

Multi-Criteria Evaluation of CLT Floor Assemblies: Life Cycle Impacts, Acoustic Performance, Design Parameters, and Reuse Potential

A. V. Juraschka¹, M. Song¹, J. Kim¹, C. T. Haas¹, A. Hojjati², J. Ahn² and M. Ghobadi²

¹ Civil and Environmental Engineering, University of Waterloo, 200 University Ave W. Waterloo, Canada

² Construction Research Centre, National Research Council Canada, Ottawa, ON, Canada,

ABSTRACT: Cross-laminated timber (CLT) offers considerable potential in decarbonization of the built environment by enhancing construction efficiency and productivity through offsite construction and providing carbon storage benefits in Life Cycle Analysis (LCA). In multi-unit residential buildings (MURBs), suboptimal acoustic performance of Mass Timber poses design challenges. Integration of acoustic dampening layers, increases material use, embodied carbon, and assembly weight. Floor thickness and reuse potential are also affected. In LCA studies, these complexities are inconsistently accounted for. A holistic evaluation integrating environmental, acoustic, and reuse metrics is needed to address this gap. Accordingly, this study evaluates four typical CLT floor assemblies – (1) concrete topping with acoustic mat, (2) concrete composite floor, (3) acoustic products without concrete topping, and (4) raised access floor – using a cradle-to-cradle approach. Tally® LCA was used for environmental impact assessment, supplemented by manufacturer Environmental Product Declarations (EPDs) where data gaps existed. Sound transmission class (STC) and impact isolation class (IIC) data from studies by WoodWorks Wood Products Council was used to assess acoustic performance. Design parameters, including assembly weight, and thickness, were also evaluated. Reuse potential of structural elements was evaluated based on disassembly potential. Findings of this study indicate that substituting concrete toppings with raised access floor systems reduces embodied carbon by up to 64%, without compromising acoustic performance. These substitutions also reduce assembly weight, enabling the use of lighter structural members. Mechanically fastened acoustic layers improved reuse potential by simplifying disassembly. This research highlights the importance of holistic evaluations to inform the optimized design and application of CLT floor systems.

1. INTRODUCTION

The building and construction sector is responsible for 37% of global anthropogenic greenhouse gas emissions (UNEP 2024). With the increasing demand for housing and infrastructure, reducing this impact is crucial. Mass Timber has emerged as a promising solution due to its renewable nature and low environmental impacts (Younis et al. 2022). Life cycle analysis (LCA) is essential for evaluating building material impacts. Cradle-to-cradle LCA, encompassing all life cycle stages (product, construction, use, end-of-life, and beyond), is critical for understanding the environmental impacts of material choices at the design phase to reduce embodied carbon. Cross-laminated timber (CLT), a type of Mass Timber, has gained attention due to benefits including a low carbon footprint, high strength-to-weight ratio, aesthetic appeal, and ease of installation (Younis et al. 2022). Its prefabricated and panelized nature allows for rapid on-site erection and dimensional stability (Brander 2013). This enables improved construction productivity and labour cost savings (Younis et al. 2022). However, CLT's environmental performance in design contexts is

influenced by factors beyond the material itself. For CLT floor panels, elements including acoustic toppings, assembly weight and thickness, and end-of-life (EoL) disassembly potential all play critical roles in assessing the impact of an assembly. Yet, many of these factors are commonly omitted from LCA studies, whose system boundaries may be unrealistically narrow from both building assembly and longitudinal perspectives.

A systematic literature review by Younis et al. (2022) revealed that most LCA studies on CLT over the past decade focused solely on structural components, and none of them conducted cradle-to-cradle analyses (Younis et al. 2022). This exclusion of non-structural elements creates uncertainties surrounding the LCA impacts of other design parameters, particularly serviceability requirements including fire and acoustics that often govern design. Bare CLT assemblies generally do not meet required acoustic performance standards (Hindman et al. 2020) and thus require additional acoustic layers (e.g., concrete topping), which are often omitted from comparative LCAs, limiting their validity. Furthermore, neglecting Module D (reuse) can significantly influence total life cycle carbon footprint (Younis et al. 2022). While data limitations often explain this omission, proper characterization of EoL scenarios can have significant impacts on environmental indicators. Darby et al. (2013) conducted a case study analysis analyzing different EoL scenarios for a CLT building and found that reusing CLT resulted in global warming potential (GWP) reduction of more than 50% compared to incineration with energy recovery. This highlights the potential benefits of a cradle-to-cradle LCA for CLT, which have historically been neglected in the literature. Existing LCA studies have also generally omitted investigation into design for disassembly (DfD) principles, which are a key factor in the feasibility and likelihood of a building achieving multiple life cycles in practice. This leaves a literature gap to provide a combined investigation into a cradle-to-cradle LCA and DfD assessment. Furthermore, it is commonplace within existing literature to independently evaluate performance characteristics of CLT (e.g., focus solely on LCA or structural design parameters). This reduces the applicability of findings to real-world contexts, where there is a necessity for integrated decision making to optimize performance across multiple objectives and identify potential trade-offs or synergies. From an industry perspective, decisions are often made based on data collected using inconsistent and incompatible methodologies, yielding results which may be incomparable or misleading (e.g., comparison of qualitative assessment of DfD and quantitative LCA analysis). This highlights a gap in the existing knowledge base for a framework to holistically evaluate multiple key performance criteria of CLT floor assemblies.

This study provides a multi-criteria evaluation framework for key CLT performance criteria through an investigation into four CLT floor assemblies with same grade and layer count. It explores cradle-to-cradle LCA, assembly weight and thickness, acoustic performance, and disassembly potential, to provide insights into the performance of CLT floor assemblies under various design criteria. By integrating these diverse criteria into a single comparative analysis, this study aims to provide stakeholders tools to make informed and comprehensive early design decisions for mid-rise residential construction.

2. METHODOLOGY

This section describes the methods and assumptions used in the holistic quantitative assessment of four CLT floor assemblies. Collected data included: GWP emissions based on a cradle-to-cradle LCA, acoustic performance, design parameters including assembly thickness and weight, and disassembly potential to assess structural reuse. Assessment of each floor assembly was conducted based on its hypothetical application in a mid-rise residential building, considering relevant code compliance. A methodology used to compare the floor assemblies through a holistic lens is also presented.

2.1 Characteristics of studied flooring assemblies

Selection of the CLT floor assemblies was established based on categories defined by WoodWorks Wood Products Council (WoodWorks): CLT with concrete/gypsum topping, CLT without concrete/gypsum topping, CLT-concrete composite floors, and CLT with raised access floor or wood sleepers (WoodWorks Wood Products Council 2024). This range of floor assemblies provides a variety of options which may be selected based on the design objectives for a particular project. Based on the constraints, project goals, and typical construction practices, certain assemblies may be more tailored to a particular project. The

critical limiting factor for the selection of the analyzed assemblies was availability of published acoustic performance data. As such, the assemblies were selected in accordance with the Inventory of Acoustically Tested Mass Timber Assemblies published by WoodWorks (WoodWorks Wood Products Council 2024). These assemblies were further limited to exclude data which incorporated floor finishes in acoustic performance data. This omission provides a more reliable baseline for the assembly’s acoustic performance, regardless of any owner-driven aesthetic modifications of floor finishes. A final condition placed upon the selected assemblies was a minimum sound transmission class (STC) of 47, as per compliance with the National Building Code of Canada (NBC) 2020 requirement for floor assemblies separating residential units (National Research Council Canada 2020). Table 1 details the investigated assemblies.

Table 1: Investigated Floor Assemblies

Assembly Name	Assembly Layers			
	Layer 1	Layer 2	Layer 3	Layer 4
CLT with Concrete Topping	5-ply CLT	100 mm Concrete Topping	Pliteq GenieMat™ FF10	Pliteq GenieMat™ FF6
CLT-Concrete Composite Floor	5-ply CLT	60 mm Concrete	10 mm Maxxon Acousti-Mat®	25mm Gyp-Crete®
CLT without Concrete Topping	5-ply CLT	12 mm Cement Board	12 mm Cement Board	12 mm Wood Fiberboard
CLT with Raised Access Floor	5-ply CLT	Akustik+ Sylomer® Floor Mount 25 with mineral wool insulation in cavity	22 mm OSB on 50 mm x 76 mm Wood Sleepers	25 mm Gypsum Fiberboard

2.2 Quantitative Analysis

2.2.1 Life Cycle Analysis

To gain perspective on the environmental impact of the investigated floor assemblies, a cradle-to-cradle LCA was conducted. Tally® LCA software (Tally) was used to conduct the environmental impact assessment based on a 1 m² representative section of each floor assembly. Tally was selected to conduct the LCA study, as it is commonly used to make high-level design and material decisions. Furthermore, Tally utilizes average EPD data from across North America, yielding more generalized LCA results that are project independent. Tally references several standards for its LCA methodology. These include ISO 14040-14044, ISO 21930:2017, ISO 21931:2010, EN 15804:2012, and EN 15978:2011 (Safari et al. 2021). Data for Tally is sourced from GaBi and the EC3 database of EPDs. Material selection for the representative floor assemblies was based on the information outlined in Table 1. Default Tally inputs were used for project information including service life and transportation distances. Material data gaps in Tally were addressed by manufacturer-published Environmental Product Declarations (EPDs) that are publicly available, and when such data was not accessible, direct communication with manufacturers was initiated to obtain the necessary EPDs. In the instance where manufacturers could not provide the required information or did not respond to the request for information, engineering judgment was exercised to find a comparable material with a publicly available EPD. A comparable material was determined based on regulatory production, region, and material composition and used for the analysis.

Total GWP impact category was utilized as the LCA output for this evaluation. The total life cycle GWP outputs were calculated based on the combination of the Tally outputs and the manufacturer sourced EPDs multiplied by the 1 m² representative floor assembly, across the entire life cycle, as summarized in Equation 1.

$$[1] \text{ Total GWP} = \sum_{\text{Stage A}}^{\text{Stage D}} (\text{GWP}_{\text{Tally}} + \text{GWP}_{\text{Manufacturer Area}})$$

Total life cycle GWPs were used to compare the environmental performance of each of the floor assemblies.

2.2.2 Acoustic Performance

Acoustic performance of assemblies was assessed through studies conducted by WoodWorks (WoodWorks Wood Products Council 2024). Both the STC and impact isolation class (IIC) were utilized to assess the acoustic performance of the investigated assemblies. For the following assemblies: CLT with Concrete Topping, CLT-Concrete Composite Floor, and CLT without Concrete Topping, STC performance was determined in accordance with ASTM E90 and the IIC performance was determined in accordance with ASTM E 492. The STC and IIC performance for the CLT with raised access floor assembly was determined in accordance with the prediction method referenced in ISO 10140. Collected acoustic performance data was then compared with the minimum required STC of 47 as per the NBC 2020 (National Research Council Canada 2020), as well as the more stringent requirements outlined in LEED v4.1. Under LEED v4.1, an additional point can be earned for multi-family residential dwellings by meeting a minimum STC and IIC rating of 50 for assemblies separating dwelling units (U.S. Green Building Council 2024).

2.2.3 Design Parameters

Assembly thickness and weight were evaluated for each floor assembly, due to their critical role as key design parameters. These parameters can be influential in a variety of design considerations including overall building height, required ceiling heights, and required structural capacity of gravity members. Assembly thickness was calculated based on the specified dimensions outlined in Table 1. If a material thickness was not specified for a given product, the thickness was determined based on manufacturer published datasheets. Weights for each of the materials were sourced from manufacturer reported weights and dimensions of products. If a manufacturer was not specified in the acoustic testing data, weights and product dimensions were established based on the published weights and dimensions from common distributors. After collecting the weight data for each product, the total assembly weight was calculated on a kg per m² basis.

2.2.4 Potential to Disassemble

To assess the reuse potential of the structural elements, the potential to disassemble the various acoustic layers was considered. Based on DfD principles, the fixation method of building components can greatly impact the future salvage value of a material and the potential for direct reuse of the material. The Dutch Green Building Council (DGBC) developed a framework which assesses the disassembly potential for reusability (Van Vliet et al. 2021). For the purposes of this study, the methodology to determine the disassembly potential of the connection (DP_C) outlined by the DGBC was employed. To determine the DP_C, two key factors are considered: the connection type (CT) and the connection accessibility (CA). With respect to CT, disassembly was assessed based on the criteria outlined in Table 2.

Table 2: Connection Type Disassembly Classes

Connection Type	Examples	Score
Dry Connection	Loose (no fastening material), Click connection, Velcro connection, Magnetic connection	1.00
Connection with added elements	Bolt and nut connection, Spring connection, Corner connections, Screw connection, Connections with added connection elements	0.80
Direct integral connection	Pin connections, Nail connection	0.60
Soft chemical connection	Caulking connection, Foam connection (PUR)	0.20
Hard chemical connection	Adhesive connection, Dump connection, Weld connection, Cementitious connection, Chemical anchors, Hard chemical connection	0.10

*Adapted from Dutch Green Building Council (Van Vliet et al. 2021)

CA was also evaluated based on the ease of accessing the connecting element and the resultant damage which may ensue to underlying material. Table 3 summarizes the criteria for assessing CA.

Table 3: Connection Accessibility Classes

Connection Accessibility	Score
Freely accessible without additional actions	1.00
Accessible with additional actions that do not cause damage	0.80
Accessible with additional actions with fully repairable damage	0.60
Accessible with additional actions with partially repairable damage	0.40
Not accessible - irreparable damage to the product or surrounding products	0.10

*Adapted from Dutch Green Building Council (Van Vliet et al. 2021)

CT and CA scores were given for each layer of the assembly. The total DP_C for each assembly was calculated as per Equation 2, where m is the number of layers in the assembly.

$$[2] DP_C = \sum_{n=1}^m \frac{2}{\frac{1}{CT_n} + \frac{1}{CA_n}}$$

The average DP_C of each floor assembly was used to compare the disassembly potential, where a greater DP_C score indicates greater ease of disassembly, with a maximum value of 1.

2.2.5 Multi-Criteria Evaluation

The multi-criteria evaluation of this paper highlighted strengths and weakness of the assemblies through a direct comparison of investigated criteria. To facilitate this, data normalization was performed on the collected quantitative data, and a radar chart was developed. Optimal results are obtained when values are minimized for GWP, thickness and weight of an assembly, thus were normalized using Equation 3. Contrarily, STC, IIC and disassembly potential yield optimal results when values are maximized, thus were normalized using Equation 4.

$$[3] x' = \frac{\min(x)}{x}$$

$$[4] x' = \frac{x}{\max(x)}$$

3. RESULTS

This section presents the results for the LCA, acoustic performance, design parameters, and disassembly potential of the four investigated floor assemblies. Findings indicate that floor assemblies vary across different performance criteria, thus depending on design goals, certain floors may be favoured over others. Regarding GWP, the assemblies performed similarly across all life cycle stages, except the product stage. At the product stage, all floor assemblies had a level of GWP offsetting, primarily attributed to the biogenic carbon storage properties of wood (Younis et al. 2022). This offset significantly influenced overall life cycle GWP. For instance, the CLT with raised access floor assembly performed least optimally in the end-of-life and module D stages. However, it had the greatest GWP offset from the product stage which resulted in the lowest GWP across all life cycle stages. Figure 1 visualizes the GWP of each floor assembly across each stage of the life cycle.

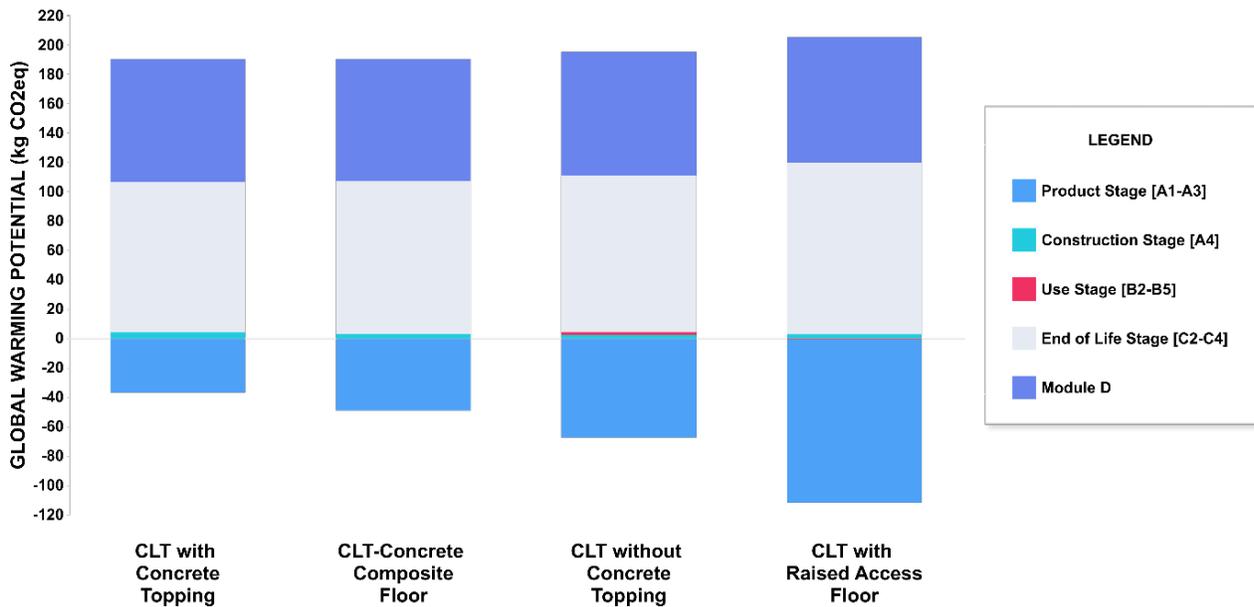


Figure 1: Global Warming Potential of Floor Assemblies across Cradle-to-Cradle Life Cycle Analysis

Investigation into thickness and weight posed an interesting correlation. For most assemblies, as the thickness increased, so did the weight, with one notable exception. The raised access floor assembly, which due to the lightweight materials used in the assembly, performed well in the weight criteria despite having the thickest profile. Acoustic performance had a correlation with assembly thickness, with the greater acoustic performance occurring as the assembly thickness increased. The disassembly potential was strongly influenced by material type and fixation method. Assemblies which favoured mechanical fixation over adhesive fixation performed most optimally. The CLT-Concrete Composite floor notably performed the worst under the DP_C criteria, due to the multiple layers of concrete sandwiched around the other assembly layers. Table 4 summarizes all collected data.

Table 4: Summary of Floor Assembly Performance Data

Assembly Name	GWP (kg CO ₂ eq)	Design Parameters		Acoustic Performance		DP _c
		Thickness (mm)	Weight (kg/m ²)	STC	IIC	
CLT with Concrete Topping	153.4	267	273.5	56	50	0.62
CLT-Concrete Composite Floor	141.5	267	253.6	52	50	0.25
CLT without Concrete Topping	127.8	212	111.6	48	46	0.43
CLT with Raised Access Floor	93.3	326	112.5	64	61	0.81

To determine the optimal floor assembly for a given project, it is essential to consider the performance of each assembly under each criterion. The data in Table 4 was normalized on a scale of 0 to 1 to evaluate performance across design parameters (thickness and weight), acoustic performance, disassembly potential, and GWP. Figure 2 illustrates the performance of the assemblies across all criteria. From the figure, it is apparent that no single assembly excels in every category. For example, the CLT with raised access floor performs most optimally or almost most optimally across all categories, except thickness.

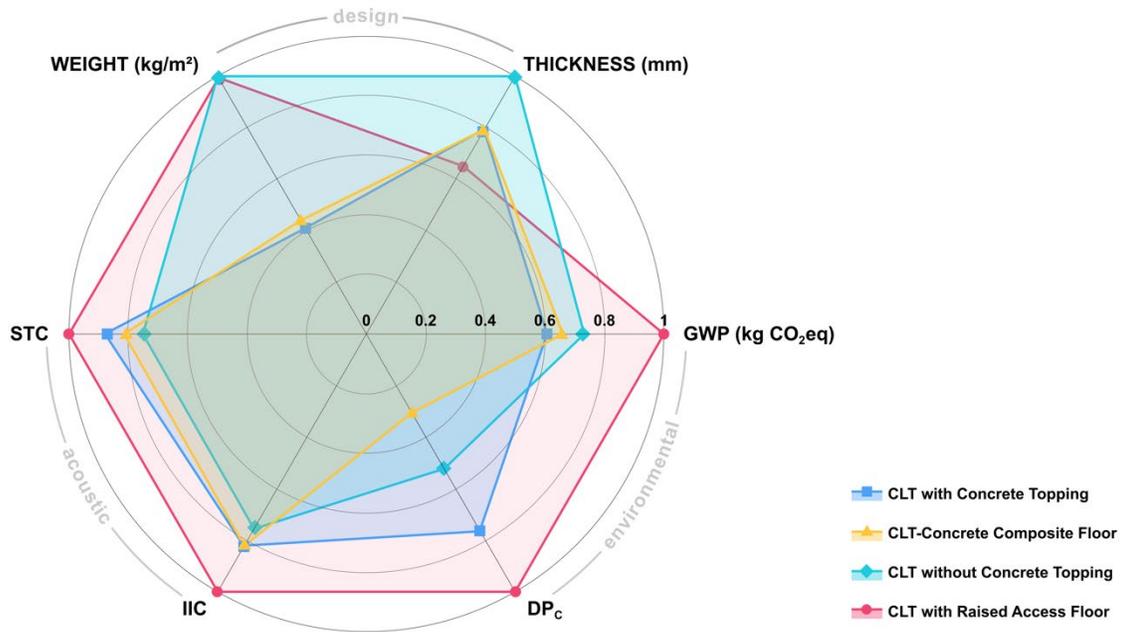


Figure 2: Evaluation of CLT Floor Assemblies based on Multiple Design Criteria

The results underscore the importance of conducting a holistic investigation into the selection of a floor assembly. It also highlights the necessity to take a data-driven approach to ranking and assessing floor assembly performance.

4. DISCUSSION

The results of this study indicate that design decisions for floor assemblies are multifaceted and dependent on a project's design objectives. This discussion provides insight into the key findings of floor assembly performances through the investigated metric. Discussion of the practical implications of the findings of this study is included. Factors including MEP (mechanical, electrical, and plumbing) and structural integration are explored. Generalizability of the study's findings to other building types is discussed. Finally, limitations of the study and future research will be outlined.

Key findings from the analysis are as follows:

- **LCA Findings and Impacts:** The LCA revealed variations in GWP across assemblies, driven by material composition, particularly in Module A. The CLT with raised access floor assembly performed most optimally, exhibiting 37% less GWP than the next best alternative, the CLT assembly without concrete topping. This is largely attributed to the use of several wood-based materials in the assembly, resulting in carbon savings at the product stage. When investigating Module D, most assemblies performed similarly, which is unexpected based on the greatly varying performances of the assemblies with respect to disassembly potential. This raises concerns about the accuracy of current LCA methodologies in capturing the long-term carbon benefits of material reuse and the role that material composition and fixation mechanisms plays on this. Specifically, tools like Tally may not effectively account for the carbon savings associated with multiple life cycles. Further study is needed to evaluate tool-specific assumptions and calculation methods for CLT assemblies under various realistic EoL scenarios (e.g., reuse, scrap, recycle, etc.). While not covered here, future research should investigate material-specific and assembly layer GWP contributions within each assembly to inform targeted optimization.
- **Acoustic Performance:** The CLT assembly with raised access floor performed well with respect to acoustics, exceeding the required STC and IIC. The flexible nature of this assembly also enables the profile to be thickened, making space for additional mineral wool insulation if greater acoustic performance is desired. The CLT assembly without concrete topping, despite its relatively low GWP, performs significantly worse acoustically than the other assemblies, failing to meet both the LEED v4.1 STC and IIC requirements and barely meeting the minimum STC required by building codes in North America (e.g., the National Building Code of Canada and the International Residential Code in the US) for residential buildings. This highlights a critical challenge in Mass Timber construction: balancing environmental performance with occupant comfort. Therefore, innovative acoustic solutions for CLT systems are needed to minimize environmental impact while achieving code compliance and occupant comfort. These solutions could include different material combinations (e.g., recycled or bio-based acoustic insulation), innovative design strategies (e.g., decoupled ceiling systems, hollow-core systems with integrated acoustic insulation), or a combination of both, to achieve the required acoustic and environmental performance targets.
- **Reuse Potential:** Investigation into disassembly potential provided insights into how fixation mechanisms between floor assembly layers impacts the future potential to harvest undamaged materials for direct reuse. Material choice weighed heavy on this potential with cementitious materials, greatly reducing the potential for disassembly. The performance of the CLT assembly with raised access floor was able to outperform other assemblies by using dry and mechanical connection types. In using these connection types, accessibility of the connections was also increased, as any actions required to access the connections resulted in limited damage. What remains unclear is the direct impact this has on environmental performance metrics such as GWP and the impacts on salvage value that is resultant from implementation of DfD principles. Future research should also explore the interdisciplinary nature of economic and environmental feasibility of reuse to garner whether GWP savings from reuse can be economically substantiated based on the additional labour hours required for disassembly. In addition, the safety and quality of reusable building components should be thoroughly evaluated to improve adoption of DfD.

- Impact of Weight and Thickness:** Assembly thickness and weight varied greatly across different assemblies. The CLT assembly without concrete topping was able to obtain the thinnest profile and the lowest weight. However, thickness and weight were not necessarily correlated due to different sound insulation material combinations. The CLT raised access floor assembly had the thickest profile, however, only had a weight increase of 0.8% from the lightest assembly due to void subfloor space. The weight of the assembly has the potential to have direct impacts on the necessary strength of structural members in CLT floor design. On the other hand, the assembly thickness has more nuance. With respect to the raised access floor and concrete topping assemblies, the potential to integrate MEP systems can prove advantageous, as additional clearance height for suspended ceilings or bulkheads may be reduced or omitted. To understand the full impact of these design metrics, a full building LCA and structural analysis investigation on CLT would be beneficial, as it could provide data-driven insights into the hypothesized impacts of floor assembly weight and thickness.
- MEP Considerations:** Although not directly analyzed in this study, MEP integration is critical for CLT floor system design. The four floor assemblies offer varying degrees of flexibility and present distinct challenges for MEP installations. Raised access floors offer the greatest flexibility for installing, accessing, and maintaining MEP systems, but increase floor thickness. In typical 5-ply CLT assemblies, ceiling-mounted systems are common, but can compromise the aesthetic of exposed CLT (often desired in Mass Timber buildings) and may contribute to noise. Drop ceilings conceal services and mitigate noise but increase embodied carbon (due to the added ceiling material) and reduce ceiling height while covering the CLT. Embedding MEP services within concrete toppings is practically limited to small services like electrical conduits and radiant heating tubes and can complicate future modification and maintenance. Hence, future work should investigate the implications of different MEP integration strategies on design goals (floor-to-ceiling height, building height), ease of installation and maintenance, embodied carbon, aesthetics, noise control, and occupant comfort to optimize each approach. With various MEP integration strategies, the Mass Timber building approach can be applied to diverse types of buildings, such as commercial and industrial, to further reduce GHG emissions in the construction industry.
- Generalizability and Application of Findings:** This study assessed 4 floor assemblies with reference to performance metrics required of mid-rise residential buildings. However, the methodologies and findings of the study provide valuable insights that are applicable for other building types as well. When applying the findings of this study to other buildings it is important to be cognizant of their unique design objectives. Design objectives and constraints are typically outlined at the beginning of a project by the owner, design team, and local governing bodies. For instance, design of a school or hospital will likely require greater attention to acoustic performance than typical office spaces due to the sensitive nature of these environments. These spaces often have stricter fire rating requirements and may need to meet higher environmental performance metrics due to their use class and public nature. The greater acoustic and fire performance may lend itself towards a floor assembly with a concrete topping. However, the environmental performance objectives may suggest omission of concrete from the floor assembly. This poses a design dilemma resulting from the conflicting design objectives; a common problem faced in the industry. When weighing trade-offs between design choices for a building, it is common that data is not presented in an easily comparable manner. The framework presented in this paper can help designers determine which floor assemblies meet minimum performance constraints and then from those assemblies determine their relative performance within the design options. This enables decision-makers to make more informed decisions through a multi-criteria comparative analysis. Along with building type, the scale of the building can impact the level of importance of certain criteria including assembly weight and thickness. Floor assembly weight will have a less significant impact on the overall structural system GWP of a one-story community center than in a mixed-use multi-story building due to the compounded effects of the floor assembly weight. Additionally, limitations surrounding material use, ventilation requirements, and fire protection mechanisms will

vary across different use types, leading to divergence in implementation feasibility of certain floor assemblies.

5. CONCLUSION

This study investigated 4 CLT floor assembly types with varying acoustic treatments to gain insight into multiple performance criteria in a mid-rise residential application. Through this analysis, CLT assemblies with raised access floors were found to outperform other investigated assemblies, particularly in the environmental and acoustic domains. These findings suggest that CLT with raised access floor assemblies are an ideal choice for mid-rise residential applications when design goals align with improved environmental and acoustic performance. This study provides designers and decision makers with a framework to weigh trade-offs between different design performance criteria. Through the synthesis of existing knowledge and consideration of multiple performance characteristics simultaneously, this work contributes to supporting comprehensive decision making through a consistent methodology which can be used by industry professionals. The findings of this research also underscore the need for holistic evaluation methods within the academic community. Finally, through providing insights into the potential of specific CLT assemblies to perform well amongst a variety of design metrics, this research contributes to informing the future adoption of CLT in Canada's mid-rise residential sector.

REFERENCES

- Brandner, R. 2013. Production and Technology of Cross Laminated Timber (CLT): A state-of-the-art Report. *2013 European Conference on Cross Laminated Timber*, University of Bath, Graz, Austria, 1: 3-36.
- Darby, H.J., Elmualim, A.A., and Kelly, F. 2013. A case study to investigate the life cycle carbon emissions and carbon storage capacity of a cross laminated timber, multi-storey residential building. *2013 Proceedings of the Sustainable Building Conference*, Munich, Germany.
- Hindman, D.P. and Golden, M.V. 2020. Acoustical Properties of Southern Pine Cross-Laminated Timber Panels. *Journal of Architectural Engineering*, 26.
- National Research Council of Canada. 2020. *National Building Code of Canada 2020*, National Research Council of Canada, Ottawa, ON, CA. <https://nrc-publications.canada.ca/eng/view/ft/?id=515340b5-f4e0-4798-be69-692e4ec423e8>.
- Safari K. and AzariJafari H. 2021. Challenges and opportunities for integrating BIM and LCA: Methodological choices and framework development. *Sustainable Cities and Society*, 67.
- United Nations Environment Programme (UNEP). 2024. *Global Status Report for Buildings and Construction - Beyond foundations: Mainstreaming sustainable solutions to cut emissions from the buildings sector*. <https://wedocs.unep.org/20.500.11822/45095>.
- U.S. Green Building Council. 2024. *LEED v4.1 Residential BD+C Multifamily Homes*, U.S. Green Building Council, Washington, DC, USA. <https://build.usgbc.org/multifambeta41>.
- Van Vliet, M., Van Grinsven, J., and Teunizen, J. 2021. *Circular Buildings Disassembly Potential Measurement Methods Version 2.0*, Dutch Green Building Council, Netherlands. <https://www.dgbc.nl/publicaties/circular-buildings-een-meetmethodiek-voor-losmaakbaarheid-v20-41>.
- WoodWorks Wood Products Council. 2024. Inventory of Acoustically Tested Mass Timber Assemblies [Data set]. <https://www.woodworks.org/resources/inventory-of-acoustically-tested-mass-timber-assemblies/>.
- Younis, A. and Dodoo, A. 2022. Cross-laminated timber for building construction: A life-cycle-assessment overview. *Journal of Building Engineering*, 52.