# [**Economic and Environmental Life Cycle Assessment**](https://www.sciencedirect.com/science/article/pii/S2352550921003092)**of Alternative Mass Timber Walls to Evaluate Circular Economy in Building: MCDM Method**

**Abstract**

The construction industry is one of the largest consumers of energy and materials, which leads to it being one of the highest sources of environmental emissions. Quantifying the impact of building materials is critical if strategies for mitigating environmental deterioration are to be developed. The lifecycle assessment (LCA) consequential methodology has been applied to evaluate different methods of constructing residential double-story buildings. The ReCiPe methodology has been used for life cycle inventory. Three different forms of mass timber construction have been considered including Cross-laminated timber (CLT), Nail Laminated Timber (NLT), and Dowel Laminated Timber (DLT). These have been assessed as load-bearing panels or wood frame construction. We evaluated the global warming potential (GWP), embodied energy, and cost to identify the building type with the lowest impacts. The results revealed that total CO2 emissions for mass timbers for the construction stage are 130 CO2/M2, 118 CO2/M2, and 132 CO2/M2 of the panel for CLT, DLT, and NLT respectively. The embodied energy emission is 1921 MJ/M2, 1902 MJ/M2, and 2130 MJ/M2 related to the CLT, DLT, and NLT, respectively, for this stage. The results also indicated that the carbon emission of DLT is lowest compared to the other two alternatives in the manufacturing and construction stages. However, when the entire life cycle is considered, NLT is the most favorable material. However, based on the life cycle cost (LCC), DLT has a lower cost. Finally, multiple-criteria decision-making (MCDM) was used to normalize the results and compare the alternatives. This showed DLT to be the best alternative, followed by CLT and NLT. In conclusion, the selection of building materials needs to prioritize regulations to reduce environmental and economic impacts.

**Keyword:** Circular Economy; Engineering Wood; Life Cycle Analysis; Cross-laminated timber (CLT), Nail Laminated Timber (NLT), Dowel Laminated Timber (DLT)

1. **Introduction**

The building sector encompasses multiple industries and emits significant amounts of greenhouse gasses (Zhang & Wang, 2016). Generally, it consumes 36% of global energy and produces 39% of carbon dioxide (CO2) emissions (Abergel, T et al 2017). The sector thus has significant potential to decrease emissions by adopting sustainable approaches**.** Transitioning the built environment to a circular economy (CE) is vital to achieving sustainability goals. The circular economy's main aim is to increase the efficiency of materials and minimize resource depletion (Ogunmakinde et al., 2021). The circular economy intends to provide economic growth while alleviating the pressure on the environment (Pomponi & Moncaster, 2017). Common building materials such as concrete and steel are high environmental emission choices compared to timber-based materials (Balasbaneh 2017; Zeitz et al., 2019; Hafner & Schäfer, 2018). It is noteworthy that the use of wood as a construction material has increased in residential or public buildings worldwide (Asdrubali et al., 2017; Kosny et al., 2014; Teng et al., 2018). Timber as a building material considers around 70% in some European countries, 46% of buildings in Japan, and up to 90% in North America (Nunes et al., 2020).

There are many types of engineered wood that are manufactured and used by the construction industry. However, there are few robust studies that determine the differences in environmental emissions among these materials. This study assesses three different wood-based materials as the load-bearing wall frame construction for a residential building to identify their environmental and economic differences. The materials selected are mainly used as prefabricated wall panels and do not function as columns or beams. There is widespread agreement in literature that wood and mass timber have lower environmental emissions than steel and concrete (Nässén et al., 2012; Balasbaneh et al., 2018; Walbech et al., 2021; Konnerth et al., 2016). Therefore, this study focuses on evaluating three different engineering wood products to reveal which is the most sustainable choice. Previous studies have shown that mass timber is an attractive sustainable construction material (Cadorel & Crawford, 2019). Many studies have conducted life cycle assessments (LCA) of mass timber products and compared them to other construction materials (Takano et al., 2015). For example, Upton et al., (2008) evaluated CO2 emissions by comparing wood with concrete and steel as building materials. They showed that wood produced up to 50% less emissions than other alternatives. Petrovic et al., (2019) also used LCA to compare non-wood and wood materials, showing that wood had lower CO2 emissions. Häfliger et al., (2017) assessed the LCA of concrete and wood, identifying wood as the most sustainable material by virtue of its lower total environmental impact. On a global scale, substituting timber materials for steel and concrete structures can reduce global CO2 emissions by up to 31% (Oliver et al., 2014). Additionally, other researchers have recognized timber-based materials as a remedy for climate problems (Himes & Busby, 2020).

It is evident that a new era of wood is emerging. The use of engineering wood such as Cross-laminated timber (CLT) has gained popularity in the past decade for double-story and midrise construction (Balasbaneh & Sher, 2021a; Sotayo et al., 2020). Even another study (Skullestad et al., 2016) claimed that substituting an engineered wood such as CLT material for concrete could result in savings of greenhouse gas (GHG) emissions of up to 100 %. Chen Z. et al., (2020) assessed CLT structures based on a multi-story concrete building. They showed that CLT has 21 % lower emissions than concrete during building life spans, excluding benefit and loads stages. Peñaloza et al., (2016) used LCA to show that CLT has potentially lower CO2 emissions than a concrete building. Jayalath et al., (2020) assessed the GHG emissions and LCC between reinforced concrete and CLT in identical residential buildings. The results showed that CLT reduces GHG by an average of 31% and is on average 1% lower in cost. Liang & Gu, (2021) evaluated the LCA for high-rise mass timber construction compared to concrete buildings. They showed that the mass timber construction technique performs better than conventional concrete building by 3153 kg CO2-eq versus 3203 CO2-eq per m2. Liu et al., (2016) compared concrete with CLT in a 7-story building. Their results revealed that using CLT could reduce CO2 emissions by nearly 40%. Lechón et al., (2021) assessed the CO2 emissions and LCC of CLT for a single-family house. They showed that the building produced 34 kgCO2eq per square meter. Chen C. X. et al. (2019) evaluated the cradle-to-gate of LCA for CLT. Their results indicated that the location of the mill manufacturing CLT could help reduce overall global warming potential. On the other hand, mass timber such as CLT can be used as a hybrid component. For example, Pierobon et al. (2019) compared a hybrid CLT structure with a conventional concrete building, showing that hybrid CLT has 27% lower global warming potential (GWP). There is thus considerable convincing evidence of the environmental advantages of using timber-based construction materials.

Previous research has shown that CLT's main contribution has been enabled through the use of modern adhesives between the layers of wood. However, adhesives have attracted considerable attention in the LCA of composite wood products (Chaudhary, 2015) and this has encouraged investigations of other ways of manufacturing timber composites. There is limited research on non-glued mass composite wood. Such materials include Nail Laminated Timber (NLT) (Pereira et al., 2021) and Dowel Laminated Timber (DLT) (Smith et al., 2018). For example, Zhang et al., (2018) assessed the mechanical performance of NLT. Their results showed that NLT might serve as an alternative to light wooden framed walls or CLT walls. Derikvand et al., (2019) argued that NLT could be used as a viable alternative flooring system. Although the concept of DLT members has been around for a few decades (Dauksta, 2014; Henderson et al., 2012), research on their development and properties are limited. Pereira & Calil (2018) investigated the use of DLT panels for floor and wall components. They found that the stiffness of DLT was lower than CLT, but was satisfactory for building components. Other reports claimed that the production of DLT contributed 121.40 kg CO2e to the atmosphere per m3 (Timber & Canada, 2020). DLT can be manufactured from out-of-grade wood, creating additional opportunities to increase the use of this renewable material in the construction industry (Cherry et al., 2019).

The main aim of this study is to compare the embodied energy and environmental performance of CLT (manufactured with formaldehyde-free PUR adhesive), NLT, and DLT. To the best of our knowledge, no study has compared the LCA of these three timber products. This research fills the gap by analyzing the LCA and LCC of these different mass timber engineered prefabricated wall panels for mid-rise residential construing buildings.

1. **Method and Materials**

This research methodology is separated into five sections as following: (i) evaluation of life cycle assessment; (ii) estimation of the life cycle embodied energy; ii) evaluation of the overall life cycle cost; (iv) normalizing the previous result using multi-criteria decision making (MCDM); (v) sensitivity analysis. The LCA was implemented for identical midrise residential buildings for three different mass timber products. Using MCDM to determined the best mass timber among the alternatives has been practiced recently (Balasbaneh et al., 2021). The current research has followed the proven path for the analysis the best alternative.

* 1. **Life cycle assessment**
     1. **Goal and scope**

LCA is the best-defined method to analyses environmental impacts, and can be applied in a circular economy context (Scheepens et al., 2016). LCA has been applied to analyze the sustainability of three different mass timber products when used in building wall panels. LCA is an approach for evaluating the environmental impacts of processes and products, making it possible to analyze different stages or the entire life cycle of buildings. LCA is considered an important tool for appraising the environmental impact of different materials and design proposals (Kiss & Szalay, 2020; Hollberg, 2016). LCA is based on the relevant standards ISO 14044 and ISO 14040 (2006). Case studies in this research were modeled running SimaPro v9.1.1 software. The studies were for Cross-laminated timber (CLT), Nail Laminated Timber (NLT), and Dowel Laminated Timber (DLT). The functional unit and system boundary need to be clarified to define the goal and scope of any LCA study. A functional unit needs to be defined for an appropriate comparison between the three different mass timbers. In this study, the functional unit was defined as the building’s living area for a double-story building with a life span of 50 years (Chau et al., 2015).

Figure 1 describes the cradle to grave system boundaries when evaluating the potential environmental impacts of mass timber buildings. It consists of the manufacturing and production stage (A1-A3), construction, transport to site and erection process (A4, A5), maintenance process (B2), end of life stage (C1, C2, C3, and C4) and finally, reuse, recovery, recycling, and the landfill (D1, D2, D3, and D4) based on the EN15804 and EN15978 standards (Committee for Standardization, 2011). Due to limitations in data collection, computation of the total embodied energy includes particular processes (X) illustrated in Figure 1. Life cycle analyses were conducted within the boundaries of the production and construction, maintenance, and End of Life (EOL) stages. However, according to EN15804, EOL is not allocated in D.

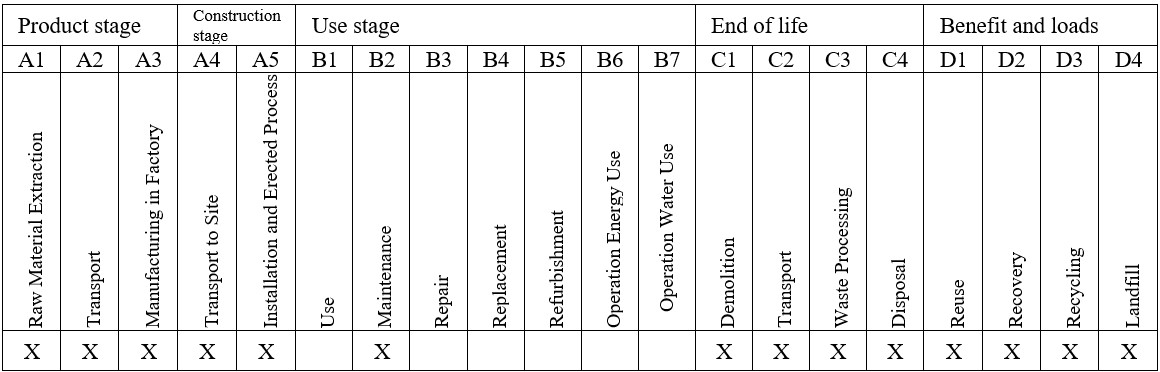


Figure 1: life cycle stages (EN 15978 2011).

EN 15978 (2011) has been accepted to define LCA as a worldwide framework. This framework splits the construction stage into multiple sections. It is recommended that the benefits and energy recovery of products and materials are calculated separately. Thus, the benefits of reuse or recycling can be considered inside the life cycle loop of the building. Building foundations, doors, windows and other applications such as wiring and piping are not included in the LCA because they have no impact on wall materials. Those functions are the same for all three case studies.

* + 1. **Life cycle inventory**

The second stage of the LCA study relates to the life cycle inventory (LCI). LCI incorporates quantifying and compiling all inputs and outputs of materials and energy for the final product into the system. This phase involved collecting raw materials requirements to construct the buildings and calculation procedures to quantify relevant output emissions of timber elements, timber structure, etc., through the whole life cycle. In parallel, the LCI database was used for appraising environmental impacts. In this study, the LCI database Ecoinvent 3.6 was used. LCI has a significant role in the reliability of the study's results. LCI emphasizes two different stages of data aggregations. Firstly, the primary data specify the characteristics of the product and process systems. Secondly, the data initially available in the Ecoinvent database is used as background to define the product system. The Ecoinvent database comprises substances related to a specific region. Thus, to avoid misleading results, this database needs to be adapted to the study region. Therefore, the database used has been callibrated to Malaysian local power electricity following (Balasbaneh & Sher, 2021b). The electricity consumption for manufacturing the different mass timber sections in the sawmill and assembly on-site has been considered fossil fuel consumption since an average of 96% of the national electricity produced in 2019 was produced from coal. Modelling of marginal energy requires careful examination and must avoid inconsistency and incomplete assessment. Preparation of raw materials, including diesel used for transportation and fuel for manufacturing was adjusted for the Malaysian scenario to provide accurate results using mixed sources of local power.

The consequential LCI modeling principle has been used to assess the LCA studies (Ghose et al., 2017). Various definitions are presented in literature for consequential LCI, including "system modeling approach that activities in a product system are linked. Thus, activities are included in the product system to the extent to change as a consequence of in demand for the functional unit." Unlike the attributional (cut-off) approach, consequential LCI captures the consequences of decisions for the future. Consequential LCI addresses multifunctionality by expanding the system boundaries to avoid normative allocation and includes the fate of coproducts in other markets (i.e., displacement). By doing so, the problem of normative allocation is avoided. Thus, the consequential approach includes recycling and reuse at the end of the life cycle of products. A further challenge is the lack of environmental inventory data for these building materials. The Simapro software lacked relevant inventories for the mass timber products used in this study. Thus, the pre-stressed laminated timber process: "Laminated timber element, transversally pre-stressed for outdoor use, at plant/RER U." was adopted for analysis of the CLT. For NLT and DLT, the sawn lumber, softwood, planed kiln dried were used for assembling the analysis. "Steel, low-alloyed" has been used for nails inside the NLT panels, and steel drag strap connections are used to attach the panels. MY-LCID (Life Cycle Inventory Database for Malaysia) was used in the LCI, especially for raw materials such as wood processing, to produce results applicable to Malaysia. Supplementary data were sourced from the Ecoinvent database and adapted to Malaysian conditions 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 electricisty were assumed for construction.

* + 1. **Life cycle impact assessment**

Life cycle impact assessment (LCIA) is the next stage in analyzing different mass timber buildings. ReCiPe midpoint has been applied to transfer the LCI result into a specific impact category such as global warming potential. Goedkoop et al. (2008) developed a LCIA method called ReCiPe, which provides harmonized characterization factors at midpoint and endpoint levels. The characterization factors that have been selected for this study are climate change and embodied energy. These factors are representative of the global scale instead of only the European scale. They also provide an overview of value choices, i.e., visions related to environmental decision-making, quantified via clustering into three perspectives as normalization. The normalized results of the LCA comparing the three building types are human health, ecosystem quality, and resources. This can be seen as a series of effects that create a certain level of damage to a specific impact category. Each perspective represents a set of choices for issues such as time and the expectation that appropriate management or future technology development can avoid future damage. For this impact assessment, the hierarchies perspective was selected. The criteria that were assessed are, GWP, Human toxicity Potential (HTP), Acidification Potential (AP), terrestrial ecotoxicity (TE), and fossil Depletion (FD).

One of the critical sectors of energy demand in the construction industry relates to embodied energy. This contributes to the relative energy embodied during the various stages such as production, construction, maintenance (replacement by new materials), and disposal at the end of life and is considered to be up to 50% of total life cycle energy consumption (Cellura et al 2014). Life cycle primary energy demand is only related to embodied energy, which will contribute 100% in future houses EU (2010). Despite this, most building regulations neglect embodied energy (Hollberg, 2016). Assessment of embodied energy is vital for future sustainability. Since all three case studies are evaluated wooden materials, we assume their operational energy is the same. Thus, operational energy has not been considered as a system boundary for this investigation. On the other hand, the scope of this study is to compare the three different mass timber structures to reveal differences in their energy consumption during manufacture and demolition. The LCIA method used to evaluate the primary embodied energy is Cumulative Energy Demand (CED) method 1.04. The result is expressed as non-renewable energy based on the Ecoinvent database incorporated into SimaPro software (PRé. 2019) to estimate the energy consumption of products along with their process (Hischier et al., 2010). The CED results are expressed in megajoules (MJ) unit per Kg.

* 1. **Life cycle cost**

Economic assessment or life cycle cost (LCC) is assessed based on the system boundaries of current research. LCC refers to the direct monetary value of services and products included in the case studies. In other words, it includes all the costs of acquiring materials, workers' wages, transportation, and demolition costs (Hunkeler, 2008). The LCC was calculated using an Excel spreadsheet for a life span of 50 years. The data were estimated based on data sourced from the National Construction Cost Centre (CIDB Official Portal) and standard construction costs (Construction Cost Handbook MALAYSIA, 2020) in Malaysian Ringgit (MYR) (ArcadisMalaysia, 2020). This study supersedes other LCC studies as it is based on consequential LCC estimation. The consequential method calculates all building stages encompassed within the system boundaries and the end-of-life costs of materials. The assessment method for the consequential analysis model is different from the attributional and conventional methods. The differences relate to the additional evaluation of the benefits of re-selling waste materials such as steel sheets or steel reinforcement at the end of the life of the building (Balasbaneh et al., 2018).

The first stage of assessing the LCC involves calculating material production costs that incorporate the total cost of raw materials used in construction. The future cost is calculated subsequently. Since the reference time is the current year, the future cost needs to be discounted, as shown in the following equation 1.

Equation (1)

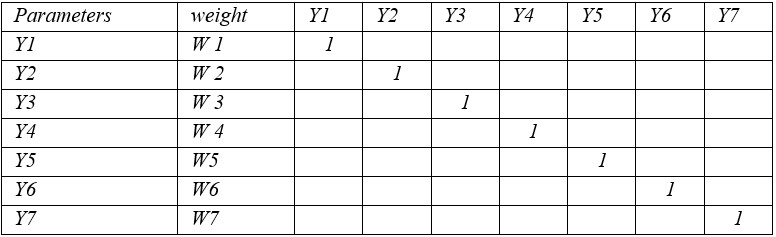
PC is material production cost, LC is labor cost, TC is transportation cost, and MC is machinery cost, r is the discounting rate and t is the time. Additionally, the benefit of re-selling the materials when a building has reached its end of life has been considered. The assessment of end-of-life costs was evaluated using the equation below. This has a positive impact on the total cost following the consequential method for LCI.

EOF is considered the most defining of the end-of-life costs of materials in the future in the equation above. The assumptions made when assessing the LCC in the case studies below are as follows. The discount rate was 3.2 % based on the average discount rate for Malaysia (CEIC), and the electricity rate was 38.53 Cent/ kWh (Malaysiakini data). The inflation rate was 3%, following the average Malaysian rate for 2020.

* 1. **Multi-criteria decision making**

An AHP model was implemented to determine the dependency of the result on the case studies and explore the system of values and weights of the criteria (Turskis et al., 2009). In this study, TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) was used to characterize the most appropriate material as the seven parameters used different weights in the construction sector. There are sixty experts incorporated from three specific construction sectors: designer, industrial engineering, and construction manager who have experience in the renovation sector. The experts needed to choose between the seven alternatives mentioned above. The questionnaire needed to be completed by experts by giving weightings to their priorities. Their responses were analyzed using the Analytic Hierarchy Process (AHP) method, an essential tool for solving the problem. As we know, the AHP is used to derive the weights of criteria when they are independent and outer dependent by the upper-level criteria. The comparisons were made using a scale of outright discernment that indicates how much one component outweigh another for a given attribute (Saaty, 2008). AHP is used to identify the global relative importance weights for different sustainability criteria and rank different alternative mass timber building systems. The criteria and their corresponding weights (W) need to be placed in the pairwise comparison matrix, in line with Saaty (2008): GWP (Y1), ODP (Y2), AP (Y3), TE (Y4), FD (Y5), Embodied energy (Y6), and LCC (Y7). Table 1 illustrates the pairwise comparison matrix.

Table 1. Comparison matrix



Since the importance of each criterion is different and has a distinctive value, analysis of expert opinion using the AHP method involves the allocation of weights to highlight the significance of each criterion. To determine the weight for different criteria for each of the seven different scales, three different categories of expert were selected (based on the AHP technique and Saaty's evaluation). The experts were design engineers, designers, and construction managers who worked and cooperated in the timber industry. The purpose of the survey was to investigate which of the four different scales and their related weightings might influence MCDM outcomes. The relative significance scale ranged from one to nine (the most extreme). It is worth mentioning that the computed Consistency Ratio (CR) must be not more than 0.1 to ensure the consistency of the comparison framework.

The TOPSIS method was developed to define the concept of suitable alternatives when faced with a complicated decision. Choosing a process or product needs to be based on the shortest distance considering the positive ideal solution. On the other hand, the alternative should be furtherest from the negative ideal solution to solve the decision-making process. The TOPSIS method followed the following six steps. The first step is to normalize the decision matrix to calculate following equation 2.

Equation (2)

In this stage, the weighting described previously is multiplied by the weight of this criterion. The weighted normalized value is calculated using equation 3.

Equation (3)

In the next step, the negative ideal solution and positive ideal solution using equation 4.

Equation (4)

Nest, the distance between alternative and positive and negative ideal solutions is computed using equations (5) & (6). The separation measures are based on Euclidean distance, andof each alternative from the negative-ideal and positive-ideal solutions, respectively.

Equation (5)

Equation (6)

Calculate the relative closeness of each alternative using equation (7).

Equation (7)

The larger the relative closeness value, the better the performance of the alternative. The ranking order of for different mass timber will be between 0 to 1, and the case study closest to one will be determined as the best choice.

* 1. **Case study building**

The case study used is a hypothetical double-story building located in Kuala Lumpur, Malaysia. Its area is 112 M2, as shown in figure 2. NLT, DLT, and CLT were used for wall panels and floors, allowing large-sized building elements to be installed quickly in panel form (Demertzi et al., 2020). The market for NLT, DLT, and CLT as a building material is still limited in many countries including Asia at present. Thus, there is no specific design standard for mass timber in Malaysia. In this research, Eurocode 5 and relevant documents (European Committee for Standardization (CEN)) were adopted as the design standards for timber mass structures. Mass timber panels are manufactured from wood veneers in a factory and may be used instead of solid timber. Various manufacturing methods were used for the three specimens in this study. Unlike other engineering woods such as glued laminated timber (GLT) or Parallel-strand lumber (PSL) that are used as posts and beams (Kesik & Martin, 2021), all mass timbers in this study are used as wall panels and frames using softwood. The construction practice was considered to be prefabricated panel components transferred to site. The NLT and DLT panels were manufactured by either nail-jointing (for NLT) or dowel-jointing (for DLT) planks together. The wood grain of all planks was aligned in the same direction. CLT was manufactured by edge-gluing lumber planks with the wood grain of planks aligned in different directions in each layer (5 layers) (Niederwestberg et al., 2018).

The first option to be considered was CLT (Chaudhary, 2015). Adhesive is applied to planks, and these are then pressed together and cut to size. The adhesive used is polyurethane and is formaldehyde-free. As mentioned above, CLT is generally manufactured using five layers of wood with the grain oriented in 90 degrees to adjacent layers (Nairn, 2017). The glue is applied automatically over the entire surface of each plank at a rate of 0.2 kg/m². A very high-quality level of adhesion is achieved due to the high pressure applied (6 kg/cm²). The density of CLT was considered as 510 kg/m³. Therefore, the mass of a typical CLT wall panel of 180 mm thickness is 90 kg/m2.

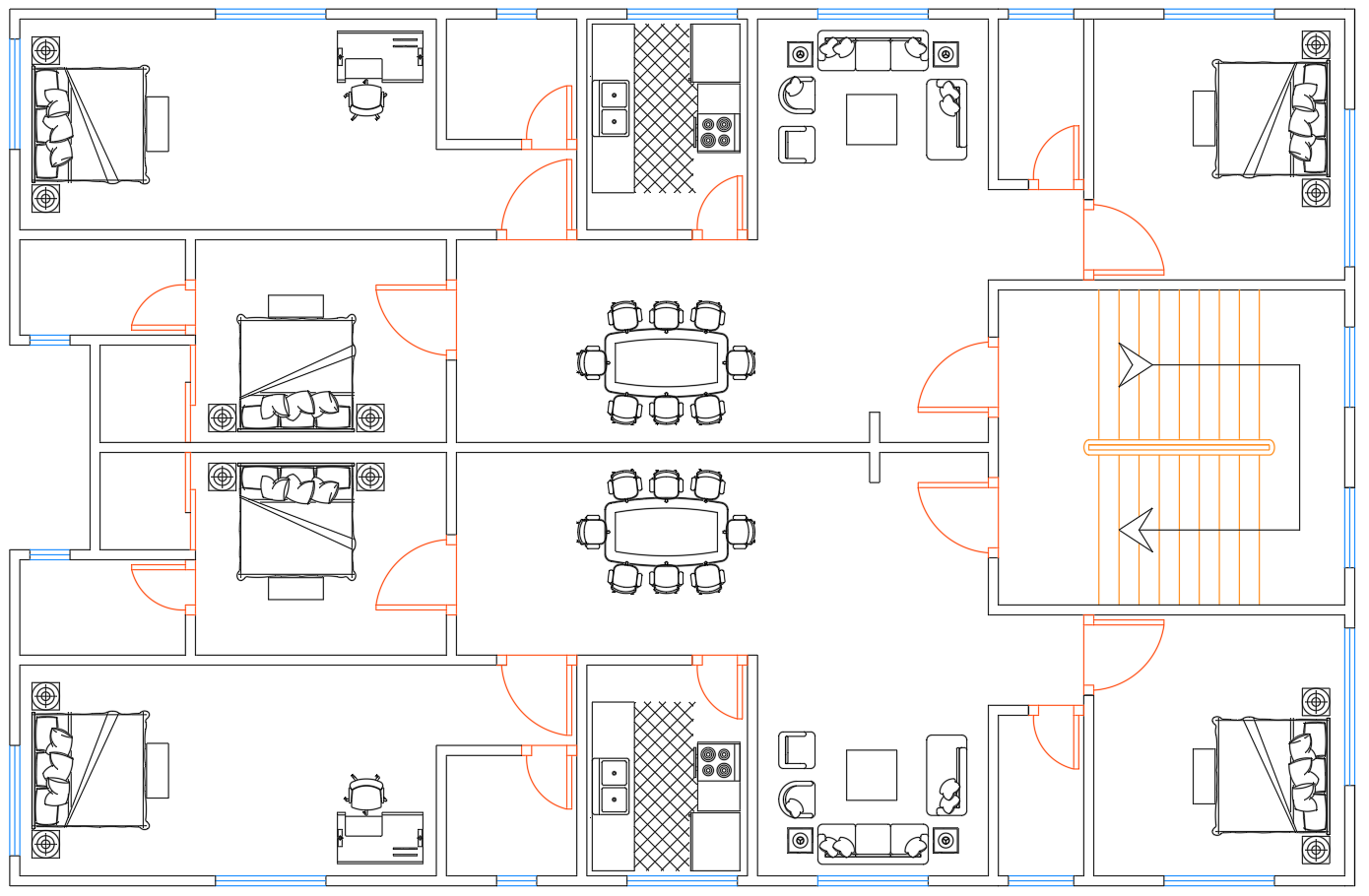


Figure 2, schematic design of double story building

The other two specimens were non-glued mass timber. They included nail-laminated timber (NLT) and dowel-laminated timber (DLT). The main differences between these two mass timber products relate to details and the materials used in their manufacture. NLT is created by fastening individual pieces of solid sawn lumber stacked on edge into one structural element with nails. NLT creates monolithic slab panels that support various structural and design needs (Rebecca Holt, Tanya Luthi, 2018). Firstly, wood is transferred by truck to the sawmill, where it is trimmed, dried, and graded. Secondly, the timber is transfer to a factory to be manufactured into NLT. This is achieved by attaching each layer of wood to the next one using nails. This results in a solid mechanical structural element (Rebecca Holt, Tanya Luthi, 2018). Each timber layer is attached by rows of 100 mm nails. On average of 100 nails are needed in each M2 of panel with a specific weight of 1.56 kg/m2. The physical properties of the NLT panels are 184 mm thick and weight 105 kg/m2 (Mahn et al., 2018). The density of NLT was considered as 570 kg/m³.

|  |  |
| --- | --- |
| A) |  |
| B) |  |
| C) |  |

Figure 3, detail of three different mass timber, A) cross-laminated timber, B) dowel laminated timber, C) nail laminated timber

Table 2 shows the characterization of the different mass timber buildings considered in this paper. The third case study is DLT. It does not use glues, resin, or nails (Sotayo et al., 2020). DLT is a mass timber panel product created by stacking timber planks together on their edge or cross-laminating them. They are fixed together with softwood dowels with a density of 510Kg/m3 ( Timber & Canada, 2018; Cesar et al., 2021) as shown in figure 3. The lumber needs to be cut to 20 x 20 x 200 mm dimension to create the dowel rods. These are then turned into round rods the weight which is 0.35 kg per meter. Five dowels (spaced 20 cm apart) are required for each m2 of the wall. Figure 3 shows the three different mass timber panels used in this study.Some assumptions related to raw materials production have been made to simplify the evaluation of the different alternatives. The EN 15978 framework defines the cradle stage as starting with raw material extraction (A1) followed by transportation (A2) and manufacturing of mass timber in the mill (A3). The next phase is transporting NLT, CLT, and DLT prefabricated panels to the site. The distance for this transfer was considered to be 50 Km. The next step is the installation and assembly of the panels using machinery (A5). Each material used in the case study has its own manufacturing process. Thus their energy requirements differ. Joints between walls were assumed to be via steel joint brackets (Kržan & Azinović, 2021). The weight of external wall insulation (assumed to be rock wool) is 9 kg/m2. The density of the vapor barrier used is 0.24 kg/m2, while that of the Gypsum Plasterboard wallboard used is 6.4 Kg/m2.  The density of the 50mm thick fiber cement cladding panels was 18 kg/m2. The distance from the factory to the site was considered to be 120 km. A 30 t truck was assumed to be used for this purpose, based on a real scenario.

Table 2, characterization of different mass timber building materials

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Building Types** | **Materials** | **Thickness MM** | **Density Kg/m3** | **Total Weight/Kg** |
| Cross-laminated timber  (CLT) | Fiber cement Cladding | 50 | 300 | 1584 |
| External wall insulation | 50 | 90 | 792 |
| Vapor barrier | 6 | 150 | 54 |
| Gypsum Plasterboard wall- interior | 12.5 | 530 | 562 |
| Lumber | 180 | 500 | 31610 |
| Adhesive | - | 641 | 70 |
| Steel drag strap connections | - | 2400 | 120 |
| Threaded screws | - | 780 | 80 |
| Nail Laminated Timber  (NLT) | Wood wool boards, wall Cladding | 50 | 300 | 1584 |
| External wall insulation | 50 | 90 | 792 |
| Vapor barrier | 6 | 150 | 54 |
| Gypsum Plasterboard wall | 12.5 | 530 | 562 |
| Lumber | 184 | 560 | 28964 |
| Nail | 100\*5 | 7860 | 549 |
| Steel drag strap connections | - | 2400 | 120 |
| Threaded screws | - | 780 | 80 |
| Dowel Laminated Timber  (DLT) | Wood wool boards, wall Cladding | 50 | 300 | 1584 |
| External wall insulation | 50 | 90 | 792 |
| Vapor barrier | 6 | 150 | 54 |
| Gypsum Plasterboard wall | 12.5 | 530 | 562 |
| Lumber | 190 | 449 | 28800 |
| Dowel | 20\*20\*200 | 500 | 123 |
| Steel drag strap connections | - | 2400 | 120 |
| Threaded screws | - | 780 | 80 |

Maintenance (B2) was considered for the three cases in anticipation of damage occurring to panels and walls. This was considered to be non-structural, and able to be remedied using average carpentry skills. Although NLT or CLT can provide good resistance against structural damage, additional bracing increases their stability (Sutton et al., 2011). Regular checks and maintenence of timber buildings leads to a reduction of possible defects and an increase in the lifespan of these buildings. Therefore, B2 incorporates replacing damaged parts of buildings and repairs based on their average expected lifespan. New materials require repair as part of the manufacturing process. It was assumed that 10% of panels needed to be repaired as there is limited data available in the literature.

The end of life of the building relates to demolition and disassembly of building components into separate materials (C1 & C2). For example, NLT panels need to be separated from the wood and nails used inside the panel. The distance from the site to the demolition factory has been assumed to be 50 Km. Steel was assumed to be sent to a factory for recycling (D3). Ninety percent of steel was assumed to be recycled and 10% was assumed to be sent to landfill. At the end of life for wood products, it was considered that 60% of wood would be reused (D1) while 40% would used for energy recovery (D2) and incinerated to generate electricity. The other non-structural materials such as gypsum board and wool insulation were assumed to be sent to landfills (D4) as their potential to be recycled and / or reused is uncertain .

1. **Results**
   1. **Environmental assessment**

This study investigates the impacts of carbon emissions, embodied energy, and economic variations among mass timber products used as a prefabricated wall panels in wood structure buildings.Since no LCA study has evaluated NLT and DLT and contrasted it with CLT, we have illustrated relevant variations in figure 4. The GWP result is presented in figure 4 and figure 5. Firstly, figure 4 shows the manufacturing details of CO2 emission of their assessed scenarios. Since the wall carried the weight of building loads, only high-quality wood from plantations was considered to produce the sawn timber. Therefore, the plantation stage shows its contribution to manufacturing the engineering wood. This item is generally neglected in previous research.

Figure 4. GWP of manufacturing and production of three mass timber-based, Kg CO2/M2

The contribution of plantation wood for 1 M2 of CLT wall is considered to be 30 Kg CO2eq/M2, which is 23% of total emissions. The significant emission contribution relates to the seasoning of wood prior to being cut to size in the sawmill. The manufacturing and seasoning stage contributes 87 KgCO2eq/M2, equal to 67% of CO2eq emission, the highest among other stages and processes. In the next stage, the timber planks are placed side by side and sprayed with adhesive, which contributes 3.8 KgCO2eq/M2 (3% of total emission for 1m2 of the wall). The next process involves the application of hydraulic pressure, to press the layers together. This contributes 5.7 KgCO2eq/M2, equal to 4% of emissions. Finally, the CLT panels needs to be cut to the required size. This occurs in the prefabrication factory, and the emissions generated in this stage is 3.5 KgCO2eq/M2, which is 3% of the total emissions.

The manufacturing of DLT is entirely different as it does not use any glues or nails. The manufacture of wood results in the highest emission of 78 KgCO2eq/M2 followed bywood plantation at 30 CO2/M2 These are responsible for 66% and 25% of total emissions for manufacturing 1 M2 respectively. Other stages are dowel manufacture, hydraulic pressure, and fabrication. These are assumed to contribute 2 KgCO2eq/M2, 5.7 KgCO2eq/M2, and 2.5 KgCO2eq/M2, respectively.

The third case, NLT, generates 133.5 KgCO2eq/M2 during its manufacturing stage. Similar to the previous mass wood case, the highest contribution of emission is for the manufacture of timber at 87 Kg CO2eq This is followed bywood plantation at 30 KgCO2eq. These stages contribute 65% and 25% of total emissions for manufacturing 1 M2,respectively. The nails used in NLT emit more than the glue used in CLT and the dowels used in DLT. The contribution of nails is about 12 KgCO2eq and is responsible for 9% versus 3% for adhesives and 2% of dowels, compared to the other two cases. These results reveal the importance of choosing appropriate materials. The last stage is fabrication, when panels are cut to the required sizes. It contributes 3% to emissions at 4.5 Kg CO2eq. The total emissions for 1 M2 of the three different products are as follows: NLT has the highest emission of 133.5 KgCO2/M2 followed by CLT KgCO2eq/M2 and DLT KgCO2eq/M2 with 130 KgCO2eq/M2 and 118 KgCO2eq/M2 with the same thickness. Put another way, the production of 1M2 of NLT has higher emissions by 1.5% and 11% than CLT and DLT.

Figure 5 shows the LCA for the three alternatives. Details of emissions for the construction stage for all materials are provided in appendix 1. The manufacturing and construction stage has the highest emissions. Among all the cases, NLT had the highest emission of 55761 KgCO2eqfollowed by CLT and DLT with54959 KgCO2eq,and51251 KgCO2eq, respectively. The following emissions relate to thebenefit and loadsstage. The end-of-life emission is slightly higher for NLT due to the separation of the nails from the panel's wall, roof, and floor. The emissions for end-of-life of NLT is 30% higher than the other cases as the building is demolished and materials are transferred away from the site by truck. The emissions for end-of-life are 850 KgCO2eq, 850 KgCO2eq, and 1200 KgCO2eq for CLT, DLT, and NLT respectively.

Figure 5. LCA for whole structure comparing of three alternatives engineering woods

However, NLT has a higher net positive impact than the other two alternatives in thebenefit and loadsstage (D1, D2, D3). The NLT has a 30% higher net positive compared to other cases. The total benefit loads are -22000 KgCO2eq, -22000 KgCO2eq, and -28000 KgCO2eq for CLT, DLT, and NLT respectively. This shows the importance of the demolition stage and emphasizes the consequences of avoiding sending materials to landfill sites. Thus, if reuse and recycling are adequately managed, positive impacts follow. The results showed that 12000 KgCO2eq avoided emission is related to the reuse scenario, and 8500 KgCO2eq is contributed to the recovery of materials. However, for steel recycling the scenario is different as 1500 KgCO2eq, 1500 KgCO2eq, and 7500 KgCO2eqis contributed for CLT, DLT, and NLT respectively.

In the following section, other environmental criteria identified as compulsory by EN 15804 have been assessed. Figure 6 shows the differences among the cases for different life cycle stages. Figure 5 and figure 6 show different environmental criteria and their contributions for each timber building. The manufacturing and construction stages contribute the highest emissions, followed by the maintenance and end of life stages. For the second environmental category, Human Toxicity Potential (HTP), the result is consistent with GWP, and NLT has a lower emission. The HTP result shows the Manufacturing & construction stage of NLT has a 2% and 3% higher impact than CLT and DLT, respectively. On the other hand, thebenefit and loadsstage (D1, D2, D3, and D4) have approximately 23% and 15% net positive impact compared to DLT and CLT due to recycling of nails. The accumulation of different stage results for HTP show that NLT has 14% and 9% lower emission than CLT and DLT.

The next environmental categories are AP, TE, and FD. The results for these criteria are not consistent with previous assessments for GWP and HTP. The high impact of AP, TE, and FD for NLT relate to the use of nails. The manufacturing and construction stage (A1, A2, A3, A4, and A4) of AP shows that NLT has a 12% and 18% higher impact than CLT and DLT, respectively. This impacts of this stage for AP are 379.6 kgSO2eq, 354 kgSO2eq and 428.9 kgSO2eq for CLT, DLT and NLT. Additionally, the end of life stage for NLT also has a higher impact for NLT due to removal of the nails from panels by 5.9 kgSO2eq, 5.9 kgSO2eq, and 9.2 kgSO2eq, showing a 33% higher impact. Additionally, the benefit and loads stage exploit circular economy principles by returning material to the life cycle of the building, improving the performance of NLT due to recycling (D3) of nails. The accumulation of D1, D2, and D3 for all scenarios shows that NLT outperformed the alternatives with 8% net positive impact over CLT and NLT. The wood materials only end up reusing (D1) and recovering (D2).

The TE and FD results show that DLT performs best compared to CLT and NLT. This is due to the absence of glues and nails in its structure. The TE result shows that DLT has a lower impact of 14% and 24% than CLT and NLT. On the other hand, FD categories show that DLT has a 5% and 36% lower impact than CLT and NLT. In general, two environmental categories (GWP and HTP) indicate that NLT is the preferable choice. At the same time, the other three criteria, namely, AP, TE, and FD, point to DLT as the best alternative. Thus, there is a need for additional investigation to ascertain which case is to be preferred.

Figure 6. Coefficients of three engineering woods structure

* 1. **Embodied energy**

The second criterion is embodied energy. This has been recognized as equal to GWP in recent research. Figure 7 shows the distribution for manufacturing 1 M2 of those three cases. The result showed the magnitude of energy that could ultimately vary among the alternatives. The first stage is the manufacture of lumber in the mill, which consumes more energy than the other construction processes. Figure 7 only shows the embodied energy consumed during the manufacture of the materials and does not include construction on-site. The embodied energy for the manufacture of mass timber for 1 M2 of wall surface is 1921 MJ/M2, 1902 MJ/M2, and 2130 MJ/M2 for CLT, DLT, and NLT, respectively.

Figure 7. Embodied energy for manufacturing and production of different wood materials-MJ/M2

It was found that DLT reduces the total embodied energy by about 11% and 2% compared to NLT and CLT, respectively. The embodied energy related to manufacturing CLT is 1390 MJ/M2, 64.4 MJ/M2, 208 MJ/M2, and 259 MJ/M2 for wood, adhesives, application of pressure, and fabrication, respectively, based on the percentages shown in figure 7. For DLT the contribution is 1390 MJ/M2, 100 MJ/M2, 90 MJ/M2, and 322 MJ/M2 related to wood, dowel, pressure, and fabrication. This indicates that the fabrication embodied energy for DLT is about 20% higher than CLT. This is due to the processing of the dowels in this type of engineered wood. On the other hand, the process of applying pressure is almost 2.3 times more for CLT than DLT. NLT embodied energy is 1390 MJ/M2, 400 MJ/M2, 340 MJ/M2 for wood, nails, and fabrication, respectively.

Figure 8 shows the embodied energy coefficients for the whole structure, starting with the manufacturing stage till benefit and loads. The embodied energy of manufacturing of the whole structure is 719122 MJ, 712590 MJ, and 793090 MJ for CLT, DLT, and NLT, respectively (Further details are provided in Appendix 2). The results indicated that the NLT structure has a higher embodied energy coefficient than the alternatives by 10% and 12% (CLT and DLT), respectively. What happens after demolition has a significant impact on the total energy on the whole structure. The positive net contribution of this stage is -287649 MJ, -285036 MJ, and -293737 MJ for CLT, DLT, and NLT. This indicates that NLT performs best due to the recycled steel for NLT. The steel in the NLT structure contributed to a higher impact at the construction stage, but recycling the steel reversed the result. The embodied energy for reuse and recovery are 215000 MJ and 105000 MJ.

On the other hand, the energy coefficient of steel recycling is 41000 MJ, 38000 MJ, and 146500 MJ for CLT, DLT, and NLT, respectively. Thus, considering the whole life cycle stage, including the benefit and loads, the result changed, and NLT became the best alternative. The total embodied energy of the whole structure is 471673 MJ, 467754 MJ, and 539553 MJ for CLT, DLT, and NLT, respectively.

Figure 8 embodied energy coefficients for the whole structure

* 1. **Life Cycle Cost**

For a product to be considered as sustainable, fundamental arguments that support economic performance (LCC) need to be made. Figure 9 shows the LCC of different life cycle stages of mass timber building, including the benefit and loads stage (which is interpreted as revenue). The system boundary has adopted the life cycle assessment discussed in section 2.1.1. The initial finding is that the highest cost relates to the mass timber structure itself, followed by the other materials incorporated in the building scheme (including wall insulation, gypsum plasterboard, and steel). The CLT option has a highest initial cost of 281600 MYR followed by NLT (274560 MYR) and DLT (264000 MYR). CLT is thus 3.5% and 6.2% more expensive initially compared to NLT and DLT. The cost of the other materials is 23450 MYR for all structures. The economic cost of wages, transportation, maintenance, and demolition are 3600 MYR, 7500 MYR, 2400 MYR, and 15000 MYR, respectively.

End-of-life costs need to be adjusted to account for the re-sale of building materials generated at their end of life. The cost for mass timber is 48000 MYR, and for steel, are 500 related to the CLT and DLT structure and 1600 for NLT that comprises steel connection and nail inside the panels. The final cost of DLT is lower from cradle to the grave by 267450 MYR, followed by NLT with 276910 MYR and 285050 MYR for CLT. Surprisingly, the cost of DLT and NLT are 7% and 3% lower than CLT. This is as a result of the re-sale of used materials and considering revenue of materials have decreased the total cost of building by approximately 15%.

Figure 9 costs of life cycle phase for alternatives timber mass

* 1. **Multiple-criteria decision analysis (MDCM)**

MCDM was performed to rank the alternatives by balancing their environmental, embodied energy, and economic impacts. Firstly, designers, industrial engineers and construction manager experts evaluated the importance of each criterion. They allocated weightings to prioritize the seven criteria by considering their importance towards sustainability. The results are shown in Table 3. A computed CRa of less than 0.1 indicates that the comparison matrix is consistent. The first group of respondents was building designers who have experience with engineered wood. Their first priority is GWP, being weighted twice as much as cost. Designer believed strongly that CO2 emissions should be prioritised when choosing building materials. They considered other environmental impacts as secondary. Moreover, they believed that embodied energy should be the second priority, followed by FD and cost. Unlike the designers, the industrial engineers and construction managers believed strongly that cost should be considered the highest priority when choosing engineered wood. The industrial engineers considered embodied energy and GWP as second and third, respectively. However, the construction managers’ second priority was GWP, followed by HTP, AP, as third and fourth choices. Finally, the accumulation and average of these three-groups of respondents revealed that cost was considered most important followed by GWP and embodied energy.

Table 3. The results of the generalized survey (Weighting=W; Priority=P)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Criteria** | **Designer** | | **Industrial engineering** | | **Construction Manager** | | **Total** | |
| **W** | **P** | **W** | **P** | **W** | **P** | **W** | **P** |
| GWP | 0.24 | 1 | 0.14 | 3 | 0.19 | 2 | 0.19 | 2 |
| HTP | 0.11 | 5 | 0.12 | 4 | 0.12 | 3 | 0.12 | 4 |
| AP | 0.1 | 6 | 0.1 | 5 | 0.12 | 4 | 0.11 | 6 |
| TE | 0.09 | 7 | 0.08 | 6 | 0.11 | 5 | 0.09 | 7 |
| FD | 0.15 | 3 | 0.07 | 7 | 0.11 | 6 | 0.11 | 5 |
| Embodied energy | 0.19 | 2 | 0.19 | 2 | 0.1 | 7 | 0.16 | 3 |
| Cost | 0.12 | 4 | 0.3 | 1 | 0.25 | 1 | 0.22 | 1 |
|  | CRa= 0.045 <0.1 | | CRa= 0.051 <0.1 | | CRa= 0.063 <0.1 | | =1 |  |

The initial decision-making matrix for the different construction methods and materials is presented in Table 4 (drawn from Figures 6, 8, and 9). The first step is to define which criteria are beneficial or non-beneficial. The beneficial dimension in this study is considered as the minimum amount or value. For example, comparing the cost of three cases (table 4), DLT has the lowest cost of 267450 MYR. This is also indefeasible for embodied energy, GHG and Land use, etc. Therefore, the minimum amount is considered beneficial for all seven criteria.

Table 4 Initial decision-making matrix

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Criteria | GWP | HTP | AP | TE | FD | Embodied  energy | Cost |
| CLT | 36363 | 505.46 | 251.17 | 1561.46 | 12745.79 | 471673 | 285050 |
| DLT | 32600.1 | 453.15 | 225.18 | 1358.34 | 10516.16 | 467754 | 267450 |
| NLT | 31481.5 | 437.6 | 217.45 | 1776.41 | 13687.61 | 539553 | 276910 |

Table 5 shows how MCDM is applied using the TOPSIS method. This method determines the best of the three alternatives based on seven criteria comprising five environmental impacts, embodied energy, and cost. First, the normalized matrix needs to be calculated using equation 2. The result of this stage is shown in Appendix 3. Next, the weighted normalized matrix is calculated using equation (3). Following this, the positive ideal value and negative idea value are determined using equation 4. The non-beneficial value is the minimum value that is considered as ideal for all criteria such as cost, GWP, etc. Therefore, the ideal best values (are 0.07740, 0.07615, 0.07204, 0.07256, 0.07153, 0.07916 and 0.07976 respectively for GWP, HTP, AP, TE, FD, EE, and cost. The maximum value for each criterion considered as ideal worst is 0.0894, 0.08795, 0.0936, 0.09048, 0.0979, 0.0881, and 0.0850 respectively for GWP, HTP, AP, TE, FD, EE, and cost. Next, the Euclidean distance from the ideal best ( needs to be calculated using equation (5). The Euclidean distance from ideal worst is determined in a similar manner using equation (6) as shown in table 5. Finally, the relative closeness performance score ( is evaluated using equation (7). Based on the performance score ranking the alternative buildings, DLT was identified to be the best timber material with 0.8363 followed by 0.4969 and 0.3844 relevant to CLT and NLT.

Table 5, result of MCDM using TOPSIS

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Criteria*** | GWP | HTP | TE | HTP | LUP | FDP | Embodied  energy | Cost |  |  |  |
| CLT | 0.1189 | 0.0718 | 0.0600 | 0.0545 | 0.0581 | 0.0882 | 0.1329 | 0.1189 | 0.0227 | 0.0224 | 0.4969 |
| DLT | 0.1066 | 0.0677 | 0.0538 | 0.0474 | 0.0551 | 0.0875 | 0.1247 | 0.1066 | 0.0066 | 0.0338 | 0.8363 |
| NLT | 0.1029 | 0.0622 | 0.0699 | 0.0591 | 0.0754 | 0.1009 | 0.1291 | 0.1029 | 0.0305 | 0.0190 | 0.3844 |

1. **Sensitivity analysis and Discussion**

Two sensitivity analyses were performed to determine the outcome of this study. Firstly, an analysis were was conducted to determine the impact of each criterion's weighting on the result. The priority of different each of the seven criteria is dependent on different variables including national priorities, organizational perspectives, and different attitudes to the use of timber construction in different societies and countries. The first sensitivity analysis was conducted to support decision making. It is particularly helpful and important when criteria are closely ranked, such as HTP, AP, TE, and FD in the present study. In such a case, all the criteria are considered and rechecked when they have the same weights (all criteria have the weight of 0.14). The result showed that the ranking for different timber mass buildings did not change (as shown in appendix 4), but unique performance scores ( were obtained: CLT (0.5542), DLT (0.8496) and NLT (0.3004). With this in mind, the sensitivity analysis identified DLT as the best choice with the highest ( value.

The second sensitivity analysis drew on the basic assumptions made in the previous section (Section 2.3) about raw materials. However, these assumptions pertained to the reference building characterizations using softwood as building materials. The analysis highlighted alternative scenarios and investigated how the system reacts to changes in different input parameters. Given uncertainty regarding future life cycle interventions, an additional manufacturing scenario was included as a sensitivity analysis. In the general scenario, a sensitivity analysis reanalysis was conducted using hardwood Air-dried as life cycle inventory with a density of 720 kg/m3.

The result is shown in figure 10, assuming that hardwood is used instead of softwood for all the three cases. By changing the raw materials from softwood to hardwood, the manufacturing stage emission rose from 45408 KgCO2 to 4858 KgCO2, from 41700 KgCO2 to 44619 KgCO2, and from 46210 KgCO2 to 49444 Kg CO2 related to the CLT, DLT, and NLT, respectively. Thus, emissions increased by approximately 7% for all alternatives. Other changes resulting from the reuse scenario indicate that the net positive influence changed from 12000 KgCO2 to 12840 KgCO2. Consequently, the total benefit and loads from the demolition stage became 22840 Kg CO2, 22840 KgCO2 and 28840 KgCO2 for CLT, DLT, and NLT. This result shows that changing to hardwood results in only a 3% difference for reuse compared to softwood. Finally, the result showed that using hardwood instead of softwood as a raw material has not changed the ranking of different emissions for mass timber. CLT has the lowest priority because it releases the highest emissions compared to NLT.

Figure 10 GWP coefficients using hardwood for alternatives

Previous LCA studies that compare materials typically consider one form of wood, either softwood or hardwood. These studies do not consider the emissions resulting from the plantation stage. This study compared the manufacture of hardwood as an alternative to softwood to reveal differences when tehse materials are used interchangeably. Moreover, none of the previous studies compared different engineered wood products as load-bearing walls. In this application, DLT is not as strong as CLT because the constituent timber planks in DLT tend to slip relative to each other. Nevertheless, the goal is to manufacture a 100% wood product that is easier to produce than CLT and does not need adhesive. Since the wood materials considered in this study are only for panels, our result is valid and sufficient for those who use this popular construction method.

At present, there are no studies about the LCA or LCC of different timber mass materials such as NLT or DLT. Previous research, such as Balasbaneh & Sher, (2021a), has shown that CLT is considered superior to glued laminated timber as a building material. Therefore, based on the current result that NLT and DLT have lower GWP emissions than CLT, we can conclude that these materials have lower emissions (CO2) than glued laminated timber. The cradle-to-cradle assessment (construction stage) of GWP shows that DLT has a lower environmental emission. At the same time, by expanding the boundary to cradle to grave and considering the end-of-life scenario, NLT is the most favorable choice. This evaluation is also consistent for embodied energy.

The result for LCC is different. In this context, DLT is considered as the best economic choice throughout the life cycle stages. Although DLT shows better performance, it has not been used to the same extent as CLT around the world. This can be addressed in future research. One reason may be that the manufacturing process that is not skilled up and remains in its infancy in many countries (Sorathiya et al., 2019).

1. **Conclusions**

Previous research has indicated that mass timber has a lower environmental impact than steel or concrete. Thus, wood or mass timber is recognized as a sustainable choice for constructing buildings. The current construction practice in Malaysia is to use concrete. Wood is uncommon and this is mainly due to a lack of knowledge and information about different engineered timber products. Mass timber materials have gained popularity recently, having been revived worldwide because of their renewable and low environmental emissions credentials. Furthermore, timber is widely recognized as reducing the embodied energy of buildings compared to other alternatives. Despite this, timber is not as popular in many South Asian countries because of a lack of reliable information on different mass timber products. In this study, we have compared the environmental impact of alternatives to disclose which performs better over their entire lifespan, based on three criteria (global warming potential, embodied energy, and cost). The LCA result of GWP and embodied energy shows that nail-laminated timber is preferable to cross-laminated timber and dowel laminated timber. However, the life cycle cost result also revealed that dowel laminated timber has a lower cost. MCDM was used to normalize the results among seven criteria to enable the result to be compared. The MCDM result showed that DLT is considered the best alternative. The information included here is supplemental to wood design and construction best practices and is specific to using mass timber as a wood frame construction technique. Based on this study, there are opportunities for future work to explore areas. Firstly, LCA can be expanded to compare other criteria and attributional LCI for those case studies. Secondly, the social aspect of alternatives warrants evaluation as this can influence the uptake of the technology and therefore sustainability. The result of current research can be used as a road map for stakeholders to select the most valuable and optimum choices in mass timber construction among different alternatives.

**Declarations**

The authors declare that they have no known competing ﬁnancial interests or personal relationships that could have appeared to inﬂuence the work reported in this paper.

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**Appendix 1, GWP**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | ***Unit*** | ***CLT*** | ***DLT*** | ***NLT*** |
| Manufacturing | KgCO2 | 45408 | 41700 | 46210 |
| on site | 4.51E+03 | 4.51E+03 | 4.51E+03 |
| cladding | 1.59E+03 | 1.59E+03 | 1.59E+03 |
| insulation | 1.13E+03 | 1.13E+03 | 1.13E+03 |
| Plasterboard wall | 253 | 253 | 253 |
| steel ledgers for floors | 442 | 442 | 442 |
| steel drag strap connections | 6.5 | 6.5 | 6.5 |
| Threaded screws | 1.62E+03 | 1.62E+03 | 1.62E+03 |
| Transportation | 353.5 | 298.6 | 320 |
| Maintenance | 2200 | 2200 | 2200 |
| End of life | 850 | 850 | 1200 |
| Benefit and loads | -22000 | -22000 | -28000 |

**Appendix 2, embodied energy**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | ***Unit*** | ***CLT*** | ***DLT*** | ***NLT*** |
| Manufacturing | MJ | 719122 | 712590 | 793090 |
| construction | 4100 | 4100 | 4100 |
| Transportation | 17500 | 17500 | 17500 |
| Maintenance | 12200 | 12200 | 12200 |
| End of life | 6400 | 6400 | 6400 |
| Benefit and loads | -287649 | -285036 | -293737 |

**Appendix 3**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| ***Criteria*** | ***GWP*** | ***HTP*** | ***AP*** | ***TE*** | ***FD*** | ***Embodied***  ***energy*** | ***Cost*** |
| CLT | 0.6258 | 0.6157 | 0.5625 | 0.5839 | 0.5286 | 0.5512 | 0.5951 |
| DLT | 0.5611 | 0.5804 | 0.5043 | 0.5079 | 0.5007 | 0.5466 | 0.5583 |
| NLT | 0.5418 | 0.5330 | 0.6552 | 0.6333 | 0.6855 | 0.6305 | 0.5781 |

**Appendix 4**, same weighting

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Criteria*** | ***GWP*** | ***HTP*** | ***AP*** | ***TE*** | ***FD*** | ***Embodied***  ***energy*** | ***Cost*** | ***Si+*** | ***Si-*** | ***Pi*** | ***Rank*** |
| CLT | 0.0894 | 0.0880 | 0.0804 | 0.0834 | 0.0755 | 0.0787 | 0.0850 | 0.0227 | 0.0293 | 0.5633 | 2 |
| DLT | 0.0802 | 0.0829 | 0.0720 | 0.0726 | 0.0715 | 0.0781 | 0.0798 | 0.0073 | 0.0420 | 0.8519 | 1 |
| NLT | 0.0774 | 0.0761 | 0.0936 | 0.0905 | 0.0979 | 0.0901 | 0.0826 | 0.0404 | 0.0170 | 0.2962 | 3 |