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Cross-Laminated Timber Workshop: Pathways and Priorities for Cross-Laminated Timber Building Systems

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Disclaimer

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List of Acronyms

AEC	architecture, engineering, construction
BTO	Building Technologies Office
CLT	cross-laminated timber
IBC	International Building Council
CNC	computer numerical control
DOE	U.S. Department of Energy
DLT	dowel-laminated timber
FSC	Forest Stewardship Council
GHG	greenhouse gas
GWP	global warming potential
IIC	Impact Insulation Certification
LCA	life cycle analysis/assessment
LCCA	life cycle cost assessment
MPP	mass plywood panel
NLT	nail-laminated timber
NREL	National Renewable Energy Laboratory
RC	reinforced concrete
SFI	Sustainable Forestry Initiative
STC	sound transmission class
VOC	volatile organic compound

Executive Summary

The building materials and construction sector is a major contributor to global CO_2 emissions. In 2018, as much as 11% of global emissions were from this sector (Global Alliance for Buildings and Construction, 2018), making buildings a priority for decarbonization. Mass timber construction is one of the low carbon alternative construction options being considered. Mass timber construction panels vary by how the timber layers are joined. Cross-laminated timber (CLT) is glue laminated whereas dowel-laminated timber (DLT) and nail-laminated timber (NLT) are mechanically fastened. In addition to contributing to fewer carbon emissions than concrete from material extraction, processing, production, and building construction, wood can store carbon from the atmosphere for the duration of its use, thus acting as a carbon sink. Compared to concrete buildings, some studies have found CLT buildings to be less energy-intensive in the operational stage (Guo, Liu, Meng, et al. 2017).

CLT is a wood panel system, having high strength and resistance to compressive forces, manufactured by alternate lumber panels glued at right angles, and can be used in multiple building elements, including the roof, stairs, walls, and load bearing elements. CLT panels are primarily manufactured from softwood lumber, which is dried, processed, planed, glued (typically using phenol-based adhesives such as polyurethane or melamine), and cured. NLT and DLT panels are manufactured using similar process steps, except that the gluing and curing stages are replaced with layup using the corresponding mechanical fastener—nails or dowels, respectively. Since CLT panels are prefabricated, they can be customized at the factory for a specific project, reducing the time and costs required for construction. This prefabrication could also make it easier to "design for disassembly" of CLT buildings in the future, resulting in easier deconstruction, material recovery, and reuse at end of life. However, since CLT is a relatively new construction material, there are few current projects focused on end-of-life questions. As a result, there are uncertainties around the lifespan of CLT buildings and the end-of-life material streams.

A virtual workshop titled "BTO Cross-Laminated Timber Workshop: Pathways and Priorities for CLT Building Systems," was held on April 19, 2021, to identify research and development pathways, including the embodied energy content, operational energy efficiency, wall moisture profiles, structural connector durability, and health monitoring systems for CLT wall systems. In the workshop, perspectives were gathered from a wide range of stakeholders across North America from academia, the mass timber industry, trade groups, and federal government departments. The participants had knowledge in one or more areas of CLT building performance, production and construction, supply and demand dynamics of CLT panels, building codes, and recycling of CLT panels. To capture potential research opportunities from the participants in the mass timber field, the workshop was structured with the following objectives:

1. Identify the research and development opportunities to overcome technology gaps, integration issues, and market adoption challenges that are currently preventing the greater deployment of CLT, and
2. Understand what priorities and pathways are needed to advance energy efficient, high-rise CLT building systems.

The workshop was divided into two parts focusing on (1) research perspectives and (2) market perspectives, and each was comprised of plenary presentations and Q&A, followed by breakout discussion sessions. Table ES-1 documents the presentations delivered in the workshop and the breakout session topics. The key findings from the breakout sessions and response forms are summarized below. The topics are arranged in the order of their occurrence in a CLT building's life cycle.

Table ES-1. Invited Talks and Breakout Sessions for the Two Focus Areas of the Workshop

	Research Perspectives	Market Perspectives
Presentations	Supply Chain Impacts on Cradle-to-Gate Primary Energy Consumption and Global Warming Impact	Overview of Tallwood Design Institute
	Mass Wood Research at ORNL: Building Envelope Materials Research	Supply and Demand, Building Codes, Integration, Adoption
	Recent Research Endeavors on Seismic Performance of CLT	Future of Building Design for Manufacture and Assembly
	Influence of Edge Joint Gaps on CLT Properties	
Breakout Sessions	Timber & CLT Production & Construction	Production Challenges and Re-X Opportunities
	Resilience and Building Performance	Supply Demand Dynamics and Building Codes Integration and Adoption

Key Findings

1. Process Efficiency

There are inefficiencies present throughout CLT processing, including the timber drying process, forest and log utilization, and panel processing. The timber drying process uses waste timber residues for heating, which is considered carbon neutral if the sequestering of carbon at the time of tree growth is considered. However, there is debate around this accounting method, and burning wood releases carbon that could have otherwise been stored in wood. Thus, using log residues for drying makes it a major source of carbon emissions and does not incentivize efficiency. CLT production does not take advantage of all parts of the log, which leads to wasted energy for transportation of timber materials that are ultimately discarded during panel production. Forest utilization is currently limited to spruce-pine-fir (SPF) lumber for mass timber panels. Widely adopted machining processes for finishing mass timber panel billets are not able to minimize material waste and finished panel cost.

Recommendations

To address CLT processing inefficiencies and reduce carbon emissions, the heat and material processing efficiencies of timber drying need to be increased. Increasing process efficiency requires identifying alternative markets for residues that would no longer be used as fuel. Forest utilization should be improved by including hardwoods, low-value timber, reclaimed timber, and residues in the mass timber industry, which will require new property rating systems for timber and new production methods. Finally, supply chain efficiencies need to be further improved by utilizing all parts of the log, producing CLT locally in the U.S., reducing customization of fasteners and connectors, and increasing competition among CLT producers and wood CNC machining companies. New panel manufacturing methods, including streamlining pre-fabrication of mass timber systems, can also reduce panel costs and waste, and enable reuse and recycling of the panels.

2. Design

Since CLT is a novel material for construction and CLT building design is a developing field, a set of design and modeling requirements different from traditional construction are needed for CLT. However, AEC firms currently have limited experience designing with CLT. This lack of experience is a barrier to CLT deployment and limits the development and use of innovative and multi-functional panel designs. Multi-functional panels integrate multiple building systems into finished, delivered panels, and could reduce construction cost and improve performance and durability depending on which layers and functions are integrated. Additionally, better design can increase the amount and type of materials that can be reclaimed from the deconstruction of a CLT building.

Recommendations

The limited knowledge among AEC firms of how to take advantage of CLT properties and benefits to design and build effectively with CLT needs to be addressed. One solution is to increase and make consistent the research funding for mass timber construction to increase the faculty pool and thus the ability to recruit and train students to develop their expertise in this field. CLT manufacturers should also explore methods to add functionality into layers of CLT to reduce costs by minimizing additional on-site work.

3. Adhesives

For CLT production in North America, polyurethane adhesives are used widely, along with melamine formaldehyde and phenol resorcinol formaldehyde, to glue the layers in the CLT panel. In the workshop, participants highlighted the high carbon footprint of these adhesives currently used in CLT production.

Recommendations

Novel adhesives, including bio-derived adhesives need to be further explored, tested, and deployed in projects. These new adhesives should match the performance of current adhesives with respect to bonding strength, chemical stability, and resistance to delamination when exposed to heat and flames.

4. Building Envelope Performance

For CLT buildings, thermal bridging is not a major concern, and integrating insulation can further minimize this effect. Uncertainty, however, exists in whether CLT will yield consistent air sealing. Other areas of uncertainty are external moisture impacts on thermal performance, indoor air quality, and dimensional changes.

Recommendations

There is an opportunity to empirically assess CLT panels for their envelope performance, including air leakage and the impact of large-scale external moisture on thermal performance. Real-world empirical data on the effect of mass timber construction on operational energy use and heat and moisture transfer in the envelope is needed. Methods to integrate endemic moisture sensing into the building structure also need to be investigated. Additionally, indoor air quality, including the impacts of volatile organic compounds (VOCs), and occupant comfort for CLT buildings still need to be investigated further.

5. Re-X

To be able to efficiently reuse or recycle building materials, it is important to integrate the principles of design for disassembly and design for retrofit in a cost-competitive way. Constructing reusable buildings with flexible design could enable increased reuse. Additionally, challenges are posed to the reuse and recycling of CLT building materials by certain adhered materials (e.g., vapor barriers) and other high performance envelope air sealing materials that are liquid-applied or are otherwise inseparable from the substrate.

Recommendations

Strategies need to be developed that can be integrated into initial building designs to facilitate retrofit to extend building lifetime and to catalogue building construction details in a long-lived repository to simplify disassembly and facilitate efficient panel reuse. Exploring methods for automated deconstruction to reduce labor costs, grading reclaimed materials to make them reusable, as well as focusing on constructing reusable buildings instead of materials with flexible design leading to multiple uses throughout the life of materials are a few possible strategies. To address the adhered material challenge, the use of dry, mechanically fastened materials that can be separated or the use of a separable barrier layer for, e.g., floor plate topping, will be helpful.

6. Life Cycle Assessment

To examine the potential of CLT buildings to reduce environmental impacts, especially carbon dioxide (CO_2) emissions, life cycle assessment (LCA) has been extensively performed on CLT buildings. However, current LCA practices need a standardized and consistent methodology for accounting for biogenic carbon. An accepted methodology will not only enable comparing impacts across studies but can also be used to give credits for sequestering carbon to CLT buildings. This standardized methodology for carbon accounting can be eventually integrated into building codes. To account for the eventual liberation of CO_2 upon decomposition of the materials, certainty around the building lifespan and the end-of-life disposal method of the materials (incineration, landfilling, etc.) plays a major role. Additionally, there is a need to establish baseline data about the impacts of manufacturing energy efficiency and sustainable forestry on the LCA results. Other important assumptions for LCA include improvements in manufacturing energy efficiency and the extent of regional adoption of sustainable forestry practices.

Recommendations

A consensus needs to be reached among researchers and industry around a methodology to include biogenic carbon in CLT LCA. Identifying the service life of CLT panels and buildings is also important to understand the trade-off between construction, maintenance, and use of chemical preservatives that increase the lifespan of a building compared to replacement at an earlier time. Additionally, streamlining environmental documentation and modifying existing certifications (e.g., from the Forest Stewardship Council [FSC] and Sustainable Forestry Initiative [SFI]) to be better suited to construction materials is recommended. Evaluating energy and carbon implications of hybrid CLT construction and modeling the end-of-life treatment pathways of wood products was also recommended.

7. Building Codes

Existing building codes and standards pertaining to connectors, panel dimensions, and general national design standards for mass timber construction all pose challenges to the deployment of more CLT buildings. Similarly, codes for acoustic performance to meet sound transmission class (STC) or impact insulation class (IIC) certification could be market barriers to CLT. Additionally, the ANSI/APA PRG 320 standard prevents the consideration of alternative options for CLT configuration and input materials.

Recommendations

Revising existing codes and standards is required to address multiple challenges to the deployment of more CLT buildings and increasing use of low-value timber in CLT panels. A performance-based rather than a prescriptive approach will help ease such market barriers. However, there is concern that a performance-based code might lead to designs which allow fire to spread easily, and thus, trade-offs between fire performance and material exposure need to be studied. Accelerating adoption of codes that open additional CLT construction options would also alleviate a structural barrier to CLT construction. The ability to expose more timber in taller structures, currently hindered by code, needs to be considered to reduce the cost of CLT construction and improve the prospects for material reuse.

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1 Introduction

The purpose of this report is to address existing questions regarding the research, development, and demonstration of technologies to advance energy-efficient, high-rise cross-laminated timber (CLT) building systems by developing, building, and evaluating CLT wall systems for embodied energy content, operating energy efficiency, wall moisture profiles, structural connector durability, and health monitoring systems. To gather perspectives on CLT construction from a wide range of stakeholders, BTO hosted a workshop entitled "BTO Cross-Laminated Timber Workshop: Pathways and Priorities for CLT Building Systems," virtually on April 19, 2021. Participants included representation from academia, the mass timber industry, trade groups, and government departments. This report describes the background, structure, and findings of the workshop.

2 Background

Building materials and construction accounted for 11% of global CO_2 emissions in 2018 (Global Alliance for Buildings and Construction, 2018). Considering their significant contribution to global emissions, decarbonization of buildings is a priority for achieving global emission reductions. New technologies to help reduce buildings CO_2 emissions are being explored, including cross-laminated timber (CLT), dowel-laminated timber (DLT) and nail-laminated timber (NLT). Previous studies have found the average embodied carbon of 4, 7, 11, and 17 story reinforced concrete buildings for the construction phase to be 284 kg/m^2, compared to -91 kg/m^2 (including sequestration) for CLT (Guo, Liu, Meng, et al. 2017), and when the demolition phase is included in the assessment, reinforced concrete has 335.6 kg/m^2 embodied carbon, compared to 157.7 kg/m^2 for CLT buildings (Darby, Elmualim, and Kelly 2012). In addition to sequestration lowering the embodied carbon of CLT buildings, wood is also a renewable resource.

These properties of wood, along with a code change approved by the International Building Council (IBC) introducing new building types (Type-IV A, B, and C) that will allow wood construction of up to 18 floors in the U.S. in 2021 (Breneman, Timmers, and Richardson 2019), make CLT a potential environmentally friendly alternative to mid-rise concrete and steel construction. High-rise mass timber construction might be possible but is not allowed under current codes. CLT panels are manufactured by gluing alternate lumber layers at right angles (Figure 1). These panels are known to have dimensional stability and high strength and resistance to compressive forces. The perpendicular angles between grains ensure that the panels have equal strength in all directions. CLT can be used in floors and roofs of the building, as well as vertical or horizontal load resisting elements (Evans n.d.). However, mass timber construction typically uses glulam, a wood beam of adhesive bonded wood laminations, for the frame and CLT or DLT for roofs and walls (DeStefano and Epp 2019).

Figure 1. Perpendicular grains of alternating lumber boards used for CLT panels

Photo from Wikimedia Commons

Softwood lumber species (Douglas-fir, Hem-fir, southern pine, etc.) are typically used as the raw material for CLT panels. The CLT panel manufacturing process begins from planting the seeds in the timber forest, growing the trees, and then harvesting them for timber. The harvested timber is sent to sawmills where it is dried, processed, and planed into lumber boards, which are then sent to CLT manufacturing plants. In the CLT manufacturing facility, the lumber boards, varying in thickness between 0.675 to 2 inches, are further dried to a moisture requirement of 12% by weight. Then the panels are laid up and adhesives such as polyurethane, melamine, or other phenol-based adhesives are applied for gluing the panels. This step is followed by curing, pressing, and finishing the panels, which are then packaged and transported to a storage facility or the building construction site.

CLT panels can be manufactured in different sizes, but since they are prefabricated, they can easily be customized to a specific project, which reduces on-site construction time, and potentially reduces construction costs. Prefabrication also makes it possible to apply the “design for disassembly” principle to CLT buildings, which involves designing the building for easier deconstruction, material recovery, and reuse. However, not much data is available on the construction and demolition process of CLT buildings. During the operational phase, research has indicated that CLT buildings have lower energy consumption and carbon emissions than comparative concrete buildings (Guo, Liu, Chang, et al. 2017). Fire performance, moisture performance, occupant comfort, and durability are other properties that can differ between CLT and reinforced concrete (RC) buildings.

In the United States, CLT is a nascent industry with a number of pilot projects, CLT manufacturing facilities, and design firms across the country. The performance and properties of CLT buildings are often compared to those of traditional concrete and steel buildings. As wood is a renewable resource and can store carbon, mass timber construction is considered an option for decarbonization of the buildings sector. End-of-life scenarios and material streams of the CLT building are uncertain at the moment, but there is recent interest in understanding the lifespan of CLT buildings, what happens at the end of its useful life, and how the carbon in the wood can be stored for a longer time in useful product.

Given the breadth of research possible in CLT buildings, construction, manufacturing and associated activities, this workshop sought to capture targeted research and deployment opportunities across the life cycle of CLT buildings. The following sections describe the structure and discussions from the workshop.

Figure 2. Construction using CLT panels

Photo from Structurlam Mass Timber Corporation

3 Workshop Structure

The workshop, titled "DOE CLT Workshop: Priorities and Pathways for Cross-Laminated Timber (CLT) Building Systems," was conducted on April 19, 2021, over four hours, with speakers and participants joining from across North America. Following a welcome greeting from DOE, the workshop proceeded with four research-focused presentations, each followed by a brief Q&A session, and then four simultaneous breakout sessions. Each of the breakout sessions focused on research perspectives. A similar sequence was repeated after a short break, with three presentations focused on market perspectives with interspersed Q&A sessions, followed by four simultaneous breakout sessions. These four breakout sessions were focused on market perspectives.

The objectives of the workshop were to (1) identify the research and development opportunities to overcome technology gaps, integration issues, and market adoption challenges that are currently preventing the greater deployment of CLT, and (2) to understand what priorities and pathways are needed to advance energy efficient, high-rise CLT building systems.

3.1 Participants

The participants that registered and attended the workshop belonged to various organizations with some connection to CLT. The participants are shown by organization type in Figure 3.

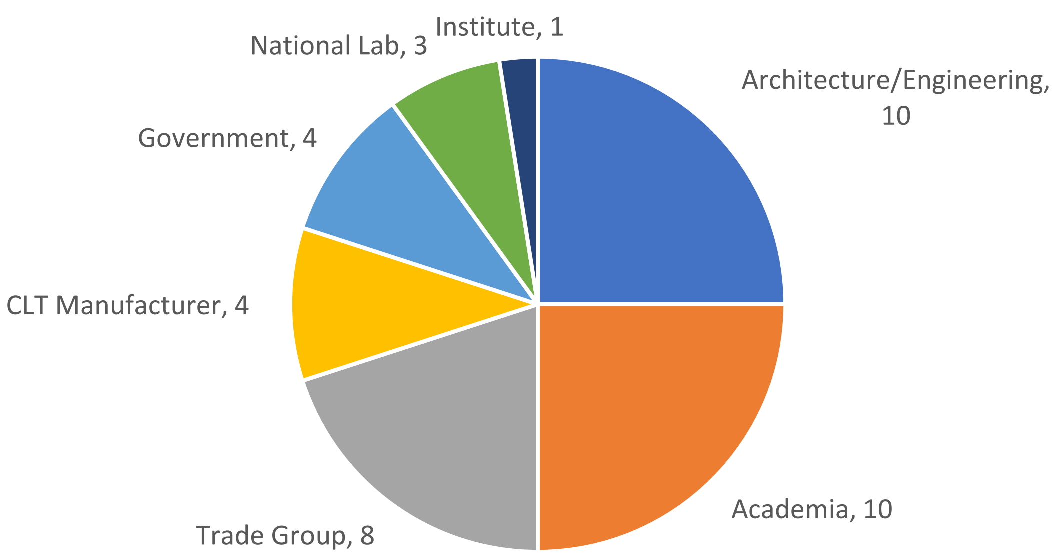

Figure 3. Workshop participant affiliations. A total of 40 participants registered and attended the workshop and represented various stakeholder groups in the industry.

The participants had expertise and knowledge in one or more of CLT building performance, production and construction, supply and demand dynamics of CLT panels, building codes, and recycling of CLT panels.

3.2 Invited Talks

The workshop had a total of seven presentations by invited speakers focusing on either research or market perspectives. The presentations were 7 minutes long and were each followed by 3-minute Q&A sessions. Table 1 documents the presentations given in the workshop.

Table 1. Invited Talks: Titles and Presenters

	Presentation Title	Presenter	Organization
Research Perspectives	Supply Chain Impacts on Cradle-to-Gate Primary Energy Consumption and Global Warming Impact	Swaroop Atnoorkar	National Renewable Energy Laboratory
	Mass Wood Research at ORNL: Building Envelope Materials Research	Mikael Salonvaara	Oak Ridge National Laboratory
	Recent Research Endeavors on Seismic Performance of CLT	Arijit Sinha	Oregon State University
	Influence of Edge Joint Gaps on CLT Properties	Stephen Shaler	University of Maine
Market Perspectives	Overview of Tallwood Design Institute	Judith Sheine	Tallwood Design Institute
	Supply and Demand, Building Codes, Integration, Adoption	Erica Spiritos	Swinerton/Timberlab
	Future of Building Design for Manufacture and Assembly	Kris Spickler, Alex Zelaya	Structurlam

3.3 Breakouts

The workshop had two sets of four simultaneous breakout sessions each focusing on the research and market perspectives, respectively. The breakout session topics and moderators are outlined in Table 2. Participants were assigned to one breakout group for each session based on their preferences expressed during registration and their expertise. In each breakout session, the moderator asked open-ended questions to encourage discussion among the participants, which was recorded by note-takers. The key findings and takeaways from these discussions are outlined in Section 4.

Table 2. Breakout Session Topics and Moderators

	Breakout Session Topic	Moderator
Research Perspectives	Timber & CLT Production & Construction	Heather Goetsch
		Chioke Harris
		Carl Shapiro
	Resilience and Building Performance	Swaroop Atnoorkar
Market Perspectives	Production Challenges and Re-X Opportunities	Swaroop Atnoorkar
		Samuel Petty
	Supply Demand Dynamics and Building Codes Integration and Adoption	Heather Goetsch
		Chioke Harris

4 Breakout Session Key Findings

In the following sections, research needs discussed in each of the breakout sessions are organized by topic area. The main research topics and themes are synthesized first in bullet points. All topics discussed during the breakout session are described in further detail in the table following the synthesis of main topics. Empty parts of the table do not indicate that there are no issues in that topic area, but that the breakout session did not include discussion around these topics.

4.1 Research Perspectives

4.1.1 Timber & CLT Production & Construction

The discussion in this breakout session focused on the timber and CLT construction stages and the associated research opportunities. Table 3 describes all the topics brought up in the breakout session.

Table 3. Timber & CLT Production & Construction Breakout Session Discussion Summary by Topic

Topic	Research	Deployment	Codes and Standards
Biophilia	Consider the advantages and disadvantages of living in CLT or wood structures compared to concrete buildings.		
Codes			Overcome code barriers that result from regional and state jurisdiction differences of acceptance of code standards. Any testing done outside the U.S. will need to be done in the U.S. to prove viability to U.S. standards
Costs	Demonstrate the viability of CLT to be cost-competitive for 6-18 story buildings where stick-build is not feasible	Mass timber should be considered for affordable housing Cost and timing are the biggest issues concerning CLT production. Energy is not a driver of CLT production conversations.	
Cross-functionality	Add functionality into layers of CLT to minimize additional on-site work to improve costs		Codes to recognize cross-functionality of CLT
Connectors	Overcome the challenge of the necessary performance of connectors during use with the need to remove or reuse during demolition of building Verify fireproofing of connectors	Understand where glulam beams are used instead of two connected panels. Proprietary, custom made, and imported connectors add to the connector cost.	
Design			Need different set of design and modeling requirements for CLT
Durability	Need for vapor barriers and new coatings during construction to prevent leaks Address decay issues if CLT is to enter the 5–10 story building market		
Energy Performance	Incorporate energy efficiency performance into CLT		
Hybrid construction		Explore opportunities of hybrid systems with concrete cores and CLT framing which could be a good way to increase market share in multi-rise buildings	

Topic	Research	Deployment	Codes and Standards
Life cycle assessment	Need for consistent methodology of how to consider biogenic carbon in LCAs of CLT buildings and to determine whether long-lived timber products are a long-term strategy for carbon storage Quantify the effect of embodied carbon on different forest management practices and different timber species Need consensus around what is considered sustainable forestry and embodied carbon Determine impacts of drying timber regarding the fuel used (biomass vs natural gas). Drying process is the same for other wood building materials (studs). Need a holistic comparison to show efficiency over other building materials and not just incremental improvements in the CLT process	Overcome issues around damage to tools by specific tree types (e.g., fir)	
Lifespan	Explore the true lifespan of CLT buildings, especially when comparing the costs to other building types with different lifespans		
Low value timber	Evaluate highly variable timber sources like reclaimed timber, hardwoods, wood from fire suppression or anti-deforestation Need new production methods to be able to use hardwoods and marginal timber Explore additional panel configurations (e.g., MPP) that facilitate use and reduce the cost of incorporating marginal timber		Overcome code challenges when considering low value wood for CLT which increases biodiversity needs and utilization Need new grading methods for using hardwoods and marginal timber since properties are more variable
Manufacturing energy	Determine manufacturing energy efficiency of the CLT process. Increase the drying efficiency at the manufacturing plant (e.g., keeping the plant at an optimal temperature,		

Topic	Research	Deployment	Codes and Standards
	determine how waste materials can be used for drying).		
Materials	Reduce carbon intensity of CLT adhesives Evaluate dowel-laminated timber and nail-laminated timber for building performance	Need for manufacturing capacity for dowel-laminated timber	
Outreach	Educate market and workforce to be able to work with CLT	Foster interest in using CLT with stakeholders and industry leaders Increase awareness of CLT's energy efficiency performance and the impacts of climate change Overcome builder confidence barriers for CLT use. (e.g., wood rots, decay, change in dimension)	
Re-X	Explore dry systems and make more widely available to enable reuse efforts. Liquid applied membranes and other wet applied materials make recycling difficult Build in disassembly during design to make disassembly easier and reduce waste. Consider the separability of panels to make recycling and reuse less challenging and less costly Explore options of avoiding penetrating the panel to improve reuse Design for retrofit to extend the useful life of a building structure by planning for needed retrofits for components with a shorter life than the building structure Research other components beyond panels of CLT construction that can be reused Determine how byproducts in the production process might be used elsewhere (e.g., door and window cutouts for school	Need approaches that are viable long-term to retain construction material information throughout the life of the building to enable reuse Overcome the issue of bidding on disassembly and whether the materials will be marketable at end of life Minimize or eliminate on-site modifications to increase feasibility of panel reuse. Improve costs for design of CLT buildings for disassembly and reassembly	Need standards and methods to rate and evaluate highly variable timber sources and reuse of timber from demolition

Topic	Research	Deployment	Codes and Standards
	desks, CNC process products for wood fiber insulation). Only 50% of log is used for timber products and the rest is discarded currently.		
Seismic	Research how to create buildings that can be reused and repaired after earthquakes Research seismic impacts on structural strength and connectors		
Standards			Need improved methods for conveying timber sustainability, specifically for mass timber construction products. Existing certification like SFI and FSC are not designed for these types of timber applications
Supply Chain		Determine how steel connectors can be more easily manufactured in the U.S.	Consider other dimensions and volumes of wood. The largest cost driver is the volume of wood, and the thickness of wood cuts are limited by the U.S. lumber industry set at 2" dimensions which leads to excess wood used to accommodate mill standards.
Waste Reduction	Develop methods that minimize or eliminate construction waste and inefficiencies while also not pushing the waste upstream (e.g., shifting waste to the CLT panel fabricator)	Need for design tools that facilitate and simplify the effort to design for minimal on-site waste and make them easily available to AEC firms	

4.1.2 Resilience and Building Performance

The discussion in this breakout session focused on the performance of CLT buildings and resilience topics specific to CLT buildings. Table 4 describes all topics brought up in the breakout session.

Table 4. Resilience and Building Performance Breakout Session Discussion Summary by Topic Area

Topic	Research	Deployment	Codes and Standards
Durability	Determine effect of mechanical properties of CLT on delamination.		
Energy Performance	Integration of insulation to avoid thermal bridging and evaluating the effect of glazing on thermal bridging. Evaluate the need of external insulation, which needs to be non-combustible, and may increase the embodied energy of the building. Evaluate the impact of moisture on energy performance. Evaluate the ability of CLT to yield consistent as-built performance compared to other construction types.		
Fire	Research how gaps (cavities, holes, or air ducts) in the structure will affect the spread of fire and the charring of CLT panels.		
Indoor Air Quality and Comfort	Evaluate the impacts of volatile organic compounds (VOCs) from CLT panels (if any) and understand how the impacts vary with the tightness of the building. Understand noise dampening impacts from exposed CLT panels.		
Life Cycle Assessment (LCA)	Creating tools to evaluate the sustainability of individual projects to comply with goals. Ability to better capture the embodied carbon of CLT buildings.		

4.2 Market Perspectives

4.2.1 Production Challenges and Re-X Opportunities

The discussion in this breakout session focused on the timber and CLT production challenges of the industry and opportunities to reuse or recycle CLT. Table 5 describes all topics brought up in the breakout session.

Table 5. Production Challenges and Re-X Opportunities Breakout Session Discussion Summary by Topic Area

Topic	Research	Deployment	Codes and Standards
Connectors	Scope out research for developing structural connector standards.	Self-tapping screws can save costs in construction.	Standardizing the design of reinforcing screws.
Costs and Supply Chain	Create a long-term outlook on planning for the future where the demand exceeds the current production capacity to avoid bottlenecks. Composite construction (concrete and CLT) is more costly than using thicker CLT but could offer other benefits justifying further research.	Create alternative revenue sources for CLT facilities for achieving economies of scale. Increasing the number of CLT manufacturing facilities to reduce transportation distances and providing the right grade and species to sawmills is an opportunity to increase supply chain efficiency.	Standardize CLT panel sizes to enable designers to optimize costs by selecting a manufacture early in the design process.
Durability	Inform the useful life of CLT buildings and CLT panels by extending the cyclic delamination test to see how long it takes to delaminate CLT among others. Understand the customer perception of and market forces operating on the useful life of a CLT building.		
Expertise		Early education for CLT designers to eliminate inefficiencies, take appropriate benefits of CLT panels, plan for deconstruction and re-use.	
Moisture		Develop methods for integrated moisture sensing into building structures to detect locations of leaks to prevent damage and best practices for water management during construction.	
Re-X	Identify markets for residues in CLT production, appropriate recycle streams (e.g., furniture) for CLT panels and opportunities to recycle wrapping material. Evaluate the trade-offs between construction, maintenance, use of chemical or preservatives as	Focus on constructing reusable buildings Flexible design can lead to multiple uses throughout the life of materials. Develop methods to grade reclaimed materials and creating a digital inventory of the type and quantity of available materials to be reused.	

Topic	Research	Deployment	Codes and Standards
	compared to early replacement. Develop dry assemblies for the floor plate that can be separated using a barrier layer for easier re-use. An example can include putting the acoustic barrier below the concrete topping.	Develop methods for automated deconstruction to reduce labor costs and retain the quality of harvested materials.	
Standards		Increase the number of "approved assemblies" by UL to augment CLT deployment.	Allowing performance-based standards to allow more efficiency in CLT manufacturing by accommodating flexibility in species, dimensions, and sizes. instead of the current standards that are based on overly conservative lumber values.

4.2.2 Supply-Demand Dynamics and Building Codes Integration and Adoption

The discussion in this breakout session focused on CLT and mass timber market conditions, including timber supply, as well as issues related to current and future building codes support for CLT and mass timber construction and code adoption. Table 6 details the specific issues discussed during the breakout sessions on this subject, categorized by topic, and structured as actions to address issues identified. These topics and the corresponding discussion questions were principally focused on market-facing challenges, however, Table 3 includes research needs in multiple topic areas.

Table 6. Supply-Demand Dynamics and Building Codes Integration and Adoption Breakout Session Discussion Summary by Topic Area

Topic	Research	Deployment	Codes and Standards
Acoustics	Develop materials and practices to achieve acoustic performance that meets sound transmission class (STC) or impact isolation class (IIC) requirements, especially for residential buildings		
Codes			Support accelerated state adoption of codes that allow or expand options for mass timber construction Increase flexibility in acceptable approaches to meet performance requirements (e.g., structural, fire)
Cost		Reduce the cost of tracking chain of custody for CLT panel certification Investigate decoupling of CLT billet manufacturing and panel machining and customization (as in Europe)	
Expertise	Support university research to grow faculty base and thus grow cohort of students joining AEC firms with expertise in mass timber construction	Increase knowledge among AECs, particularly construction firms, on how to build and execute CLT projects successfully Develop workforce experienced in CLT construction	
Fire	Obtain needed supporting data to reduce code restrictions in the use of exposed timber materials in Type IV (9–18 story) buildings Develop materials and methods to further increase timber fire endurance to allow for full evacuation of taller all-timber structures (beyond 2021 Type IV code) Develop materials and methods that enable open-plan spaces while limiting fire spread and increasing		Build confidence among practitioners in fire performance of new code compliant CLT construction and potential options for furthering all-timber construction Investigate implications of performance-based codes that do not require compartmentalization to reduce fire spread (as in the United Kingdom) Investigate alternative construction options that

Topic	Research	Deployment	Codes and Standards
	fire endurance (Rackauskaite, Kotsovinos, & Barber, 2020)		balance timber exposure with fire performance
LCA		Support ongoing education for practitioners on embodied carbon, especially regarding how to best communicate impacts, benefits Facilitate robust supplier documentation of environmental data Facilitate development of timber sustainability certification(s) suited to mass timber construction materials	Investigate adding GWP/GHG emissions to energy codes
Outreach		Accelerate student awareness of mass timber construction with CLT buildings at tertiary (post-secondary) institutions Amplify CLT project successes to increase awareness and familiarity across the market	
Policy		Integrate carbon accounting into assessment of new construction projects (as proposed in Washington state)	
Standards			Explore options to enable ANSI/APA PRG 320.18 to allow for more diverse input feedstocks for CLT panel materials
Supply Chain	Understand supply chain dynamics in a future where CLT construction influences timber costs	Investigate supply chain innovations to find cost efficiencies Address supply bottleneck arising from the lack of CNC capability at glulam manufacturers	

5 Recommendations

After reviewing the breakout session topics discussed and the themes of topics iterated across breakout sessions, the following topic areas are provided as future opportunities for CLT. The topic areas are listed in no specific order.

- Improve processing efficiency (e.g., heat, materials, etc.) and carbon emissions of timber drying.
- Improve forest utilization to include hardwoods, low-value timber, reclaimed timber, and residues in the mass timber industry. This will require new markets, rating systems, and new production methods.
- Improve supply chain efficiencies (e.g., utilizing all parts of the log, domestic production and reduced customization of screws and connectors, increased competition among CLT producers, CNC machining companies, etc.)
- Focus on constructing reusable buildings with flexible design which can lead to multiple uses throughout the life of the materials.
- Integrate design for retrofit and disassembly in building design and make it cost competitive.
- Need for unique design and modeling requirements for CLT.
- Continue to improve adhesives by exploring bio-derived adhesives, using dry materials for floor plate topping that can be separated, and avoiding liquid-applied inseparable adhered materials.
- Holistic, consistent methodology of life cycle analyses (LCAs) for CLT buildings to include biogenic carbon calculation consensus, manufacturing energy efficiency, sustainable forestry, and appropriate building life span assumptions.
- Identify the service life of CLT panels and buildings to include trade-offs between construction, maintenance and use of chemicals and preservatives compared to earlier replacement.
- Investigate multi-functional panels that integrate capabilities, features, and building systems into finished, delivered panels that could reduce construction cost and improve performance and durability.
- Investigate indoor air quality and comfort, including the impact of volatile organic compounds (VOCs) in tighter spaces.
- Investigate moisture performance, including the large-scale impact of external moisture on energy performance and methods for integrating endemic moisture sensing into building structures.
- Investigate thermal energy performance of CLT panels.

- Need for new or revised standards for CLT building-specific challenges (e.g., to allow for more use of low-value timber and reclaimed material, for connectors and panel dimensions, and general national design standards for mass timber construction).

- Investigate building codes for CLT construction application (e.g., adding GHG/carbon emissions accounting to codes, acoustic performance or impact insulation certification can be challenging and market barriers to CLT, trade-offs between fire codes and material exposure codes need to be better understood).

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7 Appendix

7.1 Agenda

BTO Cross-Laminated Timber Workshop: Pathways and Priorities for Cross-Laminated Timber Building Systems

Workshop Objectives:

1. To identify the research and development opportunities to overcome technology gaps, integration issues, and market adoption challenges that are currently preventing the greater deployment of CLT, and

2. To understand what priorities and pathways are needed to advance energy efficient, high-rise CLT building systems.

Time (EDT)	Topic	Speaker
12pm	Welcome	Sven Mumme, DOE BTO
12:10pm	Presentations: Research Perspectives	
	Supply Chain Impacts on Cradle-to-Gate Primary Energy Consumption and Global Warming Impact	Swaroop Atnoorkar, NREL
	Mass Wood Research at ORNL	Mikael Salonvaara, ORNL
	Recent Research Endeavors on Seismic Performance of CLT	Arijit Sinha, Oregon State University
	Influence of Edge Joint Gaps on CLT Properties	Stephen Shaler, University of Maine
	Q&A (after each presentation)	Chioke Harris, NREL
12:50pm	Breakout Session 1: Focus on research perspectives Timber & CLT production & construction Resilience and building performance	Moderators: Swaroop Atnoorkar, Heather Goetsch, Chioke Harris, Carl Shapiro
2pm	Break	
2:10pm	Presentations: Market Perspectives	
	Overview of Tallwood Design Institute	Judith Sheine, Tallwood Design Institute
	Overview of Supply Demand, Building Codes Integration and Adoption	Erica Spiritos, Swinerton/Timberlab
	Future of Building Design for Manufacturing & Assembly	Kris Spickler/Alex Zelaya, Structurlam
	Q&A (after each presentation)	Chioke Harris, NREL
2:40pm	Breakout Session 2: Focus on market perspectives	Moderators: Swaroop Atnoorkar, Heather Goetsch, Chioke Harris, Sam Petty

Time (EDT)	Topic	Speaker
	Production challenges and Re-X opportunities Supply & demand dynamics and building codes integration & adoption	
3:55pm	Farewell	Sven Mumme, DOE BTO

7.2 Registration Form Responses

The invitation sent to workshop participants included a registration form for invitees to indicate their participation and some general questions to prime the workshop structure and discussion. Questions asked were (1) what the registrant thought the most important research, adoption, or deployment challenge to address immediately, (2) what additional research opportunities are available to the CLT industry, and (3) what additional adoption or deployment challenges are associated with CLT. Below are high level topics synthesized from the responses, followed by all responses organized by topic area.

- Further innovation in on-site construction methods could reduce cost. Automation and robotics are possible approaches.
- New panel/billet manufacturing methods (including streamlining pre-fabrication of mass timber systems) could reduce panel costs and waste, enable reuse and recycling.
- Real-world empirical data on the effect of mass timber construction on operational energy use, heat and moisture transfer in the envelope is needed.
- Evaluation of energy and carbon implications of hybrid construction.
- Evaluating embodied carbon as a function of timber species.
- Modeling the end-of-life treatment of wood products and understanding these pathways.
- Approaches that integrate envelope control layers, and CLT systems that integrate wood fiber insulation.
- Making CLT more cost competitive by identifying costs (life cycle cost assessment [LCCA]) and employing cost reduction strategies including increasing construction efficiency, improving contractor education, and understanding factors driving fluctuations in timber prices.

Topic	Research	Deployment	Codes and Standards
Acoustics	Evaluating the acoustic performance of CLT buildings and incorporating acoustic materials in engineered wood panels	Engineering approach for CLT panels and systems for vibration performance	

Topic	Research	Deployment	Codes and Standards
Affordable Housing	What is the connection of CLT with affordable housing?		
Biophilia	Developing a better understanding of and quantifying the biophilic benefits of exposed wood surfaces.		
Codes		Address barriers due to local jurisdiction code adoption cycles and hesitancy.	Adoption of codes that allow for mid-rise CLT construction (Type IV- A, B, C) Adoption of codes that facilitate CLT construction adoption. Continued focus on adoption codes that ensure structural review of materials is more prescriptive. Adoption of tall wood building provisions worldwide. Additional testing and provisions to allow more adoption of Type IV construction (allowable heights, occupancy, wood exposure, etc.) Ensure energy code recognition of mass timber enclosure assemblies.
Costs	Developing a life cycle cost analysis for CLT buildings and identifying strategies to reduce construction cost. Innovating the CLT panel beyond a “monolithic slab” to reduce cost. Developing solutions that are multifunctional and cost effective	Driving down construction costs by advancing efficiencies in construction by automation and the use of standardized connectors, among others. Cost reduction and transparency to make a specialty product like CLT attractive to general contractors. Improving mass timber manufacturing technology and creating hybrids to reduce cost. Making costing data accurate and projects cost-competitive by improving design team understanding and contractor education.	
Construction	Evaluating and calculating reduced construction risk		

Topic	Research	Deployment	Codes and Standards
	when constructing offsite (safety, efficiency).		
Design	Focus design research on resilience.		
Energy Performance	Developing approaches that integrate envelope thermal control layers or wood fiber insulation with CLT systems. Evaluating the long-term thermal performance of CLT. Gathering real world data of mass timber design influence on operational energy performance including heat and moisture. Developing CLT backed curtain wall system (constructability, cost efficiency, durability, thermal performance) Developing CLT structural bearing wall system (constructability, cost efficiency, durability, thermal performance)	Exploring the design of structures to make the best use of thermal benefits of mass wood. Incorporating thermal materials in engineered wood panels	
Expertise	Exploring use of CLT specific design practices instead of just substituting CLT or mass timber for traditional materials. Documents demonstrating studies showing and quantifying the benefits of CLT on different type of buildings and climate zones	Educating CLT producers about the appropriate species use for CLT, AEC firms about the appropriate and cost-effective applications, design, and maintenance for CLT and builders about CLT as an option and working with CLT in construction. Integration of subcontractors into the 3D planning of buildings. Training multiple skilled crews for erecting CLT buildings to reduce uncertainties in costing. Incorporate training of mass timber trades in more depth in university degrees and create a licensing system for these trades to further mass timber use and research.	Education and adoption by authorities of the IBC 2021 code including the need for use of encapsulation in different applications. Educating construction contractors for estimating, insurance, building code familiarity and adoption of the 2021 ICC for tall wood buildings.
Fire	Research fire safety of exterior wall insulation and cladding and test the use of exposed wood in CLT buildings.	Convincing people that wood does not burn.	

Topic	Research	Deployment	Codes and Standards
Forestry Impacts	Identify an effective mechanism to promote the sustainable management of forest and CLT life cycle		
Hybrid Construction	Research on hybrid panels that incorporate more functional layers for weight (reduce), strength (increase), fire (resistance) and thermal performance.		
Life cycle Assessment	Improved LCA and characterization of carbon sequestration of CLT construction. Continuing research on LCAs and development of user-friendly LCA software tools (transparent, material-agnostic, consensus-based) Understand the impacts of increased CLT production on the forest carbon stock under different climate scenarios. Developing a more accurate and complete quantitative understanding of the contributions to sustainable development, including environmental, social, and economic performance, that CLT and mass timber building systems can provide to the building and construction sector in North America. Evaluation of sustainability and resiliency impacts on hybrid systems (utilizing systems with concrete/steel/timber). Assessment of the economic and environmental impacts from CLT or other mass timber in buildings	Compiling industry-wide manufacturing average data for life cycle inventory for CLT and other mass timber product, and reliable information on biogenic carbon in wood and wood products. Bringing a consensus around biogenic carbon accounting in the research community and ensuring that this accounting system is fair to wood products. Standardizing and making public research in the carbon sequestration properties of various forest management practices, including the long term or permanent removal of carbon sequestering forests and other natural habitats, along with a transparent carbon accounting for concrete and steel mining.	
Lifespan	Studying the service life or durability of mass timber buildings		
Low Value Timber	Assessing different wood species for CLT production on cost and environmental impacts		

Topic	Research	Deployment	Codes and Standards
Materials	Exploring new wood species for use in engineering timber products and hybrid products (veneers, dimensional timber, strands). Evaluating alternatives to encapsulating CLT with gypsum board as mass timber buildings increase in height. Research on plant-based adhesives.	Having multiple material sources with short delivery times	
Modeling	Development of a database of GWP reference or benchmark buildings (to use for incentives for reducing embodied carbon in procurement policy and other incentives) Looking into whether current energy modeling tools can accurately model CLT.	Implementing BIM use for pre-construction coordination.	
Re-X	Researching designs for CLT, mass timber buildings that plan for end-of-life to maximize reuse/recycle rate. Researching deconstruction and end-of-life opportunities and programs for CLT buildings and investigating end-of-life scenarios. Understand the end-of-life pathways of CLT	Working with factories to better carry out testing for CLT panels in the facilities. Developing technology solutions to streamline prefabricated mass timber systems - through design, manufacturing, construction, and occupancy. These solutions should advance applications for Industry 4.0 for the building industry.	
Seismic	Designing for seismic performance. Assessing the seismic R factor for CLT wall systems		
Strength	Research the lateral load resisting system for CLT sheer walls.		
Supply Chain	Research the use of wood species to support manufacturing across the U.S. Understand the market drivers and barriers of CLT deployment in different regions, e.g., developed countries versus in developing countries like China	Utilization of sustainability managed and harvested timber where best practices were used at every stage in the upstream (of CLT manufacturer) supply chain. Expanding pre-fabrication capacity and domestic CLT manufacturing. Strategizing for alternative products for CLT to keep	

Topic	Research	Deployment	Codes and Standards
		manufacturing plants consistently operating between buildings. Improving supply chain logistics to reduce cost and GHG emissions. Ensuring local supply of CLT for building in urban centers. Ensuring that market demand can meet supply should more policies around mass timber be enacted through legislation or executive order. Making the chain of custody of sourcing more transparent	
Urban Area Impacts	Understand the impacts of CLT on urbanization and rural-urban connections. The deployment of CLT may change the future landscape of urban areas.		

Comments that were brought up in the registration form responses but have not been categorized because they were either not specific enough, conflicted with other points, or were observations:

- Evaluate whether the massive amount of wood use makes envelope facades an appropriate application
- Assessment of the economic and environmental impacts from CLT or other mass timber in buildings
- Continuous testing for resilience
- Structural codes for a variety of applications (point supported assemblies, post-tensioned timber rocking walls, etc.)
- Building code limitations
- Cost in U.S. vs Europe
- Cost-competitiveness
- Cost of lumber
- Incentives for mass timber construction
- Work on the public perception of CLT
- Cost volatility due to fiber cost fluctuation
- Dimensional changes due to thermal and moisture performance

- Thermal issues
- Fire, durability, seismic, nondestructive assessment, insulation and acoustics
- LCA, EPD criteria
- Life cycle assessment
- Assess opportunities to contribute to the decarbonization of the building sector
- Sustainability concerns due to lack of transparent and peer reviewed data
- Demand-side: Embodied carbon building policies, manufacturing incentives
- GHG dynamics of the CLT product and building system supply chain
- Sustainability (impact of embodied carbon)
- Inclusion of low-grade wood species
- CLT that uses hardwoods that are more readily available in the northeast
- Wall, roof, and floor prefab assemblies
- Available software that can extend from building design through digital fabrication and building assembly
- Control of construction moisture
- Moisture barrier issues
- Corporate procurement policies that set embodied carbon goals (e.g., a 20% reduction in embodied carbon)
- End-of-life treatment of the mass timber products in buildings
- Reuse of CLT
- Design standards that include connection options for diaphragms
- NFPA 285 testing of exterior walls with CLT structure
- More research is needed for R value for CLT shear walls
- Three hours for rating tests for assemblies used in buildings above 12 stories (Type IV-A building type)
- Supply-side: Log and lumber supply, economical COC sourcing, workforce training.
- Durability
- How can we integrate CLT with other buildings system?

7.3 Breakout Session Discussion Questions

The following questions were asked by moderators to participants in each breakout session.

7.3.1 Timber & CLT Production & Construction

- Currently, CLT construction is most suitable for what building types?
    - What opportunities or barriers exist for expanding to other building types?
    - Is CLT a good option for affordable housing?
- What is the level of research in structural strength and connectors for CLT buildings?
- How important is more research in this field for advancing CLT building design?
- What level of standardization in order to streamline construction and facilitate reuse or recycling in structural connector methods for CLT exists?
- What are the opportunities and challenges for using different timber species or low-value lumber?
- What are the opportunities to improve the energy efficiency or reduce the carbon emissions of CLT production?
- What are the opportunities to improve the energy efficiency or reduce the carbon emissions of CLT feedstock production?
- What are the most energy- and carbon-intensive elements of the construction process and where are the opportunities to minimize the carbon impacts?
- What are the needs that must be addressed to minimize carbon emissions for the on-site construction phase for CLT buildings?
- What are outstanding questions around how to utilize hybrid construction to maximize the energy and carbon savings for a project?
- What are the challenges and opportunities for minimizing waste streams in CLT manufacturing and marketing waste byproducts?
- Are the best practices for minimizing waste in CLT feedstock production, panel production, and building construction baked into the processes widely adopted in industry today?

7.3.2 Resilience and Building Performance

- What is known about the use-phase efficiency of CLT buildings as compared to equivalent buildings constructed using traditional materials?
    - What opportunities are there to modify CLT panels to improve CLT building energy efficiency?

  - What other changes to the design of CLT panels themselves or to the configuration of CLT buildings might be feasible to reduce building energy use?
  - What opportunities exist for reducing thermal bridging in CLT buildings?
- How do CLT buildings fare in terms of their ability to retain temperature and conditioned air for human comfort? How does CLT construction affect the thermal mass of the buildings?
  - Do thermal, moisture cycles (either due to the weather, or internal air conditioning) affect the strength of the CLT structure?
  - Which insulating materials are best used in CLT buildings? If there are preferred materials, what properties make them favorable?
- What benefits or potential issues do CLT buildings have with regard to indoor air quality, occupant comfort and well-being?
- How do CLT buildings perform in areas with varying levels of humidity or flood prone areas?
- To what extent are potential moisture issues (surface mold, corrosion, etc.) driven by wetting during construction versus occupancy? What additional data are needed to establish the primary moisture risks for CLT buildings?
- Are new capabilities needed in use phase building energy modeling for CLT buildings to support design with CLT? If yes, what are the expected energy flows that are not being captured now?
  - What modeling software tools are currently being used by industry that need improvement with respect to how they represent CLT (across all phases)?
  - What specific improvements are needed?
- What type(s) of health monitoring systems are needed for CLT buildings?
  - What parameters need to be measured to monitor the condition of CLT buildings? What off-the-shelf capabilities are available for health monitoring of CLT buildings?
  - What research is still needed to develop these systems?

7.3.3 Production Challenges and Re-X Opportunities

- What opportunities exist for improvements to the timber supply chain that supplies CLT producers with the aim of reducing cost and waste?
- What is the short- and long- term production cost outlook for CLT manufacturing? What factors impact production cost, and what are the opportunities for reducing production cost?

  - To what extent might production methods use low value and underutilized wood species?
- What opportunities exist for improvements to CLT panel design to minimize cost and waste?
- What other areas offer opportunities to minimize cost and waste for CLT buildings?
- Is recycling of used CLT panels from buildings a part of contemporary discussion? What are the current barriers to mainstream reuse/recycling of used CLT panels (technical, economic, etc.)? If the industry for used CLT panels is too young, what do you expect the barriers might be in the future?
  - What other construction materials are extensively reused? Could the methods for reusing/recycling these materials be a model for how to recycle CLT?
- What is the expected service life or replacement rate of a CLT panel and/or of a CLT building? Are there efforts being made to extend this service life? What are the possible changes which can be implemented to extend the service life?
- Towards the end of the useful life of the CLT panels, what is done to dispose them and/or recycle or reuse them?
- How do standards for CLT panels affect the CLT industry? How does the current level of standardization affect streamlining modular construction using the panels?
  - Is the technical information regarding the standards easily available?
  - In what other areas (e.g., structural connectors) are standards needed?
- What do we know about how big of a problem moisture or water management challenges are during construction?

7.3.4 Supply and Demand Dynamics and Building Codes Integration and Adoption

- What is the supply and demand outlook for CLT? Are clients asking for more CLT?
  - If yes, is construction supply-constrained and where are the bottlenecks in the supply chain?
  - If no, what factors are preventing the adoption of CLT?
  - What types of projects are clients looking to use CLT for?
  - What are client expectations regarding the energy efficiency and carbon emissions of CLT/mass timber construction?
- What is the level of awareness about CLT among key stakeholders in the buildings industry? What strategies could be used to address awareness shortcomings?
  - Labor and skill requirements

    - Customer awareness
    - AEC firm experience and confidence
    - Structural engineer expertise and confidence
- Which aspects of building codes are the most important for CLT?
- Are building codes being modified to allow the use of timber in high rise construction?
    - Is there client interest in such a use case?
- Will increased adoption become a problem for other parts of the industry/supply chain if such code changes are made?
- Codes currently focus on energy parameters. What would inclusion of carbon measures in building codes mean for CLT?

7.4 Uncategorized Points Mentioned in the Breakout Sessions

The following comments were brought up in the breakout session but have not been categorized because they were either not specific enough or a simple observation. Closely matching categories, if present, are indicated in parenthesis.

7.4.1 Resilience and Building Performance

- Proprietary systems vs. non-proprietary systems. Market will not expand until CLT is more affordable. A cost competitive market for light industrial and light commercial construction to replace walls with timber is needed. (Costs)
- Research and development and certification drives the increase in cost of connectors. (Connectors)
- Design-build optimization of the building structure can make minimizing waste easier compared to traditional bid processes. (Waste Reduction)

7.4.2 Timber & CLT Production & Construction

- Type IV and Type V can go up to five stories without exterior insulation combustion limitations, this is based on egress requirements
- Advantage of CLT is that the panels should have less thermal bridging based on the natural R-value of the wood
- Architects do not prefer full walls of CLT
- Determine large-scale impacts of external moisture. (Moisture)

7.4.3 Production Challenges and Re-X Opportunities

- Life of mass timber buildings is comparable to the service life of timber. With good maintenance and envelope, the building should last 100 or 1,000 years (others had different points). Oldest glulams in the U.S. date to 1939 and they are still holding.
- CLT is not the best product for utilizing low value and underutilized wood species. Higher grade needed for CLT; other applications may be better suited for low value.
- Adding chips to panels (in the context of Re-X opportunities).
- Water is more of a concern during construction than occupancy.
- More failures due to water occur during operation. Water infiltrates unnoticed and causes rot. People do not realize it's there and you get rot. If you used the existing building standards and acceptable practices are used during construction, it's very low risk. Plumbing or envelope failures during operational use cause much more damage.
- More research into using recycled materials is needed.
- Need to know material properties of other products as soon as possible to confirm use in CLT and reduce waste.

7.4.4 Supply and Demand Dynamics and Building Codes Integration and Adoption

- New shear wall codes are anticipated (Codes)
- Reducing total project cost to be competitive with concrete (Cost)
- Cost, especially in the residential sector, is a market barrier (Cost)
- Pricing is a market barrier (Cost)
- Comparison to industry standard materials (Standards)
- Fire safety, including the assumption of automatic sprinkler systems, is limiting for CLT (Fire)
- Life-cycle concerns are market barriers to CLT (LCA)
- Customer awareness (Outreach)
- Student interest in sustainability does not always translate to interest in timber building research (Outreach).

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