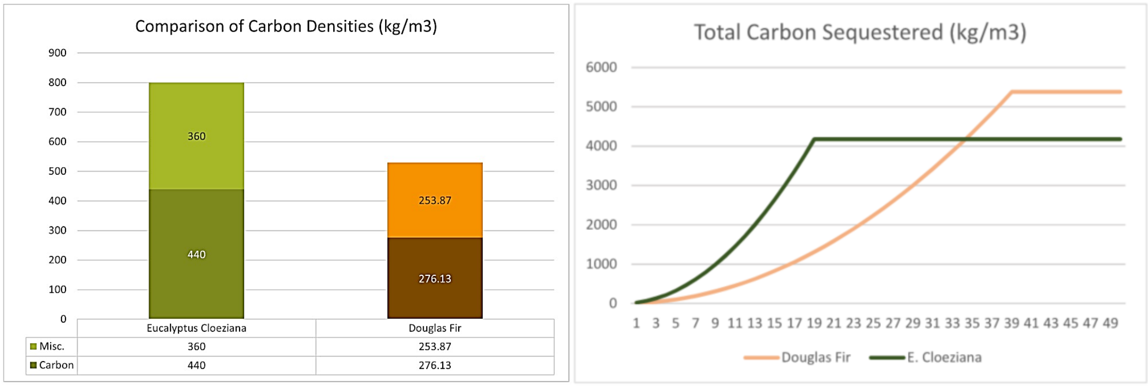
Figure 4: Fresh water use at end of life.

3.2 Carbon sequestering potential

Carbon sequestration is the process by which plants take CO2 out of the air and create useful biomass. At harvest, the lumber of American softwood species contains 52.1% carbon (Birdsey 1992), and E. Cloeziana's contains 55% carbon (DOA 2013). With an average carbon percentage, the densities of two species can be used to compare the amount of carbon in each (Fig. 5). The average air-dry density for Douglas fir, a typical structural timber, clocks in at 530 kg/m3 (33 lb/ft3) (The Engineering toolbox 2021). At 52.1%, 265 kg/m3 (16.5 lb/ft3) of the fir tree is carbon. Plantation-grown E. Cloeziana has an average density of 800 kg/m3 (46.8 lb/ft3) (Business Queensland) with 440 kg/m3 (27.5 lb/ft3) being carbon. Comparing the two numbers, the Eucalyptus contains 110 kg/m3 (6.9 lb/ft3) more carbon than the Douglas fir. The speed at which each species matures is another important factor when comparing the carbon sequestering potential.

3.3 Growth speed

Douglas Fir takes 40-60 years before it can be harvested for lumber (Loucks 2021) whereas E. Cloeziana can be harvested starting at 20 years (DOA 2013). If both trees are planted at the same time, the Cloeziana sequesters more carbon in 20 years than the Douglas fir does in 40, as shown in Figure 5. If continuously planted and harvested in a plantation, the accumulated carbon in the Eucalyptus plantation is exponentially higher than the fir plantation. To find the carbon sequestering rate, the total carbon at the end of the tree's life is divided by the years it takes to grow it, e.g., fir takes forty years to be harvested, and will contain 276.1 kg/m^3 of carbon at that time. 276.1/40 gives it a rate of 6.9 kg/m^3 of carbon absorbed per year. This does not accurately represent the actual rate of carbon sequestration throughout a tree's life, it simply provides a means of comparing the carbon in each species over time. The quick growth of the Cloeziana also bolsters the timber, for its shorter juvenile phase means it reaches its mature mechanical properties quicker than other eucalyptus species (Bailleres et al 2008). E. Cloeziana has clear advantages due to quick growth, especially when evaluating from a quicker replenishment potential.



Carbon measured assuming 1 tree/year planted, with a calculated rate of sequestered carbon per year based on [(440 kg/m3)/(20 year)] for E. Cloziana and [(276.13 kg/m3)/(40 year)] for Douglas Fir, or 22 kg/m3/year/tree and 6.9 kg/m3/year/tree, repectively.

Figure 5: Carbon densities (left) and carbon sequestered per year (right) in kg/m3 of Eucalyptus Cloeziana & Douglas Fir

3.4 Durability class

Gympie messmate produces wood rated durability class 1, lasting more than 25 years below ground and over 40 years above ground. The five classes are defined according to the EN 350-2 standard, with 1 being the most durable and 5 being the least (BSI 1994) (Wild Deck Company 2021). Along with resisting natural decay, E. cloeziana is resistant to Lyctine borer and termite attacks (DOA 2013). Native grown timber typically has better structural properties than the plantation grown timber of the same species, however the plantation grown trees show equivalent performance (Bailleres 2008) and the only major difference is the plantation trees typically have a smaller log size on average (Harding et al 2012).

3.5 Strength class testing and results

After cyclone Larry, felled trees of multiple species were gathered for strength testing, noting that while the wind had snapped most trees along their trunk, the Cloeziana trees were intact, having been pulled up with their root ball still whole (Francis et al 2008). In testing the strength of hardwoods, EN 338 has a range of standards for timber strength. These classes range from C14-C50 for softwood species, and D30-D70 for hardwood species. To qualify for a strength class, the species must meet the minimum values for strength, stiffness, and density (Lawrence 2005). One issue with the strength class system is that while it works well for softwoods, hardwood species may fit into one class for bending, but its lower stiffness and density means it must be placed in the class below it (Lawrence 2005).

After thorough testing by the FWPA (Forest & Wood Products Australia) and Delft University of technology, courtesy of GS Timbers, E. cloeziana was given a strength class of D50. The D50 strength class boasts a modulus of elasticity of 19,800 N/mm2 (2,871,747 psi), a modulus of rupture of 89 N/mm2 (12,908 psi), and a density of 656 kg/m3 (40.95 lb/ft3) The paper goes on to say that for design that only depends upon bending strength, the fm,k and E values for strength class D70 can be used (TU Delft 2009).

4. POTENTIAL FUTURE USE

4.1 Veneer-based composites

Looking into the future of construction, E. cloeziana shows potential for use in engineered wood products. For veneer-based engineered wood products, it was shown that E. cloeziana could produce twice as many usable veneers than another Eucalyptus species (Atyeo et al 2008). Veneers from Gympie messmate had previously been graded and used in plywood panels, and testing these panels resulted in them being placed between the F22 and F27 stress grades (Harding et al 2012). For comparison, pine plywood lands itself in the F14 grade (Atyeo et al 2008). Table 5-1 from the SAA Timbers gives measured values for these grades, with F27 having almost twice the bending capacity that F14 does (Table 4 (SAA 1988), showing that cloeziana plywood has potential for heavier construction applications.

4.2 Engineered beam

While the veneer-based wood products in Harding's report were being tested for E. Cloeziana, the wood was also being tested for its potential in glue laminated beams. Four beams were created and tested for strength, stiffness, and bending. The beams ended up fitting into the GL10 glulam rating. All beam samples also passed the requirements for bonding (Harding et al 2012), proving E. cloeziana has potential for engineered beam products.

5. CASE STUDY

5.1 Introduction

The case study is a fire station, focused on a singular structural bay. The dimensions for the bay are 24'–0" by 48'-0", spanned by semi-bowstring trusses in the 48-foot direction and purlins in the 24-foot direction, as shown in Figure 6. The lateral force resisting systems are specially reinforced masonry walls, leaving gravity loads to the roof framing. To compare the 3 different materials, 3 corresponding models were created in RISA 3D structural analytical design software, in which only the trusses and purlins will be compared (Fig. 6). To account for the curved roof diaphragm, dummy members had to be placed in the model and given the designation of RIGID so RISA would not design them. In the steel model the beams were placed at 6'-0" on center while both wood models had the beams set at 4'-0" on center. The dead load is comprised of the roof sandwich and the building systems while the live load is a standard 20 psf for roof loading from ASCE 7-10. The roof is comprised of metal roof panel, vapor barrier, rigid insulation, and structural oriented strand board (OSB) for the two wood models, and metal roof decking in place of the OSB for the steel model. The building systems include ductwork, sprinklers, lights, lath ceiling, and collateral loading; in total the wood models had a dead load of 1220.9 Pa (25.5 psf) and the steel model had 1175.5 Pa (24.55 psf).

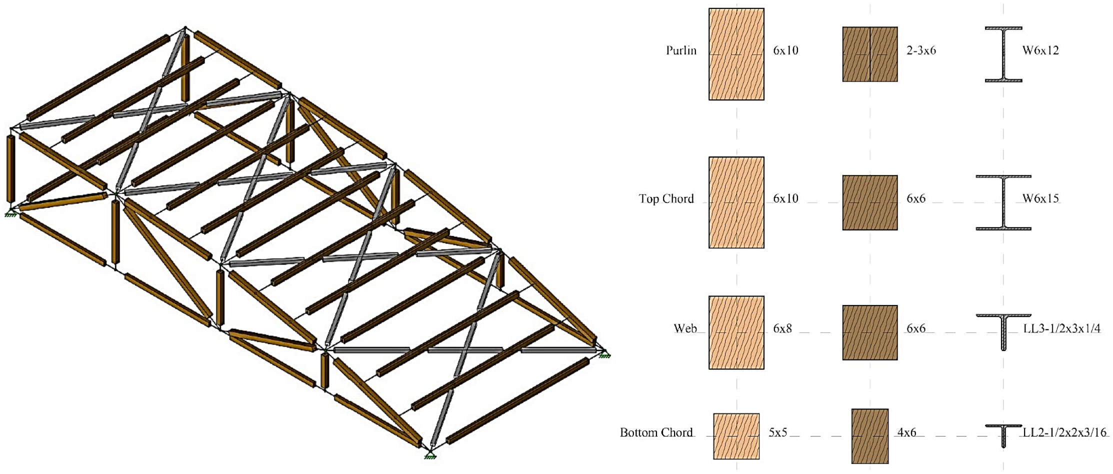


Figure 6: Bay model (left) and member sizes (right) showing the same truss design for the three materials.

5.2 RISA output

The bay models were put into the structural analysis program RISA and had parameters set to find the most economical size by beam, top chord, web, and bottom chord. As a result, the Douglas fir model returns a purlin and top chord size of 6x10, web size of 6x8, and a bottom chord size of 5x5. The E. cloeziana has a purlin size of 2-3x6, top chord and web size of 6x6, and a bottom chord size of 4x6. The steel has a purlin size of W6x12, the top chord is a W6x15, the web is a LL 3 ½ x 3 x ¼ and the bottom cord is a LL 2 ½ x 2 x 3/16. The steel model required the web and bottom chord members be changed to double angles as they were bottoming out at the smallest wide flange shape. The member shapes are visually compared in Figure 6.

5.3 Embodied carbon and structure weight

To meet the required stiffness, the Douglas fir required much thicker members, where the Eucalyptus and steel did not. In comparing the total weight of the structure for the bay, the Eucalyptus ended up at the lightest with only 2138 kg (4715 lbs.) of wood, with steel following closely at 2661 kg (5868 lbs.) and tailed by the Douglas fir with a total weight of 2999 kg (6614 lbs.) (Fig. 7). Despite the steel having a lighter dead load with the decking, it was not the lightest structural system. The weight of the eucalyptus required for the structure is only 70% of the required weight in fir. When comparing the carbon that's been created in the production of the structure, steel leads the way at 8835 kg (19481.76 lbs.) of CO_2, cloeziana is second with -2373 kg (-5233.65 lbs.), and Douglas fir has the most offset with -4301 kg (-9484.23 lbs.) (Figure 8). The embodied carbon of each system is calculated by multiplying the factors found in the production module of each EPD by the total weight of the structure. The global warming potential for each material was converted to kg of carbon dioxide per kg of material. Therefore, multiplying the total weight of each structural system by their corresponding embodied carbon factor, the total carbon of each system could be quantified. Only the value for production was used since no demolition plans would be specified. When comparing the two wood species, the Douglas fir structural system offsets more carbon than the eucalyptus system, explained by the difference in required weight between the two structures. The softwood system requires more wood than the hardwood system does, therefore sequestering more carbon (Fig. 8). When faced with these numbers it is important to remember the efficiency of a structural system, the quick growth speed of the eucalyptus, and the cost of material. The growth rate compared to traditional wood species used for construction would increase the supply to meet the increased demand, therefore bringing prices down.

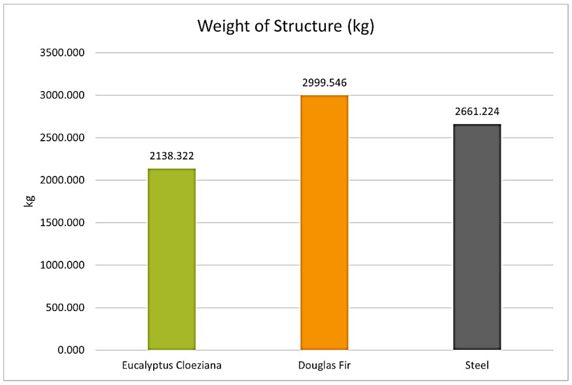


Figure 7: Weight of structure

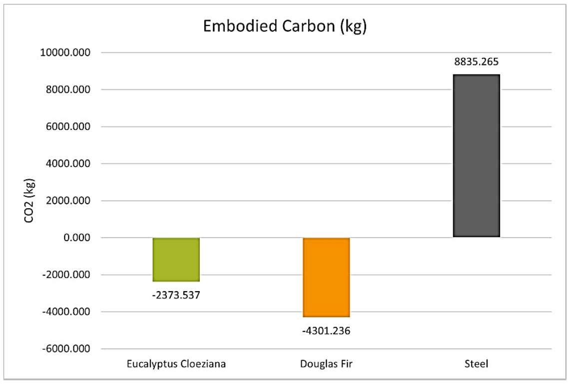


Figure 8: Embodied Carbon

CONCLUSION

Although the Douglas Fir option in the presented case study is shown to have the least amount of embodied carbon based on production, the use of Eucalyptus cloeziana should not be discounted. When considering the comparable amount of sequestered carbon and the shorter growth and harvest cycle of E. cloeziana, it can be seen that there are merits to this material that are not reflected in simply looking at the embodied carbon value. One issue is that this study highlights is the inadequacy of embodied carbon values, which focus on production alone, to reflect the environmental impacts of land use, water use, amount of material used, sequestered carbon, and growth/harvest cycles in the consideration of structural materials and their environmental impacts. To address this, further study would be required, with the possibility of devising additional metrics for these factors. It should be mentioned that some of these factors may shift some of the balance to the benefits of steel as well as E. cloeziana. However, as can be seen from the study, E. cloeziana has the potential to be a viable and sustainable option for building structure.

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