MASS TIMBER USE IN THE LIVING BUILDING CERTIFICATION:

THE IMPLICATIONS OF USING A NEW STRUCTURAL SYSTEM IN THE MOST RIGOROUS ARCHITECTURAL SUSTAINABILITY STANDARD

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A THESIS

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The LBC is the most rigorous sustainable design standard available for architectural projects. And mass timber's structural properties, health and sustainability benefits, and carbon sequestering are among the attributes that have allowed it to rise in popularity as a sustainable structural material over the years. The purpose of this thesis is to amass the available knowledge of the complications of using mass timber in buildings pursuing Living Building Challenge certification and analyze collected information to come to conclusions as to why this structural material is underutilized within this rigorous sustainable design standard. The distribution of this information can help inform architectural designers inquiring about how to pursue mass timber use while designing for LBC certification. Additionally, it alludes to how certain changes in the industry could increase the overlap between the two sustainably minded design pursuits. This thesis is a mixed-mode approach exploring the benefits and challenges of utilizing mass timber in LBC certification through precedent studies, conducted interviews with professionals involved in these precedents, a literature review, and an analysis of LBC certification requirements. In all, the complex contradictions of sourcing requiring Forest Stewardship Council certified wood as well as locally sourced materials negatively impacts LBC projects using mass timber as a primary structural material. The price premiums associated the Living Building Challenge and Forest Stewardship Council certified wood, as well as the US market's unfamiliarity to the cost distribution of mass timber's higher upfront costs, all restrict accessibility to these types of projects for many budgets and priorities. Thesis findings presented a general lack of difficulty navigating red listed adhesives and waste requirements within the LBC. And there are missed opportunities of promoting the use of mass timber in the Living Building Challenge with timber's carbon sequestration benefits until those calculations are agreed upon within the industry. This thesis addresses some of the key questions associated within the lack of mass timber use within LBC certified buildings.

KEYWORDS: Mass timber, CLT, Glulam, Living Building Challenge, LBC, Forest Stewardship Council, FSC, Sustainability, Green building certifications, Embodied Carbon

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Introduction

The Living Building Challenge (LBC) and novel construction methods that utilize mass timber both emerged in the United States shortly after the turn of the century (International Living Future Institute 2019; “Mass Timber Projects in Design & Constructed” n.d.). The LBC is a rigorous green building standard that pushes the industry of architectural construction to be more sustainable and locally minded. The aim of this thesis is to examine the relationship between these modern histories: determining if mass timber use in the Living Building Challenge is a beneficial intersection in pursuing sustainable architecture or if it comes with complications too difficult to implement into a larger scale of mass timber use. The thesis asks about the benefits and challenges of using mass timber in the rigorous certification process of the Living Building Challenge and how those may have changed over time. It questions why some projects have found immense success in utilizing mass timber as the primary structural material and how the narratives of sustainable buildings find alignment with their materials used. The thesis contains an analysis of existing literature to establish a foundational knowledge of the Living Building Challenge and mass timber, both individually and their overlap. Conducted interviews provide qualitative evidence alongside a literature review and supplemental precedent studies to create a mixed- mode approach to evaluating the benefits and challenges of mass timber utilization in the LBC. The aim of this thesis is to provide a resource for professionals wanting to pursue mass timber use in LBC certification and people interested in learning more about the nuances of sustainable design.

BRIEF HISTORY OF MASS TIMBER

Mass timber is a term that encapsulates all types of engineered wood products used in buildings. The 2021 International Building Code (IBC) defines mass timber as "structural elements of Type IV construction primarily of solid, built-up, panelized or engineered wood products that meet minimum cross-section dimensions of Type-IV construction" (International Code Council Inc. 2021). Many of these products are used both structurally and non-structurally, for aesthetic purposes or utilizing their many benefits ranging from structural increases in spans opposed to typical wood products as well as more intangible benefits like a biophilic connection to natural elements in indoor environments (Green 2021, Montjoy 2022).

Heavy timber is a traditional term used to refer to buildings made in a certain construction type, type IV (Busta 2017). While this overlaps with mass timber use, mass timber refers specifically to the material elements used. Mass timber is different from light timber framing. Its elements are typically wider than 3", and primarily refers to engineered wood products. This includes Cross-laminated Timber (CLT), Glue-laminated Timber (glulam), Nail-laminated Timber (NLT), Dowel-laminated Timber (DLT), Laminated Veneer Lumber (LVL), Mass Plywood Panel (MPP), Parallel Strand Lumber (PSL), Laminated Strand Lumber (LSL) (Forestry Innovation Investment 2023). Figure 1 illustrates some of these types. Most often, mass timber lamination is done with a glue adhesive, apart from dowel-lamination and nail-lamination (Sotayo et al. 2020). The glues are primarily formaldehyde-based for the scale of architectural pieces, and as will be discussed later, as formaldehyde is a harmful ingredient that is hard to replace because of its multitude of strength and durable qualities. The adhesives are a major difficulty in implementing mass timber in the Living Building Challenge.

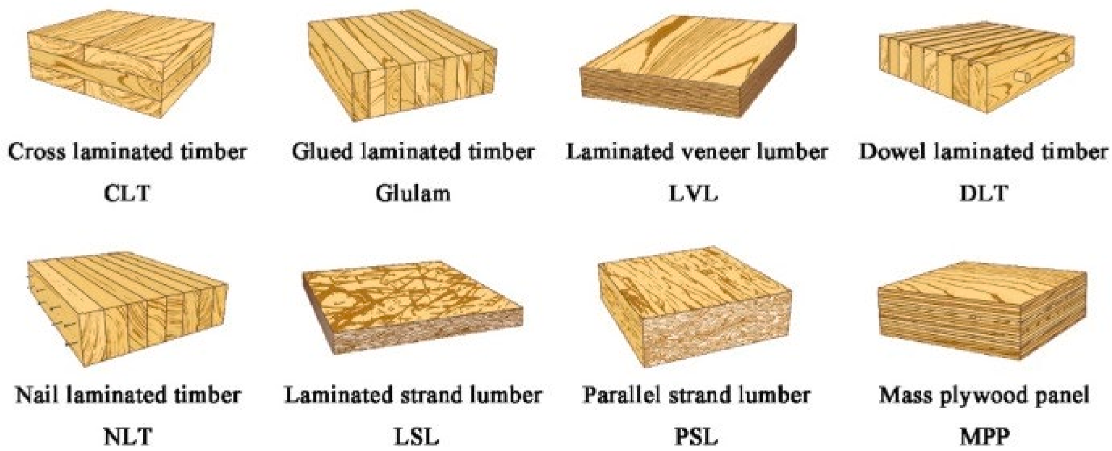

Figure 1. A visual representation of different laminations and orientations of engineered wood products, courtesy of Science Direct.

Mass timber is evolving into a more common structural material in the United States, but this comes a long time after the material was generally accepted in Europe, the leading area of mass timber development ("Global Cross Laminated Timber Market Report" 2023). Mass timber began in early stages in the 1970's in Austria and Germany and spread amongst Europe in the 90's. The United States has a growing market and interest in mass timber, but still is significantly behind Europe in terms of production of material (Cheng 2022; Rohit and Shih 2022). A product resembling modern CLT was patented in the early 1920's in Washington but remained dormant in construction use until decades later. Now, building codes have been expanding to meet the demand and interest in mass timber use structurally (International Code Council Inc. 2021). In the United States, 19 full states and 3 partial states have adopted either the 2021 or 2024 building codes that pertain to increased mass timber allowance in construction codes (Woodworks 2023).

Nowadays, Cross Laminated Timber, Glue Laminated Timber, Laminated Strand Lumber, and Mass Plywood are among the most popular structural products within the mass timber realm. Different engineered wood products (EWPs) provide different solutions to architectural projects, so this thesis discusses mass timber use broadly, as well as pointing out specific examples of EWPs in Living Building precedents and discussing unique challenges presented by using Cross Laminated Timber specifically in the Living Building Challenge.

Overview of the Living Building Challenge

The Living Building Challenge (LBC) is a certification process for buildings, both new structures and renovations, which pursues rigorous sustainable design. As stated on their website, "The Living Building Challenge is a philosophy, advocacy tool, and certification program defining today's most advanced measure of sustainability in the built environment" ("What Is The Living Building Challenge?" n.d.). Created by the International Living Future Institute (ILFI) non-profit in 2006 (International Living Future Institute 2008), the certification aims at furthering sustainable standards to go beyond design that is less harmful for the Earth, and instead design that is regenerative and healing for human occupants and the surrounding ecology; design that is positively impacting its surrounding context. To achieve this, the requirements are malleable and adjustable to fit the different needs of each project, factoring in major differences in variables such as people being served, surrounding ecology, and purpose of the building. Its requirements are intended to be holistic; for example, certification is only possible after actual performance, not anticipated performance, such as with LEED certification (Glass 2023). This measurement of actual performance means buildings can only be certified after 12 months of occupant use of the building, making the LBC stand out from many standards as a complicated and challenging certification process.

The Living Building Challenge has its name for many reasons, one being that "living" insinuates the organic aging/evolution of the certification process. The standards are constantly changing to fit current circumstances and updating based on lessons learned from completed or current LBC projects (International Living Future Institute 2023). The buildings themselves are meant to emulate organic structures that live and breathe-- they recycle water on site, create their own energy needed, use healthy materials, and are beneficial to the earth. A flower is the International Living Future Institute's imagery to explain this: an organic structure that photosynthesizes, is supporting its local environment with vegetation and pollination, expresses beauty and inspires cultures (International Living Future Institute 2023). Certified Living Buildings have innovated upon each other in the ways they have found success in recycling water, harvesting energy, and giving back to local ecology, to name a few. There are continual changes that happen in the buildings to maintain this state and to adapt to the needs of occupants & evolving technologies. Oftentimes, LBC buildings are innovating new technology and are guinea pigs, in a way, for rigorously sustainable design. Relationships between the owners, occupants, and design team are thus kept alive to maintain a commitment to keeping the buildings in-line with LBC standards and making sure the building is serving its purpose as a learning tool for sustainable design and maintaining its goals as an LBC building. Chris Helstern of Miller Hull architects spoke on the continued relationships of the design team to their living buildings, claiming that "it is unique from typical design-occupant relationships" (Chris Helstern personal communication 2023).

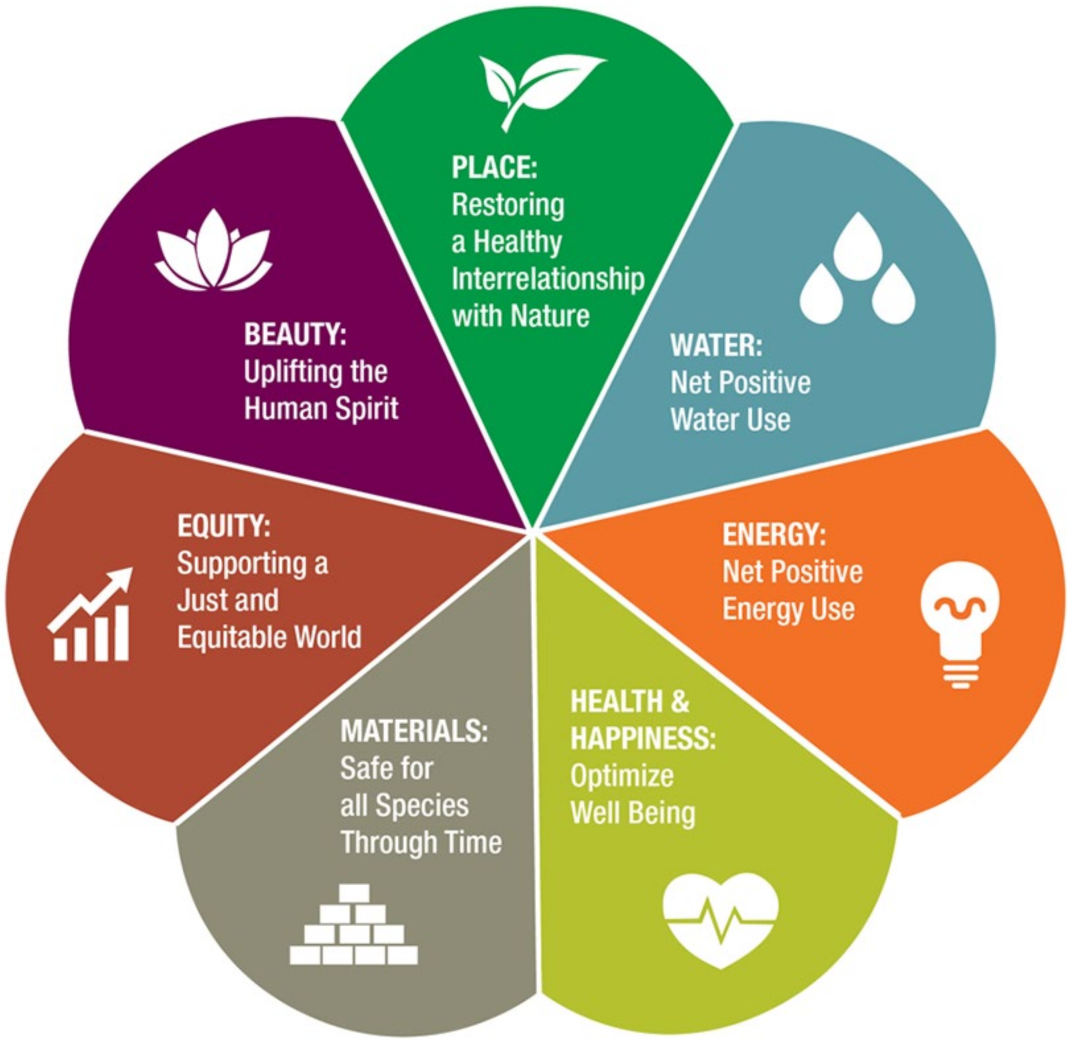

Figure 2. A visual representation of the seven categories of requirements in the Living Building Challenge displayed each as a petal on a flower, which is the main symbolism the International Living Future Institute uses for explaining their certification's organization.

There are several key requirements of Living Building Challenge certification, and they are categorized into seven Petals, playing off the metaphor of a self-sustaining flower. According to the Living Building Challenge's latest standards, version 4.0, these petals are: Place, Energy, Materials, Water, Health & Happiness, Equity, And Beauty (International Living Future Institute 2019). Place generally refers to the surrounding site and includes imperatives to help reach a regenerative state of the local environment. Energy aims at generating more energy than what is needed to power the building on site and takes steps to reduce the energy needs of the building. The Materials petal is concerned with using healthy materials in the building, avoiding materials with strong negative impacts on health and the environment, and changing the standards of the product industry to be more transparent. Water is similar to the Energy petal in principals of collecting the amount necessary to sustain the building: it is recycling all water collected on site to fill the water needs of the building, as well as reducing water use in the building as much as possible. Health and Happiness are focused on the wellbeing of the occupants inside and outside the building, and making sure the building contributes positively to mental health and avoids negative contributions to physical health and indoor air quality. The Equity petal requires the project to take extra steps to ensure the building is inclusive in catering to occupants as well as more equitable distribution of work throughout the design and construction process. Beauty is about education and inspiration, requiring that these buildings be a learning tool and be beautiful, arguing that sustainable buildings are buildings that will stick around, and people care more about beautiful buildings (International Living Future Institute 2019).

Within each of the seven petals, there are imperatives which tackle specific strategies on how to reach the overarching goals (International Living Future Institute 2019). Imperatives are the categorical term for necessary checklist items within the Living Building Challenge certification required of a project team to complete in full in order to receive certification. The imperatives fall under the categories of each petal, which define the seven categories of requirements within the LBC (International Living Future Institute 2019). Each petal has two to five imperatives. An example can be found within the Materials petal, which has the most imperatives of five. To complete the requirements for full certification or materials petal certification within the LBC, a project must complete the Responsible Materials, Red List, Responsible Sourcing, Living Economy Sourcing, and Net Positive Waste imperatives, each complete with their own detailed descriptions of requirements, exceptions, and strategies to accomplish them (International Living Future Institute 2019).

Most buildings do not or cannot focus on sustainability to the level of rigor that the Living Building certification process does. The limitations of the Living Building Challenge certification lie heavily within the barriers of cost-- with sustainable options often being more limited and thus expensive-- and expertise-- requiring certified consultants on the team adding hours to the project solely focusing on sustainable rigor, which also comes at a price. To help combat these barriers, the International Living Futures Institute created a tiered system of certifications, each tier requiring varying amounts of sustainable rigor. Full Living Certification is the highest achievable standard, completing all 20 imperatives of the challenge. Petal Certification requires core imperatives to be met in each of the petals as well as all the imperatives in either the Water, Energy or Materials petal. Core Certification requires all the designated “Core” imperatives to be met, which is 1-2 imperatives from each petal, getting at the most important imperatives according to ILFI, intended to allow for more accessibility in accomplishing a Living Building Certification. ZeroEnergy Certification follows the same 12-month performance pre-certification requirements and requires 100% of the building’s energy load to be offset with on-site renewable energy generation. ZeroCarbon is a similar option that requires 100% of the building’s energy load to be offset with either on- or off-site renewable energy generation, as well as embodied carbon reduction and offset requirements. As with all certifications, they are intended to be extremely specific to the project and its location in terms of local ecology and population needs. Therefore, it is not a one-size-fits-all approach. There are many exceptions to the rules if there is communication with the ILFI and proof that the project team is choosing the most sustainable options possible in their given context. An example of a general exception is that existing buildings can stay on their energy system or grid even if it is a combustion source. Although sustainable standards require new buildings to be combustion-free, staying on existing grids or systems may be the most sustainable approach in renovations. Another example is that a team can use a “Red List” material, ostensibly a banned material due to its harmful environmental or health-related impacts, if there is no other option available and the team has shown dedication to changing industry standards by advocating for the supply of new materials, through efforts such as letters sent to manufacturers (International Living Future Institute 2023). Since the Living Building challenge relates to many kinds of building projects-- such as renovations of existing buildings, new buildings, interior renovations, landscape, and infrastructure-- and different building types-- such as all forms of residential, commercial, institutional and medical-- there are different requirements for each building type and project scope (International Living Future Institute 2023).

HOW THE LIVING BUILDING CHALLENGE HAS IMPACTED SUSTAINABLE DESIGN

The Living Building Challenge has advocacy built into its imperatives. In the Materials Petal for example, as aforementioned, if there is not a red-list free, viable alternative to the materials necessary for the project, one must advocate for said alternative to manufacturers. Declare labels are an aspect of the Living Building challenge as well. Included in the Materials petal requirements as well, all projects must have material with a Declare Label every 200 square meters of the building's gross area (International Living Futures Institute 2023, 52). The Declare label is an aspect of a public informational database of building product ingredients for the purpose of transparency. Manufacturers voluntarily disclose product information to produce a standardized Declare Label: a uniform, legible label part of a public database promoting healthy materials (International Living Future Institute 2023, "Declare Overview"). The Declare label is an act of advocacy towards sustainable materials and transparency in the industry, built into the requirements of the Living Building Challenge. An employee of ZGF Architects is quoted as saying, "[The Red List imperative] is starting to extend beyond Living Building Challenge projects; LEED and WELL projects are asking for Declare labels and Health Product Declarations. There's enough market demand at this point that building product market transformation is gaining momentum" (The PAE Living Building 2022). The LBC is visibly challenging other sustainability standards to further the industry standards.

The same values occur in the requirement of two Just labels for project team organizations involved. This imperative, falling under the Equity petal, is meant to encourage equity and transparency in the teams involved in the building's project (International Living Futures Institute 2023, 62). These requirements of the imperatives are examples of how advocacy is built into each project to encourage local sustainable and equitable industries around the globe to amount to large impacts.

The Living Building Challenge has prided itself on being guinea pigs of sustainable design, a trailblazing method of publicizing and pushing industry sustainability standards forward. The Bullitt Center, completed in 2011, was a very early LBC project on a large, commercial scale.

When LBC began in 2006, it was inherently responding to the sustainability standards existing at the time. Leadership in Energy and Environmental Design (LEED), founded in 1994 by the US Green Buildings Council, was picking up momentum as the most popular certification program, a title that still exists today ("LEED Rating System" 2023). LEED takes a prescriptive approach to sustainable design, allowing a building to become certified if the design team checks off the required amount of LEED credits that focus on the stages of design up to construction. The Living Building Challenge is non-prescriptive (The PAE Living Building 2022), allowing for site-specific solutions to making sure the project sticks to the core values of the LBC in an understanding that a sustainable building will look very different depending on which climate it resides in. The LBC also sought to further the state of certification requirements by taking post-occupancy data and quality into account. With an LBC certification, a building cannot be certified until after a twelve-month process of documentation of the state of the occupied building. During this time, the team monitors energy and water data, monitoring performance to check that the building is on track for the performance period's goals (Hellstern 2023).

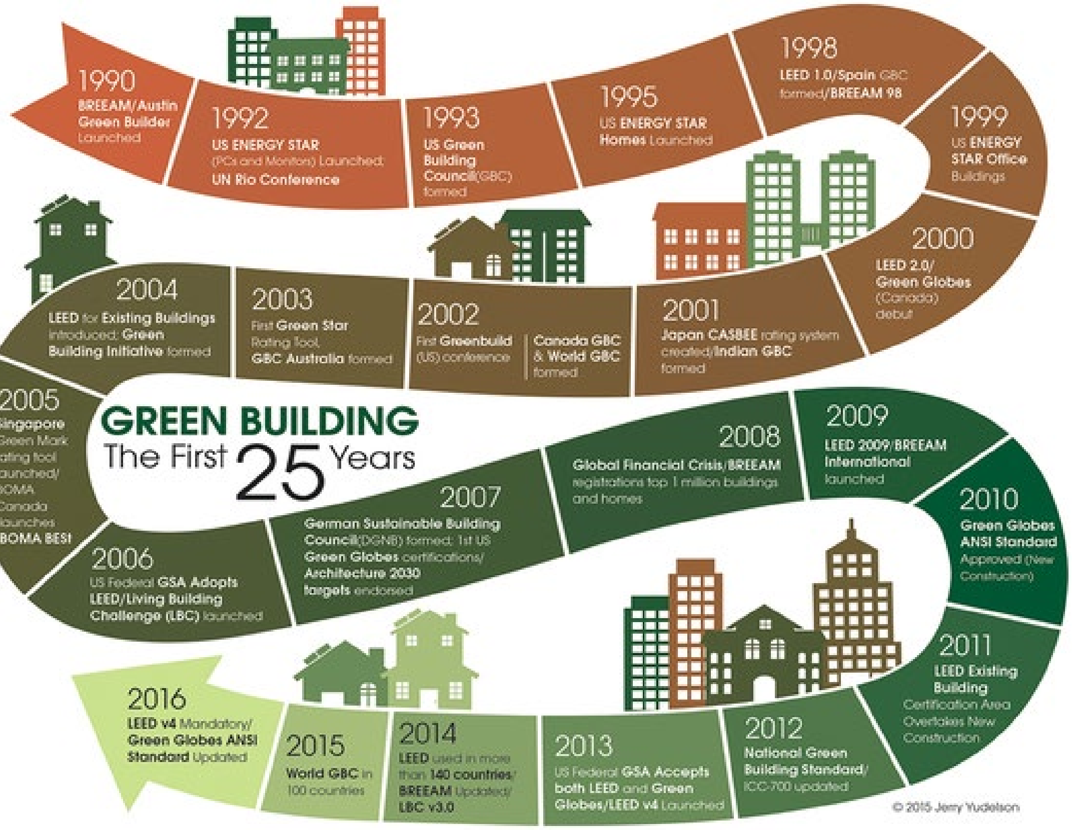

Figure 3. A visual map of the beginnings of green building certifications to ground the Living Building Challenge in context with other certifications, courtesy of Huffington Post.

PETALS OF THE LBC IMPACTED BY MASS TIMBER USE:

MATERIALS, BEAUTY, HEALTH, AND HAPPINESS

The Living Building Challenge is broken up into 7 petals that organize the requirements for building certification. Mass timber elements, when used, can act as the primary structural materials for buildings and thus have clear ties to the Materials petal that consists of intentional sourcing: locally, ethically, and free of "red-listed" toxic chemicals, and minimizing material use to be thoughtful of intentional use and waste. This petal will be covered in depth in this thesis. But the use of mass timber affects different petals as well. "Choosing mass timber is not just because of one thing: it's usually carbon savings, a beauty component, the right structural material for us…" says Miller Hull's Living Building Challenge Services Director (Chris Hellstern 2023). These factors affect multiple petals of the Living Building Challenge.

BEAUTY

The Beauty petal is associated with biophilia: "a hypothetical human tendency to interact or be closely associated with other forms of life in nature: a desire or tendency to commune with nature" (Merriam-Webster Dictionary 2023). This is acknowledged as achievable in six different realms: environmental features, natural shapes & forms, natural patterns and processes, light & space, place-based relationships, and evolved human-nature relationships (Kellert 2008). Our draw towards nature is innate, "'It's an artifact of evolution'" (Green 2021). The use of mass timber can effortlessly achieve natural shapes and forms through tree/columnar supports and glulam's ability to create curved, organic shapes. Mass timber can also reveal age through color and patina over time as categorized in natural patterns and processes because wood's exterior can change in response to environment and weathering. The warmth of wood when it interacts with light and wood's structural abilities to create spacious spaces has to do with the category of light & space. Many mass timber buildings in the LBC have connections to geographical places by using downfallen or locally harvested trees. This connection with the landscape and the interior space occurs naturally with wood elements. Biophilia, to measure beauty, is deeply tied into materiality and expression, and therefore the use of mass timber affects this petal and its imperatives.

Figure 4 (left). Reverse curved arches created with FSC certified glulam for the Silver Mountain Hay Barn in Millerton, New York, courtesy of Unalam.

Figure 5 (right). A side-by-side comparison of wood, showing a visual age difference between cherry wood one year apart, courtesy of Forma Furniture.

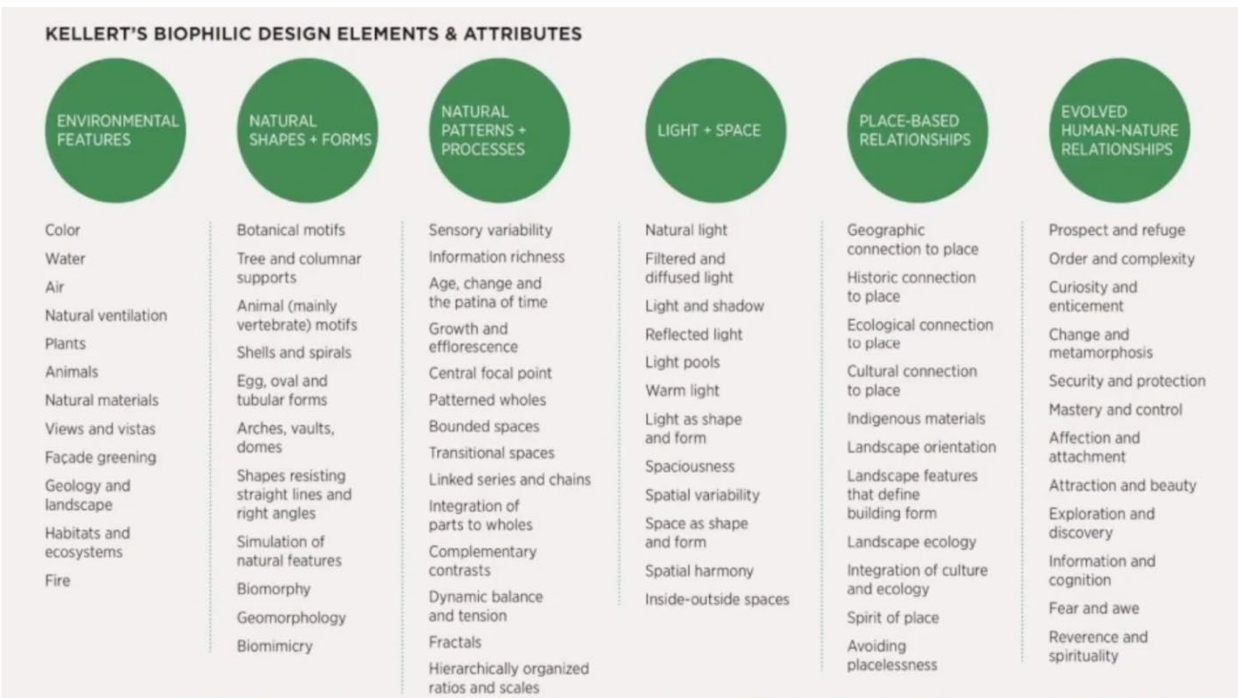

Figure 6. Biophilic design elements and attributes, courtesy of Creating Biophilic Buildings by Amanda Sturgeon.

HEALTH AND HAPPINESS

The Health and Happiness petal relates to mass timber use through indoor air quality. The World Green Building Council has suggested that better indoor air quality can lead to an increase of productivity by up to 8-11% (TRADA 2018). Wood is considered hypoallergenic, and its smooth surfaces allow for prevention of particle buildup and are easier to clean than material finishes like carpet (Think Wood n.d.), allowing for greater opportunity to maintain indoor air quality. Air quality is directly tied to the building materials used. A noteworthy concern for air quality is the use of formaldehyde in resin adhesives for mass timber. Materials containing and emitting toxins, such as lead or solvents, have been known to cause behavioral disturbances, especially in children (Evans 2003). However, adhesives based in formaldehyde do not present these same risks. The durability of these resins once cured is such that formaldehyde emissions are rendered negligible and no higher than natural emissions found in nature (Think Wood n.d.).

On the positive side, wood products help regulate indoor humidity. Wood can absorb humidity when air is moist or release humidity when indoor air is dry to maintain equilibrium with the air around the materials; it is a hygroscopic material (Laurenzi 2017, Think Wood n.d.). Resin adhesives minimize expansion and contraction due to moisture retention (Henriikka 2019). Interior environmental conditions, if too extreme, however, can devalue mass timber's long-term durability, though, and mass timber does best with interior relative humidity levels between 30-50%, and can tolerate 20-60% (RDH Building Science 2022).

Methodology

This thesis examines the existing infrastructure of the Living Building Challenge certification in cohesion with mass timber use as the primary structural system in buildings. A database does not currently exist on all certified LBC buildings in general, or on the intersection between LBC certified buildings that utilize mass timber. Readily available information was analyzed, and nine prominent precedents were identified. The elaboration of these precedents comes in the form of five interviews with experts involved in the respective projects, as well as the public information available on them. Information utilized in this thesis is from trusted publishers as well as news and articles available to the public via internet news and platforms. This publication is meant to serve as a gathering of research and learned experiences from the field for those wanting to undergo Living Building Certification while using mass timber to more fully understand the benefits and challenges associated with the overlap.

The interviews contain varying questions dependent on their individual locations and experiences, but questions fall under categories relating to different aspects of using mass timber in an LBC certified building: general experience, cost, sourcing, material ingredients, embodied carbon. Sample questions include the following:

- How did your team calculate embodied carbon? How did you factor in the sequestration benefits of mass timber?
- How was your experience in obtaining FSC certified wood for mass timber and getting Chain of Custody Certified wood? Was it a significant additional cost?
- Was the cost of carbon offsetting a major influence / issue in the project?

- How was your experience with avoiding red listed ingredients in mass timber? Did you get exceptions for wood adhesives using formaldehyde? Did you use a formaldehyde-free adhesive?
- Did your project team initially plan to use mass timber? Did any aspects of the LBC change your decisions to use mass timber in any way? How do competitive structural materials (or combination of materials used) match up? Why did you ultimately choose mass timber?
- Do you think that the future of the LBC resides alongside the mass timber industry? Why or why not?

Precedents

PRECEDENTS IN THE LIVING BUILDING CHALLENGE THAT UTILIZE MASS TIMBER:

As a generalization, the buildings that have used mass timber as the primary structural element and are certified as a Living Building did so with great intentionality. There is not a large overlap in the recent history of the LBC and in mass timber use. In most of these precedents, the narrative behind the building supported the use of timber, engineering technology or relationships with forestry in some way, which led the project teams forward in the direction of using mass timber. This could speak to a few things. The industry at large is underdeveloped, and one must seek it out and prioritize its use if one is to access the amount of engineered wood to complete a project. It could also speak to the difficulties associated with mass timber: general industry perspectives on new materials, the additional upfront cost, the complications of calculating ambiguous embodied carbon in life cycle analyses, red listed formaldehyde often used as mass timber adhesion products, the difficulties of full chain of custody and FSC certification of all the wood utilized in mass timber products, the lack of industry in mass timber juxtaposed with the need for projects to source very locally. “Most of the [mass timber] projects that we’ve worked on, to be perfectly frank, are institutional clients where the use of mass timber also fulfills some sort of moral or institutional guideline or goal, so generally speaking it's not the clients that are driven by maximizing profit that are using it,” says Christopher Nielson of Bruner/Cott & Associates (Christopher Nielson 2023).

Some projects are very transparent on the issues they ran into using mass timber, and others use their online platforms to celebrate the material. The list below is not a comprehensive list of

Living Building Challenge certified buildings that utilize engineered wood products, but it does contain buildings that have become known for their mass timber utilization. Some have utilized mass timber as a supplemental structural material and not as the primary structural element. Figure 7 below contains key details on each building, and each building has a brief description below.

TITLE	LOCATION	ARCHITECTS	CERTIFICATION	TYPE OF MASS TIMBER
Bullitt Center	Seattle, WA	Miller Hull	Full LBC certified 2.1 Year: 2011	Type-IV FSC Glulam, SIPS and LVL's
PAE Building	Portland, OR	ZGF	Pursuing full certification 3.1 Year: 2022	CLT, glulam Concrete shear walls are core of building
Kendeda Building	Atlanta, GA	Miller Hull	Full LBC certified 3.1 Year: 2019	Salvaged NLT (floor decking), glulam beams and columns
Co|Lab	Falls Church, VA	Eric Ross	Petal certified 3.1 Year: 2019	CLT walls, floors, roof decking, glulam beams and columns
R.W. Kern Center	Amherst, MA	Bruner/Cott & Associates, Inc.	Full LBC certified 2.1 Year: 2016	Glulam made up half of structure, other half of structure being light wood framing
Morris and Gwendolyn Cafritz	Accokeek, Maryland	Re: Vision Architecture	Full LBC certified 2.1 Year: 2015	Glulam trusses and glulam posts

Foundation Env Center				
Bill Fisch Forest Stewardship and Education Center	Ontario, Canada	DIALOG Architect	Petal certified 2.1 Year: 2016	Glulam beams and CLT. black spruce CLT timber, maple veneer wall panels and reclaimed ash, salvaged wood
Sustainable Buildings Research Centre	Wollongong, NSW, Australia	Cox Architecture	Full LBC certified 2.1 Year: 2013	FSC certified glulam
Te Kura Whare	Tūhoe, Tāneatua, New Zealand	Jasmax	Full LBC certified 2.1 Year: 2014	Glulam

Figure 7. A table containing basic information about each precedent to be discussed, sourced from International Living Future Institute's case study database.

THE BULLITT CENTER

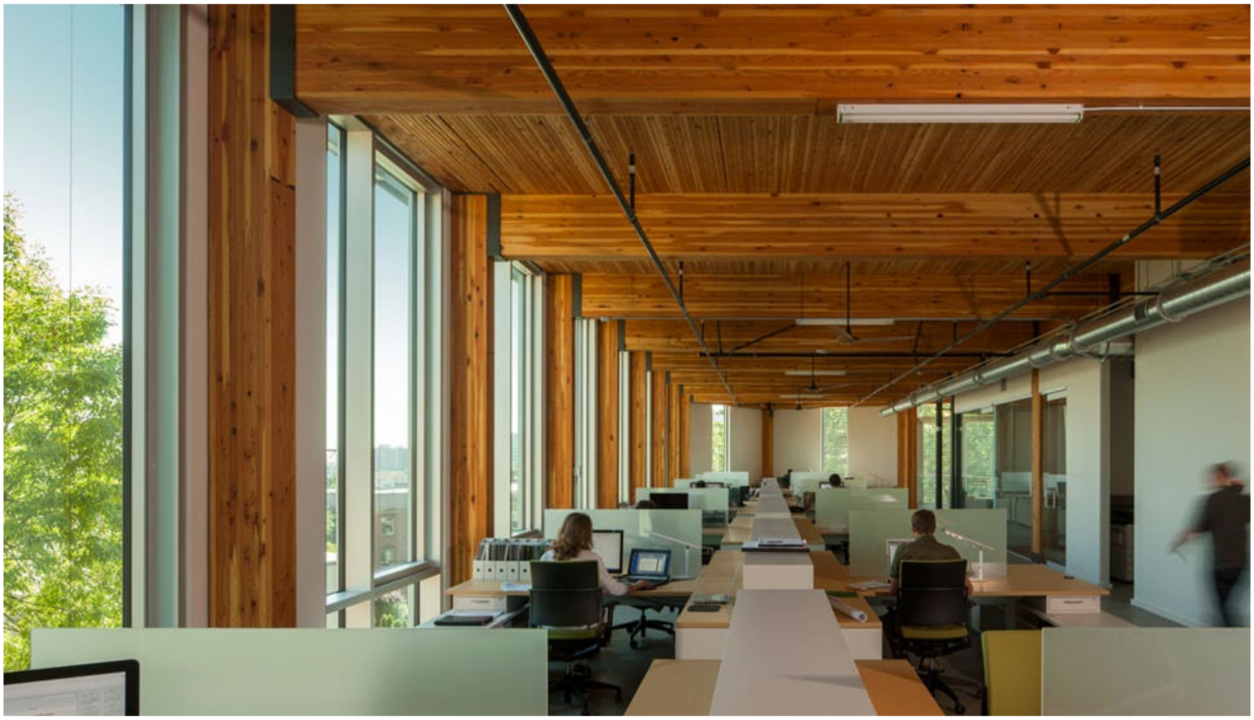

Figure 8. The Bullitt Center's top floor's engineered wood columns and beams, courtesy of bullittcenter.org.

Located in Seattle, WA and designed by Miller Hull in association with PAE engineers in 2011, this Type-IV construction utilized FSC certified Glulam, structurally insulated panels (SIPS), and laminated veneer lumber (LVL), structurally (Christ Hellstern 2023; International Living Futures Institute 2023). The building was meant to be a guinea pig for innovative, sustainable building technologies, which fits well with mass timber utilization, especially in 2011. The biggest challenge in this project was the use of mass timber: it was the first building in around 100 years to use mass timber in Seattle (Chris Hellstern 2023). Bringing back a construction style that hadn't been used made the project pursue changing building code, Miller Hull optimized timber in a pioneering way for the area. The Bullitt Center team was able to successfully advocate for a red list substitution in their glulam products, adapting products to remove Urea-Formaldehyde from its adhesive ingredient list.

PAE BUILDING

Figure 9. PAE's building construction, showing CLT framing, courtesy of Walsh Construction Co.

Finished in 2022, this mass timber structure had to deal with unprecedented issues of construction during a global pandemic. Gaining the title of the world's largest commercial Living Building Challenge (Fabris 2022), Portland's PAE building became an iconic use of mass timber certified under the world's most rigorous green building standard, since it was the first use of cross-laminated timber in a Living Building. The engineering team calculated possible structures made with concrete, steel and mass timber, and went with mass timber for its aesthetic and biophilic properties, its sourcing and low embodied carbon (The PAE Living Building 2022).

Formaldehyde (added) is a Red List ingredient not allowed for use in Living Building Challenge (LBC-Red-List-CASRN-Guide-2023 2023). Typically, however, Living Buildings that utilize glulam's or other forms of mass timber use non-urea formaldehyde-- different from urea formaldehyde-- as the adhesive type since it is a certified exception to the Red List approved by the ILFI (Ashuckian 2023). This makes the process of using mass timber a little simpler if products can have all ingredients approved. CLT, however, has other Red List ingredients, such as chlorobenzene, which are included in products for their fire-retardant properties to meet APA PRG 320 manufacturing standards (Ashuckian 2023). “The project has to balance sustainability and safety”, says Alese Ashuckian, formerly of Structurlam which was the wood supplier of the project. In the case of ingredient lists, sustainability and safety can be at odds. “From a life-safety perspective, I do see the value of having these ingredients and they were added to the code for a reason: to protect people during a fire event” (Ashuckian 2023). Allowing for use of Red List ingredients for occupant safety is an example of how the Living Building Challenge balances environmental sustainability and human/social sustainability.

The requirement of FSC certified wood interfered with responsible sourcing requirements of sourcing as local as possible. Most forests in Oregon are not FSC certified, and with much of the structure and interior finishes being engineered wood, a lot of materials were having to be sourced out-of-state within the Cascadia ecosystem of British Columbia. The embodied carbon emissions of outsourcing mass timber manufacturing to Austria and shipping it overseas was surprisingly low, but it did not fit within the intentions of the project. Thus, Canadian mass timber became the solution to finding FSC-certified mass timber. The project team had to place a $200,000 down payment to secure the large amount of wood needed in a very specific window of time (Karen Joslin personal communication 2023). This building has not yet been granted full certification but aims to be certified sometime in 2023 (No updates have been made on this in 2024).

The PAE building uses CLT, glulam's and concrete floor toppers and shear walls structurally. This combination of mostly mass timber with concrete supplementation proved to be the best option through PAE calculations. According to architect team ZGF, "'[the mass timber structure] reduces the project's embodied emissions by 30 percent'" (McKnight 2022). Part of a growing shift in the Pacific Northwest to utilize local mass timber, PAE optimized the calculated engineering benefits of the material (Thomas 2022).

In speaking on the experience of utilizing a new material in the landscape of the relatively new Living Building Certification process, mass timber specialist Alese Ashuckian said, "I was asking manufacturers lots of questions that people weren't used to getting asked. But all these extra steps built into the Living Building Challenge were inspiring to see how people cared and put so much effort into creating a healthy building. We were educating people, connecting them to how CLT is made, instead of just having materials arrive at the jobsite" (Ashuckian 2023).

KENDEDA BUILDING

The Kendeda building was completed in 2019 for the Georgia Institute of Technology campus. The building was designed and consulted for Living Building by West Coast firm Miller Hull Partnership, veterans of LBC design. It is fully LBC certified under version 3.1. As an innovative sustainable design building, it acts as an example of sustainable practices in its own design and hosts academic, research and community outreach. Mass timber was intentionally chosen as the main structural material to minimize steel and concrete use and minimize its embodied carbon as much as possible. The design team calculated the structure to account for 80% of the overall embodied carbon of a project ("Kendeda Building for Innovative Sustainable Design" 2023), so minimizing the impact of the structural system specifically was crucial in order to minimize environmental impact and cost. This team utilized Tally as an embodied carbon calculator, and factored in the idea that timber is carbon storage through its sequestration properties. The project utilizes nail-laminated timber for flooring and glulam's for column and beam structure. The timber used in the nail lamination was salvaged from movie production sets no longer in use.

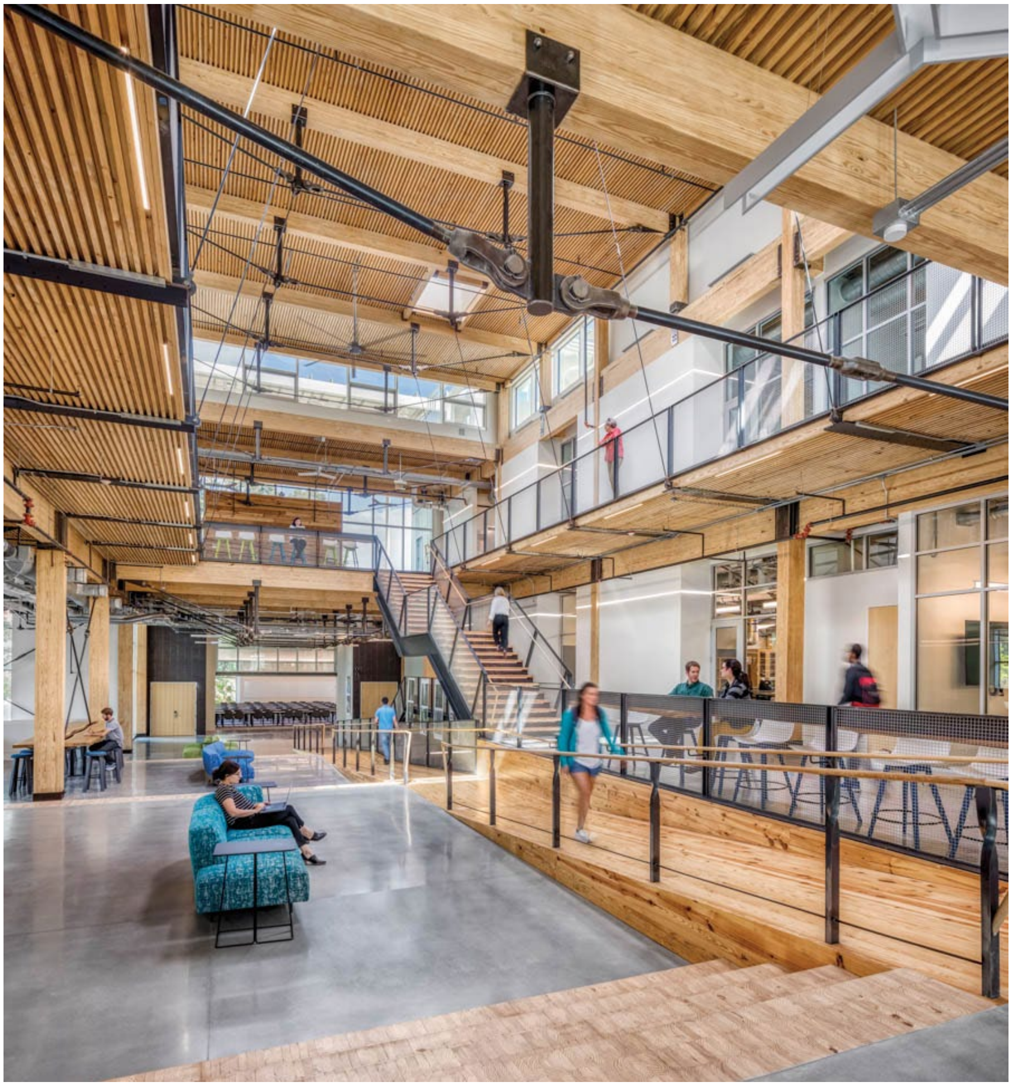

Figure 10. Kendeda's atrium, courtesy of Metropolis Magazine

CO | LAB

Finished in 2019, Co | Lab is a Material Petal Certified building in Falls Church, Virginia. The project aimed at having a high-performance building that was a vessel for advocacy, education and outreach. Because of the focus on materiality, there was focused intention behind sourcing of materials and the engineered wood used. Mass Timber was chosen primarily because of the embodied carbon footprint benefit and the advocacy stance the project could take in the industry by using FSC certified mass timber. CLT is used for the walls, floors and roof decking, and the beams and columns are glulam. All the wood is FSC certified and FSC Chain of Custody certified. The team sourced the wood from Canada. Because of limited sourcing availability, the prioritization of using mass timber meant that most other products used in the project had to be very locally sourced, limiting the other material choices.

Figure 11. Co | Lab's CLT and glulam, courtesy of ArchDaily.

R. W. KERN CENTER

Figure 12. R. W. Kern Center's atrium, courtesy of Architect Magazine.

The R. W. Kern Center was finished in 2016 under LBC version 2.1 in Amherst, Massachusetts as part of Hampshire College. It was the 16th building to become LBC certified (Christopher Nielson personal communication 2023). This precedent's design strategy was material driven. As the team states, "Materials were selected to meet the intersecting Imperatives for local sourcing, responsible industrial practices, and avoidance of Red List substances which have adverse effects on human health and the environment" (International Living Future Institute). These goals led them to choose carbon-sequestering engineered wood as their structural material which reduced their carbon footprint. But this project was a hybrid structure that utilized both engineered wood and light frame wood framing. The project carefully designed the building to be adaptable over time and simple enough so that disassembly of the project would be easier and lead to greater amounts of recycling and reuse than normal. Waste was a thoughtful consideration of the design and added to the benefits of using mass timber.

The project was committed to obtaining FSC certified wood and prioritized this so much as to receive a national FSC award after completion. Throughout the project, the team was able to provide local advocacy and expanded FSC certification in their area. This project was done relatively early in Living Building Challenge's history. A Bruner/Cott architect involved in managing the project said the FSC certification aspect of using mass timber didn't pose a large issue for the project. "[FSC] was not the biggest hurdle for the Kern Center, but market forces now have kind of created a condition where it does seem like it's becoming hard again. Within furniture and materials, [FSC products] visually feel available, so we're unsure if it was our specific team or circumstance, but it seems like within newer experiences it may be hard to obtain FSC" (Christopher Nielson personal communication 2023).

MORRIS AND GWENDOLYN CAFRITZ FOUNDATION ENVIRONMENTAL CENTER

Figure 13. Cafritz Foundation Environmental Center's interior truss systems shown, courtesy of Hugh Lofting Timber Framing.

Figure 14. Exterior shot of the Cafritz Foundation Environmental Center, courtesy of AIA.

Certified under the Living Building Challenge version 2.1 in Accokeek, Maryland, this building supports the Alice Ferguson Foundation which aims to connect people, the environment, farming, and cultural heritage to the Potomac River Watershed. The glulam structural system was chosen to reduce the embodied carbon and ensure a more sustainable disassembly (recyclability and salvaging) of the building post-occupancy. They were able to convince their glulam manufacturer to undergo FSC chain of custody certification to use their products in this project. This project was focused on advocacy, as it is also known for encouraging manufacturers to produce red list-free alternatives as well as to sign up for Declare labeling (International Living Future Institute 2023, 366).

BILL FISCH FOREST STEWARDSHIP AND EDUCATION CENTER

Figure 15, Bill Fisch Forest Stewardship and Education Center's interior, courtesy of Dialog Design.

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To understand location-specific issues in terms of mass timber use in Living Building Challenge certification, some precedents are outside the United States; in this case: Canada. Occupied in 2016, the Bill Fisch Forest Stewardship and Education Centre (BFFSEC) was built with the intention of creating an educational center that was an expression of a sustainable relationship between forestry and the built world. In this way, the use of mass timber was a seamless support to the narrative of the building. As the team states, "the building was always conceived of being 'of the forest', and not 'in the forest'" (International Living Future Institute). As a building meant to celebrate this relationship and move the industry forward in a similar direction, this may play into the fact that there is no mention publicly of the difficulties of creating a mass timber building under the Living Building Challenge.

SUSTAINABLE BUILDINGS RESEARCH CENTRE

Figure 16. The Sustainable Buildings Research Centre in Australia, exterior shot showcasing the façade's mass timber, courtesy of Cundall.

Completed in 2013 (COX 2023), The Sustainable Buildings Research Centre is part of Wollongong University in Wollongong, NSW, Australia. This building has intentions of testing sustainable building technologies and designs as well as prioritizing indoor air quality, which led them to the utilization of mass timber. The building utilizes multiple structural systems in different areas of the structure for research purposes. The project explains a dematerialization strategy within the design to fulfill multiple roles with as little material as possible. They also wanted to be very intentional with interior finishes to be in tune with occupancy health and indoor air quality. Both goals are achievable through thoughtful mass timber use. However, mass timber does not always come without complications. Adhesives for structural-grade mass timber often utilize formaldehyde, which is a red listed material not allowed in LBC buildings. The Sustainable Buildings Research Centre needed to obtain an exemption for formaldehyde use because an alternative option was not viable for the project.

Another issue confronted by this project was the responsible sourcing required of LBC certification. Most materials must be sourced within 1000 km of the project site, and wood products need to be FSC certified. In this project's case, the radii were unreasonable for a continent so geographically different from North America, so distances for materials had to be adjusted to a more fitting, expanded radius. In terms of the FSC certification for mass timber beams utilized in the project, they were able to find FSC certified wood in Australia but not full chain of custody certification for the manufacturing of engineered wood elements. Therefore, they sourced farther out in New Zealand.

Mass timber glulam's were not the primary structural element, but it was intentionally placed to show off the technology. Since the building is a building's research center, their narrative aimed to have varying structural materials throughout the building.

TE KURA WHARE

Figure 17. Te Kura Whare's exterior glulam structure, courtesy of the International Living Futures Institute.

Finished in 2014, this culturally-focused building serves to motivate the people of Tūhoe in stewardship relationships to land and sustainability in a timber building where downed logs act as structural columns. According to the posting of the building on the ILFI webpage, "The Tūhoe project's biggest challenge was to ensure that the supply 'chain of custody' from forest to building for machined structural timber elements and joinery items was watertight for FSC" (International Living Future Institute). Mass timber elements can have major benefits in a project. Using timber structurally is in line with the intentions of this building: to inspire personal ties to sustainability for the occupants, as well as alluding to the Tūhoe people's relationship with forest by emulating the feeling of being in a forest through the biophilic use of logs as posts and using mass timber for beams and trusses. Using mass timber allows the structural features to shine as biophilic elements and the sustainability of allowing less concrete to be used because of the lightweight aspects of timber. However, the logistics to make it happen are labor-intensive. Even in New Zealand, where FSC is commonplace and roughly 50% of pine plantation forests are FSC certified, obtaining engineered wood from fully FSC and Chain of Custody certified sources added enough challenge to be their largest roadblock in the project.

Material Use in the Living Building Challenge

The precedents discuss real world applications of mass timber within architectural projects that have achieved Living Building certification. There is a very limited number of precedents with LBC certification who also utilize mass timber, pointing to a question about the limitations of this overlap and why mass timber is not more commonly used in certified LBC projects. The LBC requires a thorough examination of each material used in a project. This next section goes through each aspect of material considerations that relate to mass timber elements. By dissecting the requirements of the LBC through their handbooks and requirement guidelines, and then cross referencing this information with existing precedents, conclusions can be drawn as to why there is such little overlap between mass timber being used in architectural projects and projects certified under Living Building certification.

Sourcing

The Living Building challenge requires sourcing to be on varying degrees of locality, trying to obtain the closest sourcing of materials as possible. As listen in the imperative "Living Economy Sourcing" in the LBC version 4.0,

> 20% or more of materials must come from within 500 km [310 mi] or closer.
>
> 30% or more must come from within 1000 km [621 mi] or closer.
>
> 25% or more must come from within 5000 km [3106 mi] or closer.
>
> The remaining 25% may be sourced from any location.

(International Living Futures Association 2023). The intent of this is, environmentally, to reduce transportation emissions and embodied carbon of materials. To promote social sustainability, the intent is also to foster relationships with the local community and bolster local business and economy in what they call "place-based solutions". Some projects value local sourcing over FSC sourcing, some vice versa. The limitations of supply with mass timber in North America complicate the use of mass timber as a primary structural material in Living Building Challenges.

FSC CERTIFICATION AND CHAIN OF CUSTODY CERTIFICATION

In addition to the requirements of material sourcing locality in general, there are more specific sourcing requirements for timber products. All projects must source at least 80% of their wood (by cost or volume) as Forest Stewardship Council (FSC) certified, salvaged, or cleared as one of the many exemptions approved as responsible sourcing. The remaining 20% can be from low-risk sources, which is determined by the source country with the intention to support economies that have laws in place to protect sites and species as well as refrain from trading endangered species of wood. Finding enough FSC materials is most often the biggest barrier in Living Building Projects using mass timber, according to Living Building Challenge Services Director of Miller Hull (Hellstern 2023). Included in the precedent list of this thesis have wood sourced from Canada, the United States, and New Zealand, all countries approved as low risk by The Nature Economy and People Connected tool (Preferred by Nature 2023).

FSC Chain of Custody (CoC) certification is also required by the International Living Futures Association (ILFA). This certification ensures that processed wood materials can claim FSC on the product created, by making sure all the steps in between-- production, manufacturing, distribution-- comply and separate the FSC wood from non-certified wood (Forest Stewardship Council 2023). The CoC certification is required to apply the FSC on any product label containing FSC wood, which makes it particularly important for mass timber, an engineered wood that has several steps in the creation of the material between harvest and end-product. The LBC is very much invested in advocacy of transparency, and Chain of Custody ensures the transparency of selective, sustainable wood material sourcing. FSC can be a challenge for companies who do not have Chain of Custody certification because there is a price premium required—more than both non-certified wood and other forms of chain of custody certifications (Ashuckian 2023). FSC costs a project an additional 5-15% on average (Ashuckian 2023). “When you’re not in an LBC project, FSC certification can get value engineered out very quickly, so the [LBC] certification certainly helps keep FSC as part of the project,” says Chris Hellstern of Miller Hull Partnership (Chris Hellstern 2023).

As of July 2022 statistics, the United States has 36.4 million acres certified under FSC, with 3,222 companies Chain-of-Custody certified (Forest Stewardship Council n.d). But challenges can occur regionally, according to mass timber specialist Alese Ashuckian. Southern yellow pine is abundant and available in southern United States for timber use, but there is not a lot of FSC certified southern yellow pine (Ashuckian 2023), making the decision between local material sourcing and FSC Chain of Custody-compliant difficult regionally, an issue pertinent to Living Building Challenges if pursuing mass timber use as a primary structural material. Additionally, there can be challenges anywhere on attempting to achieve FSC sourcing. A mixed credit system—of partial FSC lumber supply and partial non-FSC lumber—is an aspect of achieving LBC sourcing requirements to the best of a project's ability (Ashuckian 2023). This can be a strategy when figuring out how to accomplish LBC's FSC certifications. According to an architect in the Pacific Northwest, the FSC contractor base is another helpful resource. The FSC contractor base helps projects find supply for materials, ensuring supply is there to support the network of demand (Hellstern 2023).

Embodied Carbon

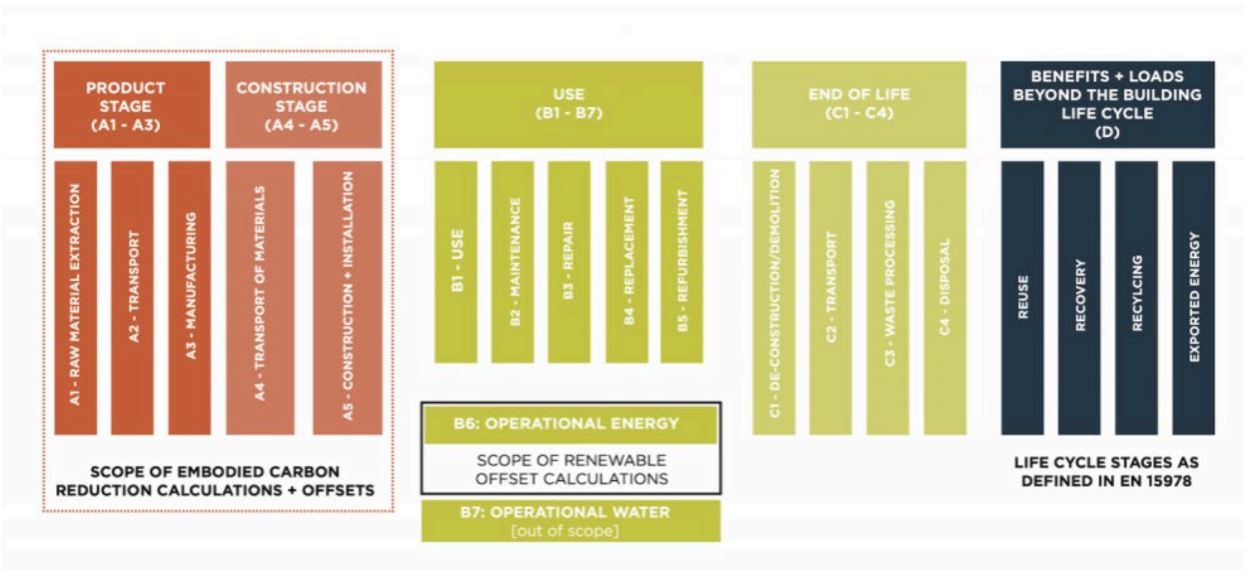

Figure 18. Life Cycle Assessment Scope Diagram shows the different stages materials go through in construction, beginning at product stage where they are extracted from points of origin to construction, transportation, and installation; to using in the building and continued repair until end of life when disposal and processing occurs. Embodied energy (right) is also included in this figure but not always included in calculations, courtesy of Trim Tab.

Because of the level of intensive documentation and advocacy required of Living Building full certification, as well as the upfront cost associated with it, it has naturally been geared towards public and commercial buildings with the infrastructure to have an individual or team managing the LBC certification process. Sustainable certifications are an avenue in which companies or governments can form public trust through transparency and visual commitment to sustainable values (Yale Sustainability 2020).

The requirements of the Living Building Challenge to reduce embodied carbon emissions fall under the Energy petal. In short, “New and Existing projects must demonstrate a twenty percent reduction in the embodied carbon of primary materials compared to an equivalent baseline.

Existing buildings may count in-situ primary materials against the required twenty percent" (International Living Future Institute 2023, p. 180). Additionally, all interior materials chosen must have lower than average embodied carbon in which embodied carbon data is readily available. Then, all embodied carbon of the project must be offset. "$10 is a good, round number to use for an average cost per ton of carbon offset cost" (Chris Hellstern 2023). This additional cost is where mass timber, as a structural element, is beneficial as compared to steel and concrete. Mass timber has carbon sequestration benefits, and its low initial embodied carbon reduces the amount of carbon offsetting needed, thus reducing the cost of the project (Chris Hellstern 2023).

The Living Building Challenge in general is very malleable to cater towards the individual nature of sustainability in the built environment. This means that although they offer up suggestions on how to achieve this 20% reduction in carbon emissions and have guidelines and requirements to meet it, the Living Futures Institute provides avenues to discuss alternative methods and exceptions to every imperative, including the embodied carbon imperative. For example, this comes in the form of using different LCA tools to calculate Whole Life Cycle data.

Projects are free to calculate life cycle analyses any way they choose, and many architecture firms use Tally, an Autodesk Revit application that works alongside the popular architectural modeling software Revit (Tally 2022). Other common assessment tools used are Athena Impact, BHoM LCA Toolkit, One Click LCA, GaBi Software, eToolLCD, and openLCA for whole-building LCA and assembly-specific design, and BEAM, EC3, Environmental Agency's Carbon Planning Tool, and One Click LCA Planetary are used for product data, all depending on location and have a variety of attributions (International Living Future Institute 2023, p. 182). Common assessment tools pull data from various sources and utilize Environmental Product Declarations (EPD's) for different materials. Although this comes with complications for mass timber usage. "EPD's in wood industry are lacking right now, so we're using some general data that's out there for certain members… We have been working for a few years now with groups like EcoTrust and FSC on studies to quantify sequestration based on factors like forestry practices and wood species to try to get more accurate data on that," (Chris Hellstern 2023). The sequestration ability of trees is sometimes not factored into life cycle analyses, and it differs in impact whether wood will be reused or if it will be landfilled and decomposed, releasing its carbon sink back into the atmosphere.

Embodied Carbon has always been an imperfect science because of the number of assumptions being made about materials and the wide variety of data pools being taken from in order to come to quantifiable numbers. Tracing materials back to exactly how much influence they had on greenhouse gas emissions has always been an estimation taken from varying data sets.

The embodied carbon of a material is required to be displayed on their Declare label. Since embodied carbon is a consideration in the Materials petal, these requirements work in tandem to ease the work of finding accurate embodied carbon data as well as completing the checklist of having Declare labeled materials every 200 square meters of the building.

Mass Timber is thought of as a sustainable alternative to other structural materials due to the carbon sequestration properties that wood possesses. An average mature tree can sequester more than 48 pounds of carbon per year (Stancil 2015), and once cut, will store this carbon in its material. A design professional stated, “We’ve done a ton of work in the last 5 years to understand the embodied cost of the materials we use, and the LBC started to emphasize being a little bit more specific and a little more critical on the ways things are being calculated. As more of that happens, I think we’ll see more wood used” (Christopher Nielson 2023). Sequestration has the potential to offset material use in the project to obtain a carbon neutral or carbon positive state. But more research needs to be done to have professionals agree on the extents of carbon sequestration’s benefits.

Cost

Alese Ashuckian stated that FSC certification in mass timber has a 5-15% cost premium that fluctuates based on numerous variables (Alese Ashuckian 2023). But this comes as no surprise to people involved in the market. Mass timber is known as an expensive material in general to use in the United States because of the relatively small market of suppliers. For perspective, the CLT market in the United States was estimated at $214.9 million USD in 2022 (Global Industry Analysts, Inc. 2023), while the European market was estimated at $815.4 million USD in 2022, accounting for 63.7% of the market share ("Global Cross Laminated Timber Market Report" 2023). In upcoming years, the global market size for CLT manufacturing is expected to increase from $1.28 billion USD in 2022 to $5.03 billion USD by 2032 ("Global Cross Laminated Timber Market Report" 2023); the growing market and demand in the United States is expected to lead to a majority of North America's increased CLT production ("Global Cross Laminated Timber Market Report" 2023). In 2020, there were 10 CLT manufacturing plants in the United States (Brashaw and Naranjo 2020).

With predictions of a growing US mass timber industry, costs associated with using mass timber may decrease. A study done comparing the different costs associated with the same building being built with concrete or mass timber found that mass timber has a 26% higher front-end cost than concrete (Gu et al. 2020) accounting for the bill of materials, labor, and overhead. However, the study was conducting a total life cycle cost (TLCC) analysis, and with mass timber's ability to increase a building's lifespan (estimated at 100 years in the study versus a concrete structure's

75 years) as well as end of life recyclability and salvage opportunities of mass timber decrease the TLCC by 2.4% compared to concrete (Gu et al. 2020). Mass timber has high recycling rates and values. But CLT and glulam are non-commodity products, which places them at a higher price point (Gu et al. 2020).

Mass timber presents a different cost distribution in a project compared to steel and concrete. Mass timber allows opportunity for prefabrication, reducing construction labor cost and time and thus making the material cost account for a greater percentage of the cost (Chaggaris et al. 2021). While this study negated the maintenance and utilities cost for the buildings as a variable and set them as equal, another study states that evidence is emerging to suggest mass timber efficiencies in reducing heating and cooling costs as well as lived environment improvements in comparison to steel or concrete (Kremer and Symmons 2015). Multiple professionals agree with the fact that the prefabrication and reduced construction time of mass timber construction could feasibly cancel out the higher upfront material cost of mass timber (Joslin 2023, Hellstern 2023, Nielson 2023).

A study conducted in 2016 found that CLT manufacturing alternatives for a performing arts center in California presented a cost reduction of up to 21.7%, depending on the extent to which CLT is used (Laguarda-Mallo and Espinoza 2016). Cost savings were calculated in a variety of comparisons, varying between $4 and $40 savings per square foot, and all options presented showed CLT as less costly than the concrete or steel alternative (Laguarda-Mallo and Espinoza 2016).

Apart from the cost of mass timber and FSC Chain of Custody certified wood, the Living Building Challenge comes with its own price premium. A study led by SERA Architects in 2009 examined four different climate zones and nine different project types, determining that during the Living Building Challenge version 1.3 the price increase ranged from 4% to 49% more, with payback periods ranging from 2-44 years (Miller 2009). The building types with the highest cost premiums and longest payback periods were residential buildings, primarily single-family homes, and particularly in warm climates. Large public projects had the smallest price premiums (Miller 2009). A project undergoing Living Building Challenge certification generally has high financial support upfront to cover these costs. Any green building certification has additional work hours and thus costs associated with it. “When you’re in an LBC project and have chosen wood, there’s no way around FSC, so the client tends to take on whatever additional costs there are,” says Chris Hellstern. This alludes to the fact that the clients taking on mass timber Living Building Projects place financial importance on the materials used and set aside financial support to see it through.

Red List

Overall, despite the red list's appearance of a complicated intersection with mass timber, in practice it does not seem to create large issues. The red list is a large list of vetted products that have been essentially banned from any building pursuing Living Building certification with some exceptions. A major example of that is formaldehyde (added) in products, a known human carcinogen with short and long term affects known and studied ("Formaldehyde and Cancer Risk" 2011). There are many materials with formaldehyde added as a stabilizer to increase structural capabilities, resistance to moisture or water, etc., including many mass timber products. Many Living Building Challenge pursuers are granted exceptions to the red-listed formaldehyde products for mass timber use. This is because some material ingredients rely on formaldehyde for life safety requirements to meet safety codes. Another reason will be for the lack of materials not containing formaldehyde on the market. In version 1.3 of the Living Building Challenge, a temporary exception was made for glulam beams containing phenol formaldehyde (International Living Future Institute 2009). Non-urea formaldehyde in mass timber products is an ILFI approved material exception and has been used in projects as well. Polyurethane is a popular adhesive used in engineered wood products but lacks structural and weather-resistant properties that formaldehyde has.

ADHESIVES IN THE MARKET FOR MASS TIMBER PRODUCTS

Formaldehyde is a known carcinogen (Kumar et al. 2022) and is found in unvented fuel burning and cigarette smoke (US EPA 2013), as well as three of the main types of adhesives used in engineered wood products—resorcinol formaldehyde (RF), melamine urea formaldehyde (MUF), and phenol-resorcinol formaldehyde (PRF) (Hexion 2023). These adhesives mainly offgas when new materials are being produced, before consumer use, but formaldehyde products can continue to release offgas for several months (World Health Organization 2010). The main benefits of these synthetic adhesives are the low cost, resistence to water and chemicals, flexibility and high thermal stability (Arias 2021). However, long term exposure to formaldehyde can result in nasal cancers and leukemia (US EPA 2013). According to the National Cancer Institute at the National Institutes of Health, “Pressed-wood products containing formaldehyde resins are often a significant source of formaldehyde in homes”.

Phenol-resorcinol formaldehyde, PRF, is known for its abilities in dealing with humidity, bulk water, and corrosion resistance (CROW 2023). It is one of the more durable adhesives since it can be used for structural materials as well as withstanding long term weather and water exposure, allowing it to be fully exposed rather than other adhesives that can only have limited exterior exposure or are limited to indoor use (Frihard 2010). It was added to the Living Future Institute’s Red List as of May 2012 in the chemical group Formaldehyde (International Living Future Institute 2023). It also has strong glue line strength. Boat building and outdoor funiture are other examples of uses due to the resistance to wetness. This is a reliable adhesive in the industry since it has hassed the ASTM D-2747, the most rigorous test of adhesive bonds at elevated temperatures (Hexion 2023).

Polyvinyl acetate (PVA) is another adhesive present in engineered wood products. PVA is a colorless, nontoxic thermoplastic. It has a low cost and high microorganism, water and weather resistance and thus has replaced natural adhesives in some industries such as with furniture

(Conner 2017). However, it tends to creep under mechnical loads, leading to irreversive deformities in products using PVA (Kaboorani 2015). This unreliability in strength is the reason it has not replaced formaldehyde-based adhesives in the engineered wood product industry (Kaboorani 2015).

Polyurethane (PUR) adhesives allows for healthier indoor air quality than other adhesives, and it is formaldehyde-free. It is also flexible to moisture and temperature changes, fire resistant, strong and durable, with a quick curing time (Henkel 2023). However, it typically can only withstand short-term bulk water soaking (Frihard 2010).

Choices of adhesives are carefully considered partially due to the fears of how mass timber reacts with fire. Char fall-off and structural member integrity during fires are directly impacted by the adhesive used in the products. Char fall-off exposes inner, uncoated layers to the fire threat. One study found that CLT samples under the same conditions may delaminate with some adhesives, while others do not. The thickness of the CLT layers also plays a factor in delamination, but the coorelation with adhesives has caused design standards that restrict adhesives permitted for use based on their glue line integrity (Mitchell et al. 2023). Adhesive behavior during fire requires more research. Standard polyurethane adhesive was one that resulted in significant char fall-off compared to modified polyurethane adhesive (Hopkin et al. 2022; Mitchell et al. 2023). Polyurethane does not contain formaldehyde, and is therefore more sustainable than other adhesives but has these fire resistance drawbacks.

VOC'S

Volatile organic compounds (VOCs) are not all bad. As one review by Adamová et al. in 2020 synthesizes, there are two major categories of VOCs: natural and anthropogenic. The latter is what is typically thought of, but the natural VOCs are from green vegetation. These emissions are uncontrollable. These VOCs aid in necessary plant survival and reproduction and can function as communication between plants and insects. Anthropogenic VOCs, however, are human-caused compounds that result in emissions. Formaldehyde exists in nature and in manufactured things, and therefore is both of natural and anthropogenic origin. The overall definition of volatile organic compounds is that their boiling points lie within the range of 50-100 degrees Celsius (Adamová 2020). Volatile Organic Compounds are a large determinant factor of human respiratory health, since humans spend 90% of life indoors, and VOC concentrations are much higher inside, affecting the indoor air quality. VOCs are emitted from building materials and furniture, at a speed and amount circumstantial to the environmental factors and construction quality of the materials themselves (Adamová 2020).

VOCs are present within wood itself and can be extracted out of it in processes during production using water or an organic solvent, an example being citric acid (Adamová 2019). These extracted VOCs are used in medical products and perfumes, since they have been known to "have a positive effect, especially on the nervous, respiratory, and visual system" (Adamová 2020). However, wood products do contribute to indoor air quality (IAQ) and thus have been studied to examine how to reduce their emissions of VOCs. One study found that untreated hemp shive had a significantly smaller number of VOCs emitted than untreated spruce, a softwood used in engineered wood products (Adamová 2019). This provides potential possibilities for increased presence of bio-based materials. But overall, mass timber does not emit concerning amounts of volatile organic compounds. According to the Engineered Wood Association, “Structural and moisture durability of formaldehyde-containing adhesive systems results naturally in very low formaldehyde emissions” (“Formaldehyde and Engineered Wood Products” 2022).

More recently, there have been specific measures to place limitations on the formaldehyde use of engineered wood products in California (California Air Resources Board 2009), raising awareness of the environmental and public health implications of this product and placing boundaries to chemical use and therefore ensuring more sustainable techniques within mass timber use. Even though adhesive chemicals have exceptions allowed in the Living Building Challenge and have not been a large issue in the overlap of mass timber use in the LBC, the Living Building Challenge does require products free of Red List materials, so more regulation and law focused on the resin side of mass timber will allow mass timber use to be more in line with the values of the LBC, which aims to “foster a transparent materials economy free of toxins and harmful chemicals” (International Living Future Institute 2019).

Waste

The reduction of waste is another imperative in the Materials petal. With the intent to create intentional processes and standards of minimizing waste in every phase of the project, a waste reduction strategy must be defined and explained for each phase which includes different diversion rates of different materials to keep them out of landfills. For example, wood products fall under the category of "all other materials" in a 90% diversion rate minimum required of the project.

The Living Building Challenge looks at end of life in two ways: the carbon emissions accounted for at the end of life, and a material management plan in which a building's materials should be accounted for in every life cycle phase including deconstruction (Christ Hellstern 2023). Within conducted interviews, waste did not present itself as a large issue. Part of this could be due to the fact that mass timber, being engineered wood products, are prefabricated (ThinkWood 2022) and designed to create less waste by using smaller wood pieces, therefore creating less on-site waste to manage. Mass timber use, then, correlates well with the waste category of the LBC.

One project even took it farther as to think about how their mass timber elements could be used as a learning tool about future demolition and thinking about waste. Christopher Nielson, on the R. W. Kern Center project, talks about future-proofing the building through mass timber design:

> "For the most part we did not use composite products, accounting for a fairly demolish-able and separatable way of deconstruction... The way we detailed the building, maybe more for educational purposes but also for deconstruction, is that we designed steel

connections to connect beams / columns / trusses, which were expressed to show visual transparency of how it comes apart and be visibly educational in how systems take place. The same is true for mass timber elements to see how details come together" (Christopher Nielson 2023).

Synthesis of Findings

An analysis of the interviews leads the researcher to the fact that sourcing, while a major complication of the interaction between mass timber use and pursuit of the Living Building Challenge certification, is an issue depending on locality and time of the project. Chris Hellstern, a pioneer in the Pacific Northwest's endeavors of LBC, claimed that FSC procurement was not an issue in his early projects of the Bullitt Center and the Kendeda building, built in 2011 and 2019, respectively (Chris Hellstern 2023). Christopher Nielson, working on the Kern Center, communicated similar sentiments for the project built in 2016, and voiced that FSC procurement was much different in a past project than it would be in today's market (Nielson 2023). Alese Ashuckian and Karen Joslin, who both worked on the PAE building completed in 2022 and Joslin, who is currently working on LBC proposals during the time of this publication, voiced the difficulty of sourcing mass timber now. This could be due to the disruption of the building material industries during the COVID-19 pandemic (Larasatie et al. 2022). Sourcing is in part dependent on the market.

Sourcing FSC Chain of Custody certified wood becomes complicated when FSC procurement is coupled with sourcing required within certain radii of locality. The interviewees closest to Canadian suppliers, Alese Ashuckian, Chris Hellstern and Christopher Nielson, experienced less issues relying on mass timber as a structural material because they could source within an area with greater saturation of mass timber in the market. Karen Joslin voiced FSC certification being a big issue within their project and talked about needing to source from Canada (Joslin 2023). Joe Agius, in an interview conducted about the Australian Living Building of The Sustainable

Buildings Research Centre, could not acquire FSC mass timber in Australia, and had to outsource from New Zealand (Agius 2023). This project only ended up, then, using mass timber as a feature in one piece of the building, not as a primary structural material. The dichotomous nature of the requirements within the Living Building Challenge of keeping within sourcing radii and maintaining that 80% or more of all wood in a project is FSC disproportionately affects projects pursuing mass timber use as a primary structural material, because of the difficulties in sourcing FSC Chain of Custody products locally. This also disproportionately affects regions without robust FSC markets, such as the example within Australia or southern United States that does not have the larger Canadian market to rely on. In all, the research points to sourcing being a varying but relatively high visibility issue in mass timber use in LBC certification.

The upfront cost is a major barrier of the Living Building challenge in general and is heightened with the use of mass timber. Mass timber redistributes the areas of cost to a higher price premium and a lower construction cost, requiring the client to have sufficient upfront funds to prioritize Living Building Challenge certification as well as mass timber use. The LBC typically recuperates its upfront cost over time through lessened cost of energy and water use. There is not enough research to conclusively say the impact of FSC mass timber on the recuperation of cost over time as it relates to the Living Building Challenge and its decreased construction and fabrication costs.

Cost in general is a large barrier for Living Buildings. As mentioned previously, the price for pursuing LBC certification ranged from an increase of 4 to 49%, with payback periods ranging from 2-44 years (Brashaw and Naranjo 2020). That same study concluded that larger, public, or commercial buildings had smaller price increases and payback periods, and thus had less financially risky positions pursuing LBC certification. Therefore, many precedents fit in this category. There is an additional cost with sourcing FSC Chain of Custody certified mass timber as well, amounting to higher costs to wood-heavy projects pursuing LBC specifically.

This project attempted to study waste and its relation to mass timber with an inquiry on whether construction waste was impacted using mass timber. Since mass timber is largely prefabricated and glues together smaller wood pieces, it inherently comes with less on-site waste. Further research should be done on the waste aspect as it relates to Living Building Certification, but as of now, inconclusive findings pointed to waste not being part of the discussion on mass timber's limited use and hinderances in Living Building Challenges.

Red-listed adhesive ingredients, although upon initial inspection seem like an obvious hinderance to projects, were found to have less impactive issues on completed projects due to a project's ability to get exceptions to red-list bans due to fire life safety or inadequate alternatives within the market. It is possible that the perception of this issue could have hindered potential projects or projects that did not get certified, but that is inconclusive and up to further research.

Mass timber use, generally as in tandem with Living Buildings, is still not widely used in the United States. Most precedents in this study have client values that tie them to their use of mass timber. The Bullitt Foundation, occupying and owning the Bullitt Center, is an environmental organization committed to being a guinea pig for sustainable design. The Kendeda Building for Innovative Sustainable Design, as well as the Sustainable Building Research Center, are both examples of institutions that value innovation in sustainable design, making them natural parties to assume higher upfront costs to cover using mass timber and pursuing the Living Building Challenge. Many of the precedents studied exemplify a similar client connection to the narrative of using mass timber and pursuing Living Building Challenge. To think of it from a cost perspective, the industries of mass timber and green building certification have not lowered their price premiums enough to be commonly available to clients who do not have deep connections and thus incentives to invest more intensely on their buildings upfront.

Mass timber, being a rising industry in the United States and a sustainable material alternative, has the potential to align with the values of the Living Building Challenge and create regenerative buildings. To further foster this relationship, multiple barriers in place could be taken down in the logistics of the LBC to allow for more mass timber use. They are as follows:

- General agreements within the industry on the amount that mass timber sequesters carbon, supported by calculators with conclusive calculations of timber sequestration could allow more focus on mass timber's low embodied carbon. This is not as much of a barrier as it is a missed opportunity for supportive examples of the benefits of using mass timber in LBC certification pursuits.
- A greater FSC Chain of Custody market to support FSC requirements or greater flexibility in the radius of locally sourcing FSC Chain of Custody mass timber so that these sourcing requirements do not clash and disproportionately affect mass timber use as a primary structural material.
- An increased mass timber market in the US in general would benefit projects by dispersing more knowledge about the material and lowering costs with increased availability.

- Clearly defining red list exceptions for CLT, one of the most popular forms of mass timber emerging. Glulam formaldehyde exceptions exist, but projects run into barriers with using CLT, as seen in the PAE building precedent.
- Codes outside of the LBC requirements restrict mass timber adhesive products based on their structural integrity. Updating codes that allow for more bio-based materials would allow greener alternatives to adhesives that include red-listed materials. Currently, polyurethane (PUR) and soy-based adhesives exist but are not widely accepted.

Further study could be done through surveying design professionals about perceived barriers and interactions between mass timber and the Living Building Challenge A survey was formulated, but not used, to send out to design professionals about professional experience and expertise regarding the use of mass timber in the Living Building Challenge. Questions were written with unbiased questioning research in mind. The survey bifurcated on the Qualtrics platform based upon whether the surveyed individual has previous experience using mass timber or designing an LBC or not. The purpose of the survey was to gain information on both experienced and presumed barriers professionals perceive. The formal interviews were conducted with people experienced on the subject, whereas it is presumed that most survey respondents would not have experience in mass timber use in the Living Building Challenge, giving the research more range in the field's perceptions on the subject.

The survey took the necessary steps to be approved by the Institutional Review Board (IRB). Results of a similar survey could be analyzed qualitatively and quantitatively and would support the topic of research by pairing the examination of the existing infrastructure of the Living Building Challenge certification as it relates to using mass timber use as a primary structural system, with the perceived challenges within the infrastructure of the LBC.

Conclusion

The Living Building Challenge and the modern use of mass timber in the United States began their histories around the same time and have built each other up through the projects that have utilized both the certification and structural material to push their industries forward. There are contradictory challenges in using mass timber within the Living Building Challenge, but the buildings that have used mass timber and are LBC certified had values that coincided with the utilization of timber and their mass timber buildings are an expression of their purpose: a sustainability center, a building research center, etc. These have been the pioneers of mass timber use in the Living Building realm but cost and FSC certified sourcing still pose major barriers that have restricted the cohesion of mass timber and LBC from becoming widely implemented. However, the many benefits of reduced embodied carbon, long term cost, reduced waste, beauty, health & happiness still make mass timber use in Living Buildings an attractive choice. "[The mass timber industry and the Living Building Challenge industry] support each other. In order to reach the climate goals we have and carbon reduction, we are certainly going to have to look to timber more," (Chris Hellstern 2023).

The topics of mass timber use in sustainably oriented design is a vast category of potential research, where there is opportunity for further development in topics adjacent to this thesis. The difference between utilizing steel, for example, which is generally a recycled/recyclable material, and using mass timber in sustainable buildings. Research comparing the carbon impact of both and doing a deeper dive into the complexities of carbon sequestration's benefits and how mass timber compares to alternative structural materials like steel could enrich dialogues on mass timber's structural use. Another topic to further research would be diving into LEED, the most renowned green building certification, and how it compares to Living Building Challenge in mass timber use. On a more global scale, one could research European use of mass timber and how it compares to the United States with mass timber use in the Living Building Challenge. Europe is the region with the most mass timber development ("Global Cross Laminated Timber Market Report" 2023), which ultimately means that the barriers the United States experiences with market cost and lack of widespread industry knowledge would impact project cost differently between locations. End of life research on the deconstructability and reusability of mass timber, both theoretical and applied research, could aid in the conversation of mass timber use in the Living Building Challenge to propose how the Living Building Challenge can perpetuate advocacy in this realm. And lastly, relating back to the unused survey to better understand industry perception within the United States, further research into the perception within the industry of mass timber utilization could aid to better understand how perception and social aspects affects mass timber use.

The Living Building Challenge is on version 4.1 of its standards, which are constantly changing ("What Is The Living Building Challenge?" n.d.). The LBC has the potential to make changes to allow for greater ease of mass timber application. The external barriers of FSC certification sourcing and market cost will decrease with the wider implementation of mass timber as it becomes a more accepted structural material in the United States. Over time, as these small changes take place, mass timber may become more widely used within Living Building Challenge Standards. For now, it remains an underutilized union.

Bibliography

Adamová, Tereza, Jaromír Hradecký, and Marek Prajer. "VOC Emissions from Spruce Strands and Hemp Shive: In Search for a Low Emission Raw Material for Bio-Based Construction Materials." Materials 12, no. 12 (January 2019): 2026. https://doi.org/10.3390/ma12122026.

Adamová, Tereza, Jaromír Hradecký, and Miloš Pánek. "Volatile Organic Compounds (VOCs) from Wood and Wood-Based Panels: Methods for Evaluation, Potential Health Risks, and Mitigation." Polymers 12, no. 10 (October 6, 2020): 2289. https://doi.org/10.3390/polym12102289.

Agius, Joe. 2023. Interview by Hadley Carlberg. Virtual interview over Zoom.

Ashuckian, Alese. 2023. Interview by Hadley Carlberg. Virtual interview over Zoom.

Brashaw, Brian, and Kevin Naranjo. "Mass Timber Momentum Expands Forest Products Markets." USDA Forest Service, October 21, 2020. https://www.fs.usda.gov/features/mass-timber-momentum-expands-forest-products-markets.

Busta, Hallie. "Mass Timber 101: Understanding the Emerging Building Type." Construction Dive, May 24, 2017. https://www.constructiondive.com/news/mass-timber-101-understanding-the-emerging-building-type/443476/.

California Air Resources Board. "Airborne Toxic Control Measure to Reduce Formaldehyde Emissions from Composite Wood Products," 2009. https://www.arb.ca.gov/regact/2007/compwood07/fro-atcmfin.pdf.

Chaggaris, Rachel, Shiling Pei, Greg Kingsley, and Alexis Feitel. "Carbon Impact and Cost of Mass Timber Beam–Column Gravity Systems." *Sustainability* 13, no. 23 (January 2021): 12966. https://doi.org/10.3390/su132312966.

Cheng, Justin. "Mass Timber in Construction - Big Buildings, Smaller Carbon Footprint." sustainalytics.com, April 14, 2022. https://www.sustainalytics.com/esg-research/resource/investors-esg-blog/mass-timber-in-construction.

Chris Helstern, January 2023. Interview by Hadley Carlberg. Virtual interview over Zoom.

COX. "Sustainable Buildings Research Centre." Accessed July 20, 2023. https://www.coxarchitecture.com.au/project/sustainable-buildings-research-centre/.

Fabris, Peter. "World's Largest Commercial Living Building Opens in Portland, Ore." Building Design + Construction, June 22, 2022. https://www.bdcnetwork.com/worlds-largest-commercial-living-building-opens-portland-ore.

Forestry Innovation Investment. "What Is Mass Timber and Engineered Wood? | Fact Sheets + Resources." naturally:wood. Accessed July 14, 2023. https://www.naturallywood.com/resource/what-is-mass-timber/.

Forest Stewardship Council®. "Chain-of-Custody Certification." FSC United States. Accessed July 26, 2023. https://us.fsc.org:443/en-us/certification/chain-of-custody-certification.

Forest Stewardship Council. n.d. "Facts & Figures." FSC® United States. Accessed July 26, 2023. https://us.fsc.org:443/en-us/what-we-do/facts-figures.

"Formaldehyde and Engineered Wood Products." APA, January 2022. apawood.org.

"Formaldehyde and Cancer Risk - NCI." CgvArticle, June 10, 2011. Nciglobal,ncienterprise. https://www.cancer.gov/about-cancer/causes-prevention/risk/substances/formaldehyde/formaldehyde-fact-sheet.

Glass, Vitro Architectural. "What to Know about LEED® Certification." Accessed July 14, 2023. https://glassed.vitroglazings.com/topics/what-to-know-about-leed-certification.

"Global Cross Laminated Timber Market Report." Construction & Manufacturing. Spherical Insights, June 2023. https://www.sphericalinsights.com/reports/cross-laminated-timber-clt-market.

Global Industry Analysts, Inc. "Cross Laminated Timber (CLT): Global Strategic Business Report." Global Strategic Business Report. Global: Research and Markets, January 2023. https://www.researchandmarkets.com/reports/5141054/cross-laminated-timber-clt-global-strategic.

Gu, Hongmei, Shaobo Liang, and Richard Bergman. "Comparison of Building Construction and Life-Cycle Cost for a High-Rise Mass Timber Building with Its Concrete Alternative." *Forest Products Journal. 20(4): 482-492.* 20 (2020): 482–92. https://doi.org/10.13073/FPJ-D-20-00052.

Green, Jared. 2021. "New Research: The Built Environment Impacts Our Health and Happiness More Than We Know." THE DIRT. June 7, 2021. https://dirt.asla.org/2021/06/07/new-research-the-built-environment-impacts-our-health-and-happiness-more-than-we-know/.

Hellstern, Chris. 2023. Interview by Hadley Carlberg. Virtual interview over Zoom.

Henriikka. 2019. "Adhesives in Engineered Timber." New Nordic Timber (blog). October 30, 2019. https://newnordictimber.com/articles/adhesives-in-engineered-timber.

Hopkin, Danny, Wojciech Węgrzyński, Michael Spearpoint, Ian Fu, Harald Krenn, Tim Sleik, Carmen Gorska, and Gordian Stapf. 2022. "Large-Scale Enclosure Fire Experiments

Adopting CLT Slabs with Different Types of Polyurethane Adhesives: Genesis and Preliminary Findings." Fire 5 (2): 39. https://doi.org/10.3390/fire5020039.

International Code Council, Inc. "CHAPTER 2 DEFINITIONS, 2021 International Building Code (IBC) | ICC Digital Codes," September 2021. https://codes.iccsafe.org/content/IBC2021P2/chapter-2-definitions.

International Living Future Institute. "Declare Overview." Accessed August 8, 2023. https://living-future.org/declare/.

International Living Future Institute. "Living Building Challenge 1.3," August 2009.

International Living Future Institute. "Living Building Challenge 4.0: A Visionary Path to a Regenerative Future," June 2019.

International Living Future Institute. "Living Building Challenge 4.0 Petal Handbooks," February 6, 2023.

International Living Future Institute. "Living Building Challenge Basics." Accessed July 14, 2023. https://living-future.org/lbc/basics4-0/.

International Living Future Institute. "The Living Building Challenge: In Pursuit of True Sustainability in the Built Environment." Cascadia Region Green Building Council, August 2008. https://living-future.org/wp-content/uploads/2022/05/Living-Building-Challenge-1.3-Standard.pdf.

Joslin, Karen. 2023. Interview by Hadley Carlberg. Virtual interview over Zoom. July 18, 2023.

"Kendeda Building for Innovative Sustainable Design - International Living Future Institute." Accessed July 18, 2023. https://living-future.org/case-studies/1503/.

Kremer, Paul, and Mark Symmons. "Mass Timber Construction as an Alternative to Concrete and Steel in the Australia Building Industry: A PESTEL Evaluation of the Potential." *International Wood Products Journal* 6 (July 1, 2015): 2042645315Y.000. https://doi.org/10.1179/2042645315Y.0000000010.

Kumar, Chandan, and William Leggate. "An Overview of Bio-Adhesives for Engineered Wood Products." International Journal of Adhesion and Adhesives 118 (October 1,2022): 103187. https://doi.org/10.1016/j.ijadhadh.2022.103187.

Laguarda-Mallo, Maria, and Omar Espinoza. "CROSS-LAMINATED TIMBER VS. CONCRETE/STEEL: COST COMPARISON USING A CASE STUDY." Vienna, Austria, 2016. https://www.researchgate.net/publication/320739097_CROSS-LAMINATED_TIMBER_VS_CONCRETESTEEL_COST_COMPARISON_USING_A_CASE_STUDY

Larasatie, Pipiet, Lech Muszynski, and Eric Hansen. 2022. “Global Mass Timber Panel (MTP) Industry During the COVID-19 Pandemic: Initial Findings.” In.

Laurenzi, Tom. 2017. “How Does the Relative Humidity Affect the Quality of Wood?” Delmhorst Instrument Co. May 24, 2017. https://www.delmhorst.com/blog/how-does-the-relative-humidity-affect-the-quality-of-wood.

“LEED Rating System | U.S. Green Building Council.” Accessed August 10, 2023. https://www.usgbc.org/leed.

“Mass Timber Projects in Design & Constructed - WoodWorks.” n.d. WoodWorks | Wood Products Council. Accessed May 4, 2024. https://www.woodworks.org/resources/mapping-mass-timber/.

McKnight, Jenna. “ZGF Completes Mass-Timber PAE Living Building in Portland.” dezeen, August 22, 2022. https://www.dezeen.com/2022/08/22/zgf-pae-living-building-portland/.

Merriam-Webster Dictionary. “Definition of BIOPHILIA.” Accessed July 21, 2023. https://www.merriam-webster.com/dictionary/biophilia.

Miller, Stephani L. 2009. “Study Examines Cost Effectiveness of Living Buildings.” Architect. May 19, 2009. https://www.architectmagazine.com/technology/study-examines-cost-effectiveness-of-living-buildings_o.

Montjoy, Valeria. 2022. “The Biophilic Response to Wood: Can It Promote the Wellbeing of Building Occupants? | ArchDaily.” March 2, 2022. https://www.archdaily.com/974790/the-biophilic-response-to-wood-can-it-promote-the-wellbeing-of-building-occupants.

Nielson, Christopher. 2023. Interview by Hadley Carlberg. Virtual interview over Zoom.

Oliphant, Margret. “Background Brief on Air Quality.” Oregon Department of Environmental Quality, June 2010.

Preferred by Nature. “Timber Sourcing Hub.” NEPCon - Preferred by Nature. Preferred by Nature. Accessed July 26, 2023. https://www.preferredbynature.org/sourcinghub/timber.

RDH Building Science Inc. “MOISTURE RISK MANAGEMENT STRATEGIES FOR MASS TIMBER BUILDINGS: A Guide for Designers, Construction Professionals, and Building Developers,” October 2022. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.rdh.com/wp-content/uploads/2022/11/Mass-Timber-Moisture-Management-Guide.pdf.

Rohit, Parimal M., and Nicole Shih. “Mass Timber’s Growing Popularity Reflected in Record-Breaking US Building.” Verified commercial real estate information, analytics and international data-driven news. CoStar, October 5, 2022. https://www.costar.com/article/592439438/mass-timbers-growing-popularity-reflected-in-record-breaking-us-building.

Stancil, Joanna Mounce. 2015. "The Power of One Tree - The Very Air We Breathe." U.S. Department of Agriculture. March 17, 2015. https://www.usda.gov/media/blog/2015/03/17/power-one-tree-very-air-we-breathe.

Sotayo, Adeayo, Daniel Bradley, Michael Bather, Pooya Sareh, Marc Oudjene, Imane El-Houjeyri, Annette M. Harte, et al. 2020. "Review of State of the Art of Dowel Laminated Timber Members and Densified Wood Materials as Sustainable Engineered Wood Products for Construction and Building Applications." Developments in the Built Environment 1 (February): 100004. https://doi.org/10.1016/j.dibe.2019.100004.

"Tally® | Revit | Autodesk App Store." 2022. April 8, 2022. https://apps.autodesk.com/RVT/en/Detail/Index?id=3841858388457011756.

Think Wood. "Mass Timber Fabrication & Construction - Think Wood." 2022. Accessed May 4, 2024. https://www.thinkwood.com/mass-timber.

Thomas, Mary Adam. 2022. *The PAE Living Building: Developer-Led, Nature-Inspired*. First Edition. Living Building Challenge Series. Ecotone Publishing.

US EPA, OAR. "Evolution of the Clean Air Act." Overviews and Factsheets, May 29, 2015. https://www.epa.gov/clean-air-act-overview/evolution-clean-air-act.

Walsh, Frank J., and Robert L. Watts. Composite lumber. United States US1465383A, filed March 17, 1920, and issued August 21, 1923. https://patents.google.com/patent/US1465383/en.

"What Is The Living Building Challenge?" n.d. *International Living Future Institute* (blog). Accessed May 4, 2024. https://living-future.org/lbc/.

WoodWorks | Wood Products Council. "Status of Building Code Allowances for Tall Mass Timber in the IBC." Accessed August 17, 2023. https://www.woodworks.org/resources/status-of-building-code-allowances-for-tall-mass-timber-in-the-ibc/.

Yale Sustainability. 2020. "Yale Experts Explain Green Building Certifications | Yale Sustainability." October 19, 2020. https://sustainability.yale.edu/explainers/yale-experts-explain-green-building-certifications.