World Conference on
Timber Engineering
Oslo 2023

TRADE-OFFS IN EMBODIED CARBON AND ACOUSTIC INSULATION FOR MASS TIMBER FLOOR ASSEMBLIES

Samantha J. Leonard[1], Mohamad B. Eddin[2], Morgan K. Prichard[3], Jonathan M. Broyles[4], Nathan C. Brown[5], Sylvain Ménard[6]

ABSTRACT: Mass timber structural systems are increasingly used in the design of low and mid-rise buildings. One of the primary motivators for using mass timber structures is their low embodied carbon emissions (EC), which reduces a building's carbon footprint. Despite this advantage, a criticism of mass timber structures in multi-story buildings is often poor air-borne and impact sound insulation. In response, this paper studies common mass timber floor assemblies for their EC and sound insulation performance. EC data is used along with previous experimental acoustic data to evaluate how acoustic insulation affects the sustainability of mass timber floors. This study found that there is no clear relationship between EC and acoustic insulation; while high-EC assemblies exist, there are many low-EC assemblies at all levels of acoustic insulation. Trade-offs instead occur in the types of assemblies that can achieve performance goals and their depth or visible finish. While other factors such as cost or structural requirements may control assembly selection, designers seeking to reduce EC should consider room design needs and select acoustic insulation strategies with favorable EC-to-acoustic insulation ratios.

KEYWORDS: Mass Timber Floors, Sound Transmission Class, Impact Insulation Class, Embodied Carbon Emissions

1 INTRODUCTION

Mass timber structures are increasingly gaining interest among building owners and developers due to their potential to positively affect the triple bottom line: sustainability, society, and economy [1]. Mass timber structural elements have been shown to require less energy during manufacturing compared to traditional structural materials such as steel and concrete [2], can improve occupant wellness [3], and have the potential to revitalize local economies in forested regions [4].

However, the relatively lightweight mass timber floor structures often pose challenges for serviceability requirements such as sound insulation [5, 6]. The 2021 IBC requires that projects meet specific acoustic performance standards for floor and wall assemblies separating dwelling units [7]. The two main acoustic insulation performance quantifiers in North America are Sound Transmission Class (STC), a measure of a floor or wall assembly's ability to prevent airborne-based sound transmission between spaces, and Impact Insulation Class (IIC), a measure of a floor assembly's ability to insulate a space from impact noise (i.e., footfall) from above [8].

Lab-based measurements for mass timber floor systems constructed using Cross Laminated Timber (CLT), a panelized mass timber product, have demonstrated that bare CLT alone cannot meet typical code requirements for acoustic insulation [9]. While several recommendations exist to improve the acoustic performance of a CLT floor system, not every recommendation improves the same acoustical phenomena. Common examples of acoustical treatments include using dense-porosity surfaces that reflect sound, adding mass to reduce vibration amplitudes, including sound-dissipating layers in the assembly to absorb sound, and providing acoustic separation between finishes and the structure to improve sound insulation [5, 10]. These strategies complicate how acoustical performance can be improved for mass timber structures. As sound insulation performance requirements can have significant effects on the floor assembly construction, designers require guidance during project decision-making. Many organizations offer resources with data on mass timber floor assembly acoustic performance, such as the FPInnovations CLT Handbook chapter on acoustics and the WoodWorks Inventory of Acoustically-Tested Mass Timber Assemblies (WW Inventory herein) [5, 11].

[1] Samantha Leonard, The Pennsylvania State University (PSU), Department of Architectural Engineering, USA, sjd5225@psu.edu, Corresponding Author
[2] Mohamad Bader Eddin, University of Quebec at Chicoutimi, Department of Applied Sciences, Canada, mohamad.bader-eddin1@uqac.ca
[3] Morgan Prichard, PSU, Department of Architectural Engineering, USA, mkp5607@psu.edu
[4] Jonathan Broyles, PSU, Department of Architectural Engineering, USA, j.broyles@psu.edu
[5] Nathan Brown, PSU, Department of Architectural Engineering, USA, ncb5048@psu.edu
[6] Sylvain Ménard, University of Quebec at Chicoutimi, Department of Applied Sciences, Canada, Sylvain_Menard@uqac.ca

https://doi.org/10.52202/069179-0117

However, there is limited guidance on how decisions related to sound insulation performance affect a mass timber floor system's carbon produced during material extraction, transportation, and manufacturing, also known as embodied carbon (EC).

Salles E Portugal et al. studied concrete versus cork flooring materials for their environmental impact [12]. Broyles et al. conducted design optimization of concrete floor slabs for embodied carbon and acoustic performance [13, 14]. Tomas M. Echenagucia et al. researched the acoustic optimization of a concrete structure for a concert hall space [15]. Mirdad et al. analyzed 28 mass timber-concrete composite floors for EC and STC and found that increasing timber thickness is generally more beneficial for sound insulation and EC than increasing concrete thickness; however, IIC was omitted, and the types of assemblies are limited [16]. Ilgin et al. reviewed 13 tall mass timber building case studies for various architectural design features, including finding an average floor-to-floor height of 3 m, which is affected by floor assembly construction [17]. Beyond these papers, current literature review did not find a comparison of acoustic performance and embodied carbon for a wide range of mass timber floor assembly types. This study builds on the existing WW Inventory by adding EC data for each assembly. By pairing acoustic insulation ratings and EC data sets, these performance objectives can be compared for a range of assembly types and configurations. Resulting findings are intended to aid early design decision making.

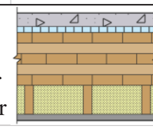
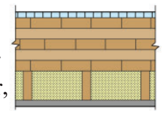
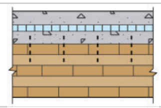
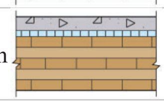
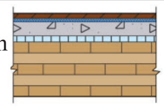
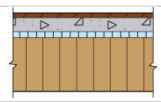
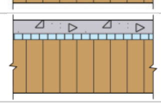
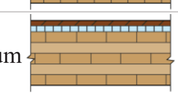
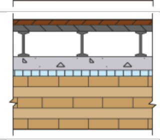
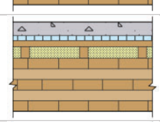
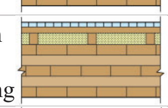
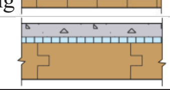
2 METHODS

The studied assemblies for this research come from the WW Inventory, which is the most comprehensive database of mass timber assembly acoustic performance test results found during the literature review process. This study calculated EC for the assemblies based on the inventory's description of their construction, and EC is compared to the inventory's acoustic performance test ratings during the data analysis process.

2.1 ASSEMBLY CONSTRUCTION

The WW Inventory included descriptions and test data for 349 mass timber floor assemblies. The inventory organized floor assemblies into six categories, which was further divided into twelve total categories in this study. The categories included in this study are summarized in Table 1. Assemblies include features such as: structural or non-structural toppings, exposed mass timber panel ceilings, suspended acoustic ceilings, and raised access floors. A variety of materials and products appear in the assemblies, including those of the following types: mass timber panel, concrete or gypsum topping, acoustic mats or systems, acoustic accessories, board-type products such as gypsum board and plywood, insulation, flooring, and acoustical underlayment. Assembly descriptions and typical material properties are used to estimate total assembly depth. In the final EC database, 92 out of 349 assemblies meet the 2021 IBC requirements, have both STC and IIC data, and have sufficient information to estimate EC.

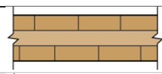
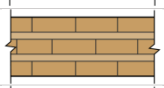
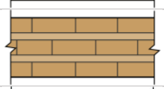
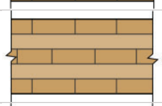
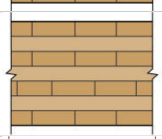
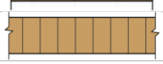
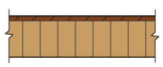
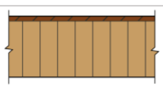
Table 1: *Categories used in this research, based on the WW Inventory. Symbols are referred to later in the results plots. The final main EC database is discussed further in section 2.3.*

Symbol	Assembly Category & Symbol	Typical Assembly Construction	Number of Assemblies	Code-compliant w/ STC/IIC data	In Final Main EC Database
●	Mass timber with ceiling side concealed, with or without finish floor		59	39	25
•	Mass timber with ceiling side concealed, with or without finish floor, no topping		31	22	17
▼	CLT-concrete composite		10	10	6
◆	Mass timber with concrete or gypsum topping		59	16	7
♦	Mass timber with concrete or gypsum topping w/ finish floor		81	17	13
⬟	GLT decking		5	1	1
★	NLT decking		25	8	5
■	CLT without concrete or gypsum topping		30	5	3
⬢	Mass timber with raised access floor		15	7	7
✖	Mass timber with raised wood sleepers		15	5	5
✚	Mass timber with raised wood sleepers, no topping		4	2	2
▲	T&G decking		15	5	1
		Total	349	137	92

https://doi.org/10.52202/069179-0117

Most assemblies in the full WW Inventory (266 out of 349, or 76 percent) use five-ply CLT panels, which can typically span about 4 to 5.5 meters [18]. Table 2 shows typical maximum allowable spans for the mass timber panels which appear in the inventory. Spans are based on IBC 2021 residential occupancy loads but can vary depending on factors such as wood species, structural loading requirements, and project-specific fire resistance rating requirements. Mass timber panel structural spans are often controlled by criteria to limit walking-induced floor vibrations. More in-depth calculations of span limits for individual assemblies are out of this paper's scope.

Table 2: *Typical allowable spans for mass timber panels appearing in the WW Index, based on publicly-available manufacturer technical guides* [18–20] *STC and IIC data is from the WW Inventory* [11].

Mass Timber Panel	Panel Depth (mm)	Span (m)	Assumed Panel Construction	STC	IIC
3-ply CLT	104.8	4.0		38	22
5-ply CLT	131.8	4.8		39	22
5-ply CLT	137.2	4.8		41	27
5-ply CLT	174.6	5.5		41	25
7-ply CLT	228.6	7.0		44	30
GLT	88.9	3.7		35	20
2x4 NLT w/ Plywood	88.9	3.7		29	-
2x6 NLT w/ Plywood	139.7	5.2		34	33

2.2 ACOUSTIC PERFORMANCE DATA

Acoustic performance test data for most assemblies consists of one STC rating and one IIC rating (270 assemblies). Some assemblies include only STC or IIC (57 assemblies), while 33 assemblies include one or more of the following ratings: Apparent Sound Transmission Class (ASTC), Apparent Impact Insulation Class (AIIC), Field Impact Insulation Class (FIIC), Field Sound Transmission Class (FSTC), and Normalized Noise Isolation Class (NNIC). Where ASTC, AIIC, FSTC, FIIC, or NNIC ratings are provided in lieu of STC and IIC, an estimated STC and IIC rating were calculated to provide a comparable rating to other assemblies. It is assumed that these metrics generally result in a lower rating by about five points due to field conditions [21], and therefore five points were added to these values to estimate equivalent STC and IIC ratings. The WW Inventory assembly ratings are obtained from various manufacturer and third-party test reports for testing performed in accordance with the ASTM E 90 and ASTM E 492 test standards [22, 23]. A limitation of this data is that there are often rating discrepancies between labs, bringing into question the expected sound insulation performance of an assembly [24]. Additionally, construction quality can vary the acoustic insulation performance [25], as air leaks can reduce performance [26]. Table 3 summarizes the standards and methods used in the WW Inventory assembly data.

Table 3: *Test standards and methods used to quantify sound insulation of assemblies in the WW Inventory.*

Standard (Short Name)	Standard (Long Name)	Number of Assemblies
ASTM E 492 [23]	Standard test method for laboratory measurement of impact sound transmission through floor-ceiling assemblies using the tapping machine	176
ASTM E 90 [22]	Laboratory measurement of airborne sound transmission loss of building partitions and elements	170
Modified ASTM E 90/E 492 [22, 23]	Floor zone testing procedures	68
ISO 12354 (ISO 15712-1) [27]	Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 1: Airborne sound insulation between rooms	36
ASTM E 1007 [28]	Standard test method for field measurement of tapping machine impact sound transmission through floor-ceiling assemblies and associated support structures	26
Multiple Methods	Combination of ASTM E 492 and ASTM E 1007 [23, 28]	20
ASTM E 336 [29]	Standard test method for measurement of airborne sound attenuation between rooms in buildings	19
Legacy from CLT handbook [30]	Various European standards	11

For the purposes of evaluating and comparing designs, levels of acoustic performance are defined per Table 4, based on the performance divisions used by Long [21].

***Table 4:** Acoustic performance tier requirements*

Performance Tier	STC/ IIC	Description
Non-code-compliant	<50	Clearly hear normal activities of neighbor
Code Minimum	50	Normal activities of neighbors somewhat muted
Good	55-59	
Better	60-64	Cannot hear normal activities of neighbors
Best	65+	

2.3 EMBODIED CARBON ESTIMATION

The assemblies studied include between 1 and 9 floor materials and components. Embodied carbon material values are obtained for each material from either the Inventory of Carbon and Energy (ICE) V3.0 database [31], product environmental declaration (EPD) sheets, or industry wide EPDs. The ICE database is a collection of EC factors that relate a construction material quantity to its corresponding carbon emissions, using a cradle-to-gate life cycle assessment (LCA). EPDs are often created by manufacturers or third-party groups and are independently validated per ISO 14025:2006. Additionally, technical product data sheets and NRC test reports were referenced to clarify typical information about some material types, and to help inform property assumptions. Note that the analysis includes only the cradle-to-gate LCA boundaries (A1-A3).

From the perspective of calculating embodied carbon, all the materials included in the studied assemblies can be classified based on their coverage, resulting in three coverage categories: area, linear, and discrete. Each material in the WW Inventory had typical properties such that EC per area could be calculated for each material. Most materials in the inventory are area-based, meaning they are installed to cover the full area of the floor. EC per area for these materials is calculated per Equation 1:

$$EC_i = EC_f * t_{i,typical} * \rho \tag{1}$$

Where:
EC_i = EC per area for a given assembly layer of typical thickness [kg CO_2 eq./m^2]
EC_f = EC factor per mass for a given assembly component [kg CO_2 eq./kg]
$t_{i,typical}$ = the baseline layer thickness assumed for the EC_i value [m]
ρ = component density [kg/m^3]

Acoustic accessories include both linear- and discrete-based materials, where linear includes items like wood furring or resilient channels, and discrete includes those such as acoustic clips or rubber isolators. EC for linear and discrete materials can be calculated per Equations 2 and 3, respectively, to determine an equivalent EC per area. Based on Equations 1 through 3, representative assembly material values are summarized in Table 5.

$$EC_i = \frac{EC_f * A_{i,typical} * \rho}{S} \tag{2}$$

Where:
$A_{i,typical}$ = the baseline component cross sectional area assumed for the EC_i value [m^2]
S = component spacing [m]

$$EC_i = \frac{EC_f * m_{i,typical}}{S_\perp * S_\parallel} \tag{3}$$

Where:
$m_{i,typical}$ = the baseline component mass assumed for the EC_i value [kg]
$S_\perp$ = spacing perpendicular to a reference span direction [m]
$S_\parallel$ = spacing parallel to a reference span direction [m]

***Table 5:** Embodied carbon of representative mass timber assembly materials (kg CO_2 eq. per m^2 per typical thickness/unit/spacing)*

Coverage Category	Material Type	Material	EC_i	Ref
Area	Mass Timber Panel	CLT (5-ply)	23.9	[32]
		GLT (88.9 mm)	14.3	[33]
	Concrete or Gypsum Topping	NW Concrete (38.1 mm)	12.4	[31]
		LW Concrete (76.2 mm)	12.0	[34]
	Acoustic Mats or Systems	Dimpled Rubber Mat (25.4 mm)	13.7	[35]
		Raised Access Floor	52.5	[36]
	Board-type Products	Gypsum (15.9 mm)	1.79	[37]
		Plywood (19 mm)	7.3	[31]
	Insulation	Fiberglass (92 mm)	0.90	[38]
		Mineral Wool (30 mm)	1.1	[39]
	Finish Flooring	Carpet	12.9	[40]
		Hardwood Flooring	3.5	[31]
	Acoustical Underlayment	Flat Rubber Mat (17 mm)	21.8	[35]
		Foam Mat	3.5	[41]
Linear	Acoustic Accessories	Resilient Channels	1.66	[42]
		Wood Furring	0.35	[31]
Discrete		Sound Isolation Clips	5.35	[31]

https://doi.org/10.52202/069179-0117

In some cases, EC information was not available for materials or products, or there was not enough information in an assembly description to reasonably estimate EC. As a result, only 217 out of 349 assemblies were included in the EC database. 92 of those 217 assemblies meet the 2021 IBC and have both STC and IIC data. Each studied assembly is evaluated for EC by a summation of each material's EC material value. The unit of comparison is kg CO_2 eq. per m^2. Because the layer EC values were first calculated based on typical properties per Equations 1-3, atypical conditions must be accounted for in each assembly estimate. While some modifications were made as needed depending on whether a layer was area, linear, or discrete-based, the general equation to estimate the full assembly EC is summarized and simplified in Equation (4):

$$EC = \sum_{i=1}^{n} EC_i * \frac{d_{i,actual}}{d_{i,typical}} \tag{4}$$

Where:

EC = total assembly EC per area [kg CO_2 eq./m^2]

$d_{i,actual}$ = the actual property (thickness, density, area, spacing, or mass) of the given component if different than typical [mm, kg/m^3, mm^2, m, kg]

$d_{i,typical}$ = the baseline property assumed for the EC_i value [mm, kg/m^3, mm^2, m, kg]

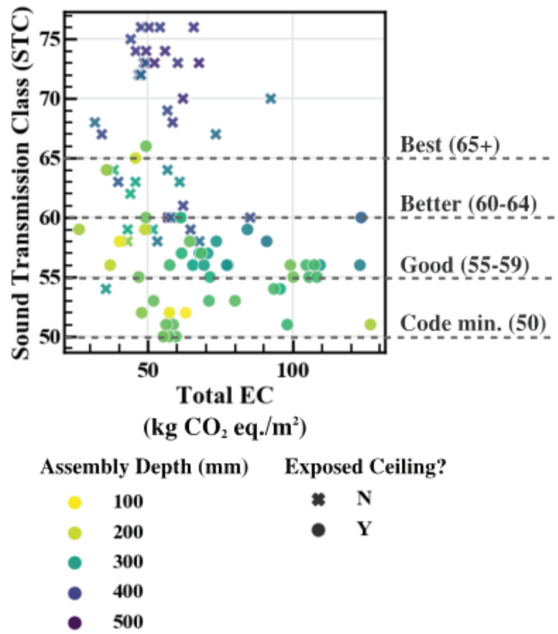


Figure 1: *STC versus EC for all studied code-compliant assemblies. Horizontal lines depict acoustic performance tiers.*

3 RESULTS AND DISCUSSION

3.1 RESULTS

After obtaining the total EC for the corresponding timber floors in the WW Inventory, the EC is plotted against the air-borne (STC) and structure-borne (IIC) acoustic performance. Figure 1 shows STC versus EC, assigning to each data point a hue based on assembly depth and a marker style based on whether the mass timber panel is exposed aesthetically to the underside. Similarly, Figure 2 compares the same data set, but for IIC versus EC. Horizontal lines in both Figures 1 and 2 depict the lowest rating of each acoustic performance tier per Table 4.

Figure 1 shows that there is no clear relationship between STC and EC; all STC performance tiers can be achieved with similar levels of EC (between about 30 to 50 kg CO_2 eq./m^2) if the right assembly is selected. While low-EC options exist, there are numerous assemblies with significantly higher EC (by 2 to 4 times, upwards of 100 to 125 kg CO_2 eq./m^2) which should be avoided if possible. Interestingly, these high-EC assemblies occur more frequently in the lower performance tiers for this data set. Figure 1 also finds that while low-depth options exist at all performance tiers (200 to 300 mm), the highest STC-rated assemblies made use of deep assemblies (of 400 to 450 mm) and concealed ceilings (i.e. underside acoustic treatment is required such that the ceiling cannot be exposed aesthetically.) Some assemblies with exposed ceilings achieve great STC performance but are limited to a maximum of STC-66 within this data set.

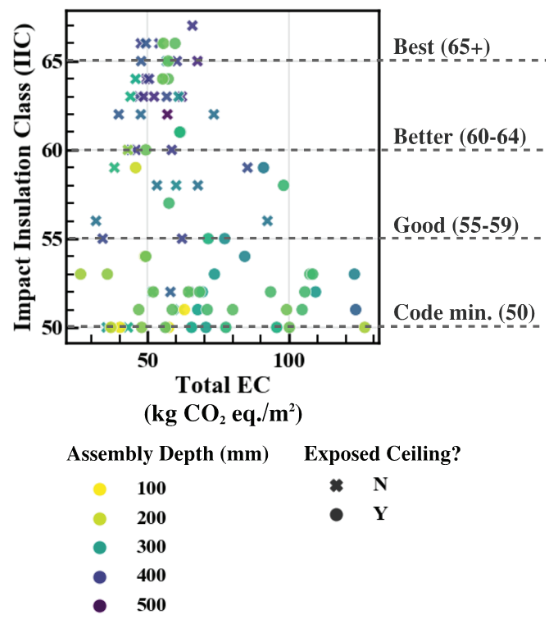


Figure 2: *IIC versus EC for all studied code-compliant assemblies. Horizontal lines depict acoustic performance tiers.*

Figure 2 shows some trends for IIC versus EC similar to those for STC versus EC. There is again no clear relationship between IIC and EC, and while high-EC options exist especially at lower performance tiers, there are low-EC options at all performance tiers. Further, there are similarly relatively low-depth options (200 to 300 mm) at all performance tiers; however, the highest IIC-ratings are not limited to the deepest assemblies. Note that maximum IIC ratings are lower than the maximum STC ratings for assemblies in this data set, which is consistent with the difficulty of achieving higher IIC ratings in general. Figures 1 and 2 show several assemblies at a given performance rating with different EC values. While designers should attempt to select the lowest-EC option that meets their project's IIC and STC requirements, other factors out of the scope of this study, such as structural requirements, cost, aesthetics, and scheduling, may restrict assembly selection.

Figures 3 and 4 use the full database of assemblies with both STC and IIC test data and sufficient EC data, including non-code-compliant assemblies. These were included here to better understand the relationship between STC and IIC amongst the assemblies included in the WW Inventory, as well as to visualize how estimated EC (Figure 3) and approximate allowable span (Figure 4) are represented within the data set.

Figure 3 shows that STC and IIC have a hyperbolic relationship. Many more of the assemblies in this data set met code for STC than for IIC, as it is often more difficult to achieve higher IIC ratings. The lowest-EC assemblies with 15 to 20 kg CO_2 eq./m^2 often do not meet code. Relatively low-EC assemblies of 40 kg CO_2 eq./m^2 occur at all combined STC and IIC performance tiers (i.e. both STC and IIC are rated at the same performance tier for an assembly.) Assemblies with concealed ceilings generally achieve the best combined STC and IIC performance.

Figure 4 shows the same data as Figure 3, but with data points assigned a hue based on approximate allowable span per Table 2 and a marker based on the presence of a topping. All acoustic performance tiers for STC and IIC have options that can span upwards of 6 meters. Longer spans are likely possible at higher acoustic performance using similar assemblies to the 6-meter-spanning assemblies; however, the number and types of longer-spanning assemblies was limited in the WW inventory.

Figures 5 and 6 take the data from Figure 3 and removes the non-code-compliant assemblies for closer analysis of STC versus IIC (Figure 5) and Depth versus EC (figure 6). In each plot, both marker hue and style are assigned based on the assembly category per Table 1. Per Figures 5 and 6, although many concealed-ceiling assemblies are the deepest assemblies, averaging around 400 mm, these represent most of the best-performing assemblies for STC and IIC while maintaining relatively low EC, with several options in the range of 45 to 50 kg CO_2 eq./m^2.

Figure 5 and 6 also show that for categories that include versions both with and without a concrete or gypsum topping (Ceiling Side Concealed and Raised Wooden Sleepers), those with a topping tended to achieve higher STC and IIC ratings with limited impact to EC. This is likely because the concrete and gypsum toppings are most often paired with an acoustical mat, which together can be a relatively efficient use of material to improve acoustic insulation. While STC and IIC are generally related in Figure 5, some assemblies with flooring can have a high IIC rating even if STC is low.

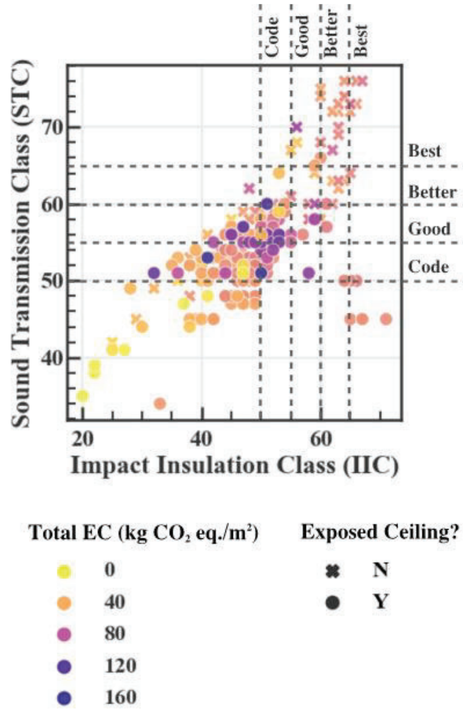


__Figure 3:__ STC versus IIC for all studied assemblies, including non-code-compliant assemblies.

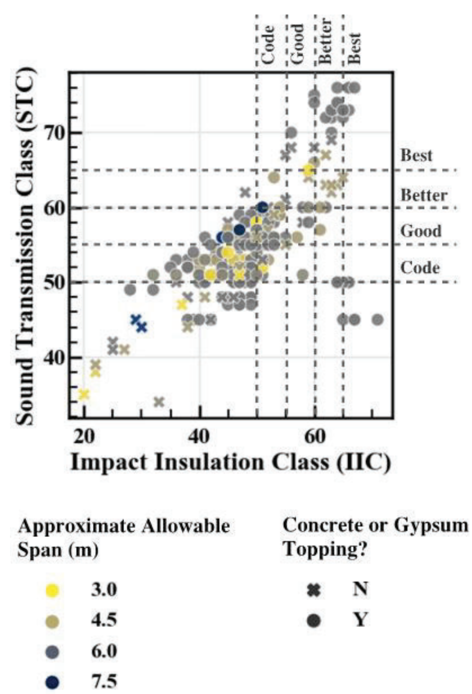


__Figure 4:__ STC versus IIC for all studied assemblies, including non-code-compliant assemblies.

https://doi.org/10.52202/069179-0117

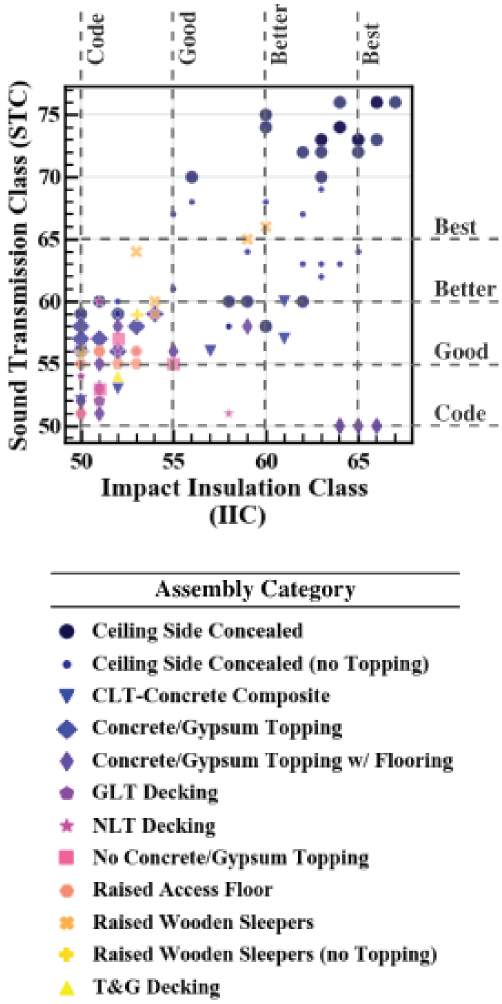


Figure 5: *STC versus IIC for all studied code-compliant assemblies*

Further, there is no relationship between EC and assembly depth, according to Figure 6. Low-EC options of 30 to 40 kg CO_2 eq./m^2 occur at a variety of assembly depths. This is likely because many assemblies use separation and air gaps between assembly components to improve acoustic performance, which makes efficient use of the materials in such assemblies.

Although Figures 1 through 6 indicate no clear relationship between sound insulation and EC, or between assembly depth and EC, options exist with higher EC. While it may be possible for designers to simply select the lowest-EC option that meets their project's STC and IIC requirements, there are most likely other factors that have the potential to control assembly selection, such as structural performance requirements, cost, scheduling, and material availability. Except for the approximate allowable spans shown in Figure 4, these factors are out of the scope of this research. However, by understanding the material efficiency of the components and systems used to improve sound insulation versus their EC, general recommendations and guidance can be provided to help reduce EC during early design decisions. Approximate component and system contributions to EC, STC, and IIC are shown in the bar chart in Figure 7.

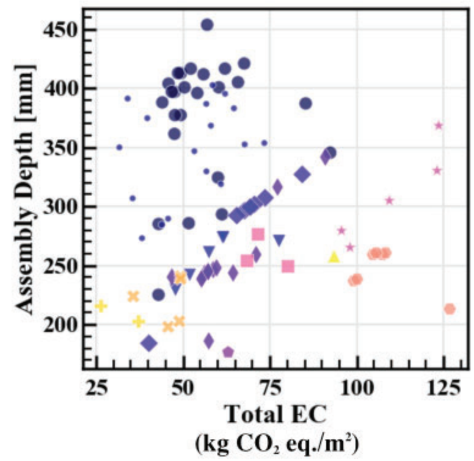


Figure 6: *Assembly depth versus EC per unit of floor area for all studied code-compliant assemblies*

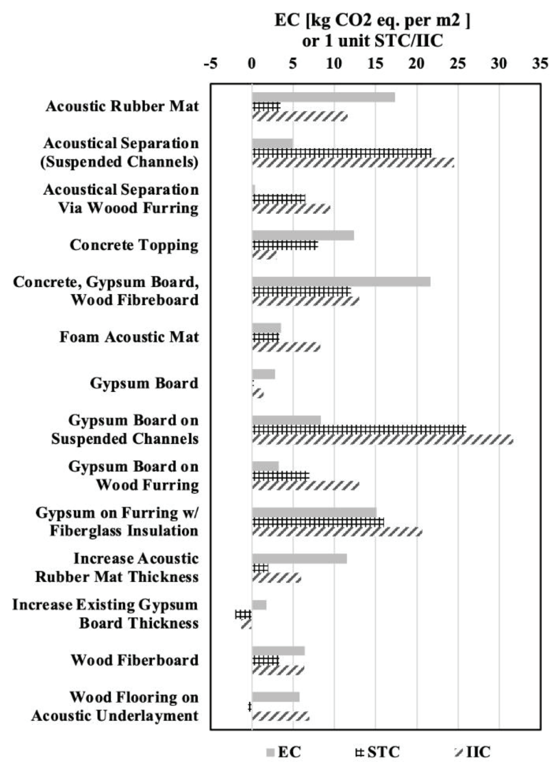


Figure 7: *EC per floor area of various materials or systems of materials and the difference in STC and IIC as compared to existing baseline assemblies without the given material or system. (Based on a selective set of assemblies with 5-ply CLT panel and 38-mm concrete topping)*

Figure 7 shows that increasing gypsum in an assembly that already has some gypsum does not add much EC but does not help STC or IIC either. Additionally, adding a separation between layers via wood furring provides the best STC and IIC improvement per amount of added EC. However, the most significant takeaway is that suspended channels and other means of providing acoustical separation between assembly layers provide high improvements to STC and IIC with relatively low EC impact to the assembly. This further validates that the typical recommendation of providing acoustic separation between layers is a materially-efficient and effective approach to improving sound insulation in an assembly.

3.2 DISCUSSION

Previous studies have shown that many mass timber floor systems without acoustic treatments have unsatisfactory air-borne and structure-borne sound insulation performance. However, adding materials and components to improve sound insulation can affect the EC of mass timber floor assemblies. By combining existing acoustic test results with EC data for a variety of assemblies, comparisons can be made to understand different assembly types and trade-offs with improved sound insulation. Because of data limitations due to lab-to-lab differences in STC and IIC results, as well as the limited availability of EC data, the findings of this research are most helpful during early design when more general and broad design decisions occur. Further analysis is needed to refine a design in the later stages of a project. This research finds that:

- Although adding acoustic treatments or systems to assemblies results in many with high EC, there is no clear relationship between STC and EC or between IIC and EC; relatively low-EC options exist at all acoustic performance tiers.
- In this data set, deeper assemblies are needed to achieve the best STC values, but low-depth options exist for all IIC tiers.
- One trade-off to achieve the best acoustic performance is that a designer may need to sacrifice exposed timber ceilings for underside acoustic treatment, which affects the architecture and results in greater assembly depth. However, because separations and air gaps are often used to achieve improved IIC and STC, these assemblies can still have relatively low EC.
- The best EC per STC or EC per IIC from separating components aligns with typical recommendations to improve sound insulation per the CLT handbook [5].
- An in-depth structural analysis was excluded; however, there are a wide variety of assemblies in this data set that can span up to 6 meters at all acoustic performance tiers.
- Experimental measurements were not taken from the same lab, which could have significant variability in results from lab to lab.
- More holistic studies including other building disciplines (for example, fire proofing, thermal insulation, cost, scheduling, etc.) may continue to reveal what the best assemblies are and for what design scenarios are best.
- There are many buildings for which code will not allow exposed timber ceilings depending on the Construction Type per the 2021 IBC, and in most cases, a non-combustible topping is required for mass timber floors [7].

4 CONCLUSIONS

This study extended the WW inventory that compiled the sound insulation performance of mass timber assemblies by extracting material information and adding EC data. The results showed that there was no direct correlation between EC and acoustic insulation. As a result, designers may select a floor assembly which meets project-specific goals for EC, STC, and IIC. Where several assemblies have similar acoustic performance, but different EC, other factors not in this study's scope may control the design selection. These additional factors include, but are not limited to, structural design requirements, cost, scheduling, and fire resistance requirements. Although this study helps extend existing research on the performance of mass timber assemblies within the built environment, a comprehensive database including additional considerations could improve initial assembly selection.

DATA AVAILABILITY

The WoodWorks Inventory of Acoustically-Tested Mass Timber Assemblies is publicly available at no cost from https://www.woodworks.org/resources/inventory-of-acoustically-tested-mass-timber-assemblies/. EC data generated for this paper, building on the WW Inventory data, is available by request from the corresponding author. Components and data sources in Table 5 are only representative. Data available from the corresponding author includes EPDs, technical data sheets, and reports for the components listed below. Most EPDs are manufacturer-specific, and as such, a multitude of manufacturers are listed below as data sources for this research; however, it is not the authors' intent to promote specific manufacturers or products.

- CLT – average of Product EPDs from various North American manufacturers: Smartlam, [smartlam.com], Structurlam [structurlam.com], Nordic Structures [nordic.ca/en/products], Vaagen [vaagentimbers.com], Kalesnikoff [kalesnikoff.com]
- Glue Laminated Timber (GLT) – Industry-wide EPD, [awc.org/wp-content/uploads/2021/11/AWC_EPD_NorthAmericanGluedLaminatedTimber_20200605.pdf]
- Mass Plywood Panel (MPP) – Product EPDs from Freres, [frereswood.com]

https://doi.org/10.52202/069179-0117

- Lightweight Concrete – Paper by Kanavaris et al. [34]
- Gypsum-based Toppings – USG Product EPD, [www.usg.com]
- Acoustic ceilings, sound reduction board, and other generic gypsum-, cement-, or fiber-based boards – Product EPDs by USG, [usg.com]
- Flooring Underlayment and Acoustic Membranes: Product EPDs by Autex Acoustics, [autexacoustics.com], Fermacell [fermacell.com/en], Isolon [isolon.lv/en], QT Sound Control, [qtsoundcontrol.com/], and Sto [stocorp.com]; Technical product data by AcoustiTech [acousti-tech.com/en], Kinetics [kineticsnoise.com/], Maxxon [maxxon.com], Pliteq [pliteq.com], Regupol [regupol.us], Soprema [soprema.us], and Sto [stocorp.com].
- Proprietary Subflooring – Product EPD by HuberWood, [huberwood.com/advantech]
- Raised Access Floor – Product EPD by Teccrete, [globalifs.com/raf-teccrete]
- Metal Channels, Studs, and Ceiling Framing – Product EPDs by Cemco [cemcosteel.com], and Clark Dietrich [clarkdietrich.com]; Design guide by USG [43].
- Insulation – Product EPDs and Technical data sheets by Johns Manville [jm.com/en/], Owens Corning [owenscorning.com/en-us/insulation], and Rockwool [rockwool.com/north-america/].
- Bamboo Plywood – Product EPD by Plyboo, [plyboo.com]
- Roof Board – Product EPD by Georgia Pacific, [buildgp.com/densdeck]
- Sand – Report by the National Stone Sand & Gravel Association [44].
- Flooring – Product EPDs by Mannington Commercial [manningtoncommercial.com] and Tarkett [home.tarkett.com/en_EU]; Industry-wide EPDs by TCNA [tcnatile.com] and RFCi [armstrongflooringpartner.force.com/ArmstrongConnect/s/article/Environmental-Product-Declaration-EPD-Luxury-Vinyl-Tile].

The ICE v3.0 database values were used for Nail Laminated Timber (NLT), tongue and groove (T&G) decking, wood subfloor, cement mortar, normal weight concrete, sound isolation clips, wood furring, wood board products such as plywood, hardwood flooring, and laminate flooring [31]. Finally, NRC reports on sound insulation research and assembly test results were used to clarify assembly construction where relevant [45],[46].

ACKNOWLEDGEMENTS

The authors would like to thank Ryan Solnosky, Kevin Parfitt, Dr. Ali Memari, and Corey Gracie-Griffin for their advisement on this work. This research is supported in part by the Graduate Assistance in Areas of National Need (GAANN) Fellowship and the J. Roger Glunt Graduate Fellowship in Housing, hosted by the Pennsylvania Housing Research Center (PHRC). Neither fellowship had any role or input in the planning and implementation of this research, and the included results do not reflect the views of these organizations.

REFERENCES

[1] P. F. Oldfield, *Tall buildings and sustainability. PhD thesis, University of Nottingham.* 2012.

[2] M. D. Webster, 'Achieving Net Zero Embodied Carbon in Structural Materials by 2050', 2020.

[3] G. Lowe, 'Wood , well-being and performance: The human and organizational benefits of wood buildings', British Columbia, 2020.

[4] H. K. D'Errico, 'Tall, cross-laminated and massive timber buildings: A United States perspective', Mississippi State University, 2016.

[5] L. Hu and S. Gagnon, 'Acoustic performance of cross-laminated timber assemblies', in *Cross Laminated Timber Handbook: 2019 Canadian Edition*, E. Karacabeyli and S. Gagnon, Eds. Pointe-Claire, Quebec, Canada: FPInnovations, 2019.

[6] M. Caniato, F. Bettarello, P. Fausti, A. Ferluga, L. Marsich, and C. Schmid, 'Impact sound of timber floors in sustainable buildings', *Build Environ*, vol. 120, pp. 110–122, 2017, doi: 10.1016/j.buildenv.2017.05.015.

[7] International Code Council Inc., *2021 International Building Code*. Country Club Hills, IL: International Code Council Inc., 2020. [Online]. Available: https://codes.iccsafe.org/content/IBC2021P1

[8] T. E. Vigran, *Building Acoustics*. New York City, NY: Taylor & Francis, 2008.

[9] D. P. Hindman and M. V. Golden, 'Acoustical Properties of Southern Pine Cross-Laminated Timber Panels', *Journal of Architectural Engineering*, vol. 26, no. 2, pp. 1–8, 2020, doi: 10.1061/(ASCE)AE.1943-5568.0000407.

[10] F. Asdrubali, S. Schiavoni, and K. v Horoshenkov, 'A Review of Sustainable Materials for Acoustic Applications', *Building Acoustics*, vol. 19, no. 4, pp. 283–311, 2012, doi: 10.1260/1351-010X.19.4.283.

[11] WoodWorks, 'Acoustically-tested mass timber assemblies'. 2022.

[12] R. Salles E Portugal, B. Lawrence, P. F. Laleicke, and A. Sinha, 'Technical note: A preliminary study to quantify the environmental impacts of concrete and cork flooring', *Wood and Fiber Science*, vol. 50, no. 1, pp. 104–112, 2018, doi: 10.22382/wfs-2018-011.

[13] J. M. Broyles, M. R. Shepherd, and N. C. Brown, 'Design Optimization of Structural–Acoustic Spanning Concrete Elements in Buildings', *Journal of Architectural Engineering*, vol. 28, no. 1, pp. 1–11, 2022, doi: 10.1061/(asce)ae.1943-5568.0000520.

[14] J. M. Broyles *et al.*, 'Shape optimization of a concrete floor systems for sustainability, acoustical, and thermal objectives', in *Structures and Architecture A Viable Urban Perspective?*, CRC Press, 2022, pp. 1121–1128.

[15] T. M. Echenagucia, A. Astolfi, M. Jansen, and M. Sassone, 'Architectural Acoustic and Structural Form', *Journal of the International Association for Shell and Spatial Structures*, vol. 49, no. 3, Dec. 2008.

[16] M. A. H. Mirdad, H. Daneshvar, T. Joyce, and Y. H. Chui, 'Sustainability Design Considerations for Timber-Concrete Composite Floor Systems', *Advances in Civil Engineering*, vol. 2021, 2021, doi: 10.1155/2021/6688076.

[17] H. E. Ilgın, M. Karjalainen, and S. Pelsmakers, 'Contemporary tall residential timber buildings: what are the main architectural and structural design considerations?', *International Journal of Building Pathology and Adaptation*, 2022, doi: 10.1108/IJBPA-10-2021-0142.

[18] Structurlam, 'Mass Timber Technical Guide for CrossLam CLT and GlulamPLUS'. Sructurlam, 2021.

[19] Structurlam, 'StructurDek GLT'. Penticon, BC.

[20] Binational Softwood Lumber Council, 'Nail-Laminated Timber Design & Construction Guide v1.0'. 2017.

[21] M. Long, *Architectural Acoustics*. Elsevier, 2005.

[22] ASTM International, 'ASTM E90: Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements'. 2016.

[23] ASTM International, 'ASTM E492: Standard Test Method for Laboratory Measurement of Impact Sound Transmission Through Floor-Ceiling Assemblies Using the Tapping Machine'. 2012.

[24] A. Meier, A. Schmitz, and G. Raabe, 'Inter-Laboratory Test of Sound Insulation Measurements on Heavy Walls : Part II – Results of Main Test', pp. 171–186, 1999.

[25] R. Öqvist, F. Ljunggren, and A. Ågren, 'On the uncertainty of building acoustic measurements – Case study of a cross-laminated timber construction', *Applied Acoustics*, vol. 73, pp. 904–912, 2012, doi: 10.1016/j.apacoust.2012.03.012.

[26] O. A. B. Hassan, 'An alternative method for evaluating the air tightness of building components', *Build Environ*, vol. 67, pp. 82–86, 2013, doi: 10.1016/j.buildenv.2013.05.007.

[27] Technical Committee : ISO/TC 43/SC 2 Building acoustics, 'ISO 12354-1:2017 Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 1: Airborne sound insulation between rooms', 2017.

[28] ASTM International, 'ASTM E1007-21: Standard Test Method for Field Measurement of Tapping Machine Impact Sound Transmission Through Floor-Ceiling Assemblies and Associated Support Structures', West Conshohocken, PA, 2021.

[29] ASTM International, 'ASTM E336-20: Standard Test Method for Measurement of Airborne Sound Attenuation between Rooms in Buildings', West Conshohocken, PA, 2020.

[30] E. Karacabeyli and S. Gagnon, *Canadian Cross Laminated Timber Handbook: 2019 Edition*. Pointe-Claire, Quebec, Canada: FPInnovations, 2019.

[31] G. Hammond, C. Jones, F. Lowrie, and P. Tse, 'Inventory of carbon & energy: ICE database version V3.0'. 2019.

[32] Athena Sustainable Materials Institute, 'EPD: Structurlam Crosslam CLT', Okanagan Falls, BC, 2020.

[33] UL Environment, 'EPD: North American Glued Laminated Timber - American Wood Council, Canadian Wood Council', American Wood Council, Canadian Wood Council, 2020.

[34] A. A. Abbas *et al.*, 'Reducing the carbon footprint of lightweight aggregate concrete', pp. 1–7, 2020.

[35] SCS Global Services, 'EPD: ECORE Products', ECORE, 2015.

[36] Intertek Health Sciences Inc., 'EPD: Global IFS TecCrete Raised Access Floor', 2020.

[37] T. Brooke, 'EPD: USG 5/8 in. (15.9mm) Sheetrock Brand Firecode X Panels', 2021.

[38] UL Environment, 'EPD: Owens Corning EcoTouch Pink Fiberglas Batt & Roll Insulation - Unfaced and Faced', 2018.

[39] Institut Bauen und Umwelt e.V., 'EPD: ROCKWOOL Stone Wool Insulation', 2019.

[40] E. Griffing and M. Overcash, 'EPD: AtlasMasland - Modular Carpet Family', 2020.

[41] L. G. F. Tellnes, 'EPD: ISOLON TX Cross-linked PE foam SkumTech AS', 2021.

[42] UL Environment, 'EPD: CEMCO Cold-Formed Steel Framing Systems', 2016.

[43] USG, 'Chapter 2 - Framing', in *The Gypsum Construction Handbook*, 7th Editio., 2014, pp. 88–100.

[44] National Stone Sand & Gravel Association, 'The Aggregates Industry - Greenhouse Gases: Low Emissions, High Resiliency', 2021.

[45] I. Sabourin, 'Measurement of airborne sound insulation of 8 wall assemblies measurement of airborne and impact sound insulation of 29 floor assemblies', 2015.

[46] S. Schoenwald, B. Zeitler, F. King, and I. Sabourin, 'Acoustics summary: sound insulation in mid-rise wood building: report to Research Consortium for Wood and Wood-Hybrid Mid-Rise Buildings', 2014.

 https://doi.org/10.52202/069179-0117