**Economic and Environmental life cycle perspectives on two-engineered wood products: comparison of LVL and GLT construction materials**

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**Abstract**

The embodied carbon of building materials and the energy consumed during construction have a significant impact on the environmental credentials of buildings. The structural systems of a building present opportunities to reduce environmental emissions and energy. In this regard, mass timber materials have considerable potential as sustainable materials over other alternatives such as steel and concrete. The aim of this investigation was to compare the environment impact, energy consumption and life cycle cost (LCC) of different wood-based materials in identical single story residential buildings.The materials compared are Laminated Veneer Lumber (LVL) and Glued Laminate Timber (GLT). GLT has less Global warming potential (GWP), Ozone Layer Depletion (OLD), and Land Use (LU), respectively by 29%, 37% and 35% than LVL. Conversely, LVL generally has lower Terrestrial Acidification Potential (TAP), Human-Toxicity Potential (HTP), and Fossil Depletion Potential (FDP) respectively by 30%, 17% and 27%. The comparative outcomes revealed that using LVL reduces embodied energy by 41%. To identify which of these materials is the best alternative various environmental categories, embodied energy, and cost criteria require further analysis. Therefore, the Multi-Criteria Decision Making (MCDM) method has been applied to enable robust decision-making. The outcome showed that LVL manufacturing using softwood presents the most sustainable choice. These research findings contribute to the body of knowledge about the use of mass timber in construction.

**Keyword:** *Glued laminated timber (GLT); Sustainability; Laminated veneer lumber (LVL); Multi-Criteria De*cision Making*; Life cycle cost; Life cycle Assessment;*

1. **Introduction**

Using renewable materials to reduce environmental emissions in the building industry has attracted increasing attention in developed and developing countries. In this regard, low-carbon materials and technologies play an important part in achieving this goal (Hernandez et al., 2019). To improve environmental benefits and generate cost savings, the use of wood-based construction materials is currently attracting attention (Lu & El Hanandeh et al., 2019). Wood materials are regaining popularity in the building industry in many countries because of their life cycle environmental benefits compared to buildings with concrete and steel structures (Tavares et al., 2019). Different mass timber materials and techniques are available, leading to different environmental impacts. The mass timber industry, construction clients as well as construction contractors are seeking evidence-based research to assist in evaluating these materials and distinguish their differences. However, few studies compare the life cycle assessment (LCA) and life cycle cost (LCC) of different mass timber and wood construction materials. Mallo et al. (2015) indicated that the level of awareness in the architecture industry about mass timber is low with only 4.3% of 351 respondents being "very familiar" with the approach. On the other hand, different mass timber products are available with various environmental impacts, economic costs and embodied energy. This study assesses the two most popular mass timber materials for residential buildings and considers different environmental emissions and economic aspects.

The construction industry is one of the largest emitters of carbon into the atmosphere. In recent years, the world has become conscious of environmental issues, specifically climate change (Chen et al., 2022a). The main advantage of applying wood or mass timber as a building material is its potential to sequester the carbon and eliminate it from the atmosphere (Hill & Dibdiakova, 2016; Pierobon et al., 2019). It is noteworthy that producing wood materials generates much lower emissions than other materials such as steel and cement (Ortiz et al., 2009). For example, replacing a cubic meter of concrete with a cubic meter of wood will lead to saving a 1,000 Kg CO2 emission (Gustavsson et al., 2006; Ramage et al., 2017; Liptow et al., 2018). The process of producing one tonne of steel requires 24 times more energy than wood. Thus, the wood manufacturing process is extremely energy-efficient compared to many other building materials (Wood: Sustainable Building Solutions, 2012, p. 5). The embodied energy of construction projects is considered as a measure of sustainability (Taffese & Abegaz, 2019). Previous research confirms that wood-based materials have a lower environmental impact and embodied energy compared to concrete and steel (Laguarda Mallo & Espinoza, 2015; Gustavsson et al., 2010; Wang et al., 2014). This research assesses two commercially available mass timber products as building materials.

Mass timber products such as laminated veneer lumber (LVL) and glued laminated timber (GLT) are potentially able to raise the value of traditional wood materials. They are simpler to install, have lighter structures, high strength, better aesthetic features, save energy, and other environmental benefits compared to concrete and steel (Jayalath et al., 2020). The use of wood (and mass timber in particular) has become more prevalent in the construction industry lately (Kremer & Symmons, 2015). This has encouraged architects and engineers to specify wood (Balasbaneh et al., 2018a; Buchanan et al., 2008; Ip & Miller, 2012). Using mass timber products such as GLT and LVL has gained popularity in recent years around the world. In 2018, the Washington State Building Council approved a wooden building 18 stories tall (Forterra, 2018).

Literature on wood and concrete or steel as alternative structural materials is available (Balasbaneh et al., 2018b). For example, Balasbaneh et al., (2017a) assessed five different types of hybrid wood structures. They showed that steel stud and wood presented the lowest CO2 emissions. Also, a variety of studies have been conducted to compare wood materials with other construction materials (Jayalath et al., 2020). Wood-based buildings are generally regarded as carbon efficient solutions. However, the impact of ancillary materials such as glue and insulation can influence the overall results. Some other studies have investigated the use of types of mass timber such as GLT. For instance, Risse et al., (2019) used LCA and LCC to analyze the recycling of recovered solid construction wood into GLT products. Their results show that recycling recovered wood is environmentally and economically beneficial compared to incineration. Bowers et al., (2017) conducted a LCA study of GLT, revealing that the production of glulam contributed 50% of GLT emission. Balasbaneh & Sher (2021) evaluated the sustainability performance of two prominent mass timber products: cross-laminated timber (CLT) and GLT. Their results indicated that, despite GLT outperforming CLT in areas such as human toxicity, fossil depletion, and cost, CLT was the sustainable choice overall.

Other research has focused on LVL as a building material. For instance, Lu, et al., (2017a) used LCA to study LVL, steel, and concrete. Their results showed that LVL performed better than steel and concrete as a structural material. In addition, LVL was the most cost effective option. Tellnes et al.(2006) also used LCA to assess a six-story building using GLT as posts and beams, LVL as flooring and concrete and steel foundations and elevator shaft. They showed that steel and concrete emit about 35% more Global warming potential (GWP) than the wood materials. Robertson et al., (2012) assessed two alternatives: a reinforced concrete frame with CLT and a glulam hybrid design with a boundary of cradle to construction site. Their results indicated that the laminated wood building had a lower environmental impact. Balasbaneh et al. (2017b) proposed a new composite approach combining GLT with steel studs and LVL with steel studs as building beams and columns. They showed that the new approach had lower GWP emissions than concrete. Dodoo et al., (2014) assessed the carbon implications of two different versions (conventional and low-energy) of three different timber multi-story building systems including massive wood building (implementing CLT elements), beam-and-column (applying glulam and LVL), and buildings made of prefabricated modules (using lightweight volumetric elements). Their results indicated that the low-energy version of the CLT building and the conventional version of the beam-and-column building contributed to the minimum and maximum life cycle carbon emissions, respectively. In another study, Balasbaneh, et al., (2018c) assessed five different building structural designs combining wood with concrete, steel or engineered wood. The composite wood and steel structure were found to have lower environmental emissions and costs.

The aforementioned literature has shown that the environmental impacts and embodied energy of wood and mass timber are considerably lower than alternatives such as steel and reinforced concrete. LVL and GLT have gained popularity in the construction industry as building materials and are increasingly accepted as cost-competitive building materials (Mallo, et al., (2015). Nevertheless, there are no studies that identify the differences between GLT and LVL. Most studies compare different mass timber materials such as LVL and GLT with alternatives (such as steel and concrete) to highlight mass timber as the best choice with a lower environmental impact (Lu, et al., 2017a; Andersen et al., 2022; Chen et al., 2022b; Teh et al., 2017). Other research is not comprehensive, being limited to embodied energy (Ramage et al., 2017). It is still unclear which of these two materials (LVL and GLT) are the most sustainable choices for columns and beams. Thus, this research bridges this gap by comparing these two-engineering woods from the perspective of embodied energy, environmental impact, and economic aspects. Two different species namely, softwood and hardwood, have been considered for the manufacture of LVL and GLT. The aim of this study is to reveal the environmental impact, cost-savings and energy efficiency of the two mass timber applications for residential building.

1. **Method**

The methodology used for this assessment is divided into four discrete sections: (i) estimation of six different environmental impacts; (ii) evaluation of embodied energy; (iii) evaluation of design strategies through LCC analysis; (iv) multi-criteria decision-making (MCDM) Weighted Aggregated Sum Product Assessment (WASPAS). Figure 1 illustrates the methodology used in this research (Luthin et al., 2021). It guides the evaluation of the environmental sustainability of the two different construction materials considered here. The materials are GLT, as used in onsite construction, and LVL when used in prefabricated prefinished volumetric construction.

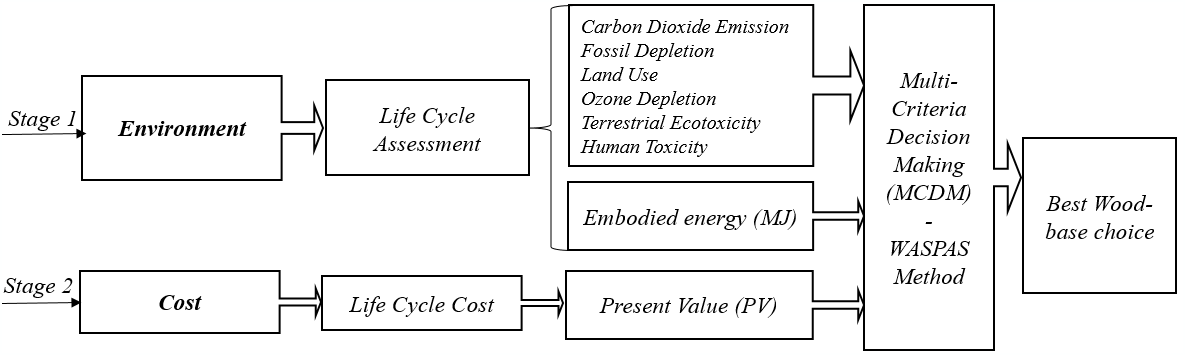


Figure 1. Systematic steps of this research

Figure 2 shows the system boundaries that correspond to the lifecycle stages of buildings. They consist of different stages of the building during its lifespan and accord with the EN15804 and EN15978 standards (European Committee for Standardization, 2011). Based on EN15804, to analyze the materials, appropriate system boundaries A1, A2, A3, A4, and A5 are compulsory and other stages are arbitrary. To comprehensively compare LVL and GLT, this study addressed the production stage (A1, A2 and A3) and the construction stage (A4, A5). Other relevant stages include maintenance (B2), end of life (C1, C2, C3, and C4), and finally, the benefit phase (D1, D2, D3, and D4). Computation of the total embodied energy includes the processes which are noted (X) in Figure 2. Life cycle analyses were conducted within the boundaries of the production and construction, maintenance End of Life (EOL) stages.

This study did not include the life cycle phases B1 (use), B5 (refurbishment) and B6 (operational energy), which fall outside the scope of this study. At the time of the study, phase B6 (operational energy) had not been assessed, and therefore was outside the scope of the study. For simplicity, we assumed both materials are mass timber and their operational energy was eliminated from the LCA evaluation.

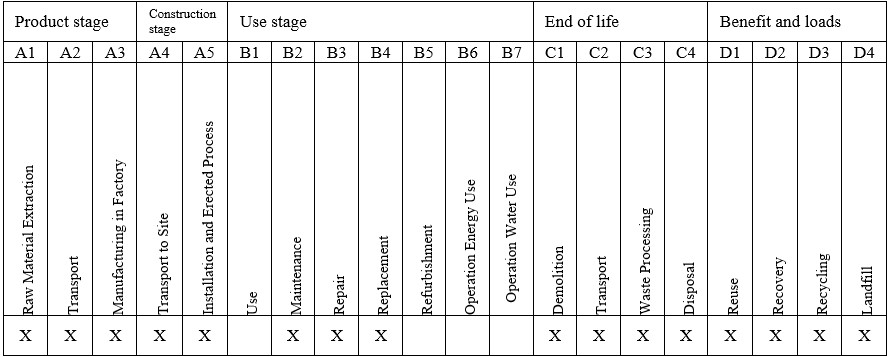


Figure 2. Building's life cycle stages from EN15804 and EN15978

* 1. ***Life cycle assessment***

LCA is widely accepted as the most suitable method for evaluating the environmental impact of processes and products. It can be applied to the building industry during all life cycle stages (Scheepens et al., 2016). In this research, Simapro software (PRé, 2010) was used to analyze materials' different environmental emissions and embodied energy. The LCA evaluations were applied in compliance with the norms prescribed in ISO 14040 (2006) and ISO 14044 (2006). A functional unit needs to be defined in any LCA study to show that comparison between different alternatives is valid. The functional unit in this study was one m2 of a wall component over 50 years (Rashid et al., 2017), which is based on prior studies (Bergman et al., 2016).

* + 1. ***Life Cycle Inventory***

An important step of any LCA methodology that encompasses producing an inventory of input and output flows such as raw materials and energy is the Life cycle inventory (LCI). This stage can be interpreted as the data collection stage of a LCA study. Thus, LCI analysis quantifies all the raw materials, electricity, diesel, and similar resources needed to produce the final goods. In addition, it assesses all the substances released into the environment as pollutants. Data for this study were collected in Kuala Lumpur, a large city located in Malaysia. These data were gathered with the assistance of contractors’ employees during visits to factories and construction sites. These were supplemented with searches on the Internet, in journals, and literature.

The LCI assessment was conducted using the [Ecoinvent version 3 database](https://www.sciencedirect.com/topics/engineering/ecoinvent-database), which is a worldwide database (Frischknecht & Rebitzer, 2005). The waste for all scenarios was considered to be 5% on average for the materials used in the construction stage. The source of electricity in Malaysia is different from European countries. In Europe it may come partially from renewable energy which has an impact on the total emissions for production. According to Dixit (2017), different fuels such as coal or renewable resources may have different impacts and emissions in relation to GWP or embodied energy. Therefore, making adjustments for this issue is vital for a reliable LCA result. In Malaysia more than 90% of power is sourced from coal or from other non-renewable energy sources. Fossil fuels are the main source of electricity generation in Malaysia (The Malaysian electricity generation, 2014). The Ecoinvent database has been adapted to Malaysia by replacing the local electricity mix data set as suggested by Horváth & Szalay,(2012). Supplementary data were sourced from the Ecoinvent database and adapted to the Malaysian MY-LCID (Life Cycle Inventory Database for Malaysia) database by replacing the local electricity mix data set following Horváth and Szalay (2012). In this study, 15 MJ/m2 of diesel and 2 kWh/m2 of electricity were assumed for construction. The type of adhesive used was phenol resorcinol formaldehyde (Konnerth et al., 2016).

* + 1. ***Life Cycle Impact Assessment***

Life Cycle Impact Assessment (LCIA) is the stage defined by ISO 14040 as analyzing the environmental impacts of the inputs from LCI (Henkel, 2005). LCIA aims to quantify and understand the significance of the possibility for environmental impacts of materials during their entire life cycle. The LCIA stage provides a bridge between LCI and LCA results. Several LCIA methods have been proposed and applied to evaluate products under different circumstances. Some only present a single issue or address European conditions. In this study, environmental analysis was based on the LCA with the ReCiPe method. This approach is recognized globally to reflect the impact of the different mass timber products. The LCIA estimated the impact of products according to various indicators such as Global Warming Potential (GWP), Human Carcinogenic Toxicity (HCT), Fossil Depletion Potential (FDP), Ozone Layer Depletion (OLD), Terrestrial Acidification (TA), and Land Use (LU). An equivalent coefficient for emissions and energy related to the LVL materials being used was obtained from the EPiC database (Crawford & Stephan, 2019).

The other impact category calculated by different LCIA methods is embodied energy. Embodied energy is measured as the quantity of non-renewable energy per unit of a building material, component or system. Embodied energy values have been calculated using the LCIA Cumulative Energy Demand method version 1.04. Embodied energy is expressed in megajoules (MJ) per unit of weight (Kg or tonne). The environmental indicator of the energy consumed for the total life cycle of a product is embodied energy. It needs to be quantified and incorporated in energy measurements of the material itself. The determination of embodied energy (energy used for manufacturing the materials, transporting them to site, incorporating them in a building, maintaining buildings as well as eventual demolition or de-construction) is complicated. It includes non-renewable primary energy and excludes the renewable energy consumed for production and construction (Malça & Freire, 2006). A building's energy for heating and cooling and for lighting should be excluded from the measurement of the product's embodied energy.

Incineration and recycling of LVL products can have positive impacts on the environment (such as GWP) and are therefore considered in this study.According to Zhang, (X. 2014), energy for demolition of a building can be assumed as 90% of the energy required in its erection. For the LVL building, a recycling rate of 40% has been assumed with 40% used for biomass energy (Liu et al., 2016). These strategies aimed to avoid the waste sent to landfills and save energy by considering reuse and recycling.

* 1. ***Life cycle costing***

LCC needs to be implemented in the design stages of construction to help decision-makers make informed choices about building materials. Buildings are long-term investments with potential environmental impacts (Raymond et al., 2000). Research regarding the cost of buildings in Malaysia (Akasah et al., 2011) has shown that most construction projects started without robust LCC assessments. Optimizing LCC is one of the main pillars of sustainability and a requirement for successful construction projects. Therefore, comparing the cost of alternative materials is essential and helps stakeholders make evidence-based choices of materials. In this research, LCC was evaluated via an Excel spreadsheet to calculate the 50-year costs of mass timber. The data relating to the raw materials, transportation, and construction wages were extracted from National Construction Cost Centre (CIDB Official Portal) in Malaysian Ringgit (MYR) and also the Malaysian construction cost handbook (JUBM & Arcadis, 2021). The data of end-of-life materials have been collected from observations of demolition sites. The fundamental elements of LCC are the production of materials, transportation, wages, maintenance costs, and end of life for each mass timber building. This study assessed costs based on the Present Value (PV) of Malaysian ringgit in 2020. The LCC was calculated using equation (1):

Equation 1

The cost estimation was based on an average discount rate of 4.5%, an electricity cost of 38 Cent/ kWh, a transportation cost of 0.31 MYR for each tonne per kilometer, and a related inflation rate of 3.4% following recent research on bulding materials costs by Balasbaneh et al., (2020). One Malaysian Ringgit was equal to 0.25 United States Dollar at the time (December 2020).

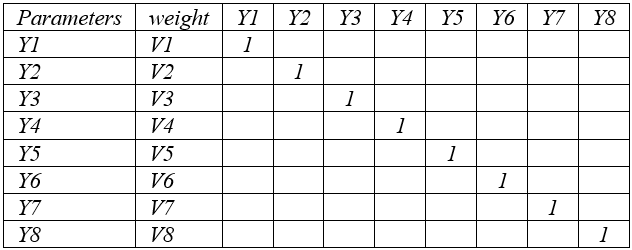
* 1. ***Multi-Criteria Decision Making***

The first step in the Analytic Hierarchy Process (AHP) method is to discover and weigh the alternative criteria cited in table 1. AHP was applied to identify the dependency and importance of each criterion on different case studies. This method shows the weights and values of eight criteria based on expert opinion (Turskis et al., 2009). Since no criterion (such as GWP, embodied energy, cost, etc) has priority and importance over another, there is no proof that all these criteria have the same value.

Sixty-two construction professionals were invited to participate in this study. They were drawn from three different sectors: construction managers, designers, and stakeholders all of whom were involved in mass timber construction. A questionnaire was administered to elicit data about eight parameters concerning each criterion's weights and their respective priorities. The criteria and their corresponding weights (w) were placed in a pairwise comparison matrix in line with Saaty (2008): GWP (Y1), HCT (Y2), FDP (Y3), OLD (Y4), TA (Y5), LU (Y6), embodied energy (Y7), and cost (Y8). The pairwise comparison matrix is shown in Table 1.

The survey was conducted to establish which of the eight different scales and their relative weightings might affect the MCDM results. The relative significance scale ranged between one and nine. The inclination scale for the pairwise comparison of the two parameters ranged from the most extreme of 9 to 1. To ensure consistency of the comparison, the Consistency Ratio (CR) value should be less than 0.1.

Table 1. Comparison matrix related to the four objectives



Secondly, MCDM is a decision-making tool that allows problems to be investigated by prioritizing alternatives. These alternatives are based on individual criteria measured in units that differ from other criteria (Hermann et al., 2007; Lipušček et al., 2010). The Weighted Aggregated Sum Product Assessment (WASPAS) method was used. This was developed by (Zavadskas et al., 2012), and is a group of two methods including Weighted Sum Method (WSM) (MacCrimon, 1968) and Weighted Product Method (WPM).The detailed procedure of the WASPAS method is as follows:

Step 1: Initialize the matrix for solving the selection problem.

Step 2: Normalize the decision matrix using equations 2 and 3

Equation 2

Equation 3

where represents the assessment values. Equations (2) and (3) are used for maximization (beneficial) and minimization (no benefit) criteria, respectively.

Step 3: Calculate the total relative importance based on the WSM method using equation (4).

Equation 4

Step 4: Calculate the total relative importance based on the WPM method using equation (5).

Equation 5

Step 5: Calculate the total relative importance based on the WASPAS method using equation (6).

Equation 6

where is a constant and equals to 0.5.

1. ***Case studies and materials***

A hypothetical case study was used to assess two different mass timber buildings. Two types of mass timber, GLT and LVL, were chosen because of their importance as building materials. The popularity of these products is that they may be used as wall panels and column-beam systems (Peñaloza et al., 2013). Each veneer in LVL is arranged in a way that provides similar strength to GLT. A single-story building comprised of three bedrooms, a living room, and a kitchen (Figure 3) was chosen as case study. The analysis provided below may be generalized for buildings that are currently manufactured in South Asia countries.

The first case study building is based on glulam or GLT. This material allows for the fabrication of components to any depth and width. The members are constructed of five wood laminations arranged in the same direction and to the length of the member. The layers are glued together, creating strong joints. The density of the GLT panels is approximately 430 Kg/M3 and 470 Kg/M3. The mass of the GLT panel for walls 140 mm thick is 72 Kg/m2 (Doka, 2003).

The second case study building uses LVL load-bearing wall panels that do not incorporate post and beam components. LVL is manufactured from timber veneers and is similar to plywood. However, the LVL veneers are laid up the entire layer running in the same direction and parallel to the length of each layer. This orientation of the same direction of the wood layer in LVL configuration is the main reason behind its high design value (Breyer et al., 2014). The density of the LVL panels is between 500 Kg/M3 and 550Kg/M3. The mass of the LVL panel for walls 120 mm thick is 72 Kg/m2 (Members, 2020). Table 2 displays the quantity and characterization of materials used in the two case study buildings . Foundations have been excluded from the study as they have been assumed to be identical for both buildings.

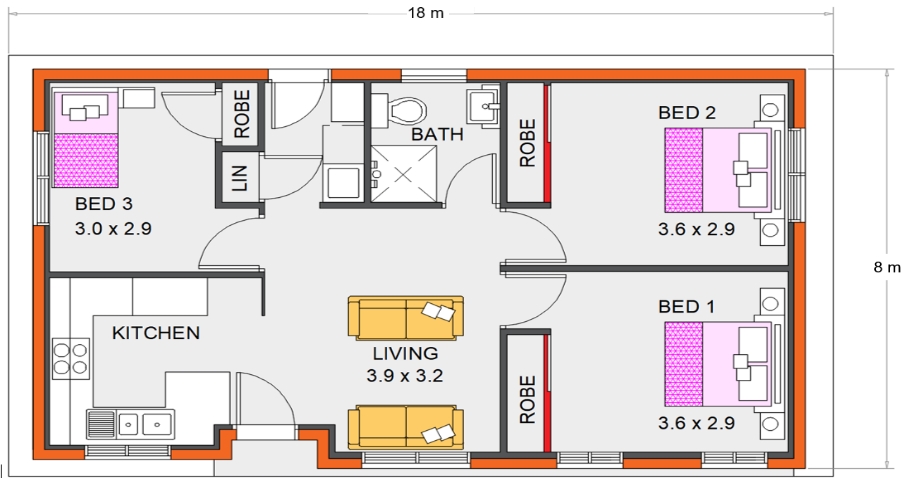


Figure 3.The schematic plan of the case study

To simplify assessment, some assumptions have been made. In the transportation stage, the distance from the factory for either raw materials or prefabricated components has been assumed to be 50 Km (Hernandez et al., 2019). The production stage of mass timber starts with the extraction of raw materials (A1), transport to the sawmill (A2), processing, and producing both types of mass timber in different ways (A3) resulting in different environmental emissions for this stage. A3 is relates to preparing the product, and has several stages. In this process, wood is cut in a sawmill and then transferred to the factory where it is converted into GLT and LVL using adhesives resins, chemical processes, pressure and heat. A4 relates to transporting LVL and GLT to site. A5 is the installation process of the GLT and LVL with each building using a different construction technique. The LVL is constructed in the factory and then transferred to the site as Prefabricated Prefinished Volumetric Construction (PPVC), while the GLT is constructed on site and comprises columns, beams, floor slabs and walls. The extraction phase of wood production involves moving logs from tree stumps to the roadside, where they are processed or piled in stacks. This process has been assumed to be the same for all species of timber.

Table 2. Details of two mass timber quantity

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Building System** | **Materials components** | **Thickness (mm)** | **Weight (Kg/M3)** | **Total (Kg)** |
| Glued Laminate Timber (GLT) | GLT panel | 140 | 430 | 14400 |
| GLT floor panel | 100 | 430 | 7200 |
| GLT roof panel | 100 | 430 | 7200 |
| Steel | - | 7850 | 50 |
| Glass wool insulation | 80 | 12 | 170 |
| Gypsum board | 13 | 724 | 1350 |
| Glulam columns and beams | 200 | 430 | 3312 |
| Laminated Veneer Lumber (LVL) | LVL façade panel | 120 | 500 | 8400 |
| Steel | - | 7850 | 50 |
| Glass wool | 80 | 12 | 170 |
| LVL interior wall panel | 100 | 500 | 6000 |
| LVL floor panel | 100 | 500 | 7200 |
| LVL roof panel | 100 | 500 | 7200 |
| Gypsum board | 13 | 724 | 1350 |

Maintenance (B2), repair (B3), and replacement (B4) have been considered for the use phase. These involve periodic replacement, minor repairs, and exterior [painting](https://www.designingbuildings.co.uk/wiki/Painting) for building materials such as walls and floors during the expected life span. It is difficult to assess the scope of the use stage. For example, the floor plan of buildings do not change, major rebuilds are not considered for this stage, and it assumed building services continue in accordance with current plans. The values for the lifespan of the building elements were estimated based on literature (Mithraratne, 2001).For work on the use phase, 1 kWh/m2 of electricity was equal to 9.12E-01 (Horváth & Szalay, 2012).

In the end of life stage (Fig 2), C1, C2, C3 and C4 denote the demolition or reassembly of building materials on-site and their transfer from the site after the building's end of life, respectively. The fuel used for demolition machinery and transport away from site was assumed to be diesel. The ‘Benefit and loads’ stage for wood products included 30% reuse ( D1), recovering energy (D2) by incinerating the material to generate electricity by 30% and 40%. recycling (D3). D2 has been used in Malaysia as an alternative to coal. Other non-structural materials such as gypsum board and insulation were considered as landfill (D4) due to uncertainty about their impact when recycled. In this study, Eurocode 5 and relevant documents European Committee for Standardization (CEN) were adopted as the design standards for LVL structures. Each mass timber product has been considered in both hardwood and softwood variants. Evergreen trees tend to be less dense than deciduous trees, and are therefore easier to cut, while most hardwoods tend to be more dense, and therefore sturdier. The hardwood trees grow at a slower rate and are generally denser than softwood trees. The types of wood evaluated in this study are oak as a hardwood species and spruce as a softwood species.

1. ***Results***

The construction methods used for GLT and LVL are different and are illustrated in Figures 4 and 5. These are limited to the construction stage for GLT and LVL (A1, A2, A3, A4 and A5). As mentioned before, all previous research has claimed that mass timber is a good alternative to concrete and steel because timber produces fewer environmental emission. In this study, the authors have focused on two types of mass timber as well as two methods of construction. For transparency, figures 4 and 5 show the differences between the manufacturing and construction stages of the case studies materials. Figure 4 shows the processing of the GLT material from extraction to manufacturing and construction. The extraction stage includes the log yard, debarking of wood and transfer to the mill by lorry. The process of manufacturing includes drying, sawing, grading, adhesive application, pressing, curing, and trimming. The GLT components are sent to site to construct the building. Two different types of GLT were assumed - GLT-h for mature hardwood and GLT-s for mature softwood. The method of construction is considered as on-site.

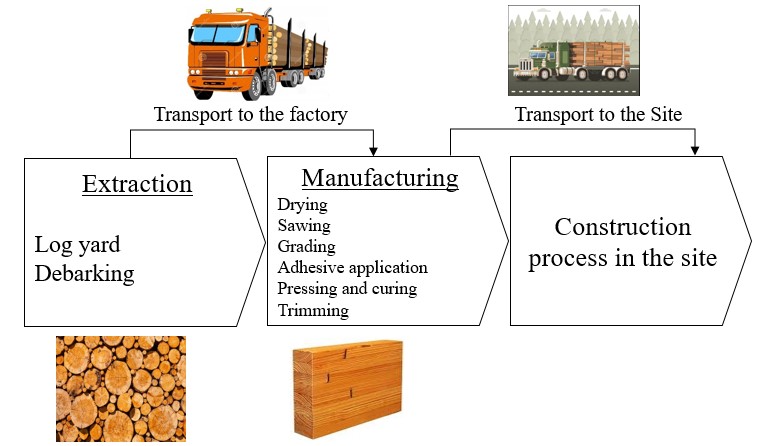


Figure 4. The process of constructing the building with GLT

Figure 5 illustrates the construction process for LVL materials. The extraction stage is similar to the GLT. Manufacturing includes steaming, veneer production, drying, adhesive application, pressing and sawing. Based on the real-life scenario, the prefabricated method was used for the construction of the LVL. In the next stage, LVL materials are sent to the factory to create prefabricated walls, columns and beams. Then, the prefabricated material is sent to site and assembled using a crane. Two different types of LVL are assumed including LVL-h for mature hardwood and LVL-s for mature softwood.

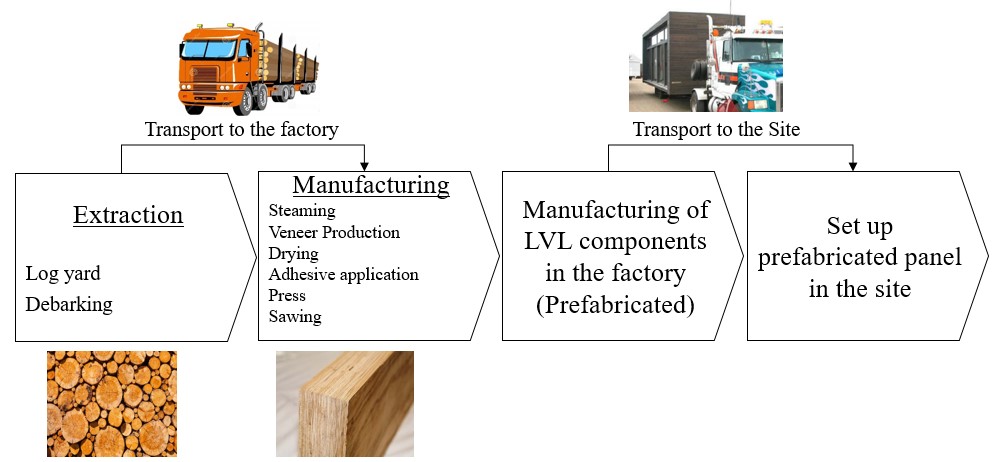


Fig. 5. The construction process with LVL

* 1. ***Life cycle assessment***

The LCA outcomes are shown in Figures 6 and 7. GLT-h has the highest environmental burden in the GWP, OLD, and LU categories. GLT-s has the second highest burden in the GWP, OLD, and LU environmental categories mainly due to existing softwood being used in its manufacture. This indicates that the materials manufactured using softwood have a lower environmental impact compared to hardwood. Furthermore, the LVL-h has the highest environmental emissions in HCT, FD, and TA, followed by LVL-s. So, it can be concluded that that softwood has a lower environmental burden than hardwood when used either as GLT or LVL. Between the two LVL options, LVL-s is the option with the lowest environmental burden. Meanwhile, GLT has a higher environment burden and emissions than LVL in the GWP, OLD, and LU categories. The impact of GLT is nearly 29%, 38%, and 35% higher for GWP, OLD, and LU, respectively. The LVL had a higher environmental impact of approximately 14%, 28% and 30% on HCT, FD and, TA, respectively.

Figure 7 shows the emissions related to each environmental category. Analyses of GWP emissions shows that material production makes the largest contribution. Transportation distance and construction process have the lowest impact. However, the two transport alternatives result in different impacts (GLT: on-site, LVL: prefabricated off-site). The emissions for GLT are 150 Kg CO2eq and for LVL are 600 Kg CO2eq for transportation. Interestingly, the emissions related to the construction process for GLT (320 Kg CO2eq) is higher than LVL (210 Kg CO2eq). This is mostly because on-site construction is resource intensive, and consequently, produces more waste. Maintenance has a negligible impact of GWP emissions although the emissions for GLT are slightly higher than for LVL (1100 Kg CO2eq versus 900 Kg CO2eq). Benefits and loads have a positive impact on total emissions, which contributes to eliminating the extra emissions by returning the materials to the cycle. This positive impact reduces the transportation impact related to transferring the materials from site. The result shows that GLT potentially has a better GWP impact than LVL.

The ‘Benefit and load phase’ has a positive net impact of its total carbon emission regarding recycling of steel, which reduced environmental impact significantly, and using wood (GLT or LVL) as energy recovery by -8500 Kg CO2eq versus -3200 Kg CO2eq respectively for GLT and LVL. The total GWP emissions are 58470 Kg CO2eq, 57730 Kg CO2eq, 41620 Kg CO2eq, and 41088 Kg CO2eq respectively for GLT (hardwood/softwood) and LVL (hardwood/softwood).

Figure 6. Life cycle results of building frame design in four scenarios. GLT-h hardwood, GLT-s softwood, LVL-h hardwood and LVL-s softwood

The second environmental category where GLT has a higher burden than LVL is OLD. The extraction and production stages (A1, A2 and A3) were the main contributors to OD. These related to the production stage for chemicals, adhesive resins, and wood, while the emissions released during maintenance and transportation were negligible. The emissions for GLT-h and GLT-s for wood, adhesive resins, and chemicals are (49 Kg CFC11eq/ 44.4 Kg CFC11eq), (67.5 Kg CFC11eq/67.5 Kg CFC11eq) and (112.5 Kg CFC11eq /112.5 Kg CFC11eq), respectively. LVL has a lower emission for both softwood and hardwood production. The wood, adhesive, and chemical emissions for LVL-h and LVL-s are 28 CFC11eq / 25.8 CFC11eq, 39.3 CFC11eq /39.3 CFC11eq and 65.5 CFC11eq /65.5 CFC11eq, respectively. This shows that GLT buildings have a higher positive value in the last stage of a building's life span. This includes deductions for the emissions from the demolition and transportation stages (C1 & C2). The total OLD emissions are 208.9 Kg CFC11eq, 204.7 Kg CFC11eq, 130.8 Kg CFC11eq, and 128 Kg CFC11eq respectively for GLT (hardwood/softwood) and LVL(hardwood/softwood).

The third environmental category where GLT shows higher emissions than LVL is Land Use (LU). The manufacturing emissions for GLT are 58% higher than LVL. The high LU impact of GLT relates to the use of chemicals during manufacturing. These contributed almost 40% of the total LU manufacturing stage emissions. The adhesives had the second major LU impact, and contributed 35% of total emissions in the manufacturing stage for both LVL and GLT. Transportation had a negligible impact (2.2%) for all four scenarios while it contributed slightly higher emissions for LVL due to the prefabricated construction method of this approach. Additionally, the end-of-life savings of GLT were higher than LVL by 34%. The total LU impacts are 72.8, 73, 47, and 46 (m2a crop eq) respectively for GLT (hardwood/softwood) and LVL(hardwood/softwood).

The total emissions for LVL from environmental impact were higher for HCT, FD, and TA of LVL compared to GLT. HCT had the highest emissions related to the chemistry of mass timber production which contributed 42%. The chemical impacts for GLT and LVL were 779 Kg 1,4 DCB and 879 Kg 1,4 DCB. Overall, the manufacturing stage had the highest HCT emission for all 4 alternatives - about 1948 Kg 1,4 DCB to 2164 Kg 1,4 DCB. The total OLD emissions are 1771 Kg 1,4 DCB, 1754.Kg 1,4 DCB, 2118 Kg 1,4 DCB, and 2084 Kg 1,4 DCB respectively for GLT (hardwood/softwood) and LVL(hardwood/softwood).

The chemical stage of FD and TA contributed about 47% to 52% of the total manufacturing process. The total FD emissions are 15414 Kg oil eq, 15414 Kg oil eq, 15414 Kg oil eq, and 15414 Kg oil eq respectively for GLT (hardwood/softwood) and LVL(hardwood/softwood). On the other hand, The total FD emissions are 281.4 Kg SO2eq, 281 Kg SO2eq, 402.02 Kg SO2eq, and 396.34 Kg SO2eq respectively for GLT (hardwood/softwood) and LVL(hardwood/softwood). In conclusion, the outcome for environmental assessment is mixed, and a transparent final decision is not obvious. On the one hand, LVL is a superior choice in OLD, LU, and GWP, while GLT is preferable for FD, TA, and HCT. Moreover, the preservatives and adhesive materials present in all mass timber products raise concerns as they are major contributors to environmental emissions.

Figure 7. Life cycle environmental emissions for four scenarios. GLT-h hardwood, GLT-s softwood, LVL-h hardwood and LVL-s softwood

* 1. ***Embodied energy***

Embodied energy has been defined in two main ways. Firstly, it may be limited to the construction stage. Secondly, other research expands its remit to the total energy consumed during construction, and end of life of a building (Brambilla et al., 2018). The latter definition applies to this study. Table 3 shows the embodied energy for different stages for each case study for new materials usage and transportation. For example, transport for the use stage relates to transferring new materials to site for the replacement stage. This shows that the Manufacturing stage consumes the most energy. This is related to the large quantity of materials that need to be manufactured.

The embodied energy of GLT is approximately 44% higher than LVL. The manufacturing stage also contributed 78% to 82% of all energy usage for the whole life span of the buildings, considering the system boundary of this research. The transportation stage was responsible for almost 5% of total energy usage.

Table 3 Life cycle embodied energy

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ***Category*** | ***Stage*** | ***Unit*** | ***GLT-h*** | ***GLT-S*** | ***LVL-h*** | ***LVL-s*** |
| *Manufacturing* | *Material* | *MJ* | *270260* | *266370* | *150545* | *149740* |
| *Transportation* | *MJ* | *4120* | *4120* | *4120* | *4120* |
| *Construction* | *Material* | *MJ* | *7230* | *7230* | *4069* | *4047* |
| *Transportation* | *MJ* | *11472* | *11472* | *11472* | *11472* |
| *Use stage* | *Material* | *MJ* | *24230* | *23120* | *13686* | *13613* |
| *Transportation* | *MJ* | *2296* | *2296* | *2296* | *2296* |
| *End of life* | *Material* | *MJ* | *8400* | *8400* | *4301* | *4278* |
| *Transportation* | *MJ* | *1592* | *1592* | *1592* | *1592* |

Figure 8 shows the embodied energy for each stage of a building’s life for the four alternative timber materials. The embodied energy for GLT and LVL is 1648 MJ/m2 and 960 MJ/m2, for one meter square of wall surface respectively. The total embodied energy for all mass timber products is 329600 MJ/Kg, 324600 MJ/Kg, 192081 MJ/Kg, and 191158 MJ/Kg for GLT hardwood, GLT softwood, LVL hardwood, and LVL softwood respectively.

Figure 8. Embodied energy of four wood-based materials. GLT-h hardwood, GLT-s softwood, LVL-h hardwood and LVL-s softwood

* 1. ***Life Cycle Costing***

The total LCC of the mass timber materials is shown in Table 4. The material cost of GLT-h (72880 MYR) is slightly higher than the GLT-s (58300 MYR). The cost of LVL is much lower than GLT. This difference relates to the manufacturing cost and types of wood used in the sawmill. The cost of LVL-h and LVL-s is 43820 MYR and 34910 MYR, respectively. The GLT hardwood is approximately 20% higher than softwood, and this applies to LVL as well. Other materials used in the cases studies included steel for joint connections, glass wool insulation, gypsum board, and plasterboard. The buildings are similar in layout and these materials were thus considered as the same for both alternatives. It is worth noting that the cost of these categories of materials contributed 32% to 46% for GLT structures. The cost of LVL is even lower than the cumulative cost of steel connections, gypsum board and glass wool insulation.

Table 4. LCC results.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| *Cost* | Unit | *Production of wood* | *other materials* | *Transport* | *Wages* | *Use stage* | *End of life* |
| GLT-Hardwood | MYR | 72880 | 40000 | 8100 | 6500 | 2025 | -13770 |
| GLT-Softwood | 58300 | 40000 | 8100 | 6500 | 2025 | -13770 |
| LVL- Hardwood | 43820 | 40000 | 28350 | 6400 | 1620 | -13770 |
| LVL- Softwood | 34910 | 40000 | 28350 | 6400 | 1620 | -13770 |

However, the transportation costs of GLT and LVL differ considerably since the LVL is prefabricated. Prefabricated materials are more time-consuming to transport to site than GLT materials. The transport cost of GLT is equal to 28% of the LVL's transport cost. In contrast, GLT maintenance cost is higher than for LVL due to the higher price of the raw materials.

This study has considered the end-of-life cost for all alternatives. The net return to the project from selling the material was 13770 MYR. This needs to be deducted from the total cost of the building. The results show that LVL-s is generally cheaper than the alternatives. However, transport costs for prefabricated wood are higher than for on-site construction. The results of the LCC evaluation for different mass timber products are shown in Figure 9. Interestingly, GLT-s is the second-best option. The total costs are 115735 MYR, 101155 MYR, 106420 MYR, and 97510 MYR respectively for GLT-h, GLT-s, LVL-h, and LVL-s.

Fig. 9. Life cycle costs of four wood-based materials. GLT-h hardwood, GLT-s softwood, LVL-h hardwood and LVL-s softwood

***3.4 Multi-criteria Decision-making (MCDM)***

MCDM was performed to rank the alternatives by balancing their environmental impacts, economic, and embodied energy impacts. It should be noted that the respondents only assessed the mass timber criteria. Other materials such as concrete, steel or brick were not considered. Respondents were categorized as construction managers, designers, and stakeholders. Construction experts’ opinions were used initially to analyze the importance of each criterion. Generally, decision-makers opted for the most important criteria among the various alternatives. The results of this exercise were rankings of the eight criteria based on their importance as shown in table 5. Six experts were selected for this study, all of whom have between 7 and 22 years of experience in architecture, civil engineering  and construction. The experts were asked to compare the eight criteria to identify their contribution to the decision-making process. The higher value represents the priority for that criterion.

Based on the opinions of construction managers and designers, cost should be the first priority when choosing mass timber materials. GWP emissions and embodied energy were the second and third, respectively. However, from the fourth choices the criteria priorities change for this group. For example, construction managers emphasized that ozone layer depletion is the next priority, while designers chose LU. Unlike these two groups, the stakeholders strongly believed that the LU, GWP, and fossil depletion should be considered as the highest priority after cost. The results of which are shown in table 5. Based on these results, the criteria were prioritized as follows: LCC (0.344), GWP (0.17), embodied energy (0.14), land use (0.098), fossil depletion (0.088), ozone layer depletion (0.067), human-toxicity (0.054), and, finally, terrestrial acidification (0.039).

Table 5. The generalized survey result, W= Weighting and P= Priority

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Parameters*** | ***Construction managers*** | | ***Designers*** | | ***Stakeholders*** | | ***Total*** | |
| *W* | *P* | *W* | *P* | *W* | *P* | *W* | *P* |
| *GWP* | *0.22* | *2* | *0.2* | *2* | *0.11* | *3* | *0.17* | *2* |
| *Terrestrial Acidification* | *0.03* | *7* | *0.01* | *8* | *0.078* | *6* | *0.039* | *8* |
| *Fossil Depletion* | *0.09* | *5* | *0.089* | *6* | *0.086* | *4* | *0.088* | *5* |
| *Human-Toxicity* | *0.02* | *8* | *0.059* | *7* | *0.085* | *5* | *0.054* | *7* |
| *Ozone layer depletion* | *0.098* | *4* | *0.10003* | *5* | *0.0056* | *8* | *0.067* | *6* |
| *Land use* | *0.0484* | *6* | *0.108* | *4* | *0.14* | *2* | *0.098* | *4* |
| *Embodied Energy* | *0.2* | *3* | *0.15* | *3* | *0.07* | *7* | *0.14* | *3* |
| *LCC* | *0.31* | *1* | *0.29* | *1* | *0.43* | *1* | *0.344* | *1* |
|  | *CRa= 0.048 <0.1* | | *CRa= 0.063 <0.1* | | *CRa= 0.043 <0.1* | |  | |

To help understand these results, all outcomes from Figures 6, 8, and 9 have been compiled in table 6 as decision-making matrix. For MCDM, the beneficial and non-beneficial criteria from table 6 need to be considered first. The beneficial parameters are those with minimum values because cost reduction is a priority. For example, the materials with lower GWP or economic cost are the best choices for decision makers. Hence, the cost beneficial parameter is considered as 97510 MYR. Therefore, all the criteria in this study considered as beneficial value for all eight criteria.

Table 6. Decision-making matrix

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Alternatives*** | **GWP** | **HT** | **FD** | **OLD** | **TE** | **LU** | **EE** | **COST** |
| **GLT-Hardwood** | 58470 | 1771.31 | 15414.36 | 208.965 | 281.4519 | 72.87313 | 329600 | 115735 |
| **GLT-Softwood** | 57730 | 1754.5 | 15390.79 | 204.6581 | 281.0323 | 73.00166 | 324600 | 101155 |
| **LVL-Hardwood** | 41620 | 2118.118 | 21052.98 | 130.8393 | 402.0255 | 47.02382 | 192061 | 106420 |
| **LVL-softwood** | 41088 | 2084.618 | 20888.6 | 128.7244 | 396.3474 | 46.06255 | 191200 | 97510 |

Secondly, the decision matrix is normalized using equation (3). The results of this stage are shown in Appendix 1. Thirdly, the relative importance is evaluated using equation 4 to disclose the amount of. The result of this stage is shown in Appendix 2 by multiplying the amount of weighing to . For example, the sum of 0.1195, 0.0386, 0.0879, 0.0333, 0.0669, 0.0619, 0.0812 and 0.2898 (Appendix 2) is 0.7791. Step 4 is related to the relative importance using using Equation 5 and the calculation is shown in Table 7. In step 5, the improved ranking accuracy is estimated by using equation 6. The result is 0.772, 0.816, 0.912 and 0.948 respectively for GLT-h, GLT-S, LVL-h and LVL-s. The case study with the higher value or score at this stage depicts as the best option. The higher score represents as a priority and best option. Thus, LVL-s is considered as the best material choice among alternatives since it achieved the highest total score.

Table 7. The results of ranking of MCDM analysis by WASPAS

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Alternatives*** | **GWP** | **HT** | **FD** | **OD** | **TE** | **LU** | **EE** | **COST** |  | **Q2** |
| **GLT-Hardwood** | 0.9418 | 0.9996 | 0.9999 | 0.9742 | 0.9999 | 0.9560 | 0.9266 | 0.9428 |  | 0.766 |
| **GLT-Softwood** | 0.9438 | 1 | 1 | 0.9753 | 1 | 0.9559 | 0.9286 | 0.9875 |  | 0.807 |
| **LVL-Hardwood** | 0.9978 | 0.9927 | 0.9728 | 0.9991 | 0.9763 | 0.9980 | 0.9994 | 0.9704 |  | 0.910 |
| **LVL-softwood** | 1 | 0.9933 | 0.9735 | 1 | 0.9772 | 1 | 1 | 1 |  | 0.945 |

The use of mass timber or wood vary from country to country for many reasons and this may affect respondents’ judgments. A sensitivity analysis was performed on the weighting results as shown in table 5. This analysis was to reveal if there was any subjective influence on the ultimate results of the research. All considered weights (Table 5) were assumed to be equal to 0.125 (one divided by eight). The results of the sensitivity analysis are shown in Table 8. It can be concluded that human subjectivity had no impact on the final decision since the LVL-s is still assigned as the first priority.

Table 8. The sensitivity analysis of ranking for the multi-criteria

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***Alternatives*** | ***Eq 3. Q1*** | ***Eq 4. Q2*** | ***Eq 5. Score*** | ***Rank*** |
| **GLT-Hardwood** | 0.7951 | 0.776 | 0.786 | 4 |
| **GLT-Softwood** | 0.8156 | 0.796 | 0.806 | 3 |
| **LVL-Hardwood** | 0.8901 | 0.882 | 0.886 | 2 |
| **LVL-softwood** | 0.9109 | 0.902 | 0.907 | 1 |

1. ***Discussion***

It can be challenging to select the appropriate mass timber when several options are available. In the results above, there were inconsistencies on six different environmental impacts, embodied energy, and economic assessments across alternatives. It was unclear which material is most efficient based on these results. MCDM was applied to determine what material was most effective overall. LVL was chosen as the most sustainable option considering eight criteria.

To the authors’ knowledge, most previous publications have compared mass timber materials (such as LVL or GLT) with steel and concrete (Abolghassem Tehrani & Froese, 2017; Fanella, 2018; Liu et al., 2016). For example, Lu & El Hanandeh, (2017b) compared softwood and hardwood LVL with concrete and steel structures. They found that LVL has a lower environmental impact in all categories. Meanwhile, a softwood LVL structure has a lower impact than hardwood LVL, consistent with current research. Previous comparisons of alternative mass timber are limited to their mechanical performance such as stiffness and load-carrying capacity (Zhang et al., 2018).

The mass timber products have rarely been compared to each other with respect to LCA and LCC. For example, Balasbaneh, et al. (2021) was the only comprehensive study that compared two mass timber products, namely CLT andd GLT. They showed that softwood was the best building material, which is consistent with this study. Head et al., (2020) evaluated the CO2 emission of life cycle inventory for different wood. They showed that LVL has a lower carbon emission than GLT per M3 which is consistent with this study. Previous studies were limited to environmental impact and neglected embodied energy or LCC evaluations. Therefore, this research is considered unique as it explores several aspects of these materials.

To assess GLT, it was assumed that raw material was located close to the sawmill. Sensitivity analysis was performed by increasing this distance to 100 Km resulting in an increase in embodied energy and carbon emissions of approximately 1.23 Kg CO₂eq per tonne and 3.43 MJ per tonne, respectively. However, no change was observed in the priority choice for any of the environmental categories. The alternative scenarios and recommendations for improving mass timber are as follows: scenario for GLT is the use of polyurethane resin that has a high emission for manufacturing the engineering wood. In another possible scenario, using prefabricated materials may contribute fewer construction emissions. However, it might also have higher transportation costs.

1. ***Conclusions***

The selection of appropriate construction methods and materials is an expensive, time-consuming, and complicated process. This is due to the plethora of alternatives and the existence of conflicting assessment criteria. In this research, MCDM was applied to compare dissimilar value parameters. For example, some production methods and materials may have a low environmental impact such as GWP while at the same time having a higher economic cost. This presents challenges to decision makers when they procure buildings. To illustrate this. We have presented a cases study using four different mass timber products. Initially, it appeared that the differences between the four alternatives were negligible. Using mass timber significantly reduces carbon emissions in the construction industry. This research has provided a comparative sustainability assessment of two main wood-based materials, GLT and LVL, considering six environmental impacts consist of GWP, HCT, FDP, OLD, TA, and LU along with embodied energy and cost, from cradle to grave. A case study demonstrated the use of four different hardwoods and softwoods to encourage low-emission and low-embodied energy building materials. Hence, the methodology of life cycle assessment was used to investigate the environmental impacts of each GLT and LVL types throughout their respective life cycles. The results between two main wood-based materials showed that each of them have their own advantages and disadvantages. The CO2 emission of the GLT and LVL are 327 Kg/m2 and 215 Kg/m2, respectively. Also, the embodied energy of the GLT and LVL are 1648 MJ/m2 and 960 MJ/m2, respectively. The main limitation of this research relates to the design of wooden building in tropical climates. The results of current research can be implied only on single and double-story buildings due to existing usability limitations of GLT and LVL in building structures. The GLT is not being used as wall materials in multi-story buildings. Instead, engineers prefer to use of LVL. LVL is not being used for load bearing components due to vulnerabilities in high-rise buildings. However, GLT and LVL are still being used as component in multi-story buildings. Thus, it is recommended that research be conducted to compare wood-based materials for multi-story buildings.

**Declarations**

Ethics approval and consent to participate: Not applicable

Authors' contributions: All authors contributed to the study conception and design. Data collection, and Software analysis were performed by Ali Tighnavard Balasbaneh, *Willy Sher, David Yeoh, Mohd Norazam Yasin*. The first draft of the manuscript was written by Ali Tighnavard Balasbaneh, all authors commented on previous versions of the manuscript. As Corresponding Author, I confirm that the manuscript has been read and approved for submission by all the authors.

Competing interests: The authors declare that they have no competing interests.

Consent to Participate Not applicable.  
Consent for publication Not applicable.

Funding information is not applicable

Data availability the datasets used and analyzed during the current study are available from the corresponding author on reasonable request

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**Appendix 1**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **GWP** | **HT** | **FD** | **OD** | **TE** | **LU** | **EE** | **COST** |
| **GLT-Hardwood** | 0.7027 | 0.9905 | 0.9985 | 0.6160 | 0.9985 | 0.6321 | 0.5801 | 0.8425 |
| **GLT-Softwood** | 0.7117 | 1 | 1 | 0.6290 | 1 | 0.6310 | 0.5890 | 0.9640 |
| **LVL-Hardwood** | 0.9872 | 0.8283 | 0.7311 | 0.9838 | 0.6990 | 0.9796 | 0.9955 | 0.9163 |
| **LVL-Softwood** | 1 | 0.8416 | 0.7368 | 1 | 0.7091 | 1 | 1 | 1 |

**Appendix 2**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **GWP** | **HT** | **FD** | **OD** | **TE** | **LU** | **EE** | **COST** | **Q1** |
| **GLT-Hardwood** | 0.1195 | 0.0386 | 0.0879 | 0.0333 | 0.0669 | 0.0619 | 0.0812 | 0.2898 | 0.7791 |
| **GLT-Softwood** | 0.1210 | 0.0390 | 0.0880 | 0.0340 | 0.0670 | 0.0618 | 0.0825 | 0.3316 | 0.8249 |
| **LVL-Hardwood** | 0.1678 | 0.0323 | 0.0643 | 0.0531 | 0.0468 | 0.0960 | 0.1394 | 0.3152 | 0.9150 |
| **LVL-Softwood** | 0.1700 | 0.0328 | 0.0648 | 0.0540 | 0.0475 | 0.0980 | 0.1400 | 0.3440 | 0.9512 |