

BLOMOP



APPLICATIONS OF LOCAL-SPECIES
CLT & FOREST PRODUCTS IN
NORTHEASTERN MODULAR HOUSING

BLAYNE BURNSIDE





BioMOD

APPLICATIONS OF LOCAL-SPECIES
CLT & FOREST PRODUCTS IN
NORTHEASTERN MODULAR HOUSING



BLAYNE BURNSIDE

M.S. Arch. – Mass Timber Design
Terminal Project 2025

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INTRODUCTION

- A1 PROJECT INTRODUCTION**
 - Project Brief | 10
 - Project Objective Summary | 12



RESEARCH

- A1 NORTHEASTERN CONDITIONS**
 - Current Conditions | 18
 - Vernacular Architecture | 26
- A2 THE NORTHERN FOREST**
 - State of the Forest Sector | 30
 - Tree Species for CLT | 34
- A3 EASTERN WHITE PINE CLT**
 - Tree Specie Selection for CLT | 40
- A4 CASE STUDIES**
 - Overview | 44
 - Green Canopy NODE | 47
 - Tieton Cabin Company | 55
 - Kalesnikoff | 63
 - Polyhaus | 69
 - Sierra Houses | 79
 - OPAL / Shelter | 91
 - Summary | 98



DESIGN

- B1 SYSTEM OVERVIEW**
 - System Conditions | 104
 - General Design Elements | 106
 - Catalogue for Variation | 116
- B2 DESIGN DETAILS**
 - Panelized Modular Strategy | 122
 - Study Condition Design | 124
 - Assembly Details | 140
- B3 PRODUCTION PROCESS**
 - The Production Chain | 154



ANALYSIS

- C1 ANALYSIS INTRODUCTION**
 - Overview | 164
- C2 CONSTRUCTION COMPOSITIONS**
 - Overview | 174
 - Assembly Compositions | 176
 - Material Quantification | 182
 - Conclusive Results | 196
- C3 LIFE CYCLE ASSESSMENTS**
 - Overview | 200
 - Cradle-to-Gate Assessment | 202
 - Biogenic Carbon Consideration | 204
 - Cradle-to-Grave: Summary | 206
 - Cradle-to-Grave: Year 30 | 208
 - Cradle-to-Grave: Year 60 | 214
 - Cradle-to-Grave: Year 100 | 220
 - Longterm Biogenic Carbon Effect | 226
 - Conclusive Results | 228
- C4 THERMAL PERFORMANCE**
 - Overview | 232
 - Thermal Resistance Values | 234
 - Heat Transmission | 238
 - Energy Analysis | 250
 - Conclusive Results | 260



CONCLUSION

- D1 CONCLUSIONS**
 - Benefits & Tradeoffs of Mass Timber | 266
 - Project Conclusion | 268
 - Future Research | 270
- D2 CREDITS**
 - Acknowledgements | 277
 - References | 278
 - Annotated Bibliography | 280
- D3 APPENDIX**
 - 1 - CLT Performance | 290
 - 2 - Sawtimber Tree Data | 291
 - 3 - Typical Modular House | 292
 - 4 - Material Quantities | 294
 - 5 - Life Cycle Assessments | 296
 - 6 - Thermal Analyses | 322





PROJECT INTRODUCTION

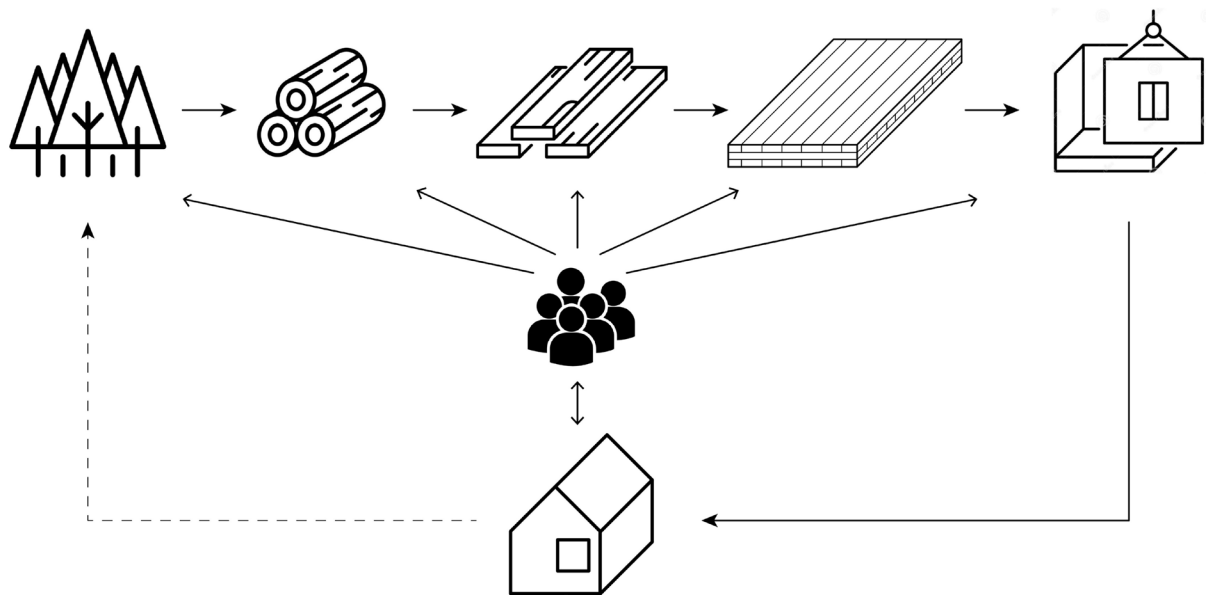
PROJECT BRIEF

ABSTRACT

The rural landscape of the Northeastern region of the United States is predominantly defined by the abundant forest and timberland that exist in the region. Socioeconomically, today's communities within these rural areas often lack economic opportunity, with a housing stock defined by the necessity for up-front affordability, such as manufactured homes. Many of the standard materials of these homes lack longevity, and are made from non-renewable and petroleum-based products. These materials are often harmful to humans, generating various health concerns while also being significant contributors to carbon and greenhouse-gas emissions through their production, short service-lives, and transportation from foreign lands.

This project aims to design an environmentally sustainable, healthy, and regenerative modular housing system that highlights current and proposed local forest products for a biogenic

construction assembly. The system is based around the proposed use of eastern white pine CLT (Cross-Laminated-Timber) for panelized construction, and designed intentionally as a system for modular addition/expansion to optimize affordability and longevity of the housing stock. Finally, the system will be analyzed and compared with a representative conventional modular house, as well as with a site-built, typical light-wood-frame-constructed version of itself. The study demonstrates that a CLT modular system greatly reduces the carbon footprint of new home construction in the rural northeast, produces healthier and thermally-efficient interior living environments, and promotes economic opportunity throughout forest sector supply chains and local communities. This study would support the development of locally manufactured CLT production, permissible by local authorities for use in low-density residential applications.



The Resilient Forested Rural Community

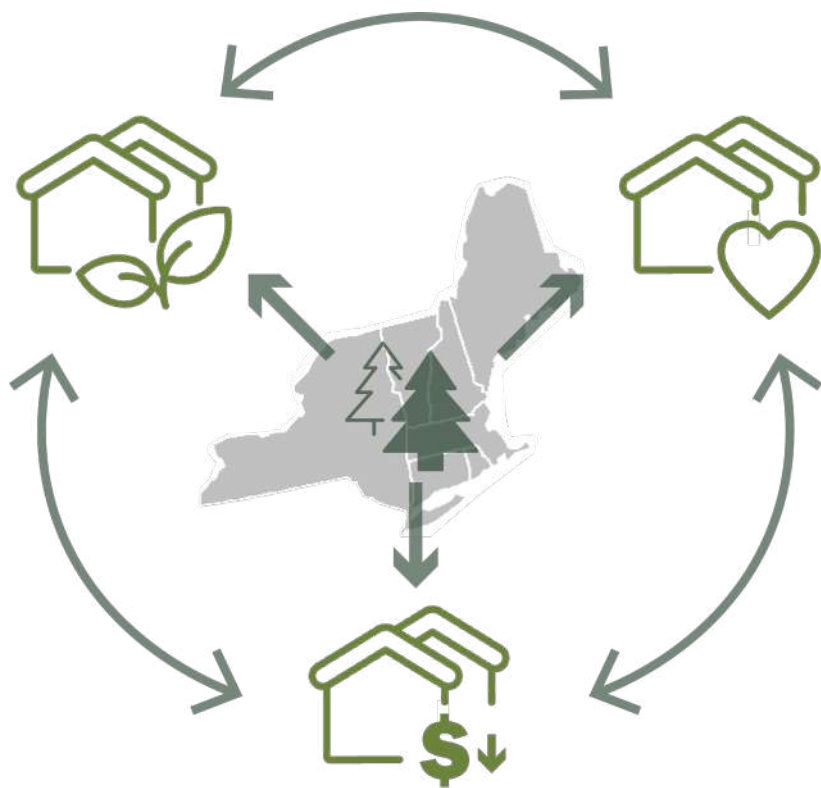


PROJECT OBJECTIVE SUMMARY

MISSION STATEMENT

At the very core, the intent for this project is to showcase the potential benefits of utilizing Eastern White Pine CLT and other forest products in the design of a single-family panelized-modular mass timber housing system for the Northeastern United States. Primary objectives include demonstrating the usefulness of locally-sourced mass timber for the Northeast in order to advocate for the introduction of a regional CLT manufacturing plant, showing the qualities of a biogenic-based building assembly that supports the regional forest sector, and comparative analyses between the

designed system and the conventional systems of related construction that are typically utilized. The modular housing system is primarily intended for rural communities, and designed to create resilience by generating forest-sector livelihoods in which the products that community members produce directly act to improve the quality of life in their homes, and the quality of the land. The resultant system seeks to holistically improve the environmental, economic, and equitable health of the Northeast.



Leveraging the Forest.

PROJECT STRUCTURE

RESEARCH

CURRENT CONDITIONS -
RURAL HOUSING

FOREST SECTOR AND MASS
TIMBER TREE SPECIES

MASS TIMBER MODULAR
HOME CASE STUDIES

DESIGN

THE DESIGN SYSTEM

DETAILS

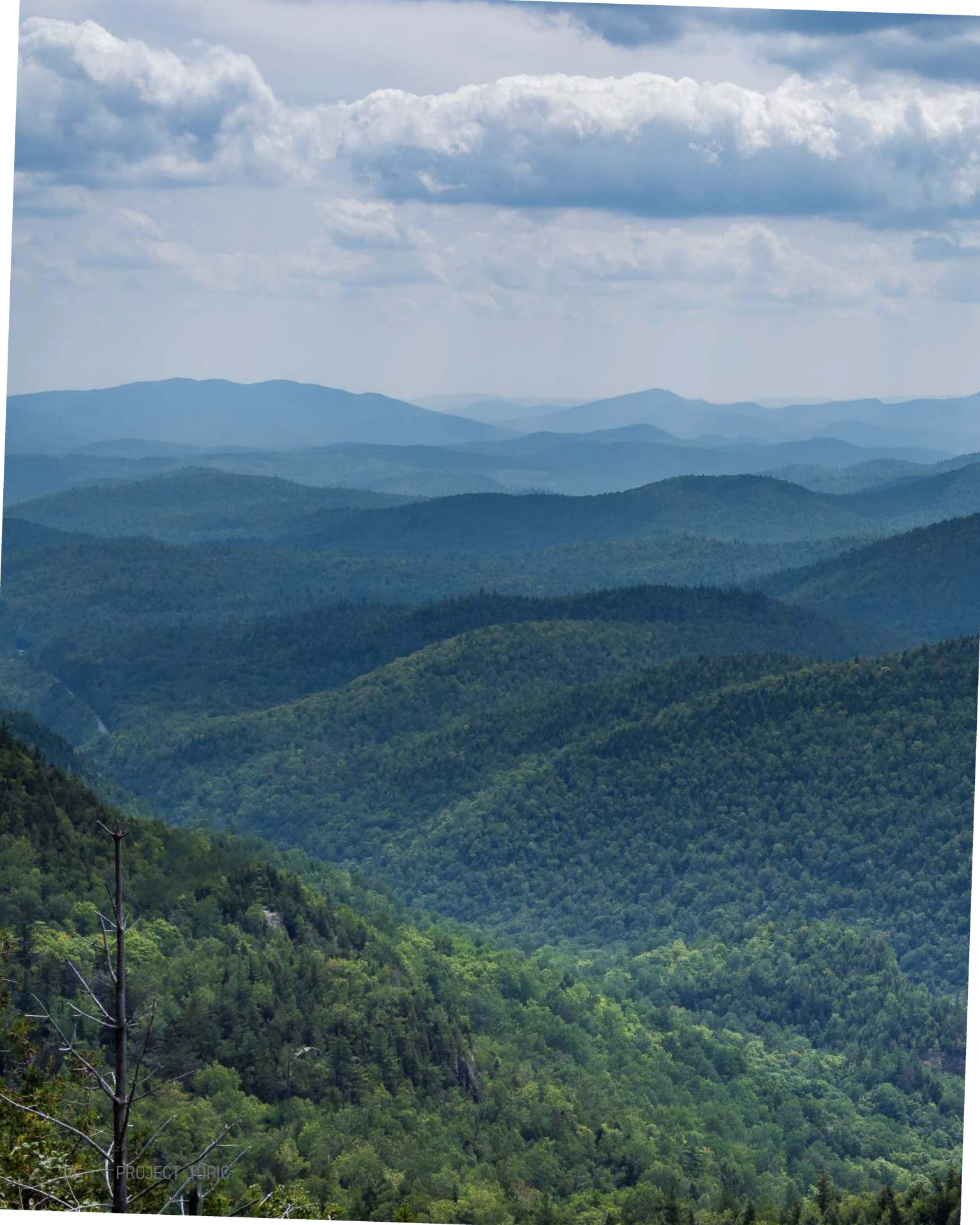
ANALYSIS

COMPARISONS TO
CONVENTIONAL MODULAR &
SITE-BUILT CONSTRUCTION
SYSTEMS

CONSTRUCTION COMPOSITION

LIFE CYCLE ASSESSMENTS

THERMAL PERFORMANCE





RESEARCH



A1





NORTHEASTERN CONDITIONS

CURRENT CONDITIONS

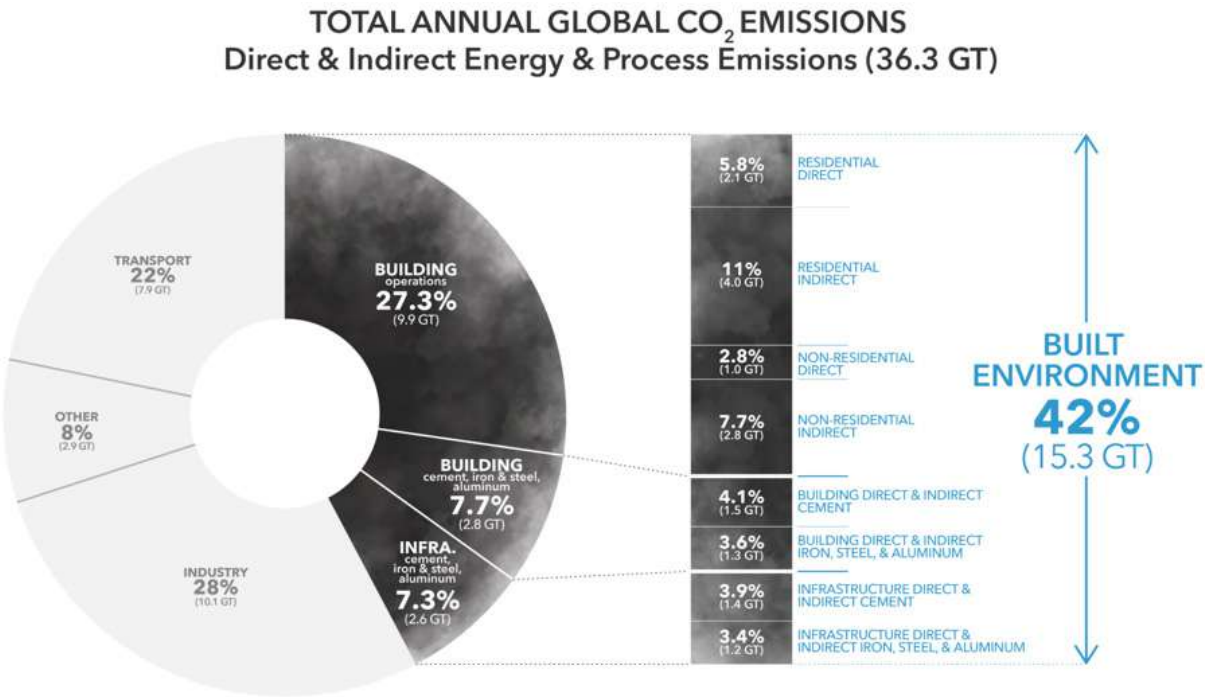
CLIMATE CHANGE

Global warming due to carbon emissions is a leading cause and concern in the topic of climate change. Extreme weather events and disasters—such as droughts, forest fires, floods, and blizzards—are becoming more frequent in recent years. These calamities put great strain on the health and economy of affected communities, as well as the rest of the world through supply chains.

Globally, the building sector is responsible for 42% of all carbon emissions, making the need to reduce the sector's carbon a crucial concern.¹ There are various avenues by which to reduce the carbon impacts of this sector, such as decreasing operational energy demand

through proper design techniques, prioritizing renewable-source, carbon sequestering materials, and sourcing these materials locally to reduce transportation-related emissions.

In light of localizing construction materials, there is no singular best material for reducing carbon that every region should use. Instead, there is a shared starting point of consideration that future construction should utilize; which is to prioritize what is natural and locally-abundant where possible. Forested regions should prioritize wood; adobe or earth for deserts, straw and clay for plains, and so on. In this case for the Northeast, the natural and abundant material is wood.



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THE RURAL RESIDENTIAL LANDSCAPE

As some of the earliest colonial-settled land since the introduction of Europeans in North America, the northeastern United States has a long history of forestry and a livelihood once deeply defined by it—where the materials of homes were a reflection of the forest and other surrounding available resources. Today, however, this residential landscape has shifted to houses defined primarily by the readily-affordable post-industrial products that have become the conventional construction standard in the United States. Beyond the retained use of light-wood framing for structural systems, and wood-based sheathing elements, the common house is largely comprised of non-renewable and petroleum-based products; from insulation, to

exterior cladding and interior finishes. These materials are being discovered as significant contributors to our current climate change crises, along with possessing compounds that are a detriment to human health.

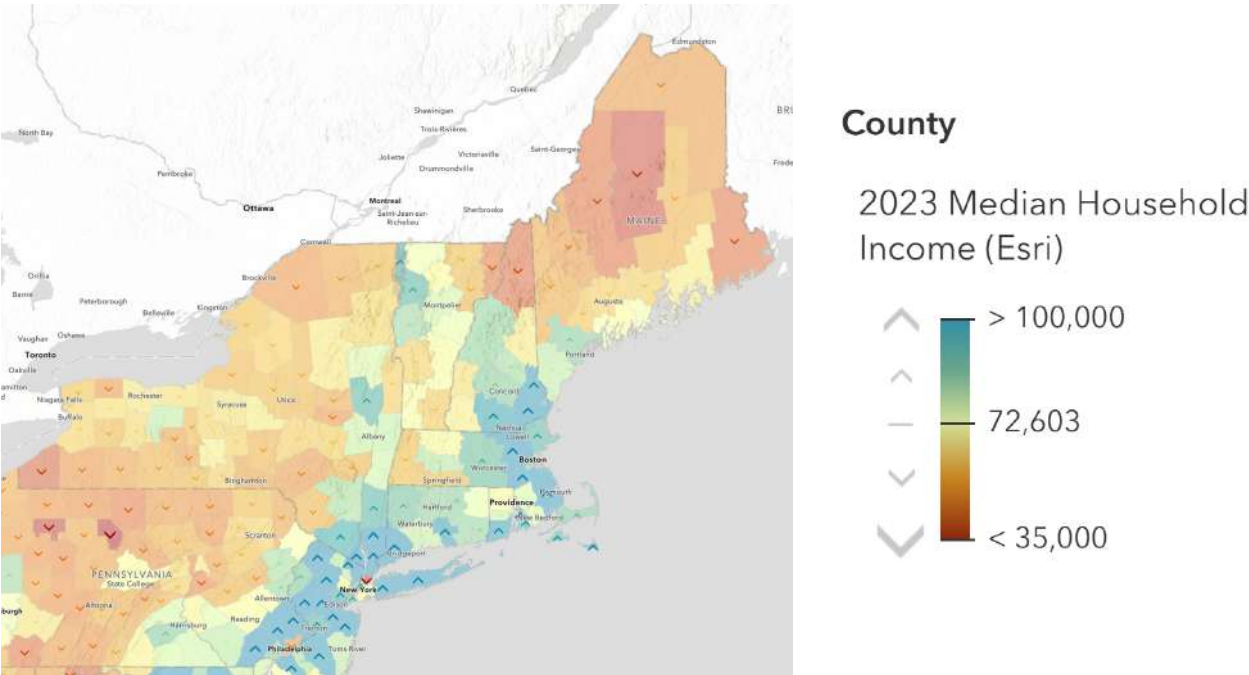
The northeastern United States is generally associated with economic prosperity, vibrant metropolitan areas, and educational institutions. However, the vast area of rural land and its communities tell a different story. The quality of life in most rural communities of the Northeast is characterized by socioeconomic disadvantages that come as a result of economic disparity from declining traditional industries and few job



opportunity, a decrepit housing stock in need of costly repair, and a general inaccessibility to quality healthy living environments. Most rural-county households in the region live on a median household income that is below the national average—and with the cost of living in all areas of the country continuing to rise, the rural communities like those in the Northeast are some of the most susceptible to their quality-of-life further declining.²

With the financial limitations amongst rural communities, their avenues and solutions for housing are often characterized by the a priority for immediate affordability. Beyond a typical site-built house, a common solution for deriving a more affordable home is through a

system of prefabrication and mass production. In this case, the two most common housing types that come from this method of production are manufactured homes (previously referred to as mobile homes) and modular homes.



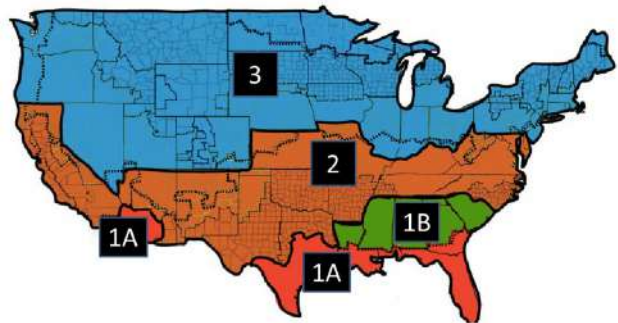
2023 Median Household Income (United States Census Bureau)
Source: ArcGIS (Esri)

THE MANUFACTURED HOUSE

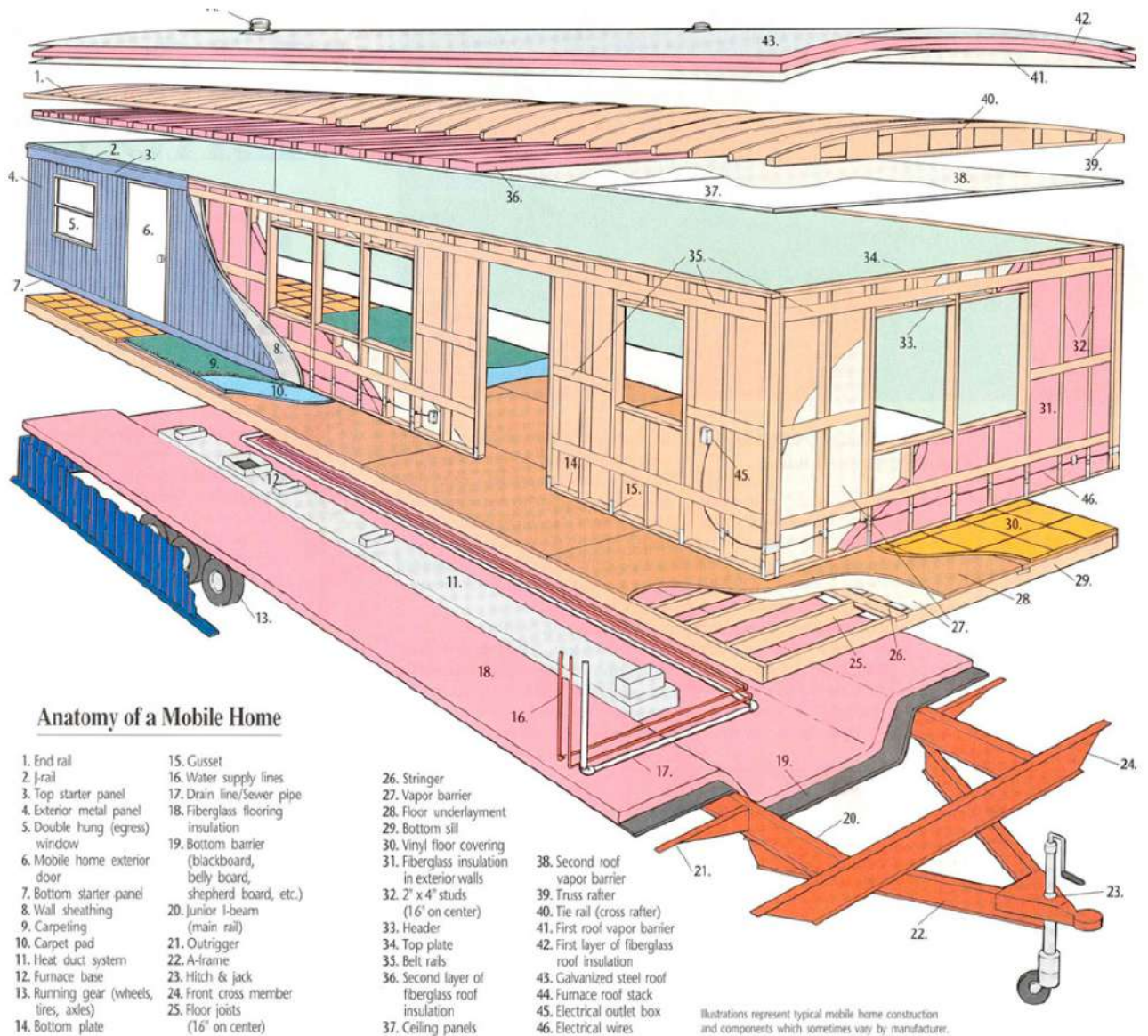
A manufactured house is a factory-built dwelling that rests on a steel chassis with wheels, being able to be transported several times in one whole piece if desired. Their affordability is derived from their greatly reduced labor and construction costs to build, which are streamlined off-site in a climate-controlled factory, and shipped to the consumer destination. Coming as “single-wide” or “double-wide” units, the shape of a manufactured home is almost always that of an elongated rectangle, mimicking the shape of a semi-truck’s trailer bed. With this, and that these homes are most commonly situated in developer-owned manufactured housing parks, they become a very attractive choice in terms of up-front cost for low-income and fixed-income-retirement households.

However, manufactured homes possess several drawbacks that work against the pursuit of prosperity amongst individuals who dwell in this housing type. One factor is that these homes are not built to IBC (International Building Code) standards like typical homes are, but instead follow HUD (U.S. Department of Housing and Urban Development) standards. HUD provides a generalized national standard for these homes, with some regional variations that cover large and diverse geographic areas, to be manufactured to. While this may streamline the permitting process by bypassing the need to follow local codes, this also results in a standard that fails to consider the wide climate-variations throughout the country—ultimately leading to poor performance in certain locations. Furthermore, this may reduce their potential to build equity, especially if they are not

located on privately-owned land. Instead, they typically depreciate at faster rates compared to conventional homes,³ and since these homes most often exist within manufactured housing parks, households must additionally rent the land that their manufactured home rests on, and pay any additional regular fees placed upon them by the park owners. In terms of durability, manufactured homes can have similar duration as traditional site-built homes before need for renovation, and have an average life expectancy of 30-55 years before the need for major repair or entire replacement (U.S. Department of Housing and Urban Development), making them unsustainable as long-term housing stock. The materials that go into the production of these dwellings apart from their structural frames are primarily characterized by steel, and petroleum-derived products, with their only biogenic components, such as the light-wood frame structure, being covered by non-biogenic finishes. These materials contribute to an increasing carbon footprint of construction.



HUD Climate Zones for Manufactured Home Standards
Source: U.S. Department of Housing and Urban Development



Assembly Components of a Manufactured Home

Source: Chini et al., (2017). *Basics of Manufactured Construction*.

THE TYPICAL MODULAR HOUSE

The typical modular house is much like a manufactured home in that its production system encourages up-front affordability through reduced construction costs. Like manufactured houses, modular houses are also fabricated primarily in climate-controlled factory settings, where volumetric modules are then shipped to the site and attached together. While very similar to manufactured houses, modular houses do not remain on a chassis with wheels, but are instead designed to be mounted to a permanent foundation. This, in turn, allows them to be treated as a conventional house, following IBC and local standards as opposed to HUD, and developing equity like typical homes do. While slightly costlier to go through a local building department inspection, this inclusion of local jurisdiction code ensures a higher potential for climate-considered design requirements. Additionally, the formal possibilities of a modular home are much more flexible than manufactured homes due to the fact that individual volumetric pieces are taken off their shipping chassis and attached to other volumes in various configurations. This allows modular homes to look similar to site-built homes, and have multiple levels.

The current state of modular homes in terms of non-structural assembly components, however, are not much different from manufactured house standards of quality, thus suffering from the same carbon and energy inefficiencies in their materials and performance. While gaining the benefits of prefabricated, climate-controlled construction and

increased construction efficiency to reduce costs, the average modular home that currently exists has yet to address construction methods that result in sustainable material utilization, or long-term durability and carbon offset, primarily due to its finishes and cladding. The average interior environment of these dwellings consists of finishes such as drywall (gypsum board) or vinyl wall panels, vinyl-laminate flooring, carpet, and latex paints. These products are predominately petroleum-based, and/or off-gas volatile organic compounds (VOC's) that are adverse to occupant health.⁴ Modular house manufacturers, of course, would not mention these conditions, but instead advertise superficial qualities [as shown in the image to the right]. With these conditions in mind, there exists great potential to improve the quality and condition of the modular housing model in the rural Northeast, which could derive greater long-term affordability and health benefits for households that choose to live in these type of dwellings, as well as more durable and sustainable construction methods for the environment and local economy.



Image of a Typical Modular Home Model.
Source: Key Homes



Note:

The steel chassis are used only for transportation, and detached after delivery to site.

Anatomy and Advertisement of a Typical Modular Home
 Source: Franklin Prefab Homes

VERNACULAR ARCHITECTURE

TRADITIONAL HOUSE CHARACTERISTICS

Vernacular architecture is a term that describes a historically regional style of building, in which its design characteristics are directly tailored to address the local climate, resource availability, and culture. Comprising some of the oldest colonial settlements in North America, the Northeast has a deeply embedded vernacular style of architecture—and while there are many different typologies that are present under this description, they all share similar core characteristics.

In a region heavily forested and with European involvement beginning as far back as the seventeenth century, wood was typically the sole material of choice and availability for homes. These

homes were designed to combat the harsh winters that define the Northeast's climate. As a result, the typical house generally featured a compact form with centralized heating for thermal efficiency, and steep roof pitches to shed the significant amount of snow and rain that the region experiences.

The lessons about form and material that can be learned through the vernacular architecture of a certain place can provide useful information for designing a building that may appropriately perform in its respective climate.



A Saltbox Colonial-style House

Source: National Register of Historic Places; National Park Service



*[Top] A Cape Cod-style House
Source: National Register of Historic
Places; National Park Service*

*[Bottom] A New England Connected-Farmhouse-style House
Source: National Register of Historic Places; National Park Service*



A2





THE NORTHERN FOREST

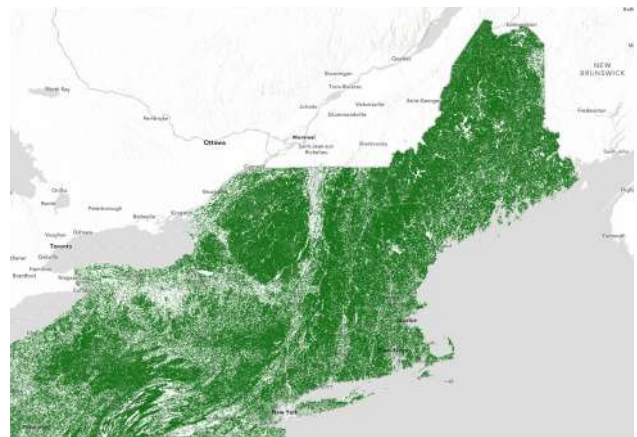
STATE OF THE FOREST SECTOR

THE NEED FOR NEW PRODUCTS

The Northeast United States is a region with bountiful forest and timberland. Similar to areas such as the Pacific Northwest, there is an abundance of sawtimber trees of sufficient structural grade for use in advanced wood products such as mass timber products. With a long history of forestry, and the sheer amount of trees existent throughout the region, there is considerable potential for sustainable forestry practice. Historic products of the Northeast range from pulp and paper products (primarily in Maine) to sawn lumber.⁵

In recent times, however, the forestry industries of the United States—including the Northeast—have struggled to produce enough conventional wood products to meet the vast housing demand. “Housing construction in Canada and the United States is undersupplied, indicating pent-up demand. Both countries face similar problems in the construction of houses: lingering [COVID-19]

pandemic effects and discrete product availability,” (Abidov et.al., 2023).⁶ One method in which this issue may be addressed is by identifying and creating new, local advanced wood products that would stimulate new production and increased revenue for the region. Among the various profitable options available to Northeastern states for developing local wood products, mass timber products from sawn lumber are among the top competitive choices, especially in New York, Vermont, and New Hampshire.⁷



Areas with > 75% Canopy Coverage per Acre in the United States and Northeast
Source: ArcGIS (Esri)



MASS TIMBER AND CLT

Mass Timber products are a category of engineered wood products, which consist of the adhering and layering of sawn lumber, veneer, or chips and strands to create large structural panels, columns, and beams. Cross-Laminated Timber (CLT) and Glue-Laminated Beams and Columns (Glulam) are two mass timber products that are made from sawn-lumber, making them viable products for Northeast production. Glulam and CLT can be substituted for steel and concrete in floors and roofs of predominately mid to high-rise buildings. CLT may also be used as a structural wall element.

Furthermore, CLT panels are prefabricated in factories, milled with precision-machinery, and can be utilized in panelized systems at all building scales. This mass timber product has a significant potential to stimulate local forestry industries in the Northeast, which would create high-value jobs for rural communities throughout the manufacturing supply chain and generate regional rural economic development. Pairing this product with non-structural forest products such as cladding elements and insulation would even further stimulate the forest sector for rural communities of the Northeast.



Types of Mass Timber Products
Source: Mass Timber Institute, University of Toronto

With the current conditions of significant carbon emissions in the building sector, the need to reduce or even reverse this intensity is of crucial concern. CLT is a carbon-sequestering biogenic structural material that can replace conventional high-carbon materials such as concrete and steel, allowing it to possess the potential for addressing carbon-reduction in the building sector. Being derived from trees—a renewable resource—CLT stores and retains its embodied carbon for the duration of its lifetime. Being an extremely durable solid panel, the lifetime of CLT may easily extend beyond 100 years with proper protection. Its panelized structural system also creates a condition in exterior wall applications where the insulation of a building must be treated as its own separate layer, as opposed to how insulation is incorporated in conventional light-wood frame construction. This separation results in more airtight enclosures with less thermal bridging and heat gain/loss, as there are significantly less seams or joints for air to potentially pass through.

With no current CLT manufacturing companies located in the Northeast, the localized benefits of this product still have yet to be fully understood and realized, with the closest CLT products being imported from Canada. Foreign CLT products from countries such as Canada and Austria frequently remain the cost-competitive choice for northeastern mass timber projects. These products, however, often embody high amounts of carbon through transportation distance, and are not immune to political-economic conditions such as tariffs. Locally-produced CLT in the Northeast could avoid these drawbacks, and allow CLT to achieve its greatest potential for sustainability.



TREE SPECIES FOR CLT

STATE OF LOCAL RESEARCH

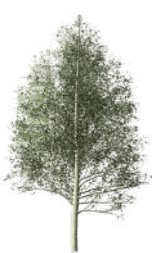
Innovative mass timber products made from local species found in the Northeastern region of the United States and Canada have become a developing interest for research. With the great diversity of worthy tree species—both hardwood and softwood—the potential for their respective applications in mass timber products are being tested and the results published. Recent developments of hardwood mass timber testing have been demonstrated in several studies, such as the testing of yellow poplar in “Mechanical Performance of Yellow-Poplar Cross Laminated Timber,” (Charles, et. al., 2015), red maple, sweetgum, and sycamore in “Compressive Properties of Cross-Laminated Timber Panels Made of Hardwood Tree Species from the Appalachian Region,” (Palacio-Betancur, et. al., 2023), red oak and soft maple in “An Evaluation of Low-Grade Red Oak and Soft Maple as Raw Material for Cross-Laminated Timber Panel Production,” (Hassler, et. al., 2024), and trembling aspen in “Evaluation of Major Physical and Mechanical Properties of Trembling Aspen Lumber,” (Wang, et. al., 2024). Furthermore, there have been several tests utilizing a hybrid approach of combining hardwood and softwood species into a mass timber panel. Examples include sugar maple & white spruce in “Mechanical Property Evaluation of Hybrid Mixed-Species CLT Panels with Sugar Maple and White Spruce,” (Ma, et. al., 2021) and black locust & eastern white pine in “Investigating the Out-of-Plane Bending Stiffness Properties in Hybrid Species Diagonal-Cross Laminated Timber Panels,” (Kurzinski, et. al., 2024).

With a clear current interest in utilizing hardwoods in mass timber panels, its viability for realization will likely only grow in potential. However, recent analyses that have been done into the hardwood and mass timber manufacturing industries of North America have revealed the current conditions that hardwood mills are generally not prepared with the proper equipment, such as a four-side planer, a certified lumber grader, and adequate kiln capacity.⁸ Additionally, hardwood lumber grading systems are currently done based on visual appeal with varying dimensions, rather than the dimensional structural grade like that of softwood lumber and CLT. “All CLT manufacturers agreed that the first step to the successful implementation of hardwood and hardwood-softwood hybrid CLT would require the production of dimensional grade hardwood lumber by hardwood sawmills.” (Adhikari, et. al., 2020).⁹ For this reason, it will take some time before hardwood species may be considered viable in CLT on a commercial scale.

In the use of Northeastern softwood species in CLT, there has been testing with virtually every species, with some species already being utilized for CLT manufacturing. One study, “Bonding Performance of the Ten Species in the Spruce-Pine-Fir (South) Lumber Grouping for Cross-laminated Timber,” (Snow, et. al., 2021) looks into the performance of the ten commonly used Northeast softwood species for CLT. Another study—directly related to this project—is, “Feasibility of Two Northeastern Species in Three-Layer ANSI-Approved Cross Laminated Timber.” (Clouston, et. al., 2021).

NORTHEASTERN TREE SPECIES TESTED IN CLT

HARDWOODS



TREMBLING ASPEN



BLACK LOCUST



YELLOW POPLAR



MAPLES



SWEETGUM



SYCAMORE



RED OAK



SPRUCE-PINE-FIR
GROUP



EASTERN WHITE PINE



EASTERN HEMLOCK

TESTED IN THE
SAME STUDY

TREE SPECIES COMMERCIALY ADOPTED



EASTERN
HEMLOCK

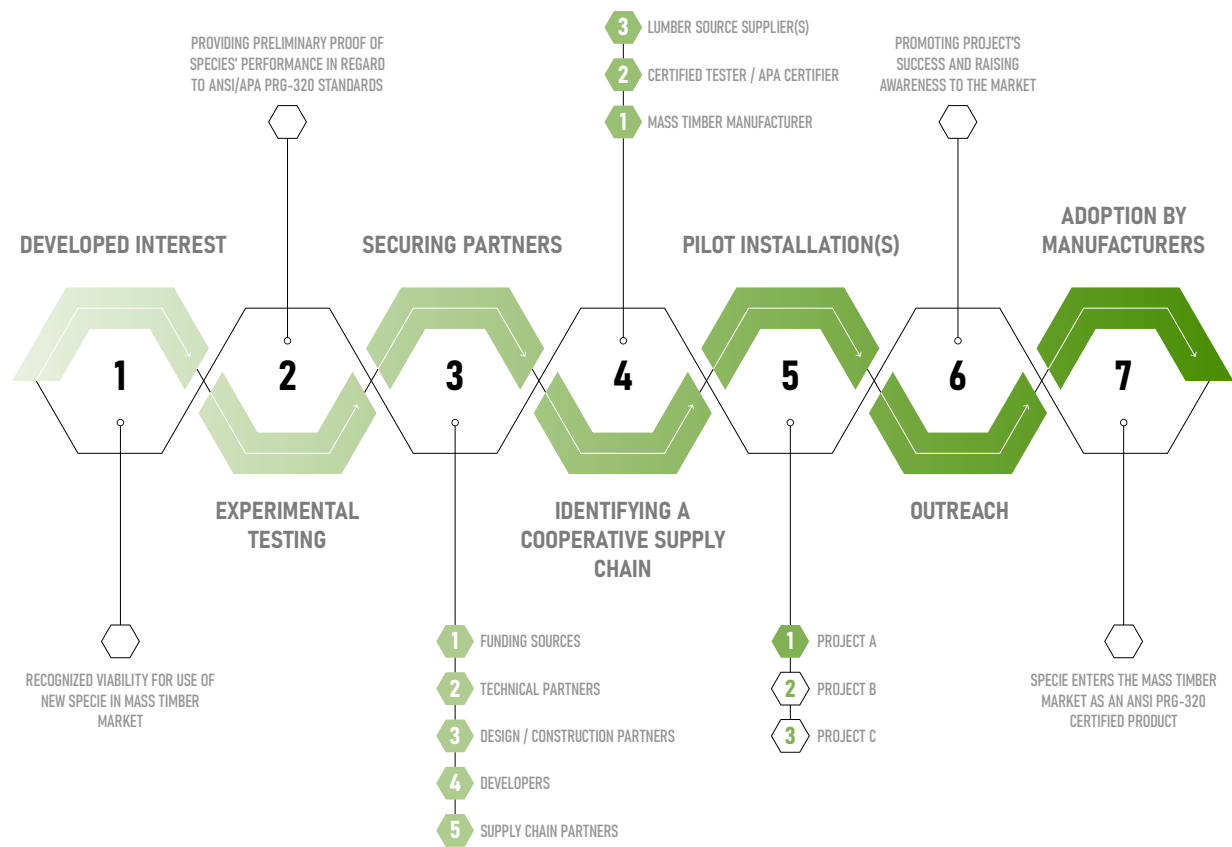


SPRUCE-PINE-FIR
GROUP

In “Feasibility of Two Northeastern Species in Three-Layer ANSI-Approved Cross Laminated Timber,” (Clouston, et. al., 2021), the two species of interest for testing in this paper were eastern hemlock and eastern white pine. The study concluded the satisfactory performance of both species for use in three-layer CLT, with Eastern Hemlock performing better than Eastern White Pine. As a result, Eastern Hemlock has gone on to be utilized in pilot projects such as the Fairbanks Museum addition in St. Johnsbury, Vermont, and has been adopted for commercial CLT manufacturing by Sterling Structural.¹⁰ Based on the case of Eastern Hemlock adoption by manufacturer, the process by which a new species makes its way into the mass timber market is mapped out below.

While eastern hemlock and eastern white pine were proven satisfactory for use in ANSI-approved CLT¹¹, the eastern hemlock was adopted by the industry and eastern white pine did not progress beyond the “Experimental Testing” stage, most likely due to its lower-end strength performance. This project seeks to explore and discover an appropriate competitive application for Eastern White Pine CLT, to support pilot installation and provide traction for adoption.

NEW SPECIES APPROVAL PROCESS







A3



EASTERN WHITE PINE CLT

TREE SPECIE SELECTION FOR CLT

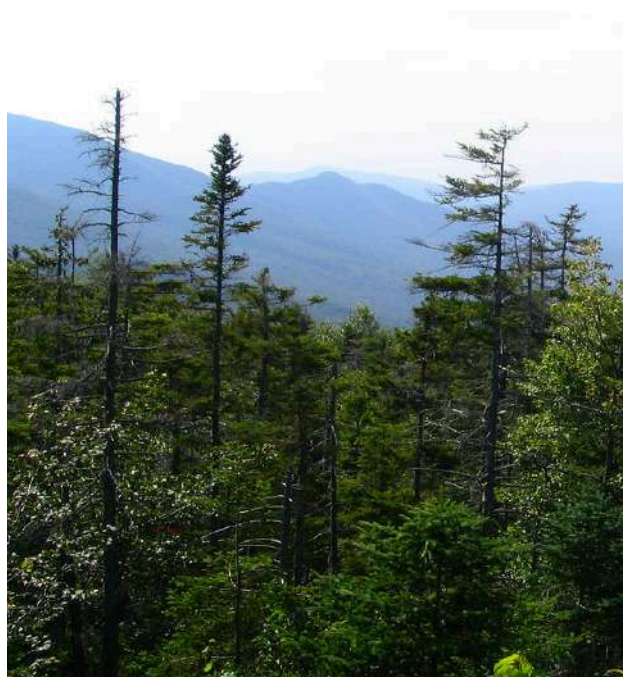
EASTERN WHITE PINE

While Eastern White Pine had been shown to meet strength-requirements for three-layer ANSI approved CLT, its performance was less competitive than Eastern Hemlock. This does not mean that it could not be used competitively in selected applications. The current CLT industry is catering its products towards mid-rise and high-rise construction and larger institutional buildings. The lower performance Eastern White Pine CLT might then be competitive in applications for low-rise structures, where the current CLT industry is not heavily focused or established. The higher performance species such as the eastern hemlock in the Northeast, or douglas-fir in the Pacific Northwest as preferred species for CLT would be better utilized to address building types with higher performance requirements. For many low-rise structures that could be constructed with lower performance requirements Eastern White Pine CLT could be a more efficient solution, and potentially be lower cost, due to the species' abundance. The eastern white pine, a species still proven strong enough for use in three-layer CLT, could fill the niche and offer competitive mass timber options for low-rise architectural applications.

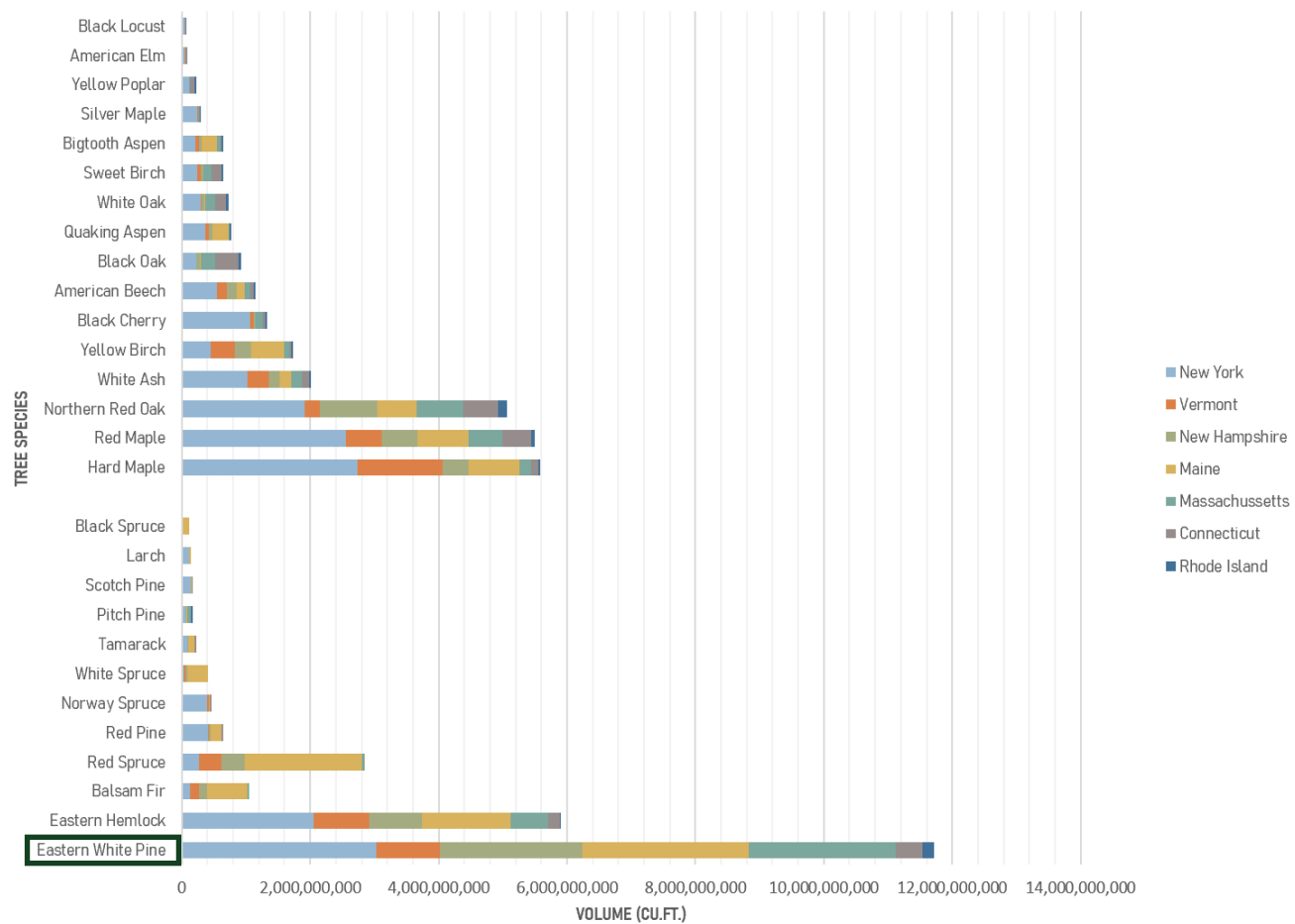
The eastern white pine (EWP) is the most widely abundant softwood tree across all northeastern states. Furthermore, it is a historically significant tree for sawn lumber in the region, with the potential for existing and robust supply chains for graded lumber likely to already have an established presence. This makes the introduction of EWP CLT in commercial manufacturing more achievable

and efficient than other local species—including the eastern hemlock; whose supply chain is not readily functional at the current time.¹²

Considering the availability and performance of EWP, this project will explore the use of the EWP CLT for single-family housing. The Northern Forest Center, an organization based in the Northeast, is currently exploring this potential market, having identified a specific need for mass timber modular housing (Northern Forest Center, 2024). Through design, this hypothetical mass timber product will be showcased for use in modular single-family housing in the Northeast, where it might be most competitive and will complement other ongoing efforts.



NET SAWLOG VOLUME OF SAWTIMBER TREES ON TIMBERLAND [cu.ft.]



Net Sawlog Volume of Sawtimber Trees on Timberland, 2023
Source: USDA Forest Service, EVALIDator Analytics Tool



Source: OPAL Architecture



CASE STUDIES

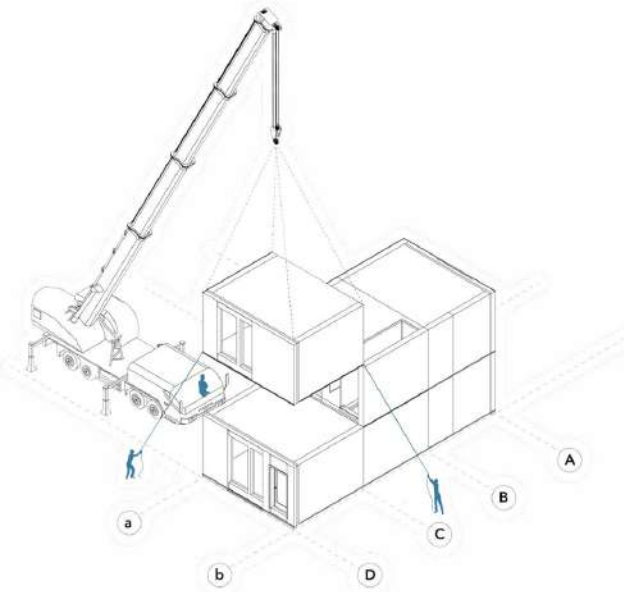
OVERVIEW

MASS TIMBER MODULAR HOUSING

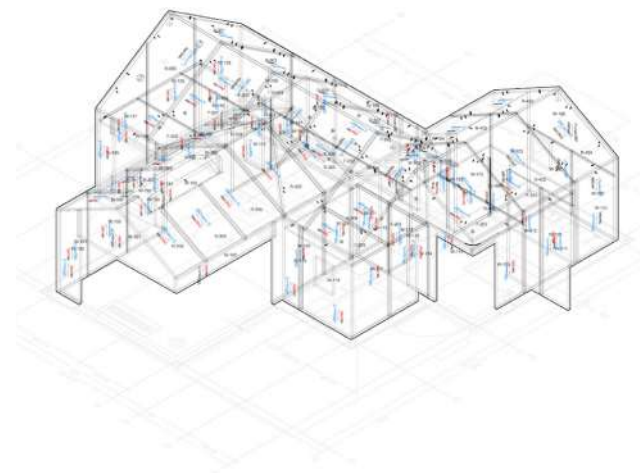
Single-family and multi-family mass timber modular housing projects have been completed in various locations throughout the world—which aids to support the interest and viability of these products in this sector.

Several North American case studies are represented in this book to provide real life examples of mass timber integration into residential architecture, with a primary focus on single-family applications. The projects were analyzed for their construction methodology, as well as the outcomes of each mass timber system. Additionally, the case studies served to inform what method of modularity that the BioMOD system would employ—being either a volumetric or panelized format for modularity. Three volumetric modular projects and three panelized modular projects were selected for analysis to represent the general characteristics of each method for modularity in construction.

VOLUMETRIC MODULAR



PANELIZED MODULAR



[Top] Volumetric Modular diagram
Source: Green Canopy NODE

[Bottom] Panelized Modular diagram
Source: OPAL / SHELTER

[Right] Mass timber interior image
Source: OPAL Architecture





01

GREEN CANOPY NODE

OVERVIEW

Green Canopy NODE is a design and development company that focuses on creating systems for change in the housing and development sector by addressing the various challenges of conventional construction systems. One method that Green Canopy NODE has created is their prefabricated mass timber building kit system, which consists of volumetric CLT modules that are craned in-place on site to aggregate into a full home. The Mass Timber Model Home was a pilot project done to test their mass timber system, which has now gone on to be offered for various housing typologies by the company.

Additional to the mass timber building kits, Green Canopy NODE also produces prefabricated utility kits, which greatly streamline MEP installation and coordination with both mass timber and stick-frame construction.

Location(s)
Seattle, WA

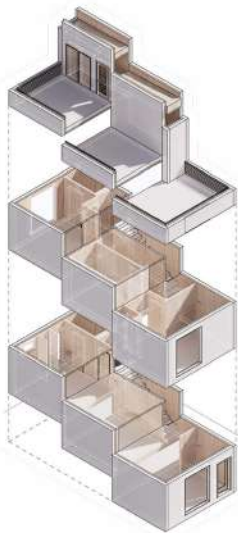
Modularity Type
VOLUMETRIC

Mass Timber Supplier
Mercer Mass Timber | Vaagen Timbers

CLT Wood Species
DF-L | SPF | HF

** Wood species based on CLT Manufacturers' information*

EST. Cost per Square Foot
BASE: \$200-\$250+
TURNKEY: \$350+



Prefabricated Mass Timber Building Kits

Prefabricated Mass Timber Building Kits deliver increased efficiency, enhanced sustainability, health benefits, and unparalleled aesthetics, making it an ideal choice for developers and investors interested in low- and mid-rise residential construction technology.



Prefabricated Utility Kits

Prefabricated Utility Kits reduces the traditional mechanical, electrical, plumbing install time by 50%, eliminating a significant source of inefficiencies and call backs. The systems are pre-constructed in an off-site factory during site work to ensure a smooth and seamless installation process during the framing phase.

*[Left] The Mass Timber Model Home exterior image
Source: Green Canopy NODE*

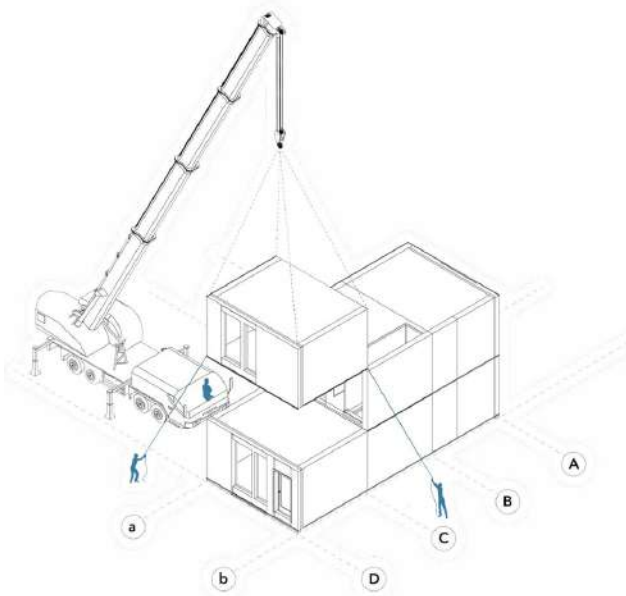
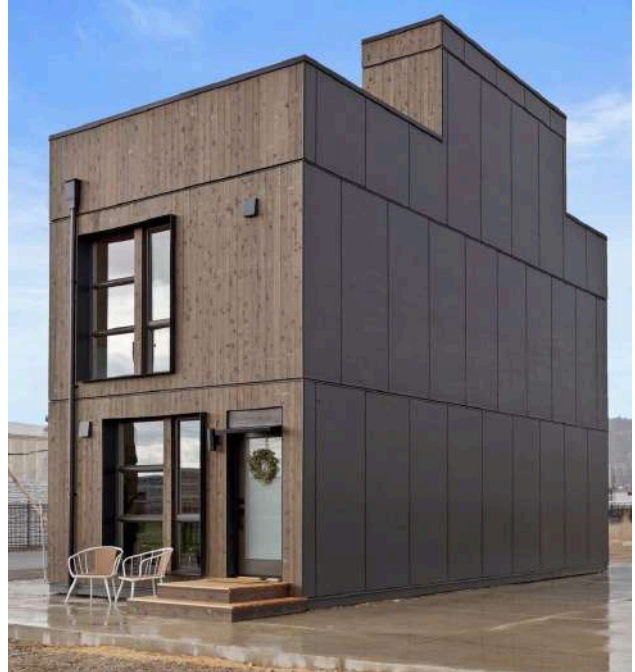
*[Right] Modular integrated kits offered by the company
Source: Green Canopy NODE*

THE MODEL HOME

SIZE: 1200 SF BEDS: 2 BATHS: 1.5

The Mass Timber Model Home is the first product to be built from Green Canopy NODE's prefabricated mass timber building kit system. In collaboration with Mercer Mass Timber, the model is comprised of six primary CLT living volumes which were fabricated in Mercer's factory. After fabrication, the modules were put on a semi-truck and shipped to the site, where they were craned into place, attached to one another, and dressed with the exterior finish cladding.

The interior of the Model Home expresses almost all of the CLT panels as the finish surfaces, retaining the biophilic benefits of the material for the space. In terms of furnishings and square footage, the design can be said to be aimed at providing a familiar scale and layout to conventional townhomes.



[Left] On-site volumetric construction diagram
Source: Green Canopy NODE

[Top Right] The Mass Timber Model Home exterior image
Source: Green Canopy NODE

[Middle Right] The Mass Timber Model Home interior image
Source: Green Canopy NODE

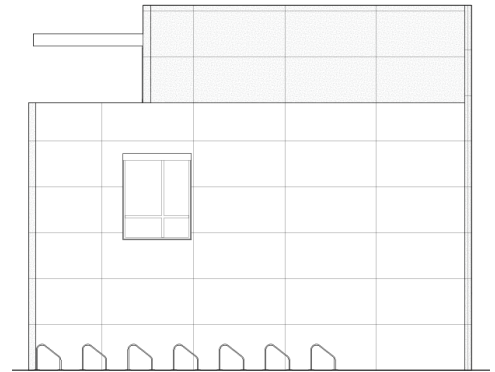
[Bottom Right] CLT modules being fabricated at Mercer Mass Timber
Source: Green Canopy NODE

TOWNHOMES MODEL

SIZE: 1439 SF BEDS: 3 BATHS: 2.5

The Townhomes model offered in Green Canopy NODE's prefabricated mass timber building kits catalogue is quite similar to the Mass Timber Model Home design, yet even larger in square footage. Moving up to be a three-story townhome, this model is likely comprised of eight volumetric CLT modules, and accommodates an extra bedroom and bathroom when compared to the Mass Timber Model Home.

Being 14'6" wide, and considering the construction's volumetric system, the prefabricated modules that make up the design will incur Oversize Load requirements during transportation, which may increase challenges in cost and logistics in shipping.



*[Top] Townhouse side elevation drawing
Source: Green Canopy NODE*

*[Middle] Townhouse front elevation drawing
Source: Green Canopy NODE*

*[Bottom] Townhouse model floor plans
Source: Green Canopy NODE*

COTTAGE HOMES MODEL

BASE COTTAGE HOME

SIZE: 1429 SF BEDS: 3 BATHS: 2

The Cottage Homes Model by Green Canopy NODE offers several home sizes for a housing development typology that has been gaining interest. The Base Cottage Home is a two-story design made from the company's volumetric module system. It is unclear exactly how many modules there are or their size, however the layout of the home indicates subjectively awkward spaces with unbalanced storage, which are a potential result of the constraints that result from working with predetermined volumes that must come together to form a specific footprint.

The Studio Cottage Home model is an affordable dwelling for individuals or couples. It is comprised of a living space, a bathroom space, and a transitional space for entry and circulation.

An ADA-Visitable model is also offered, which shares similarities to the Base Cottage Home.



[Left] Base Cottage Home elevation drawings
Source: Green Canopy NODE

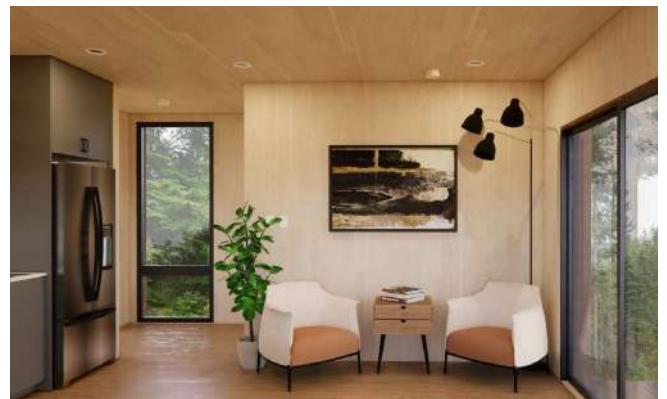
[Upper Right] Base Cottage Home exterior render
Source: Green Canopy NODE



[Lower Right] Base Cottage Home floor plans
Source: Green Canopy NODE



STUDIO COTTAGE HOME
 SIZE: 424 SF BEDS: 0 BATHS: 1



*[Top] Studio Cottage Home
 exterior render
 Source: Green Canopy NODE*

*[Middle] Studio Cottage Home
 interior render
 Source: Green Canopy NODE*

*[Bottom] Studio Cottage Home
 floor plan
 Source: Green Canopy NODE*



COMPANY FINDINGS



44% faster than traditional construction.

Controls costs with pre-planned and streamlined construction.

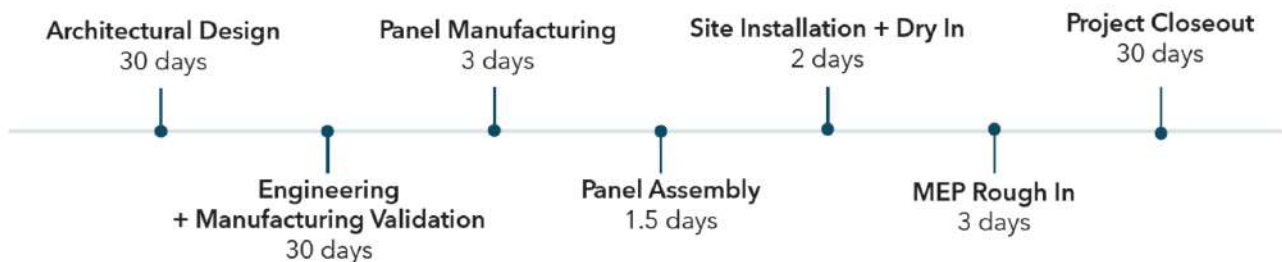
Avoids weather delays through off-site manufactured modular installation

6.6x more carbon storage than a stick-frame home

Less than 100 days from project start to completion



Mass Timber Model Home Timeline < 100 Days



*[Top] Company statements about the prefabricated mass timber building kit system
Source: Green Canopy NODE*

*[Bottom] Creation timeline of the Mass Timber Model Home
Source: Green Canopy NODE*

KEY TAKEAWAYS

-  A volumetric CLT modular system can be translated to serve various housing typologies.
-  A prefabricated utility kit is an effective way to streamline MEP installation and coordination efficiency.
-  While a volumetric modular system allows for the fastest possible on-site assembly, the cost and logistics of transportation can be challenging.
-  A multi-segment, multi-story volumetric CLT modular system utilizes more fiber as a result of doubled-up walls and/or floors.
-  Interior layouts can be limited by the constraints of the volumetric module dimensions.



TIETON CABINS

OVERVIEW

Tieton Cabin Company is a primarily high-end company that designs compact cabin spaces utilizing a structural shell of CLT. Their products are designed to be shipped as a single, finished volume, making on-site assembly as simple as placing the product on a foundation.

The company's cabin plans include designs for small homes, which could be considered for ADU's, as well as several spa cabin programs. Given the company's cost-per-square-foot range and the general use of high-end, high-embodied energy materials, the decision to use CLT in their products is likely for the primary purpose of aesthetic appeal.

The volumetric nature of the cabins, when paired with their widths, likely results in the need for Oversize Load costs in shipping.

Location(s)

Tieton, WA

Modularity Type

VOLUMETRIC

Mass Timber Supplier

Mercer Mass Timber

CLT Wood Species

DF-L | SPF

** Wood species based on CLT Manufacturers' information*

EST. Cost per Square Foot

~ \$595 - \$732



[Left] The Agate Pass Model exterior image

Source: Tieton Cabin Company

[Right] A prefabricated volumetric cabin being craned into place on-site

Source: Tieton Cabin Company

THE AGATE PASS MODEL

SIZE: 282 SF + 96 ext. BEDS: 0 BATHS: 1 COST: \$240,000 COST PER SQ.FT.: ~\$635

The Agate Pass Model is a built example of a Tieton Cabin Company product. Its fabrication was completed entirely off-site at the company's workshop, leaving only the need to attach it to a foundation when it reached the site.

Structurally made from CLT, the panels also remain as the interior finish wall material of the cabin, which provides the biophilic benefits innate in wood. The rest of the design consists of materials such as cement board, extruded metal siding, and mineral wool insulation; all of which contain a high amounts of energy to produce.



[Top] The Agate Pass Model finished interior image
Source: Tieton Cabin Company

[Middle] Prefabrication image at the facility
Source: Tieton Cabin Company

[Bottom] The Agate Pass model design layout
Source: Tieton Cabin Company



*[Top] Agate Pass Model
prefabrication image
Source: Tieton Cabin Company*



*[Bottom] Agate Pass Model
prefabrication image
Source: Tieton Cabin Company*

THE CHINOOK PASS MODEL

SIZE: 216 SF + 96 ext. BEDS: 0 BATHS: 1 COST: \$220,000 COST PER SQ.FT.: ~\$705



THE OLYMPIC PENINSULA MODEL

SIZE: 444 SF + 96 ext. BEDS: 1 BATHS: 1 COST: \$340,000 COST PER SQ.FT.: ~\$630



[Top] The Chinook Pass Model design layout
Source: Teton Cabin Company

[Bottom] The Olympic Peninsula Model design layout
Source: Teton Cabin Company

THE PANORAMA POINT MODEL

SIZE: 444 SF + 48 ext. BEDS: 1 BATHS: 1 COST: \$360,000 COST PER SQ.FT.: ~\$732



THE O SPA MODEL

SIZE: 282 SF + 96 ext. BEDS: - BATHS: - COST: \$275,000 COST PER SQ.FT.: ~\$728

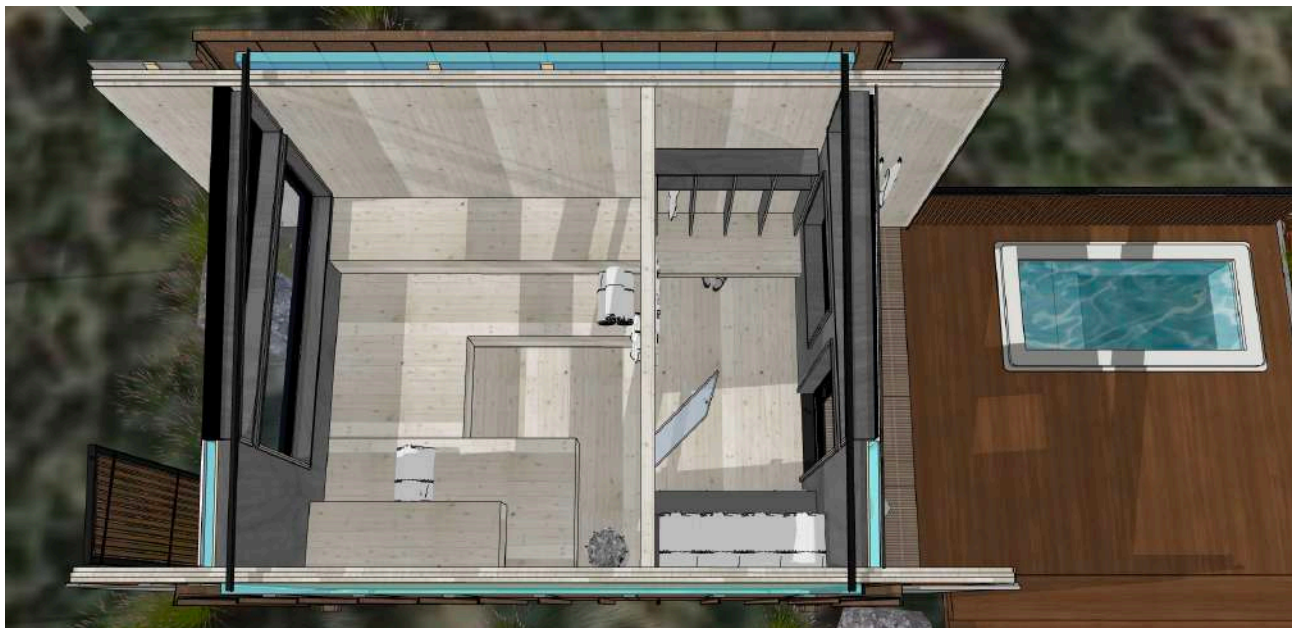


[Top] The Panorama Point Model design layout
Source: Tieton Cabin Company

[Bottom] The O Spa Model design layout
Source: Tieton Cabin Company

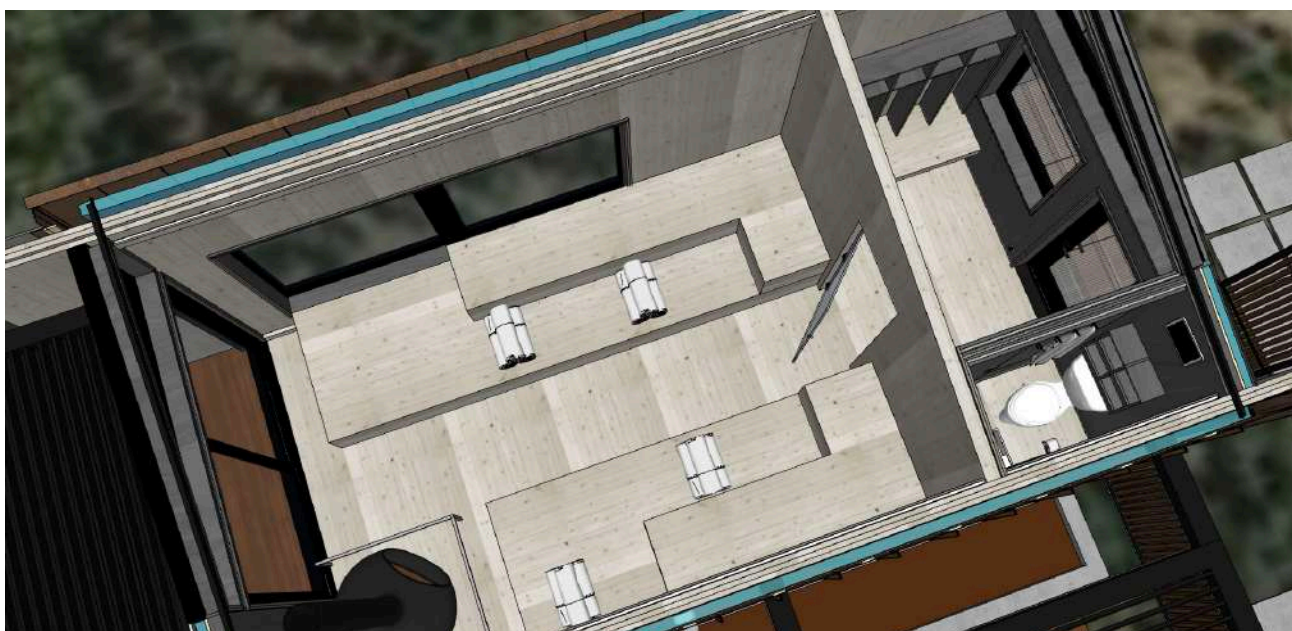
THE DRY SAUNA MODEL

SIZE: 168 SF + 96 ext. BEDS: - BATHS: - COST: \$175,000 COST PER SQ.FT.: ~\$663



THE RETREAT SAUNA MODEL

SIZE: 282 SF + 96 ext. BEDS: - BATHS: - COST: \$225,000 COST PER SQ.FT.: ~\$595



[Top] The Dry Sauna Model design layout
Source: Teton Cabin Company

[Bottom] The Retreat Sauna Model design layout
Source: Teton Cabin Company

KEY TAKEAWAYS

-  A volumetric system which entirely prefabricates a design before it reaches a site results in the utmost reduction of on-site construction costs.
-  Leveraging the aesthetic appeal of CLT in high-end design can passively bring with it CLT's carbon sequestration properties into high-cost development.
-  While a fully prefabricated space module greatly reduces on-site construction time, installation equipment and shipping logistics are likely to become more costly.
-  Combining mass timber products with high-end finishes can quickly make its cost a barrier to the vast majority.



OVERVIEW

Kalesnikoff is a mass timber manufacturing company that has also designed its own system for volumetric CLT modular units to be used primarily in multifamily housing and institutional applications. Within their modular system, the units are designed with integrated MEP systems in mind, and include prefabricated bathroom modules that can simply plug in to a module.

Being a mass timber manufacturer, Kalesnikoff is able to produce their own CLT panels, fabricate their own modules, and ship them off to be placed on site. This vertically integrated production system allows for optimized efficiency in coordination and timelines, which helps in minimizing costs.

Location(s)
Castlegar, BC

Modularity Type
VOLUMETRIC

Mass Timber Supplier
Kalesnikoff

CLT Wood Species
DF-L | SPF | H-T

** Wood species based on CLT Manufacturers' information*



*[Left] Image of Kalesnikoff's volumetric modules being fabricated in their factory
Source: Kalesnikoff*

*[Right] Attributes diagram of Kalesnikoff's volumetric module
Source: Kalesnikoff*

MULTIFAMILY HOUSING

Designed for multi-family application, Kalesnikoff's residential modules showcase a volumetric modular system for mass-repeatability, which would greatly streamline production and construction. Their unit modules are equipped with prefabricated bathroom modules, along with an efficient system for MEP integration.

Each volumetric module does not necessarily comprise an entire residential unit, but is instead intended to be combined with other modules to create finished housing units of varying sizes. This is in part to allow for efficient shipping methods, where a single volumetric module remains within the width of a semi-truck trailer bed.



*[Top] Residential Modular Unit interior image
Source: Kalesnikoff*

*[Middle] Prefabrication of volumetric space modules at the factory
Source: Kalesnikoff*

*[Bottom] On-site assembly of space modules in workforce housing
Source: Kalesnikoff & Integrated Design CUBED (IDCUBED)*

INSTITUTIONAL

Beyond residential application, Kalesnikoff has also designed a system for modular classrooms and other institutional spaces. Using the same logic as their residential modules, the finished spaces are typically comprised of multiple volumetric modules for increased flexibility and ease of shipping.



*[Top] Volumetric space modules wrapped for shipping from Kalesnikoff
Source: Kalesnikoff*

*[Middle] Modular CLT educational space interior image
Source: Kalesnikoff*

*[Bottom] Modular CLT classroom space interior image
Source: Kalesnikoff*

COMPANY FINDINGS



SPEED

With a controlled environment and minimal weather delays, modules can be constructed up to 50% faster than site-built structures.



SCALABILITY

Changes in project scope? No problem. Additional modules can be seamlessly added, allowing for expansion without disrupting operations.



QUALITY

All modules are constructed with our quality timber products to meet or exceed the same codes as conventional construction.



BIOPHILIA

Using mass timber for each module offers several physiological and psychological benefits in addition to enhanced acoustics and thermal comfort.



SUSTAINABILITY

With less waste, a reduced carbon footprint, and the ability to be reused, modular construction is a sustainable solution for a greener future.



CONSISTENCY

Through meticulous attention to detail, state-of-the-art BIM technology, and intelligent software, each module provides consistent quality and project certainty.



[Top] Advantages of Kalesnikoff's volumetric modular CLT system
Source: Kalesnikoff

[Bottom] Timeline advantages of Kalesnikoff's modular construction
Source: Kalesnikoff

KEY TAKEAWAYS

-  A vertically-integrated manufacturing and design system aids in efficiency and cohesion-logistics for a modular system.
-  Justifying the width of volumetric modules to remain easily shippable on a standard semi-truck optimizes shipping efficiency.
-  While the most efficient, a mass-repeated system within a single building may reduce variation and identity potential.
-  Shipping multiple volumetric modules to comprise a single unit proportionally increases the amount of semi-truck trips required.



04

POLYHAUS

OVERVIEW

POLYHAUS, created by Daniel Lopez-Perez, professor and architecture program-director at the University of San Diego, is a uniquely-formed panelized system for small mass timber houses and ADU's. The system utilizes a truncated-polyhedron geometry to minimize the design's footprint area, and is comprised of a carefully coordinated and prefabricated set of CLT panels. The efficiencies designed for the system were done for a primary purpose of providing a system for housing that can be rapidly produced and assembled in order to tackle the housing crises in California. While the first POLYHAUS demonstrates a 1-bedroom ADU, the company has gone on to generate designs for larger homes with the same system logic.

Location(s)
San Diego, CA

Modularity Type
PANELIZED

Mass Timber Supplier
Vaagen Timbers

CLT Wood Species
DF-L

EST. Cost per Square Foot
~ \$556



[Left] Tetra One House exterior image
Source: POLYHAUS

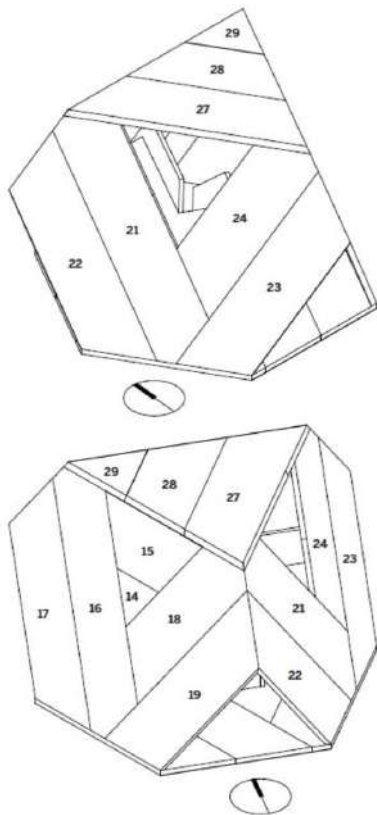
[Above] Tetra One House construction
image
Source: POLYHAUS

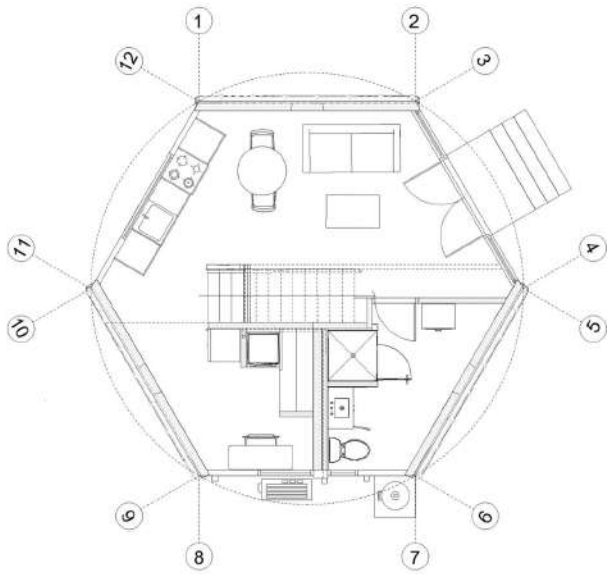
TETRA ONE MODEL

SIZE: 540 SF BEDS: - BATHS: - COST: \$300,000 COST PER SQ.FT.: ~\$556

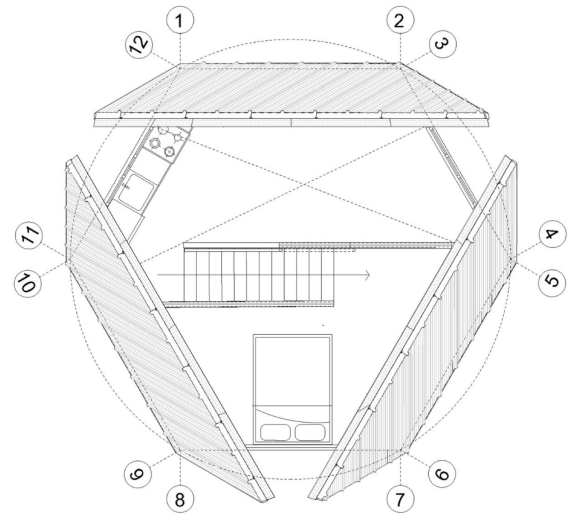
The TETRA ONE model is the pilot project of the POLYHAUS system, and is assembled from 64 individual pieces of pre-fabricated CLT components with 25 different total variations in shape. The house is comprised of 3-layer CLT for all but the floor panels, which are 5-layer.

While footprint-efficiency is a driving concept of the design, the interior spaces of the home indicate the potential challenges of making traditional spaces of a home fit within a truncated polyhedral interior.





[Far Left] CLT Panel
organization scheme
Source: POLYHAUS



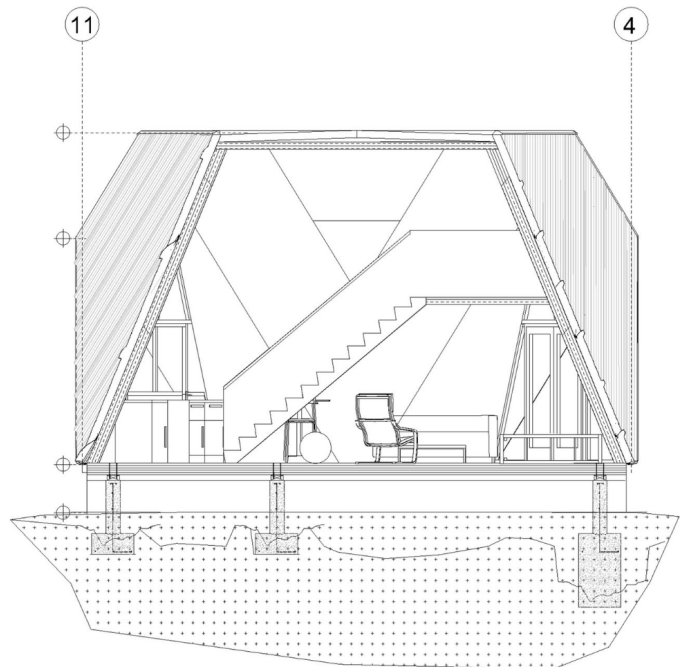
[Above] First floor plan
diagram
Source: POLYHAUS

[Top Left] Exterior image of
Tetra One house
Source: POLYHAUS

[Top Right] Second floor
plan diagram
Source: POLYHAUS

[Bottom Left] Interior image of
the Tetra One house
Source: POLYHAUS

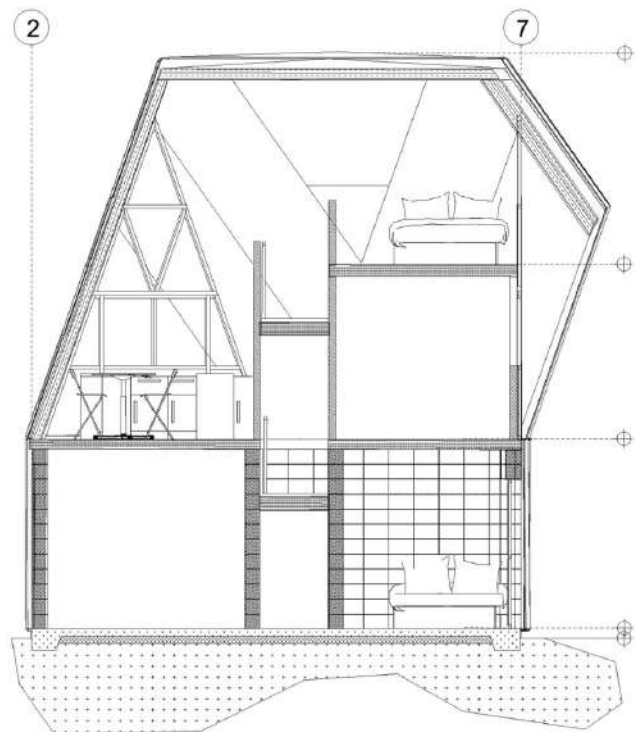
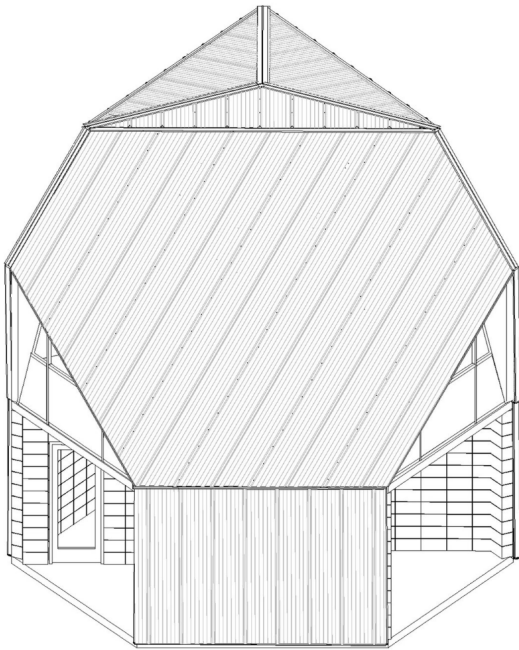
[Bottom Right] Section
diagram
Source: POLYHAUS

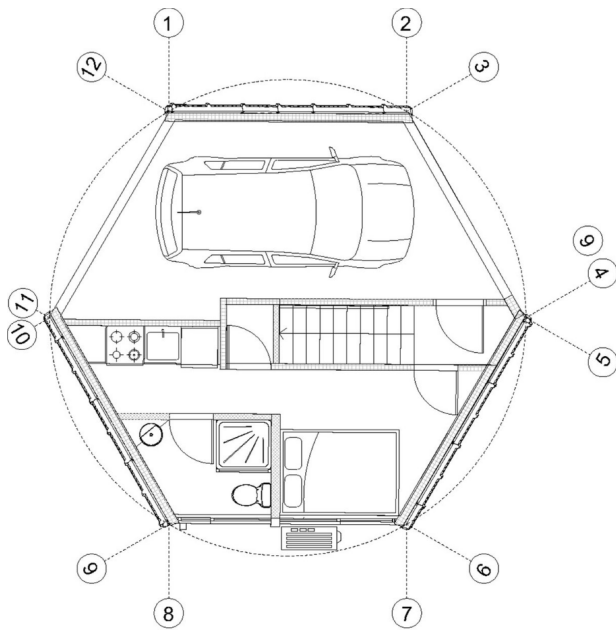


TETRA TWO MODEL

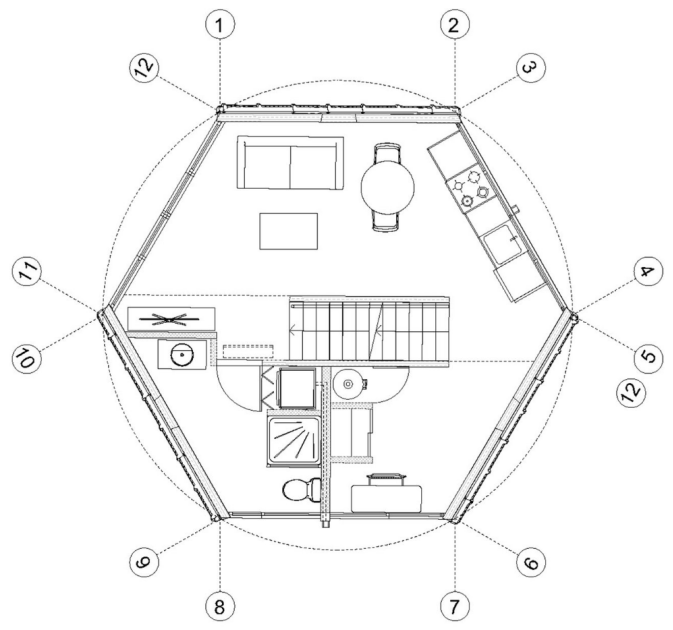
SIZE: 980 SF BEDS: 2 BATHS: 2

The Tetra Two model follows the same systematic logic as the Tetra One, but represents the possibilities for larger dwellings. Being a two-story dwelling with a loft, the design is arranged in a manner that would suggest the ability for the structure to be divided into an upstairs one-bedroom unit, and a ground-floor studio unit. This would maximize the potential of housing efficiency within the singular design.





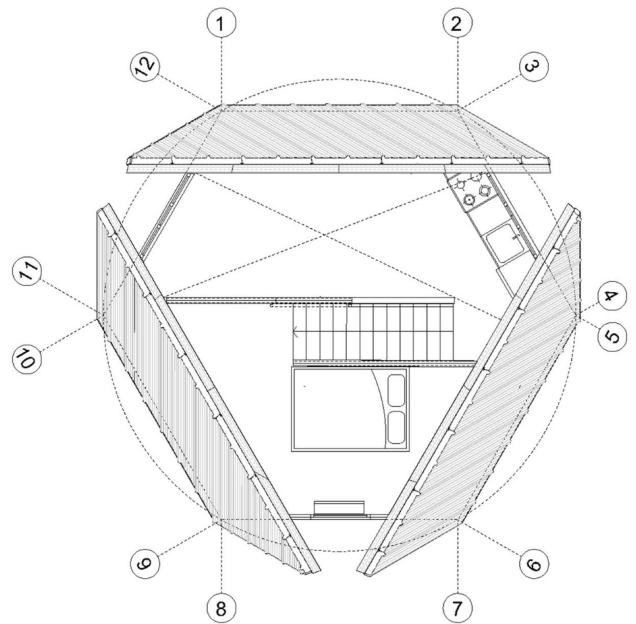
[Far Left] Tetra Two exterior
axonometric diagram
Source: POLYHAUS



[Above] Tetra Two ground
floor plan
Source: POLYHAUS

[Top Left] Tetra Two exterior
render
Source: POLYHAUS

[Top Right] Tetra Two
second floor plan
Source: POLYHAUS



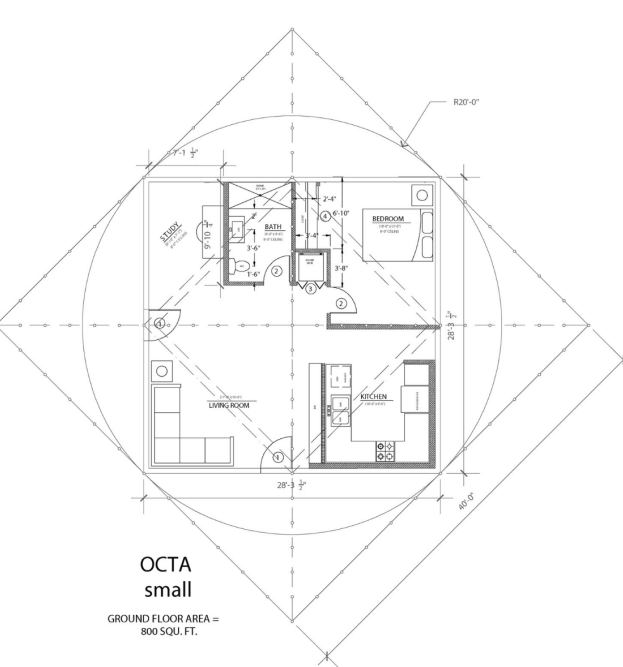
[Bottom Left] Tetra Two section
diagram
Source: POLYHAUS

[Bottom Right] Tetra Two
third floor plan
Source: POLYHAUS

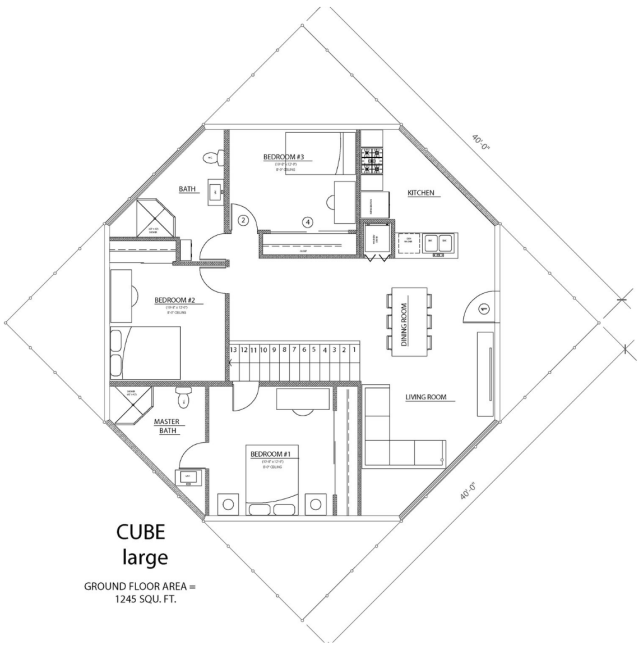
POLY-VILLAGE CONCEPT

SIZE: VARIES BEDS: - BATHS: -

The Poly-Village Concept is a vision of a community created entirely out of various POLYHAUS system designs. From one-bedroom to four-bedroom dwellings, the scope of the design system can provide a diverse development of residences.

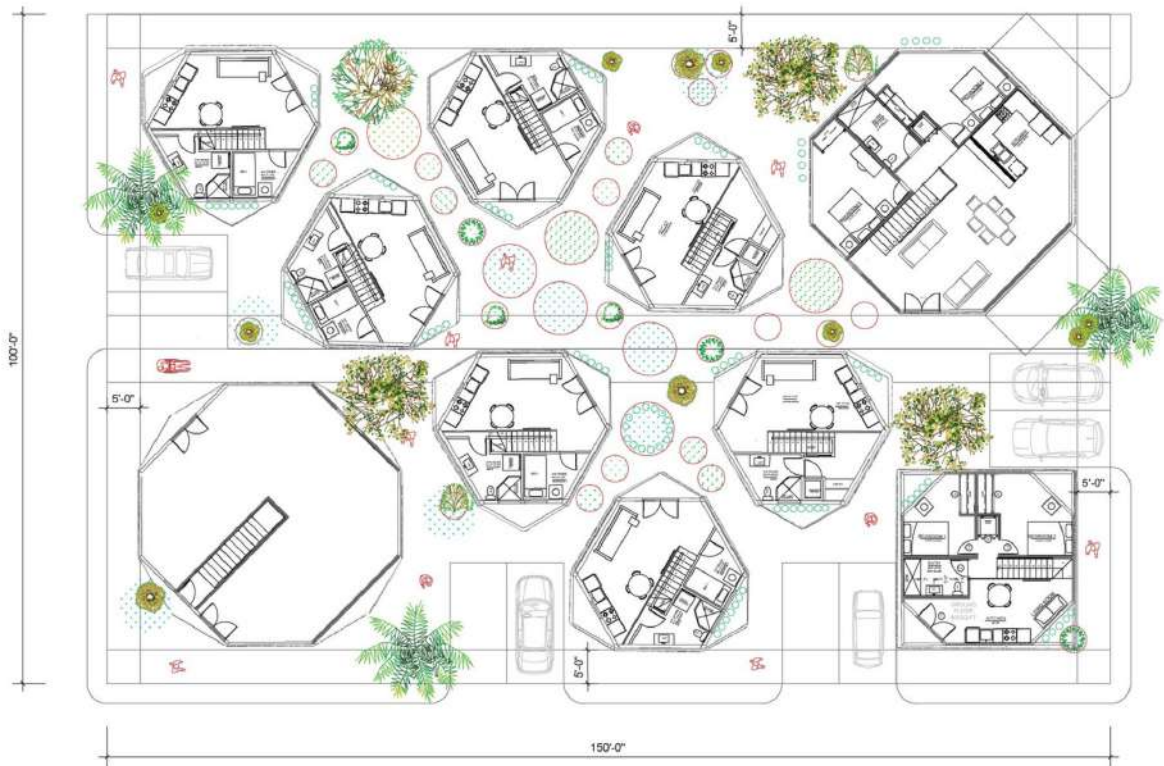


[Left] The OCTA Model floor plan
Source: POLYHAUS



[Top] The Poly-Village exterior image
Source: POLYHAUS

[Bottom Right] The CUBE Model floor plan
Source: POLYHAUS



[Top] The Poly-Village Site Plan
Source: POLYHAUS



[Bottom] The Poly-Village Roof Plan
Source: POLYHAUS

COMPANY FINDINGS



Volume-Maximizing: Polyhaus' patent-pending design methodology leverages the geometric efficiency of truncated polyhedrons, maximizing living space within a minimal land footprint. These designs also enhance orientation and use-flexibility due to their symmetry.

Rapid Assembly: Polyhaus' speed-centered building system significantly reduces time, labor, and opportunity costs. The rapid assembly is achieved by robotically (CNC) milling the Mass-timber panels that, for example, in the case of the Tetra-One model result in 64 pieces that can be assembled in just a few days, much like a puzzle.

Sustainable + Climate-Change Resilient: Polyhaus uses sustainable, highly resistant materials and advanced manufacturing techniques to achieve climate resiliency. The use of digitally fabricated Cross-Laminated-Timber (CLT) panels reduces the carbon footprint and respects ecosystems while maximizing structural and energy efficiency.



*[Left] POLYHAUS Innovation Aspects
Source: POLYHAUS*

KEY TAKEAWAYS

-  The precision achievable by prefabricated CLT components allows for immense flexibility in panelized design.
-  A minimized footprint reduces the overall costs of a project
-  While there are more space-saving shapes for homes than orthogonal shapes, typical interior space-integration may be a challenge
-  The use of Kingspan metal-and-foam exterior panels offsets the carbon benefits of CLT



05

SIERRA HOUSES

OVERVIEW

Created through collaboration between atelierjones LLC, and the Sierra Institute for Community and Environment, the Sierra Houses are a series of panelized mass timber houses designed for climate resilience against forest fires in California. Showcasing a studio, one-bedroom, two-bedroom, and a three-bedroom home, the system is comprised of panelized space modules, as well as a prefabricated wet core for efficient MEP integration. Design modules for expandability are also included within the design system.

Collaborators

atelierjones LLC | Sierra Institute

Location(s)

Greenville, CA

Modularity Type

PANELIZED

Mass Timber Supplier

DR Johnson

CLT Wood Species

DF-L

** Wood species based on CLT Manufacturers' information*



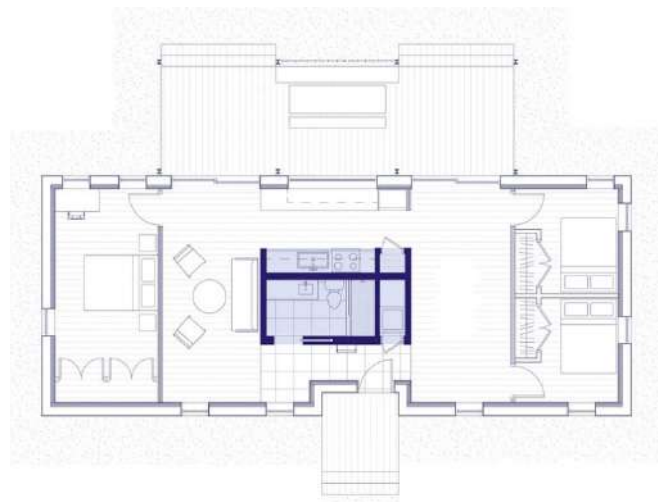
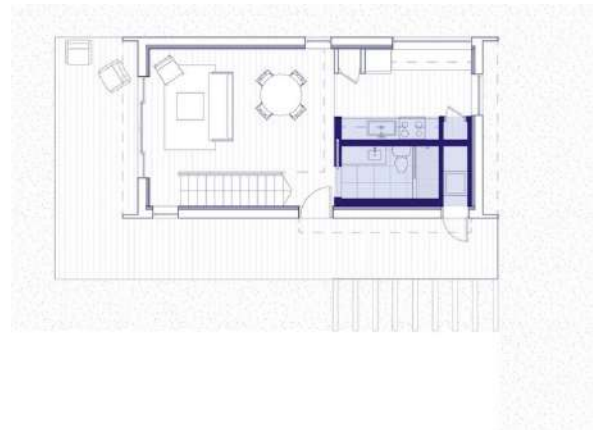
*[Left] The Sierra Houses exterior image
Source: atelierjones LLC*

*[Above] Construction image of the
three-bedroom Sierra House
Source: atelierjones LLC*

MODULAR WET CORE

The modular wet core is a prefabricated module in which all of the plumbing requirements of the home are situated in this volume. Not only does this assist in standardizing organizational layouts, but it also optimizes the efficiency of plumbing installment and integration with other systems.

The wet core comes shipped as its own volumetric module, within the design system that is otherwise a panelized modular system.

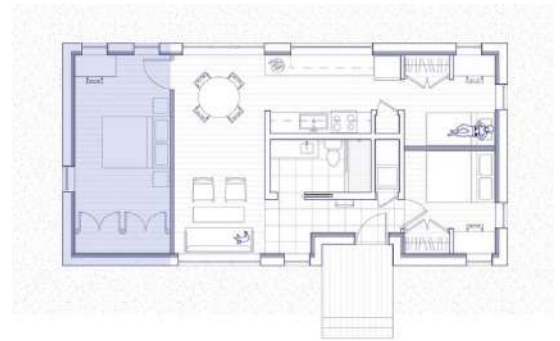


*[Left] Image of a prefabricated wet core module
Source: atelierjones LLC*

*[Above] Organizational integration of the wet core module
Source: atelierjones LLC*

ADDITIVE MODULES

Designed to accommodate the potential need for expansion in a home, the Sierra Houses are configured in a manner that would allow for future additions to be installed on to the home. This in turn provides a heightened community-side resilience aspect, as families are more easily allowed to age and grow in place.



*[Right] Sequential Addition
Diagram (top-down)
Source: atelierjones LLC*

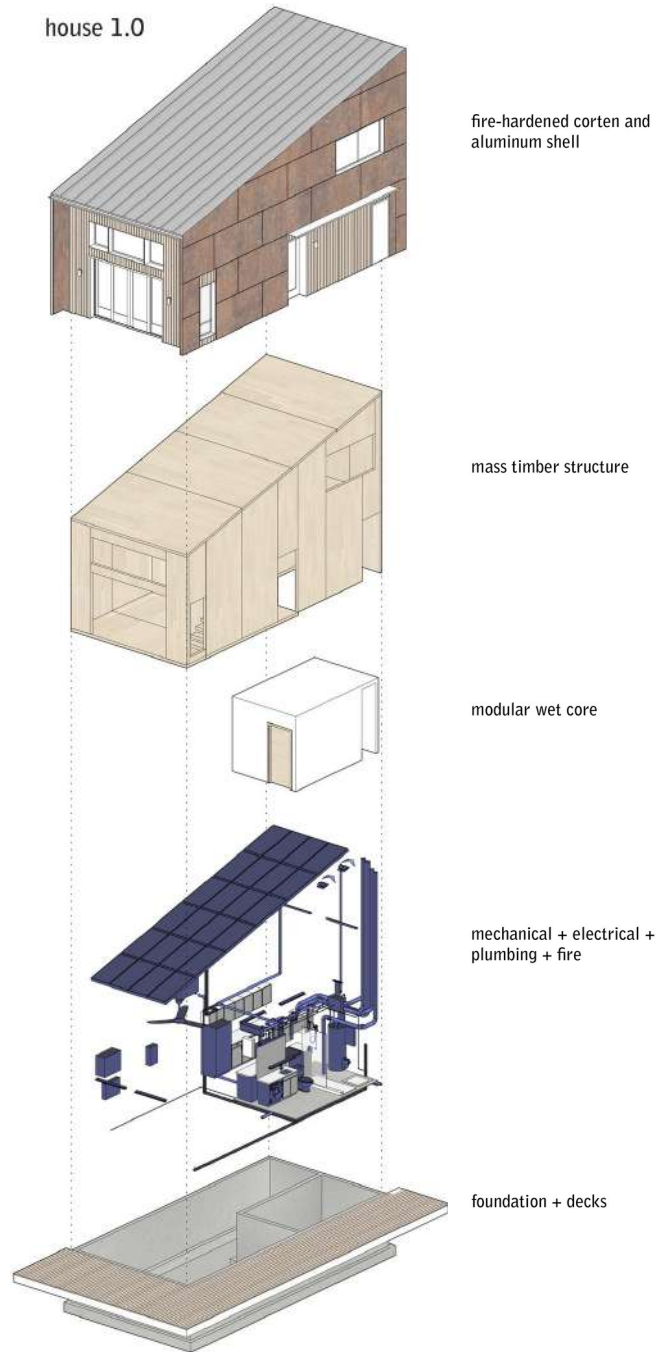
HOUSE 1.0

BEDS: 1 BATHS: 1

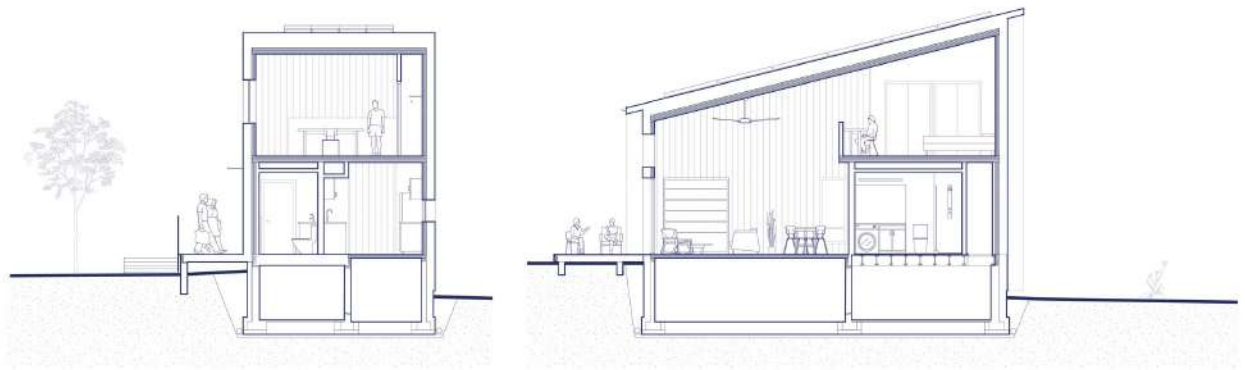
House 1.0 is the first design of the Sierra House series, and is a one-bedroom, one-bathroom home with a loft level. The design showcases careful arrangement of openings with the CLT panel layout to optimize efficiency and natural lighting where required.



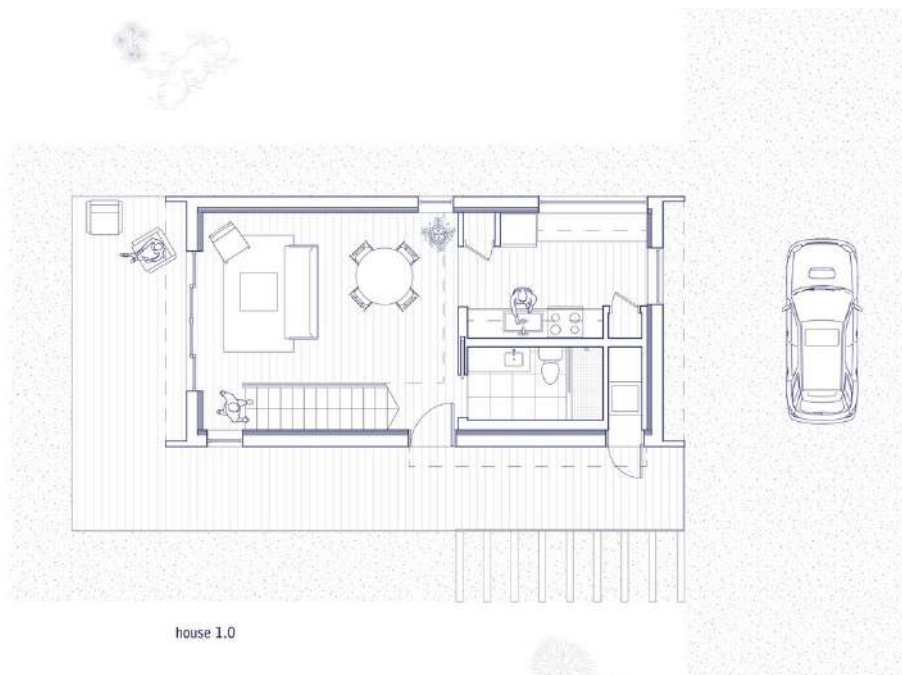
[Left] House 1.0 exterior image
Source: atelierjones LLC



[Above] House 1.0 systems components diagram
Source: atelierjones LLC



house 1.0



house 1.0

[Top] House 1.0 section diagrams
Source: atelierjones LLC

[Bottom] House 1.0 first floor plan
Source: atelierjones LLC

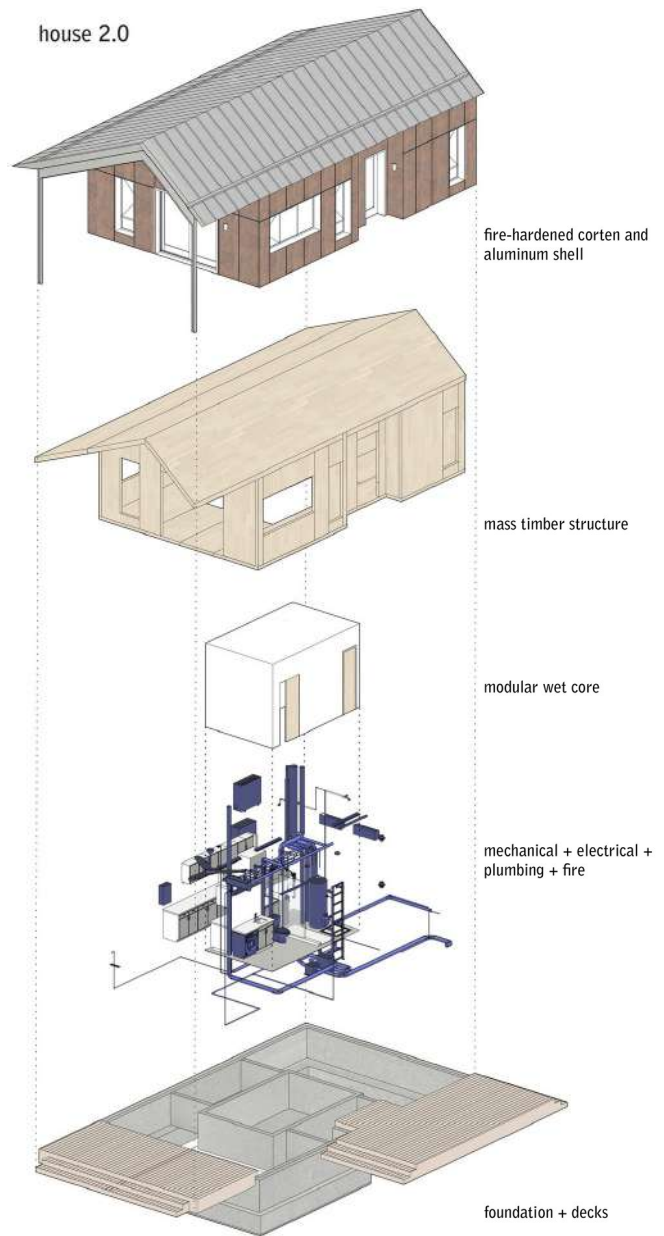
HOUSE 2.0

BEDS: 2 BATHS: 1

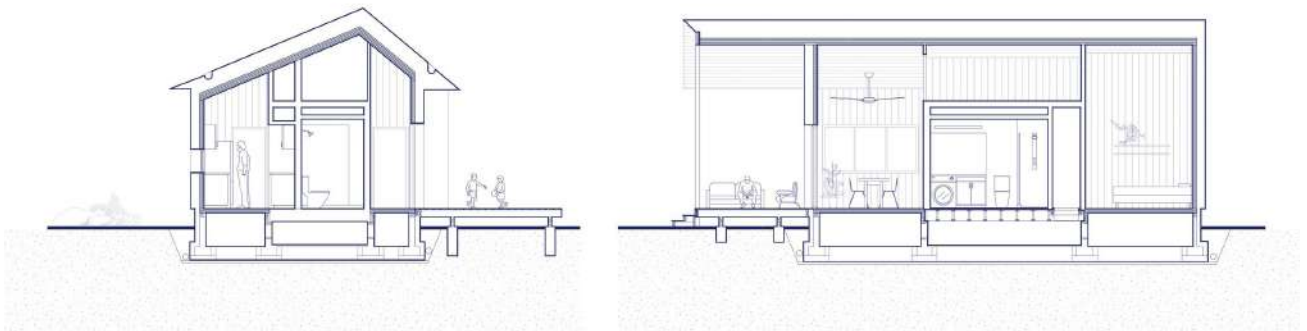
House 2.0 is the two-bedroom design of the Sierra House system and is laid out to have the modular wet core be centralized within the design to justify organization. The living spaces are all very compact, which indicates an effort to achieve optimal affordability through reducing the overall footprint area.



[Left] House 2.0 exterior image
Source: atelierjones LLC



[Above] House 2.0 systems components
diagram
Source: atelierjones LLC



house 2.0



house 2.0

*[Top] House 2.0 section diagrams
Source: atelierjones LLC*

*[Bottom] House 2.0 first floor plan
Source: atelierjones LLC*

HOUSE 3.0

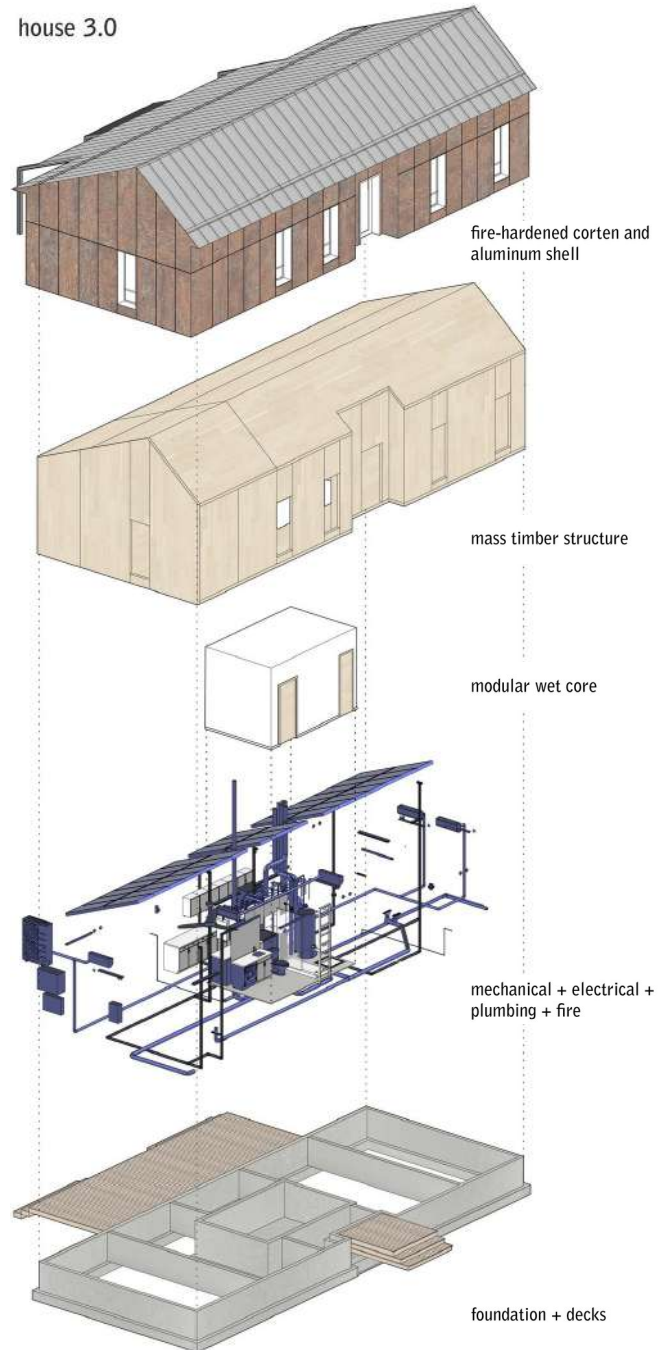
BEDS: 23 BATHS: 1

House 3.0 is the largest of the Sierra Houses, at 3-bedrooms, and is in essence an example of an expanded design from the House 2.0 layout. The third bedroom is located where the House 2.0 porch used to be, and a second living area for a dining space is added between the kitchen and bedrooms.

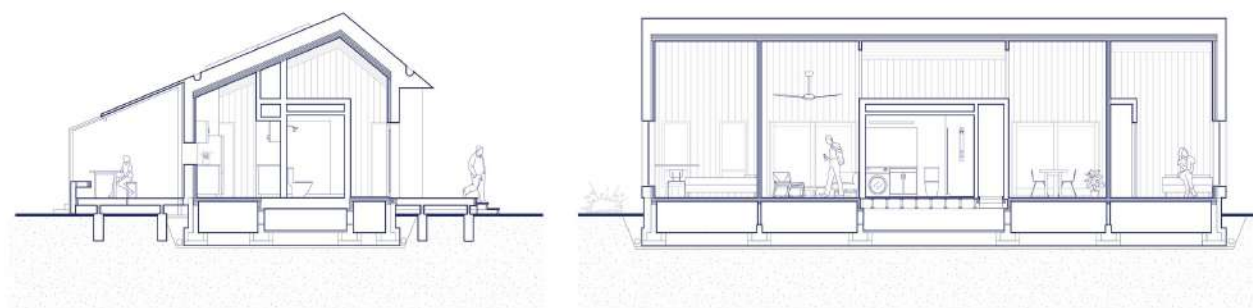


[Left] House 3.0 exterior image
Source: atelierjones LLC

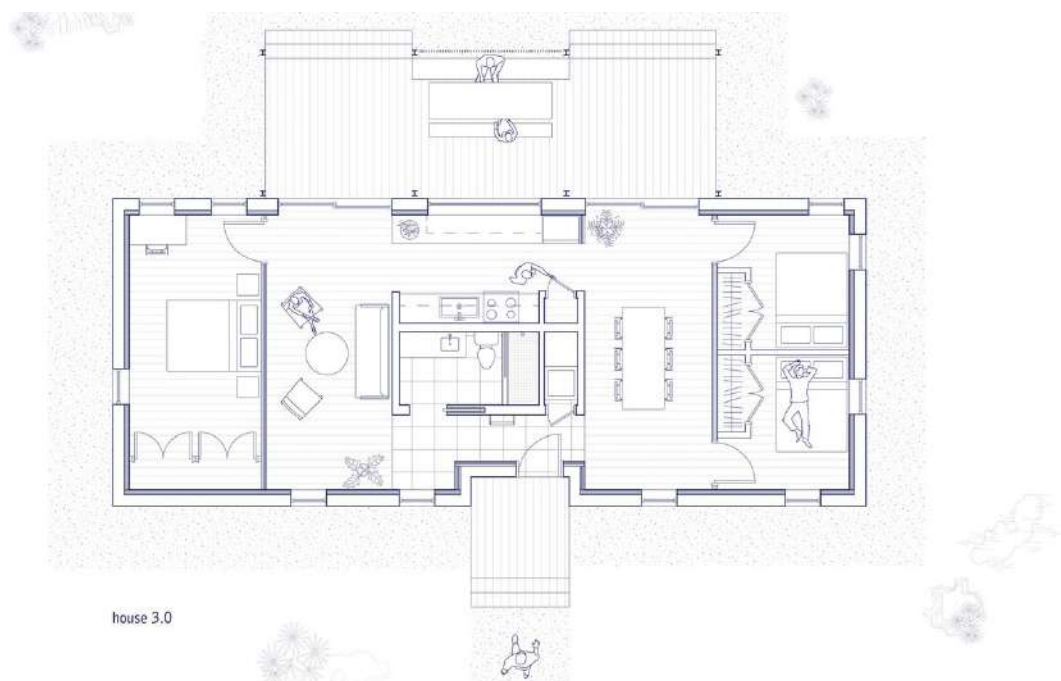
house 3.0



[Above] House 3.0 systems components
diagram
Source: atelierjones LLC



house 3.0



house 3.0

*[Top] House 3.0 section diagrams
Source: atelierjones LLC*

*[Bottom] House 3.0 first floor plan
Source: atelierjones LLC*

PROJECT FINDINGS



When sourced intentionally, mass timber supports resilient ecologies and reduces future fire risk by promoting forest health through good forest management practices...

Operational Carbon is reduced through passive house design principles, which work hand in hand with mass timber construction and WUI guidelines. The well-sited forms of the homes are compact, with airtight, highly insulated envelopes and high-quality windows. HEPA filters and air-source heat pumps allow for occupant health and comfort even during California's ever growing fire season. Reducing operational carbon also reduces cost for occupants, allowing residents to stay in their homes and stay in the community.



*[Left] Discussed design benefits
Source: atelierjones LLC*

KEY TAKEAWAYS

-  An expandable modular design provides resilience through community-member retention and growth
-  A prefabricated wet core module greatly increases the efficiency of plumbing integration
-  The panelized assembly allows for optimized shipping efficiency through a flat-pack format
-  While the designs are compact to minimize cost, the living spaces within the design may prove to not be of a livable size for all potential occupants.



06

OPAL / SHELTER

OVERVIEW

OPAL / Shelter is a sister company to both OPAL Architecture and NotchSB, and is a prefabricated & packaged panelized housing company situated in the Northeast United States in Belfast, Maine. This family of companies—which also includes the only wood-fiber insulation manufacturer in the United States, TimberHP—is in the forefront of mass timber advocacy and sustainability through design & construction in the region.

The design system provides various pre-designed modular home options, but also allows for customized variation with the same panelized kit-of-parts and space modules.

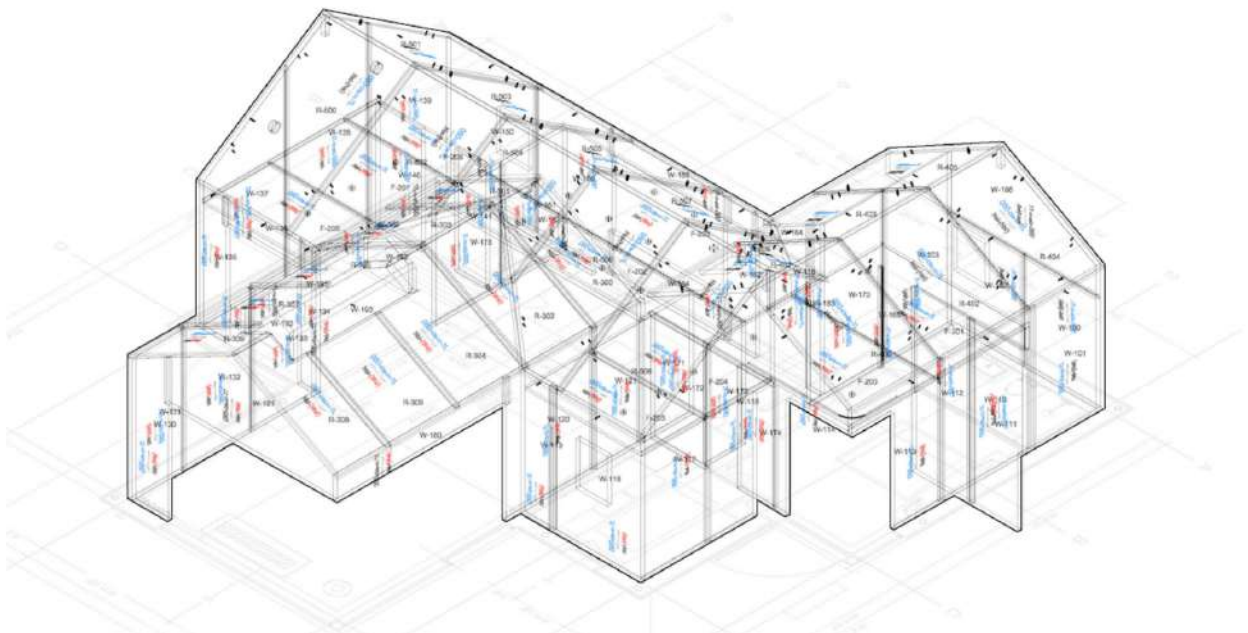
Location(s)
Belfast, ME

Modularity Type
PANELIZED

Mass Timber Supplier
Nordic Structures | *Austria

CLT Wood Species
SPF | Norway Spruce
** Wood species based on CLT Manufacturers' information*

EST. Cost per Square Foot
~ \$350-\$450



[Left] Little House on the Ferry exterior image
Source: OPAL / SHELTER

[Above] Coordination diagram of the panelized modular system
Source: OPAL / SHELTER

PREFABRICATED PANELIZED CONSTRUCTION

The designs of OPAL / SHELTER space modules feature a pre-packaged kit-of-parts, which are comprised of prefabricated CLT panels that are CNC-Machined off site at NotchSB's facility. The panels are then flat-pack shipped to site, and assembled with a small crew of workers. The unique aspect of OPAL / SHELTER's design

system is that its available space modules are created to be able to function as either standalone structures and additions, or components to aggregate with other modules in order to derive the full program of a home. This interface enhances the flexibility of possible arrangements to meet specific site and client needs.



[Top] Pre-designed kit-of-parts modules
Source: OPAL / SHELTER

[Bottom] Image of the panelized CLT construction by NotchSB
Source: OPAL / SHELTER

SAMPLE CATALOGUE PACKAGE

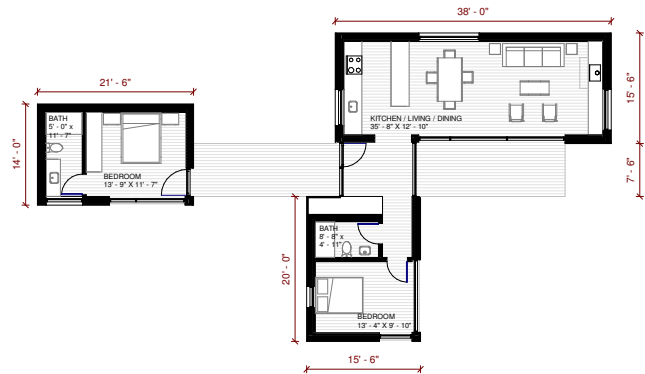
OPAL / SHELTER's modular design system also includes an array of pre-designed sample homes in a catalogue format, comprised of the same kit-of-parts space modules that could be used for custom aggregation.

In general the architectural forms of the home designs tie in vernacular architecture elements of the Northeast.



1500 SQ FT — MODEL A

- Stories: 1
- Bedrooms: 2
- Bathrooms: 2
- Additional Features:
 - Covered porch
 - Wood stove
 - Entry vestibule
- Modules:
 - KLD – A
 - BB – B
 - BB – F



OPAL / SHELTER

SCALE 1/16" = 1'

1/1

[Above] Sample Modular Home Model
pamphlet
Source: OPAL / SHELTER

LITTLE HOUSE ON THE FERRY

A built example of OPAL / SHELTER's modular design system is a project called Little House on the Ferry, designed by Riley Pratt of OPAL Architecture. The home and its documentation provides a case study of how OPAL / SHELTER's panelized kit-of-parts system can work.

The home is comprised of three separate volumes that are connected by exterior circulation decking. The two bedroom structures are constructed from the same kit-of-parts, which showcases the repeatability of the system.

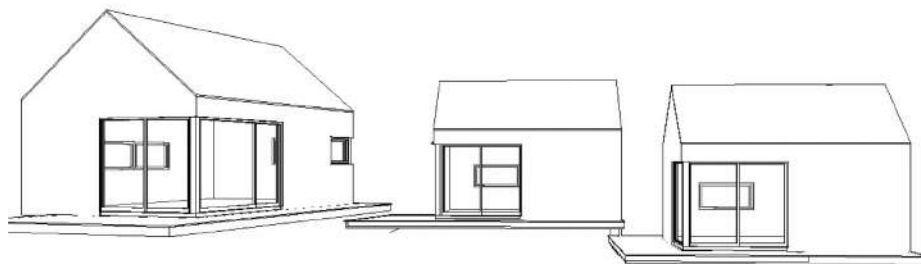
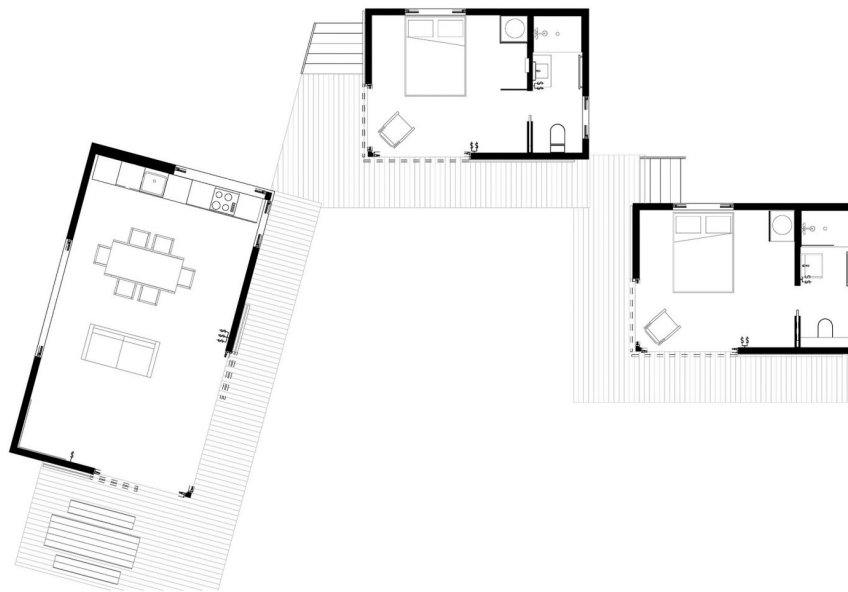


[Top] Little House on the Ferry interior image

Source: OPAL Architecture

[Bottom] Little House on the Ferry exterior image

Source: OPAL Architecture



[Above] The kit-of-parts system in action
 Source: OPAL / SHELTER

PROJECT FINDINGS



By adhering to the Passive House standard and employing sophisticated energy modeling for every building, we reduce space heating by 80 percent from that required by code...

A key benefit of solid wood construction is wood's unique capacity to lock up—or store—carbon that the living tree has sequestered from the atmosphere through photosynthesis. This carbon, stored for the life of the building, offsets the majority of the embodied carbon emitted in the production, transport, and installation of the rest of the non-biogenic building materials.



[Left] Thermal and Carbon advantages
Source: OPAL / SHELTER

[Right] Carbon comparison
Source: OPAL / SHELTER



KEY TAKEAWAYS

- ✚ Designing with a format of kit-of-parts space modules enables great flexibility for the potentials of end-result home layouts.
- ✚ A panelized, prefabricated process enables ease of shipping, and reduces the intensity of on-site construction, which aids in saving on labor costs.
- ✚ Utilizing Passive House standards in tandem with a panelized shell-system can greatly reduce heating (and cooling) loads.
- ✚ The prioritized use of biogenic materials in construction can achieve net-negative carbon levels when considering biogenic carbon.
- ✚/- Although being the current-most local or affordable options for the area, sourcing CLT from Canada or overseas can incur tariff costs, as well as increase the embodied carbon footprint related to transport.

SUMMARY

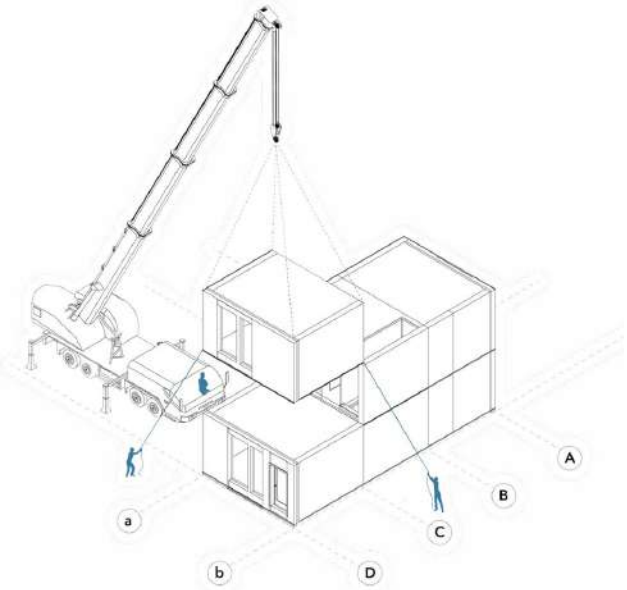
CHOICE FOR PANELIZED MODULARITY

The selected case studies provided a breadth of applications of CLT in modular housing design and construction. Throughout the projects, several benefits and considerations were identified for each system. As a general summary, the case studies express the potentials for mass timber integration into single-family construction in North America, and suggest the developing interest in this field. The greatest challenge that these systems must overcome in a competitive market is their initial price, which could be offset by the realized durability and longevity of these construction systems over time.

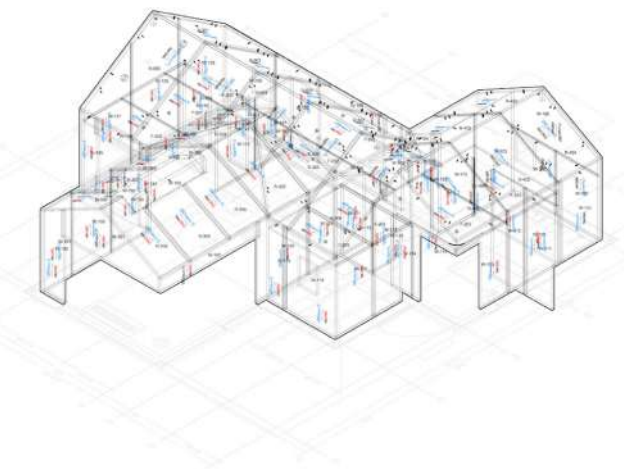
Both systems for modularity—volumetric and panelized—possess their own benefits and drawbacks between one another. In general, a volumetric mass timber modular construction method achieves the utmost shortening of on-site construction time, but with inefficiencies and potential cost premiums in shipping. A panelized system can still vastly reduce on-site construction time compared to conventional site-built methods, while also achieving the greatest shipping efficiencies with flat-pack capability. In terms of their relation to design, a panelized modular system generally allows for greater flexibility in layouts and finished forms, as it is less constrained to predetermined space volumes or shipping dimensions.

With these factors in mind—as well as for rationale in the design to come—the BioMOD design system utilizes a panelized format for modularity.

VOLUMETRIC MODULAR

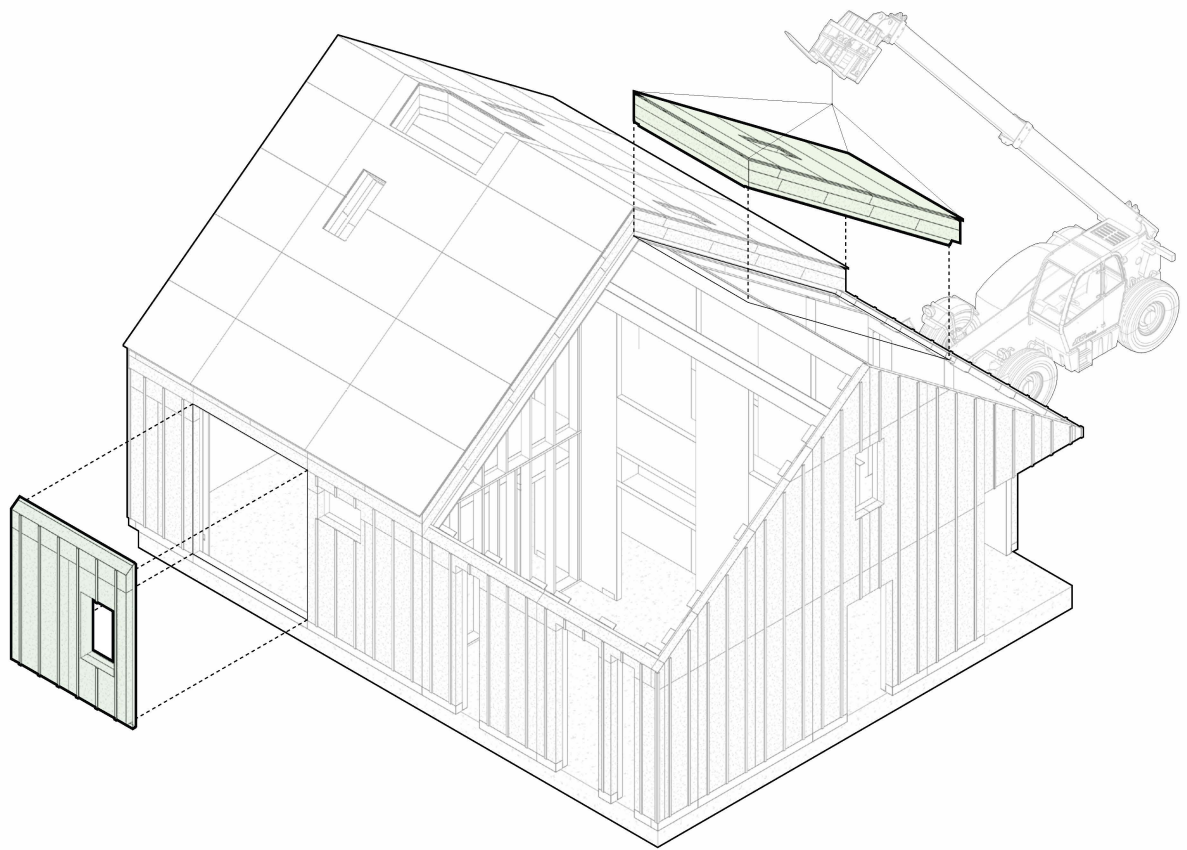


PANELIZED MODULAR



[Top] Volumetric Modular diagram
Source: Green Canopy NODE

[Bottom] Panelized Modular diagram
Source: OPAL / SHELTER







DESIGN





SYSTEM OVERVIEW

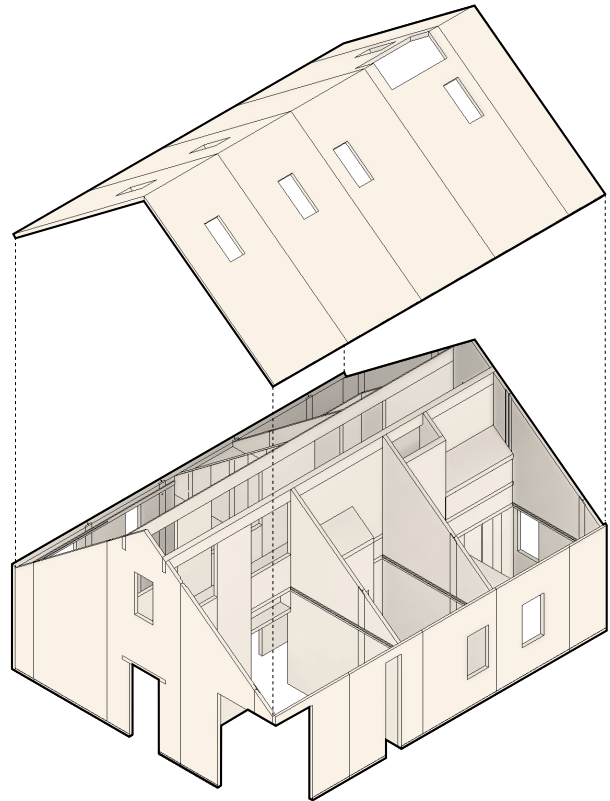
SYSTEM CONDITIONS

PARAMETERS

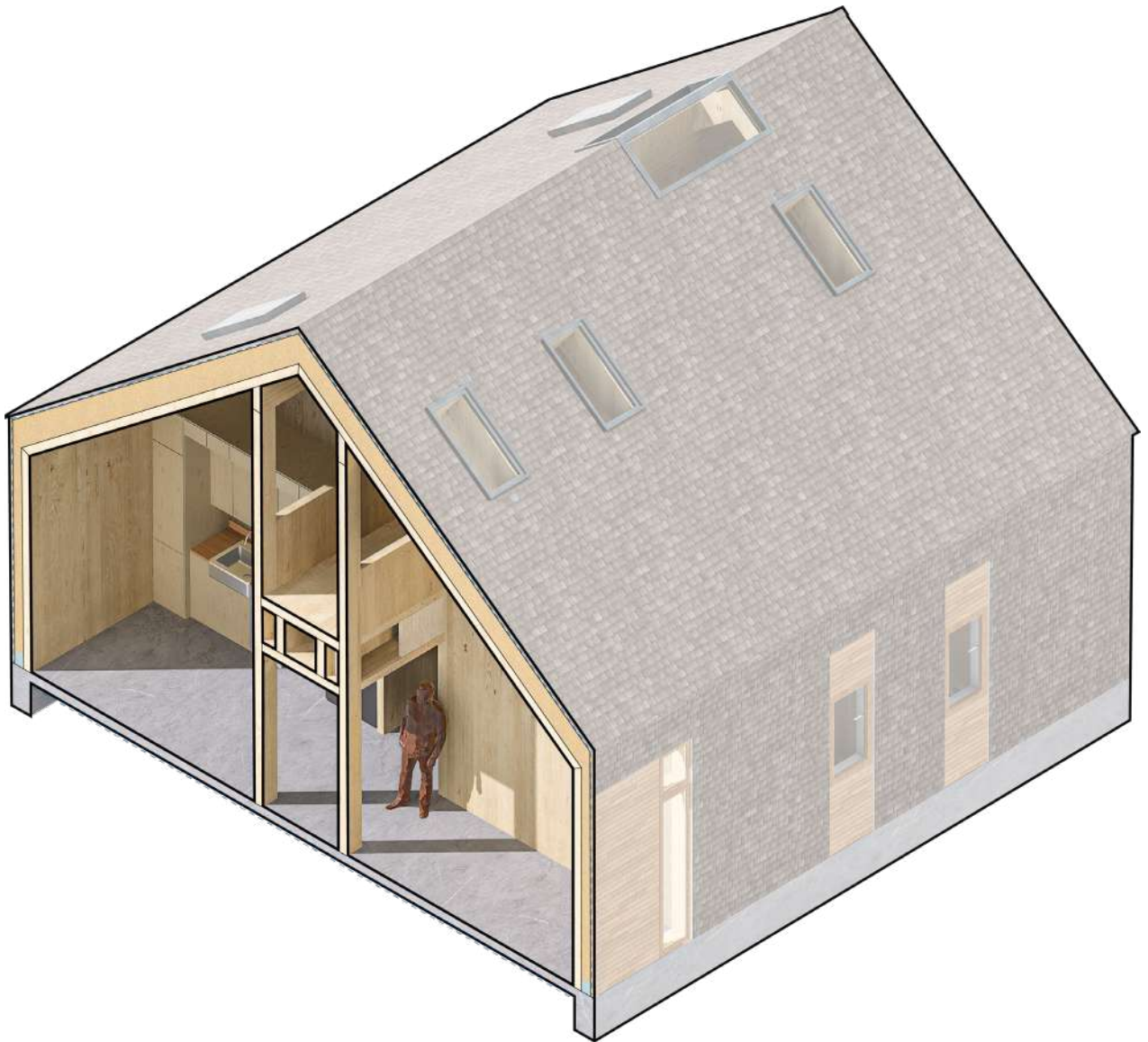
BioMOD is designed as an expandable modular system for single-family housing that is constructed from panelized mass timber. In tandem with using a structural system derived entirely from trees (and required adhesive), the remaining layers of a BioMOD house assembly are intended to be comprised of all biogenic material made from local forest products in the Northeast. The system is designed to minimize footprint-size and maximize assembly efficiency, as strategies to achieve affordability.

In order to develop an efficient and repeatable system for modularity, a framework of constraints needed to be established. As the project revolves around the use of Eastern White Pine CLT—and since this product is not yet produced by an established manufacturer—the first parameter was to determine the appropriate panel width for the whole system to be based on. It was determined through design iteration that an 8-foot CLT panel width would be logical for this application in single-family residential dwellings. As an 8-foot panel, shipping of the CLT becomes efficient, and the ability to split the panels into 4-foot and 2-foot sections where necessary gives it great flexibility in defining typical living-space dimensions with the least amount of connections or waste. The designs are compact, with airtight, highly insulated envelopes to follow Passive House design principles for reduced operational energy loads & related carbon emissions.

As a formal constraint, the BioMOD system adheres to the core principles of vernacular architecture in the Northeast—being a simple, compact shape with a proper roof pitch to manage snow and precipitation. Furthermore, the use of forest products for cladding elements, such as shingles and clapboard, is a historic choice.



BIOGENIC ASSEMBLY

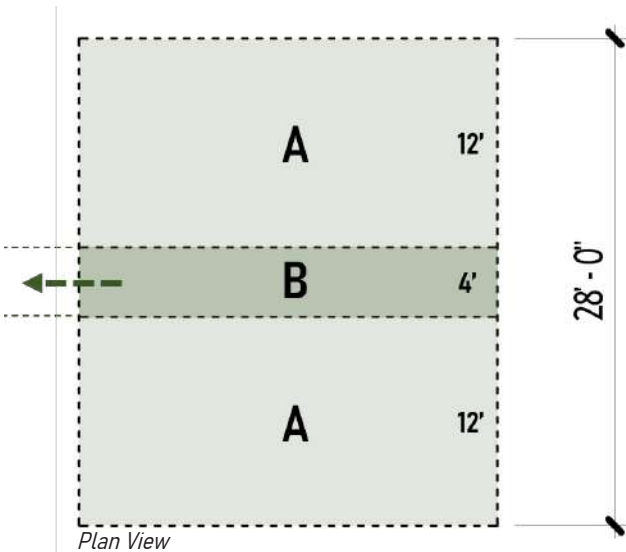


GENERAL DESIGN ELEMENTS

DESIGN ORGANIZATION

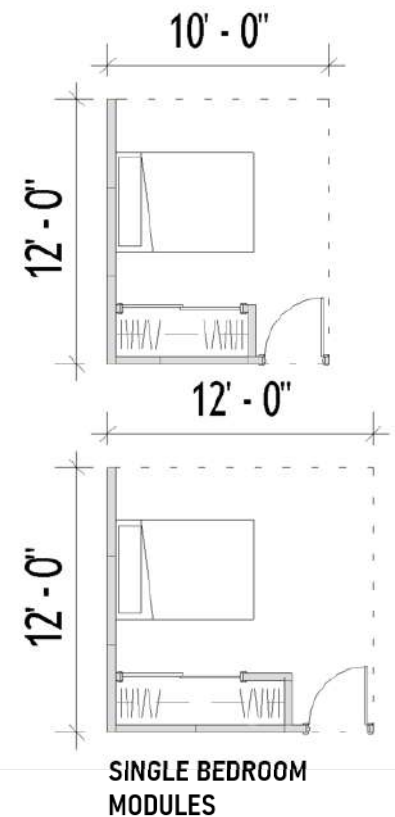
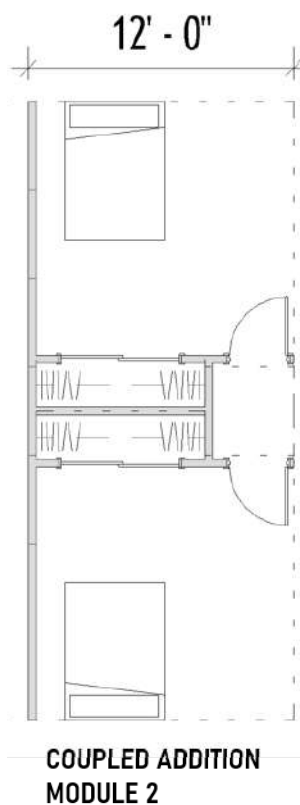
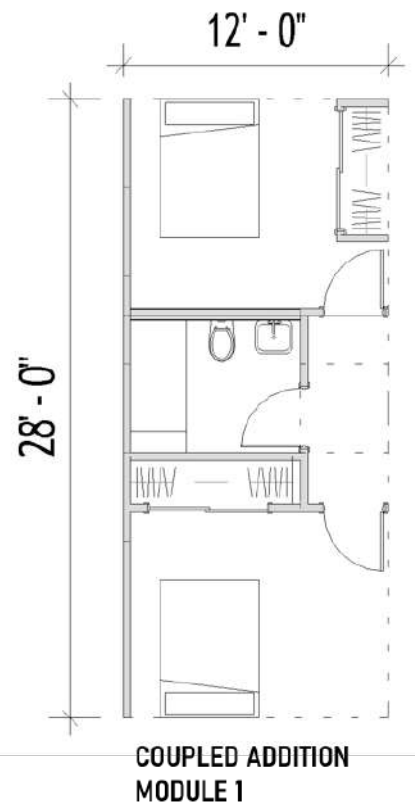
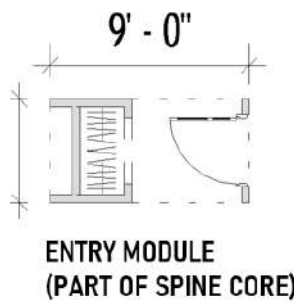
With a controlled system for expansion as a guiding principle for design, the modular system works on a consistent house-width of 28-feet, which in turn focuses the expandability component on one axis. Through iteration, the 28-foot width was determined to be a suitable dimension for the modular system, as it allows a clear organization of a 4-foot central circulation corridor flanked by 12-foot bays on each side—12 feet being a common dimension for comfortable living spaces.

To achieve simplicity in the modular system, the design components are primarily composed from a small array of possible space modules. Featuring a standard design for entry and plumbing-wall conditions, and just a few different arrangements for bedroom spaces, the system optimizes ease of expandability to an existing home. It also relies on a panelized construction method that can be flat-packed for shipping.



DETERMINED SYSTEM WIDTH





GENERAL ORGANIZATIONAL DESIGN MODULES

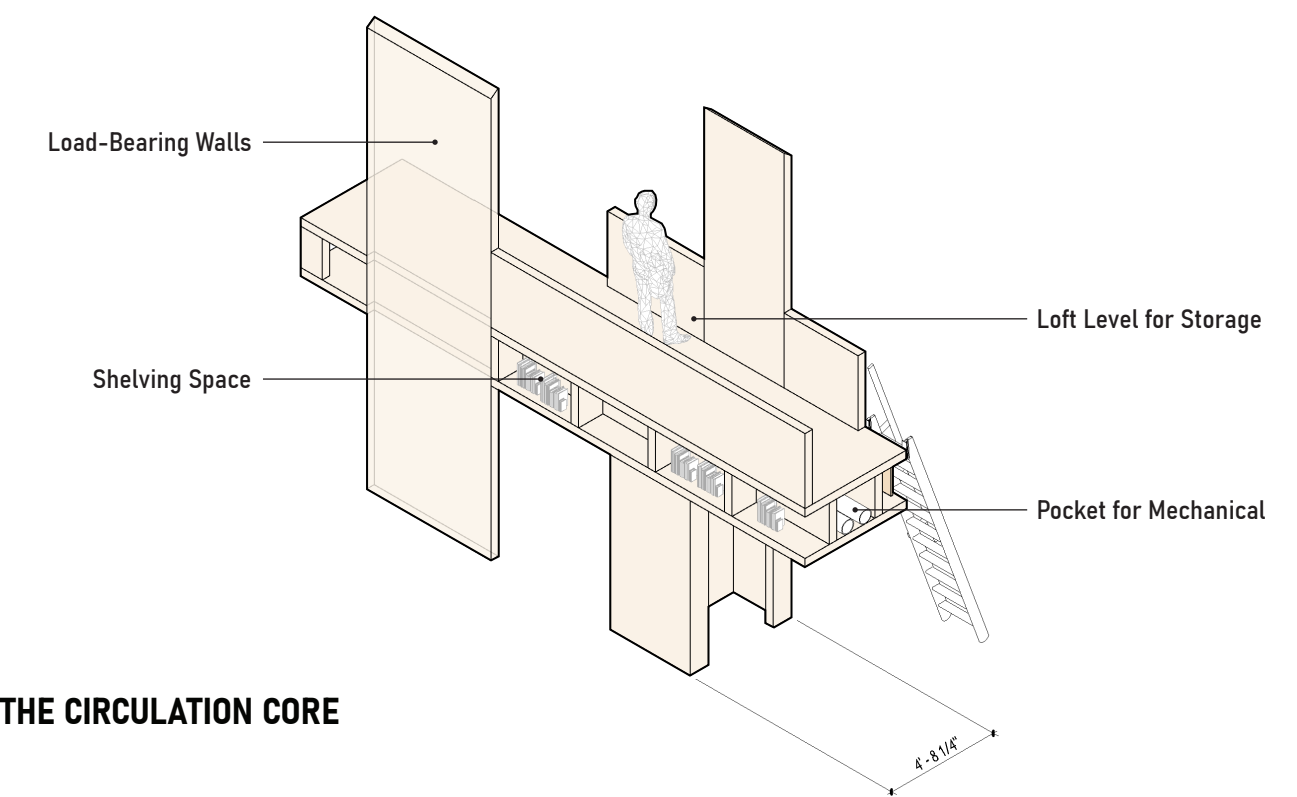
CORE KIT-OF-PARTS

To streamline construction and minimize cost, BioMOD employs two core kit-of-parts elements that every home contains, which aim to optimize MEP (Mechanical, Electrical, and Plumbing) integration in the design.

The Circulation Core embodies the central spine that runs throughout a BioMOD house, and serves several functions. Beyond acting as a driver in design layout and organization, the circulation core contains a designated zone for mechanical ducts and electrical conduit to run along the length of a house. This is achieved by a drop-ceiling configuration within the separate ceiling and floor CLT panel planes of the circulation core, which

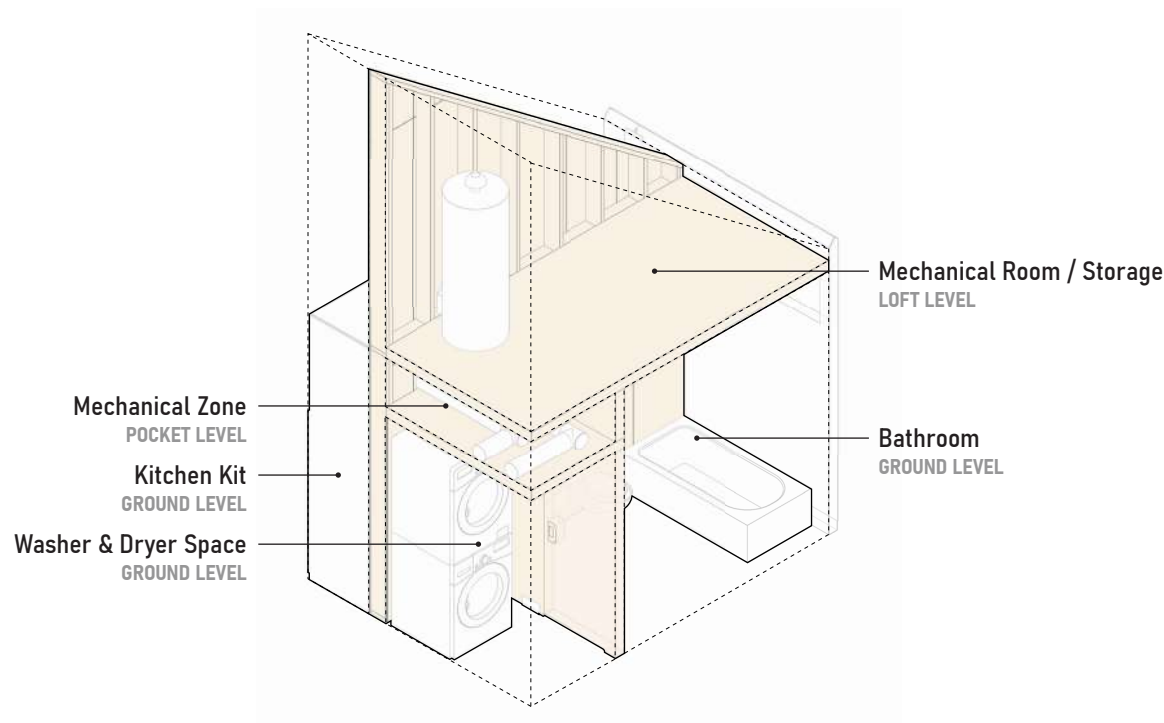
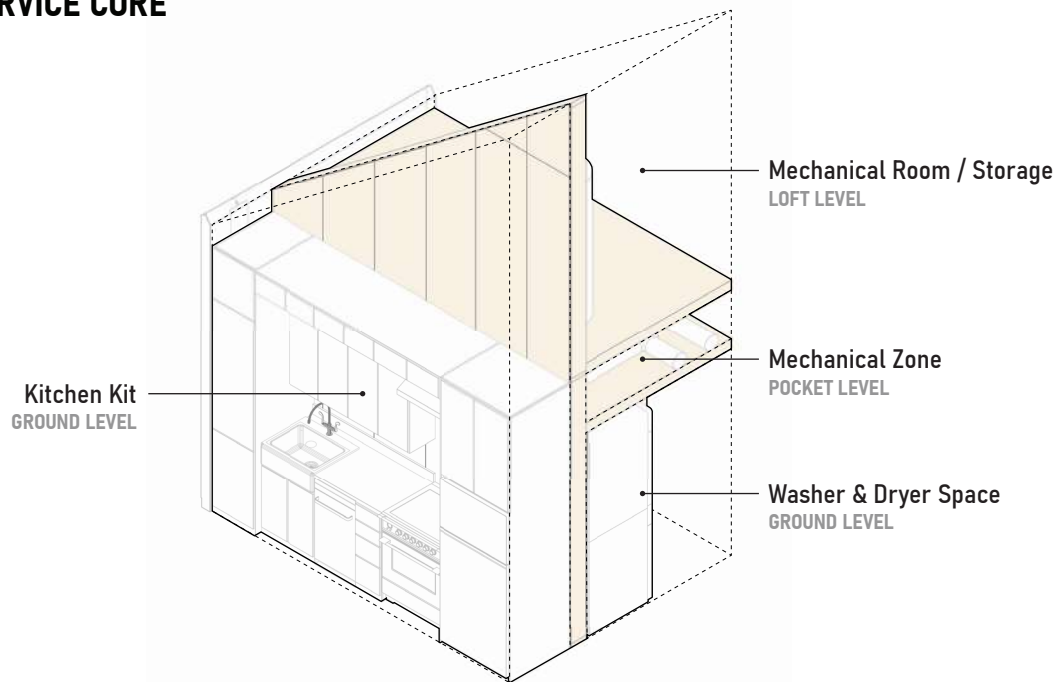
leaves a 1-and-1/2-foot tall pocket space.

The Service Core is the second kit-of-parts in every home, and is the module that hosts all of the interior plumbing needs of any 1-bathroom house model. Serving as the only light-wood-frame wall in a 1-bathroom home, the service core acts as the hub for all plumbing and mechanical inlets & outlets. This would greatly aid in rapid installment of these systems, and reduce mechanical and plumbing runs, both of which would reduce costs. The base kitchen in a BioMOD house comes as a kit as well, as is efficiently organized to remain compact. Additional counter space is possible.



THE CIRCULATION CORE

THE SERVICE CORE



THE STARTER HOME

The Starter Home is the base-condition design from which all BioMOD home plans are theoretically expanded (although any home size could also be immediately ordered in a catalogue).

Having only 672 square feet of living area, the house demonstrates the design system's intent of minimizing size in order to increase the affordability of the homes. This would allow more individuals the potential to be first-home-buyers. Not shown is a loft area for storage, which would not be included in square footage assessments.

The starter home is a 1-bedroom, 1-bathroom house equipped with the Circulation Core and the

Service Core kit-of-parts. In terms of expandability, the home is designed to primarily expand past the bedroom and core if more bedrooms and bathrooms were desired. In the case for a need to expand just the living areas, the panelized system allows for the entry wall to be moved 4-feet or 8-feet, depending on which desired CLT Panel width will be plugged in across the width of the house.



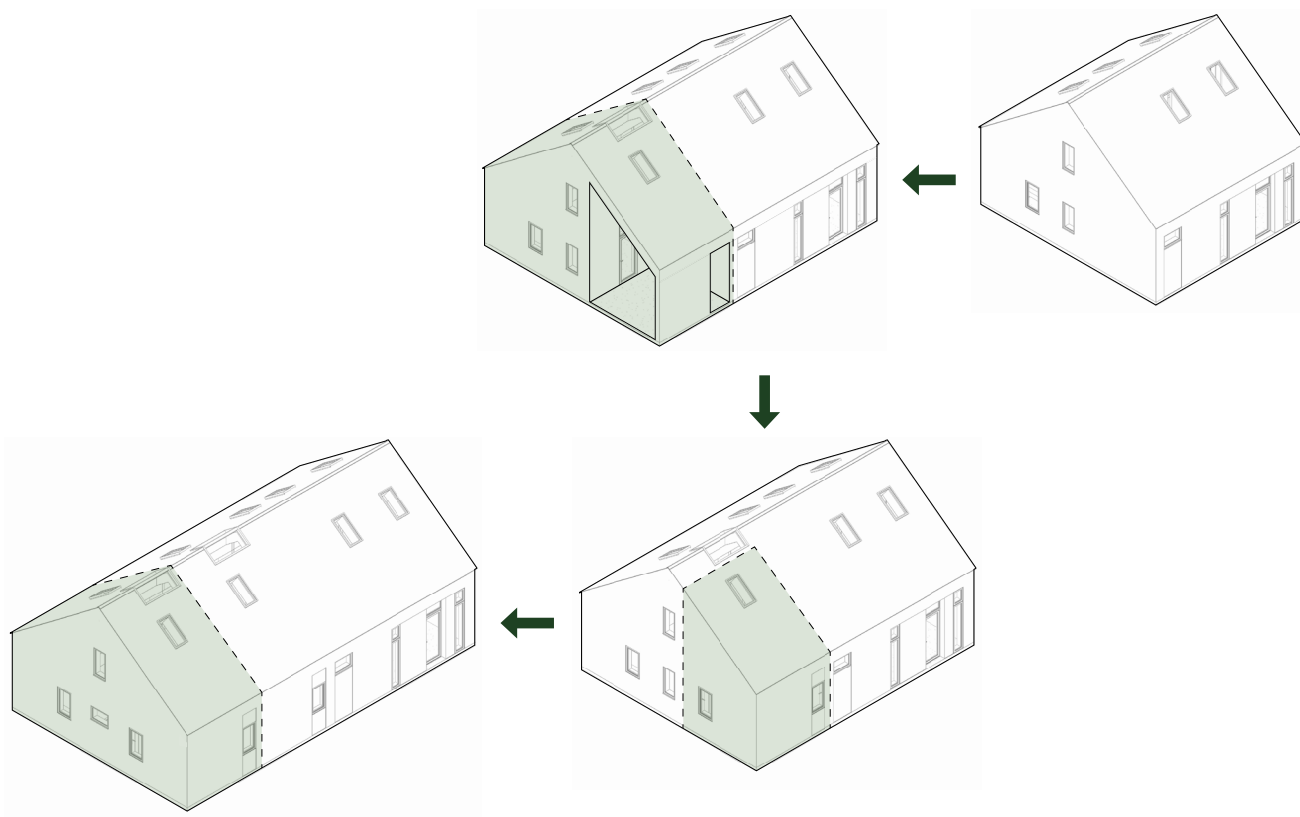


One-Bedroom House Ground Level Plan

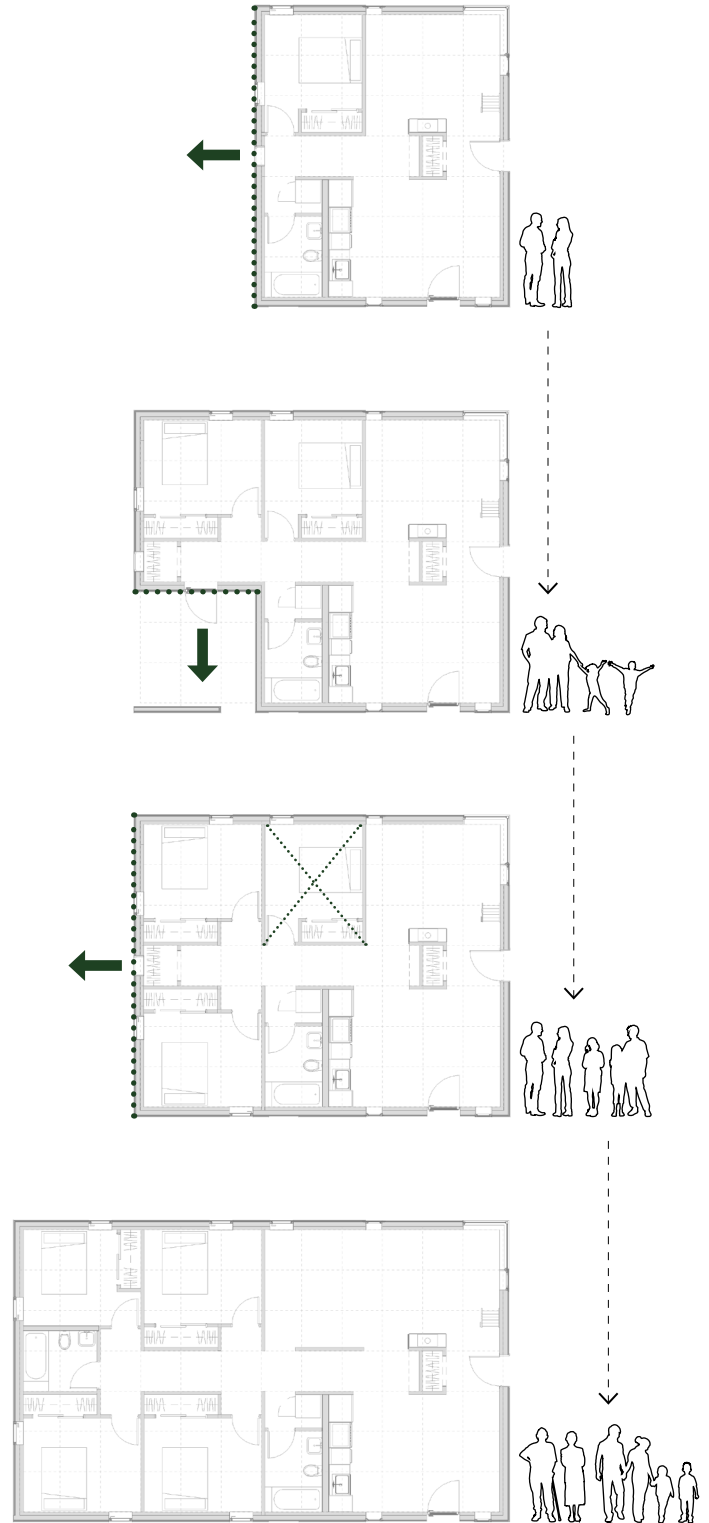
DESIGN FOR EXPANDABILITY

One of BioMOD's core design intentions is to anticipate and allow for expansion on to an existing BioMOD home. The connection methods between the assembly panels that make up the home are designed to easily be installed, un-installed, and re-installed. Notably, CLT panels possess an innate character that allows for simple connection systems and disassembly. The design system takes advantage of this, and goes a step further to include re-assembly and re-use of the same parts to minimize waste and cost.

The ability for expandability enables the possibility for families and homeowners to age in place, which, when paired with the significant durability and service-life of a CLT structure allows for a longer life of the home for the owners. Not only does this allow the possibility to reduce the barrier of up-front investment for prospective homeowners, the expandable modular system would reduce vacancy-volatility and overall material consumption in the building sector for those who would otherwise build an entire new home to accommodate their new space-requirements.



A SYSTEM DESIGNED TO ACCOMMODATE GROWTH



LAYOUT POSSIBILITIES

From the general space modules and systematized design for expandability, there are many sizes and layout variations that are possible through the modular system. Space can be added via extension, removing the initial bedroom (Opened), or adding spacing segments to make the living space larger (+ and ++). The series below is not an exhaustive display of all possible options, but portrays the overall logic of the modular system.

5-BEDROOM

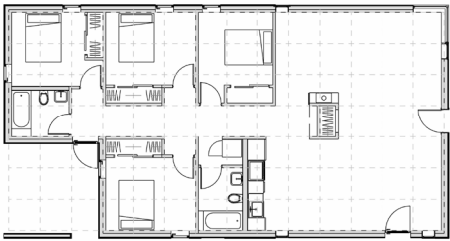


5-BED 2-BATH ++



LIVING SPACE EXTENSION
SEGMENT MODULES

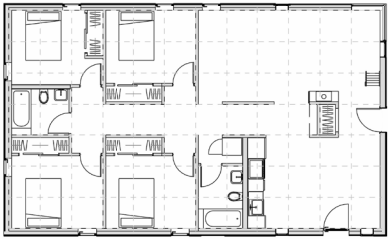
4-BEDROOM



4-BED 2-BATH ++

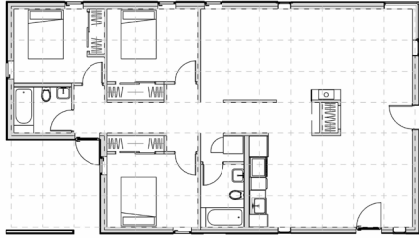


4-BED 2-BATH

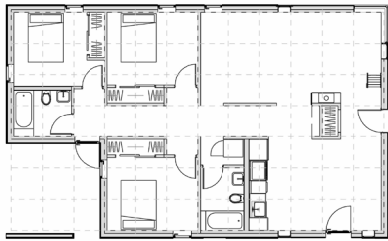


4-BED 2-BATH [OPENED]

3-BEDROOM



3-BED 2-BATH [OPENED] +



3-BED 2-BATH [OPENED]

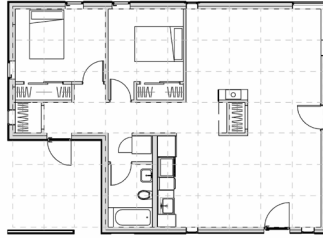


3-BED 1-BATH

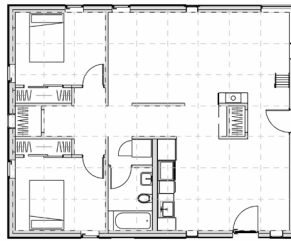


3-BED 2-BATH

2-BEDROOM



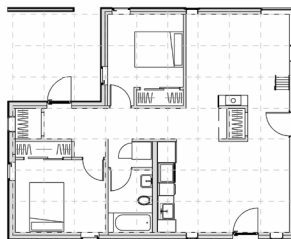
2-BED 1-BATH +



2-BED 1-BATH [OPENED]

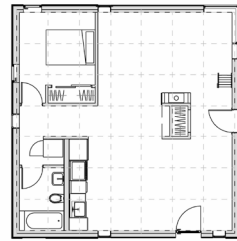


2-BED 1-BATH

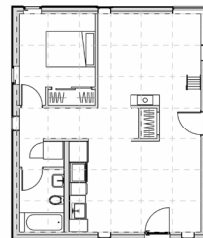


2-BED 1-BATH [FLIPPED]

1-BEDROOM



1-BED 1-BATH +



1-BED 1-BATH

CATALOGUE FOR VARIATION

EXTERIOR CLADDING POSSIBILITIES

With consideration for developing individual identity within communities where multiple BioMOD homes may exist, and simply to allow for flexibility in the system, the modular design system may consist of various types of wood cladding for exterior walls, as well as materials that go beyond forest products for the roof cladding.

While non-biogenic and possessing a higher amount of embodied carbon to produce, standing-seam metal roofing is a common choice for present-day construction due to its considerable durability and affordability.

Slate is another potential material that may be utilized as a roofing option. While non-renewable, slate is a natural material that can also be sourced locally in the Northeast. Slate roofing is one of the most durable roofing materials available, but can also be considerably expensive.

Since the design system focuses on biogenic materials as its primary condition, the all-wood exterior assembly variations remain at the core of the project. While wood cladding is more susceptible to fire, the CLT shell of the construction could provide a sufficient fire-rating to protect the interior of a home in the event of wildfire.¹³



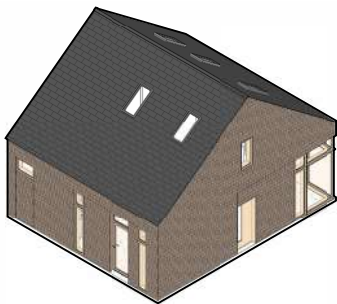
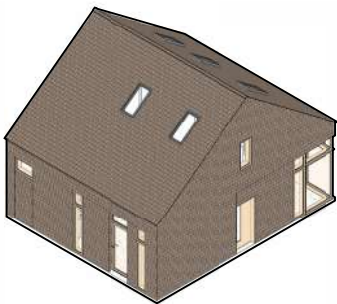
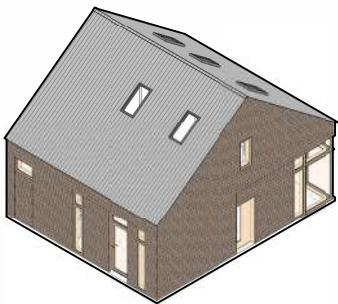
ROOFING MATERIAL

STANDING SEAM METAL

CEDAR SHINGLE

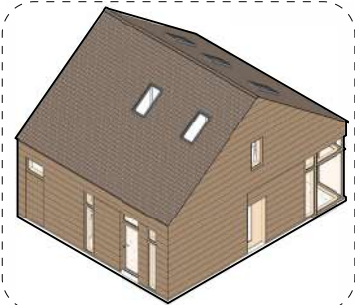
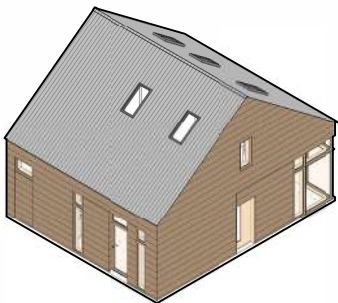
SLATE SHINGLE

CEDAR SHINGLE



SIDING MATERIAL

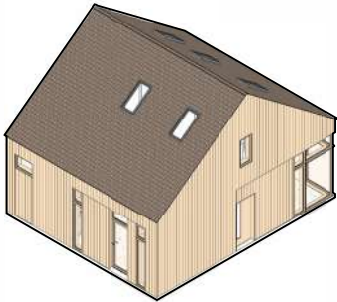
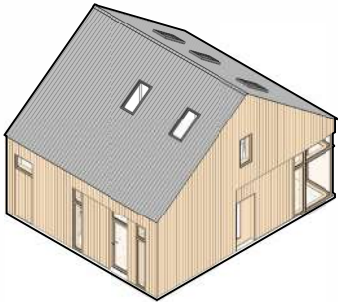
WOOD CLAPBOARD



STUDY CONDITION



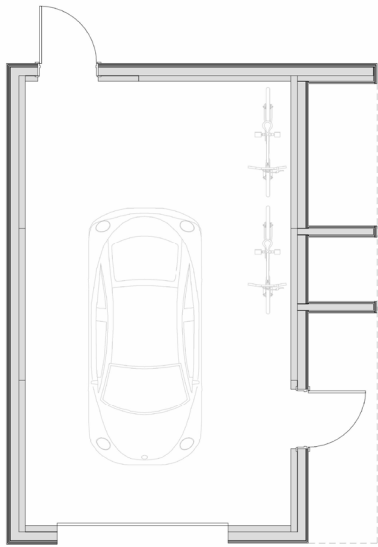
VERTICAL WOOD



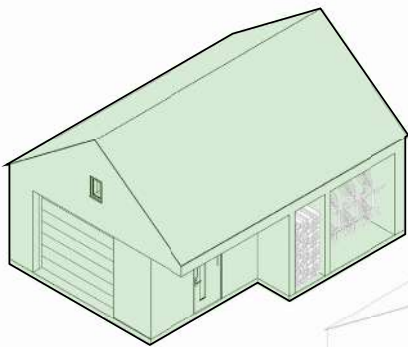
EXTERIOR ACCESSORIES

Additional exterior add-ons can further introduce variation of the homes, and address potential needs of individual households.

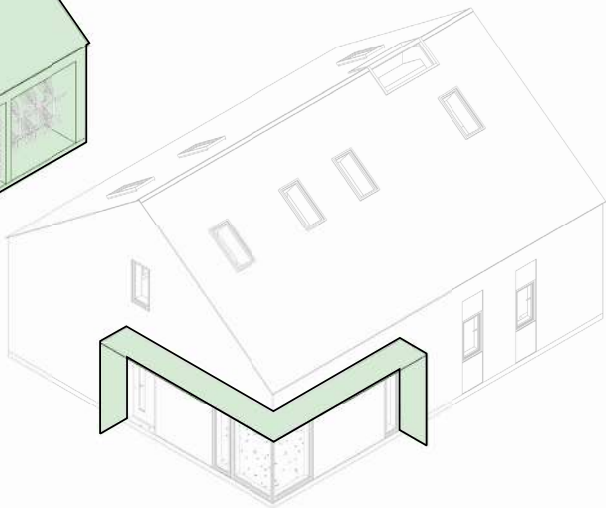
A detached garage provides a sheltered space to park a vehicles out of winter snow, as well as areas to store bikes and firewood. Depending on the orientation of a built BioMOD house, solar shading attachments can be installed to reduce unwanted summer solar gain while retaining beneficial solar gains in the winter.



GARAGE PLAN



DETACHED GARAGE



SOLAR SHADING ATTACHMENT





B2





DESIGN DETAILS

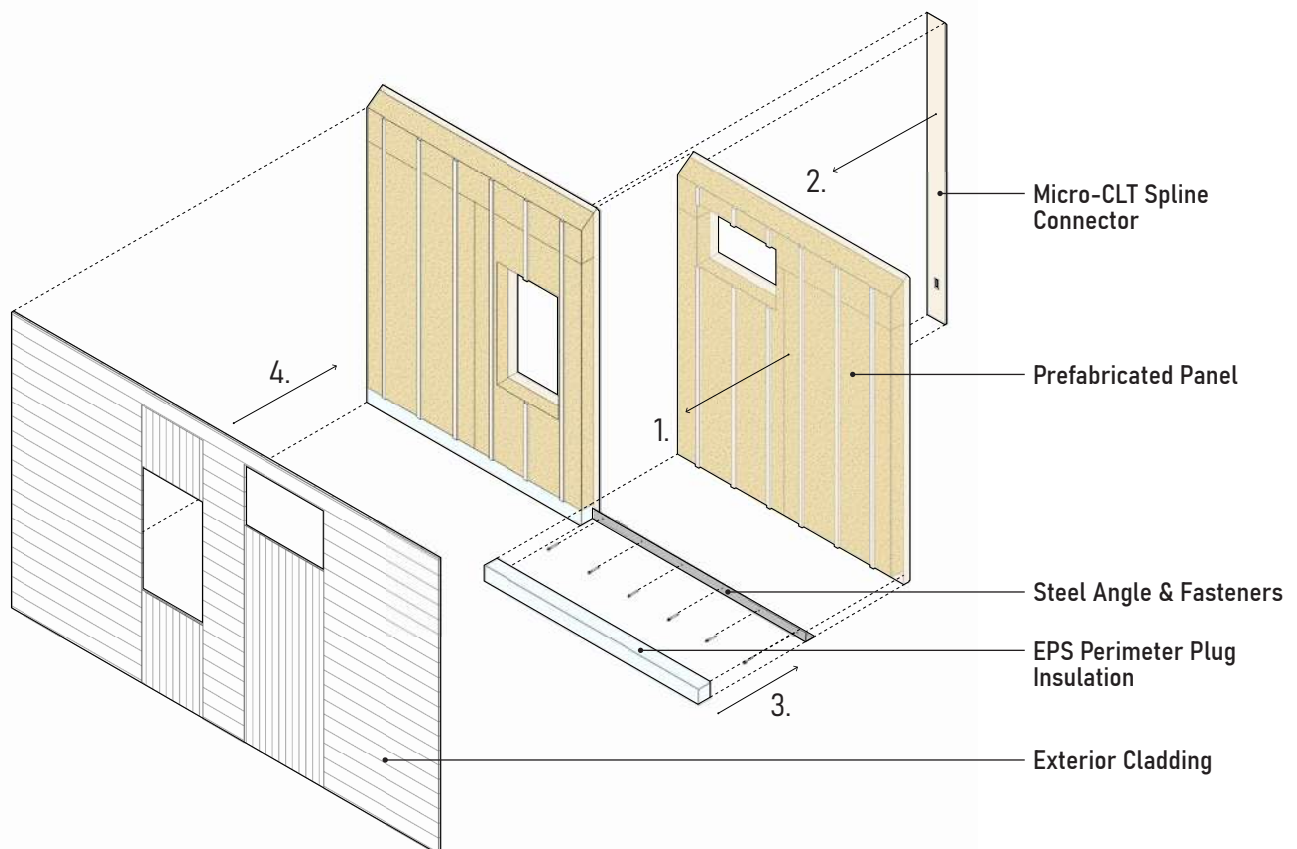
PANELIZED MODULAR STRATEGY

PANELIZED CONSTRUCTION

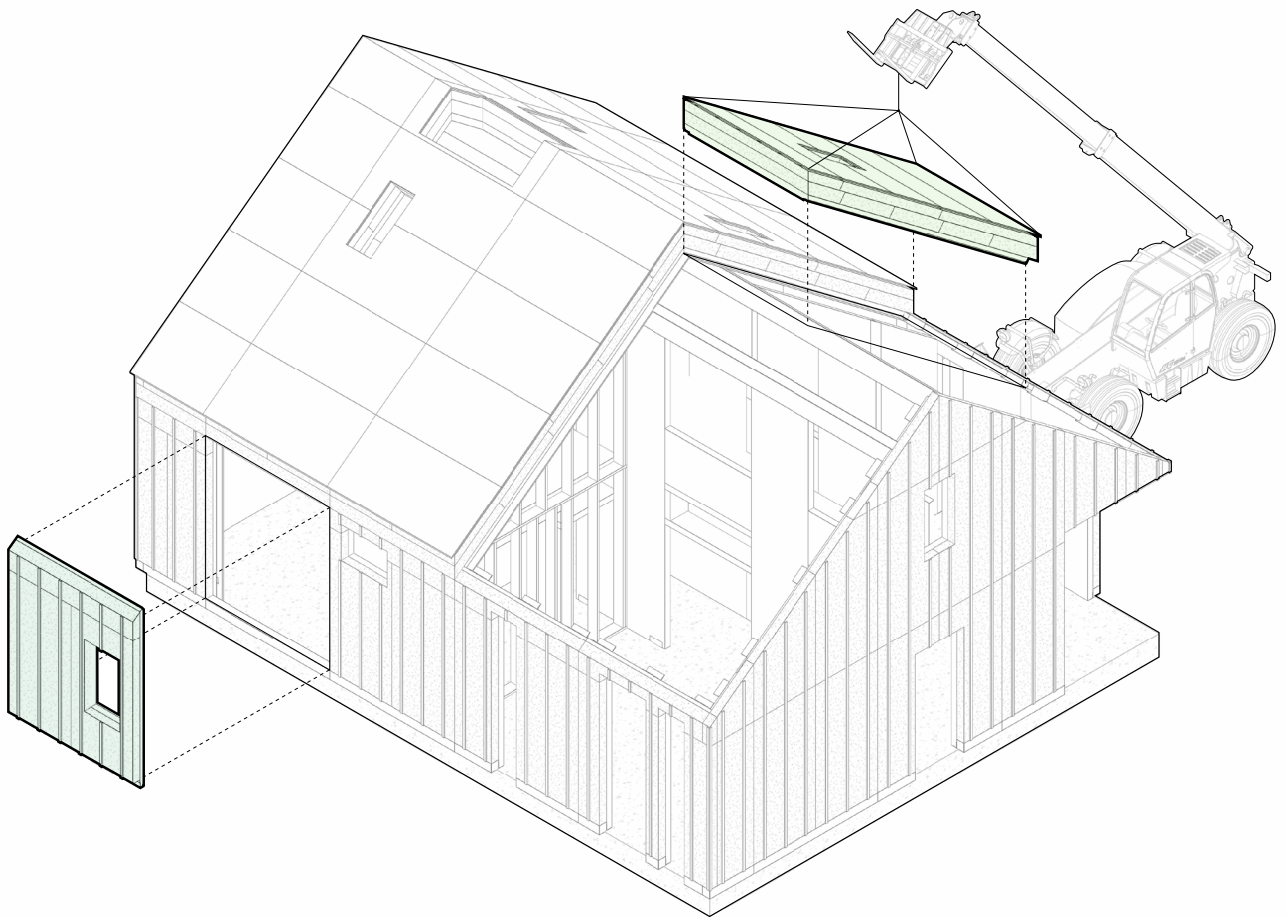
The system for modularity of the design leverages the innate strengths of utilizing CLT panels as the structural language of the project. Being already a panel by definition, the EWP CLT panels may be quickly connected to one another to form the entire shell of a house with minimized pieces and seams. Additionally, utilizing a panelized modular system instead of a volumetric modular system allows for more efficient shipping and greater flexibility in design, which better lends itself to a system for expandability.

The panels that arrive on-site are designed to have the insulation, WRB membrane, and vertical furring layers already attached to the EWP CLT panels. In a panelized modular method of construction, this greatly increases the degree of which the home is prefabricated off-site in a controlled environment—which saves time and enhances precision in assembly.

Panels are attached to the foundation with steel angles, and are attached to one another with an interior-facing spline connection made of micro-CLT to achieve a similar aesthetic finish.



RAPID PANEL CONSTRUCTION



**SIMPLIFIED
ON-SITE ASSEMBLY**

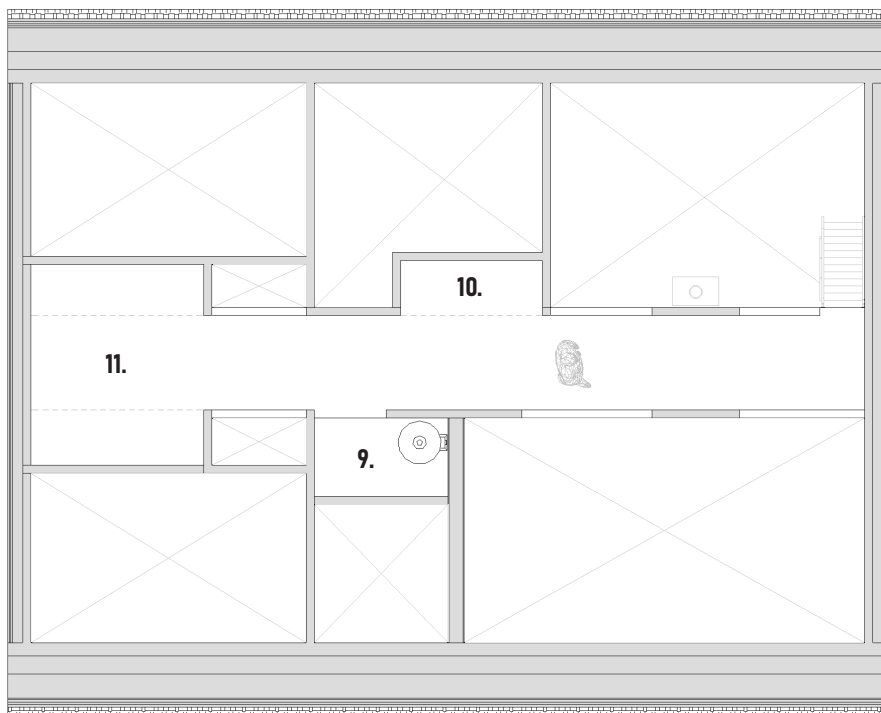
STUDY CONDITION DESIGN

THE AVERAGE BioMOD HOUSE

A 3-bedroom, 2-bathroom home represents the average modular house format, and so the same-condition BioMOD house shall be used as the condition for studying the modular design system. Additionally, the 3-bedroom, 2-bathroom BioMOD house possesses many of the possible components

of the system—making it a good candidate for representation. The following contents of this section, as well as future sections, uses the 3-bedroom, 2-bathroom BioMOD house format to showcase the system and its characteristics.





LOFT LEVEL



GROUND LEVEL

1,110 sq.ft.

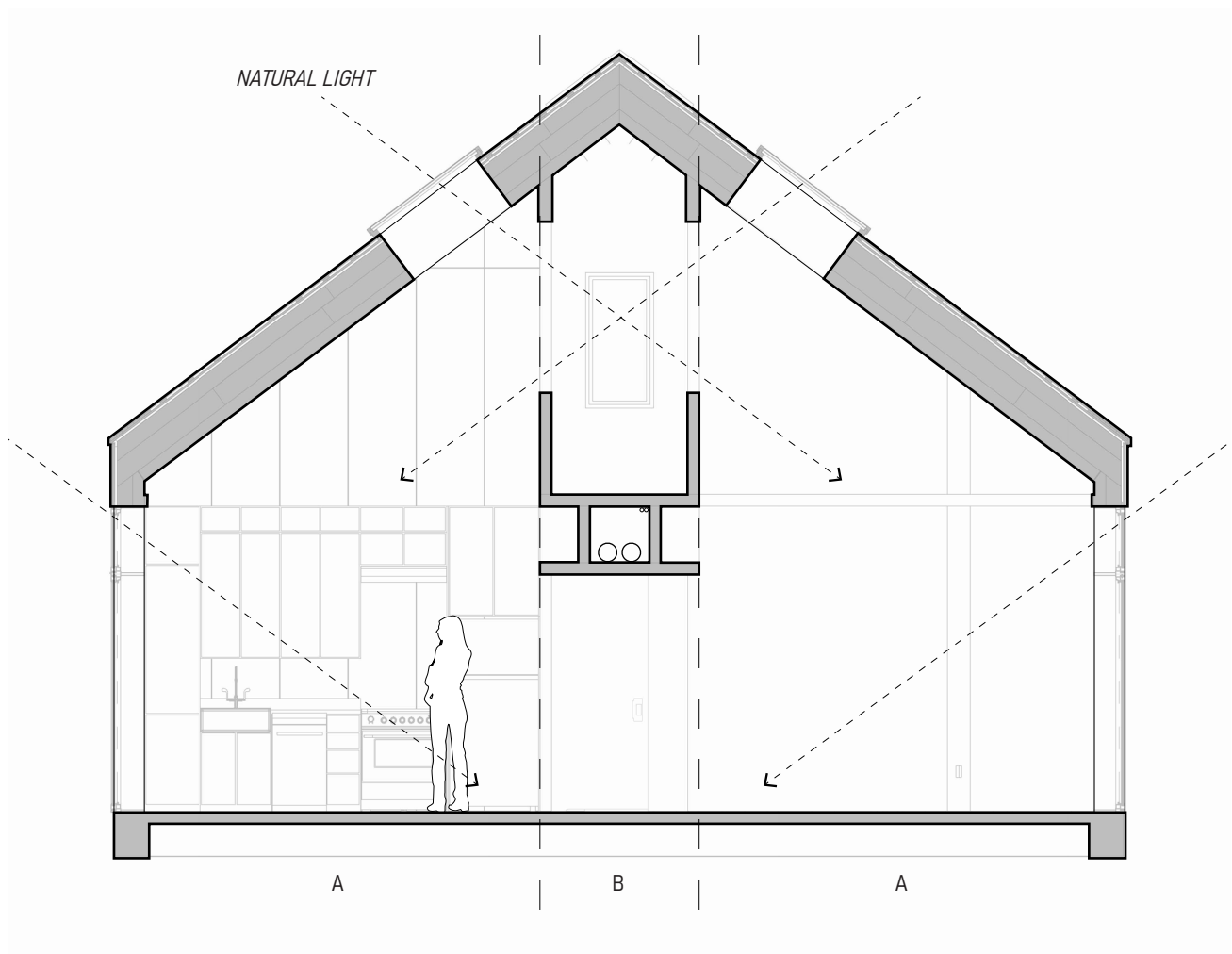
- | | | |
|--------------------------|---------------|---------------------|
| 1. Living Room | 5. Bedroom 1 | 9. Mechanical Space |
| 2. Kitchen & Dining Area | 6. Bathroom 2 | 10. Storage Space 1 |
| 3. Bathroom 1 | 7. Bedroom 2 | 11. Storage Space 2 |
| 4. Laundry Area | 8. Bedroom 3 | |

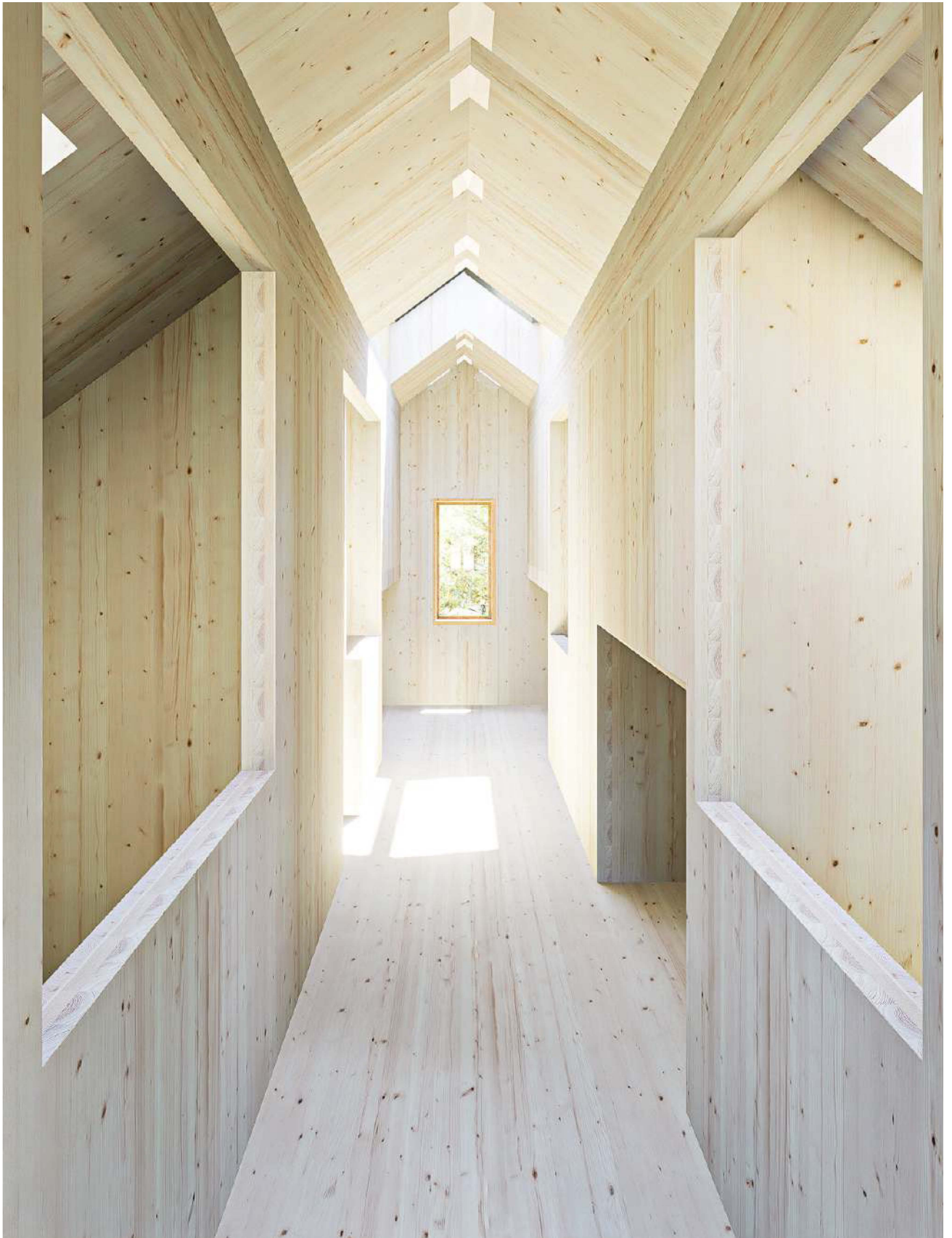




DESIGN FOR NATURAL LIGHT - LIVING SPACE

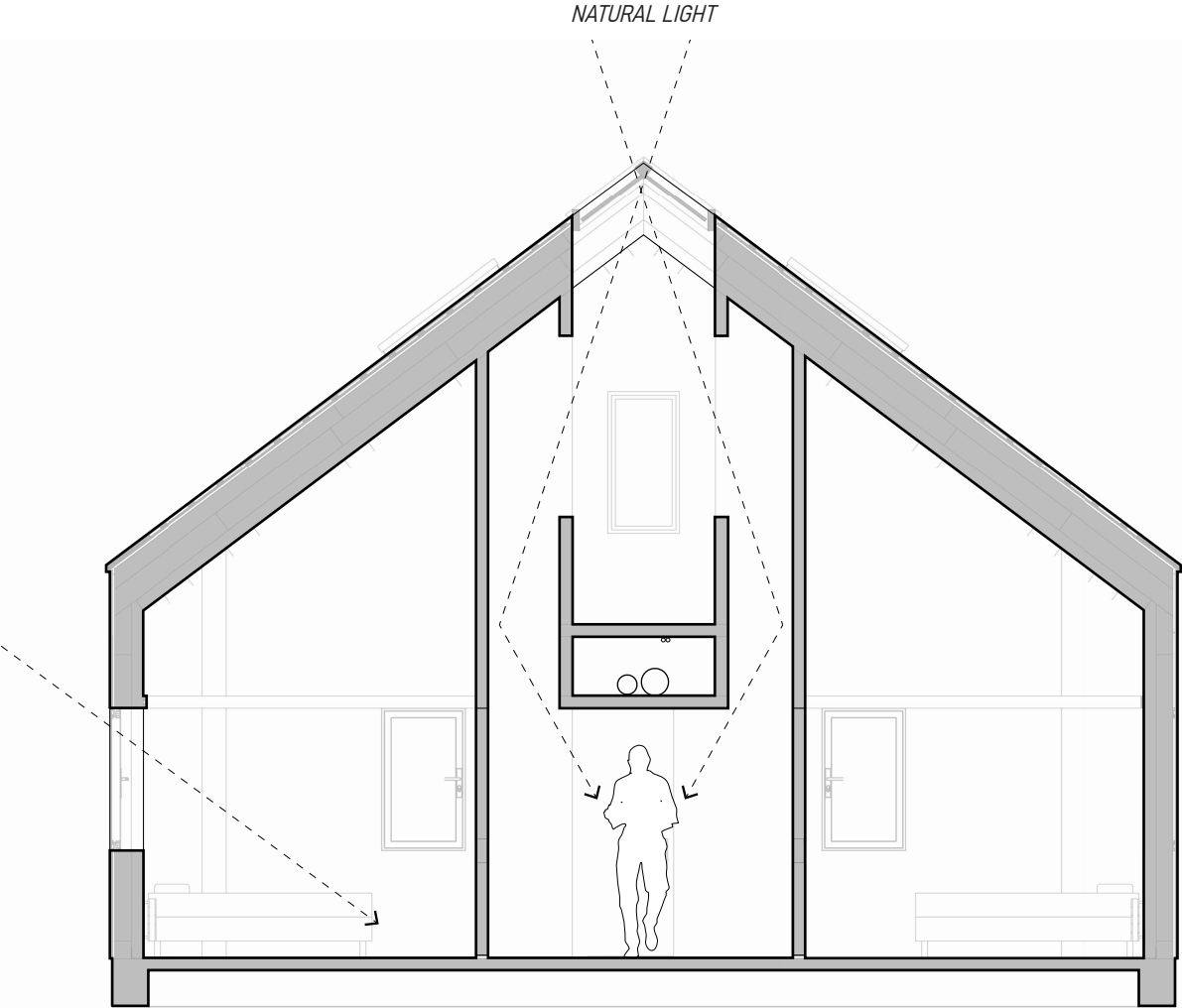
A primary consideration in the architectural design of interior space is the priority of providing opportunities for natural daylight to passively light the various areas of the house. With the cathedral-ceiling condition creating tall spacial volumes, it is important to bring light in from up high, and from several sides in order to evenly light the spaces with no “dead zones.” In the open living spaces, floor-to-ceiling windows and skylights act to achieve this.





DESIGN FOR NATURAL LIGHT - HALLWAY

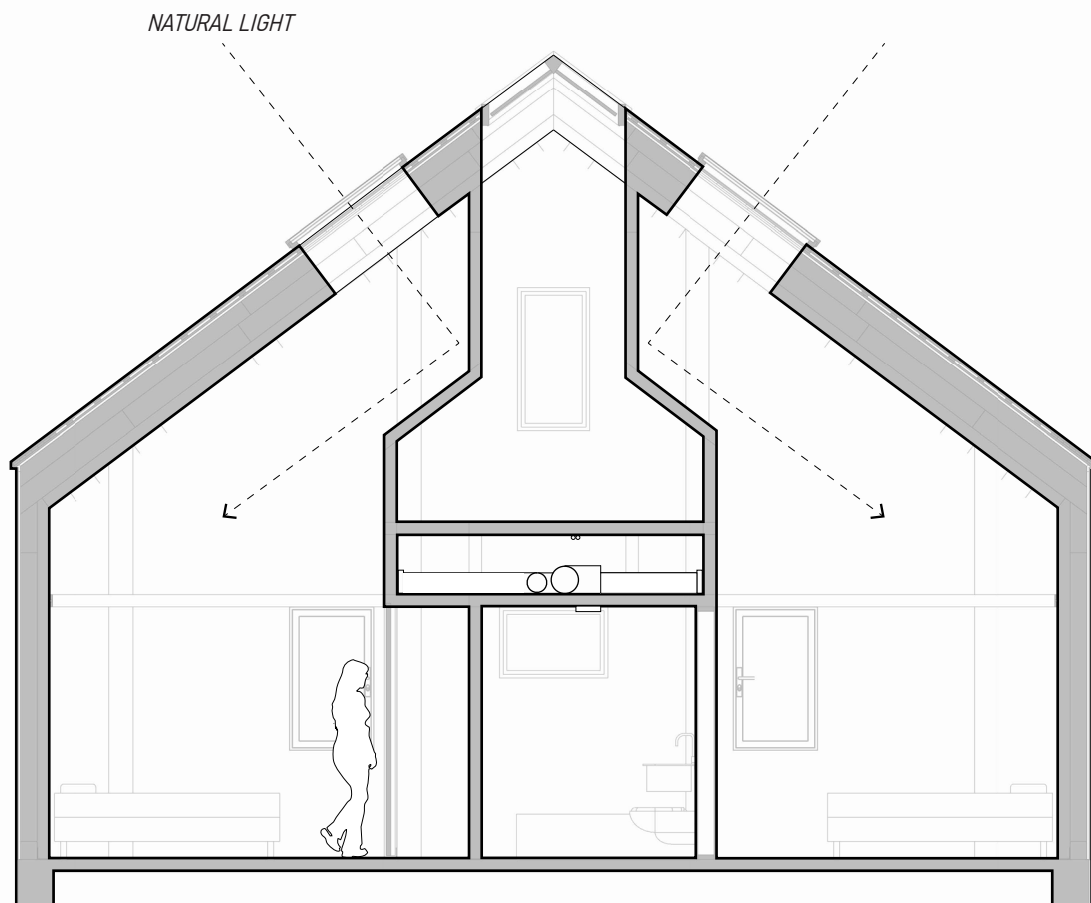
Reducing the need for artificial lighting helps to lower the energy loads and costs of a dwelling. The central hallway is designed to be daylit from above by a pair of light-wells that allow the light from a ridge-skylight to reach the ground level.

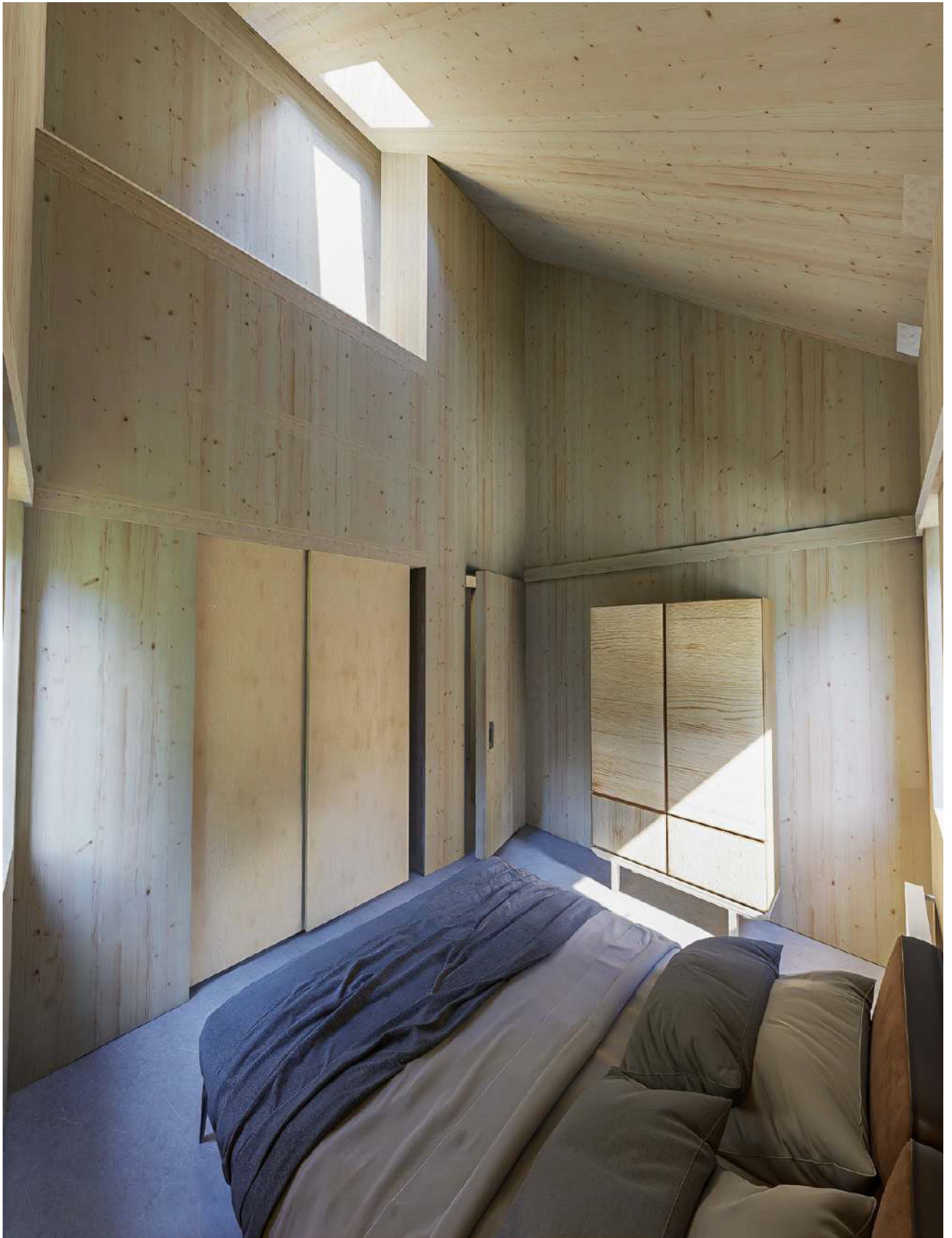




DESIGN FOR NATURAL LIGHT - BEDROOMS

Natural daylighting, especially in tandem with natural materials [wood], has been proven as an essential benefit to occupant health indoors.¹⁴ Daylight in a bedroom, especially when skylights are involved, require careful attention as to not allow the sun to shine directly onto one's face when in bed. The solution in this case is the design of angled light-shelves which are oriented to have the light from skylights wash down into the space as diffused daylighting. Tilt-and-turn bedroom windows are also present for light and natural ventilation.

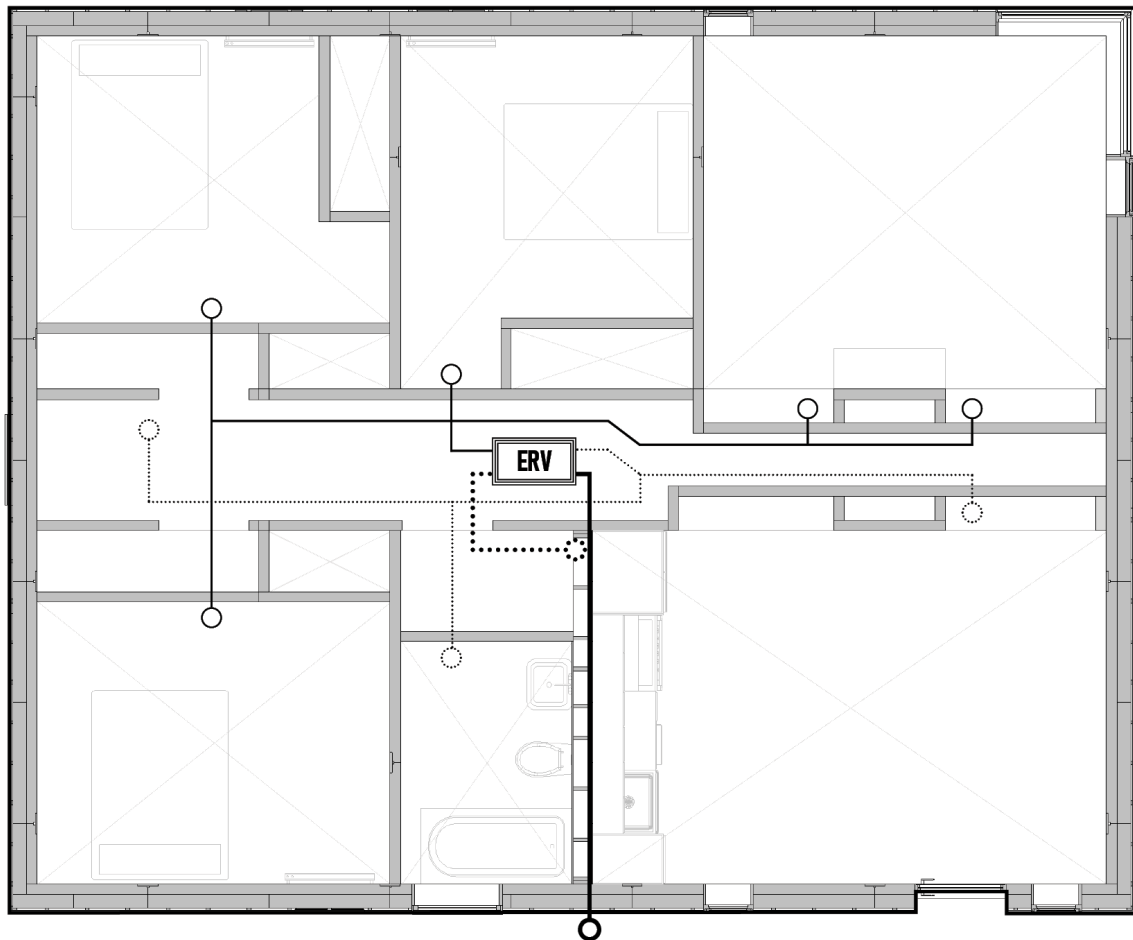




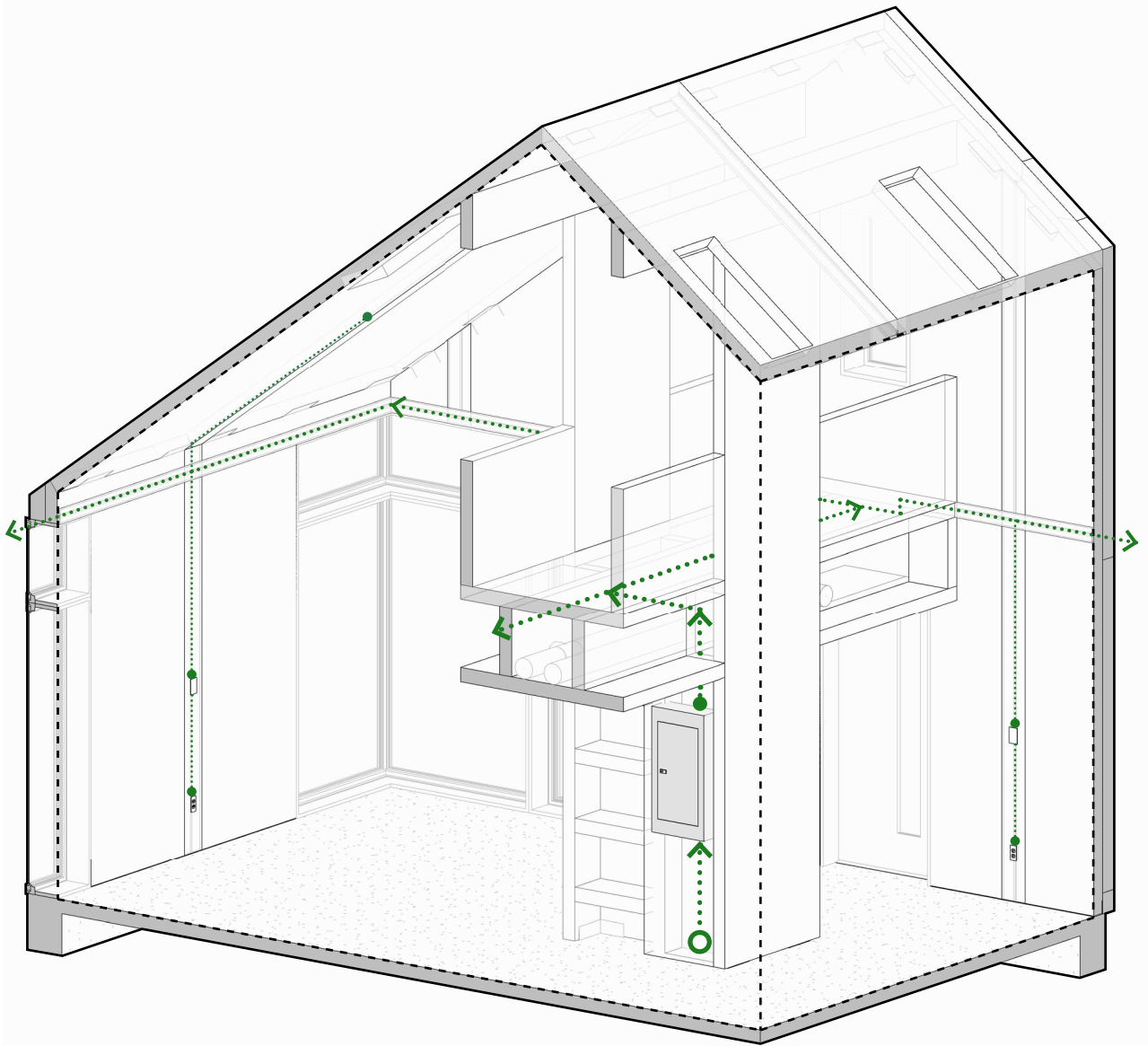
MECHANICAL & ELECTRICAL INTEGRATION

In a construction system where walls are solid panels, integration of the MEP systems requires careful consideration in design. The mechanical system of a BioMOD home is hosted within a designated drop-ceiling level in the Circulation Core, where an ERV or HRV is positioned centrally and accessed by a removable panel. The main supply air inlet and exhaust air outlet to the exterior utilizes the cavity wall of the design.

The electrical system of a BioMOD house starts with the primary access panel being located on the backside of the entry module of the Circulation Core. Conduit lines are then run centrally in the same pocket that the mechanical ducts are located, and reach electrical outlets on the perimeter walls through a series of profiled trim elements that meet up with a designated vertical channel behind the micro-CLT splines that connect two CLT panels.



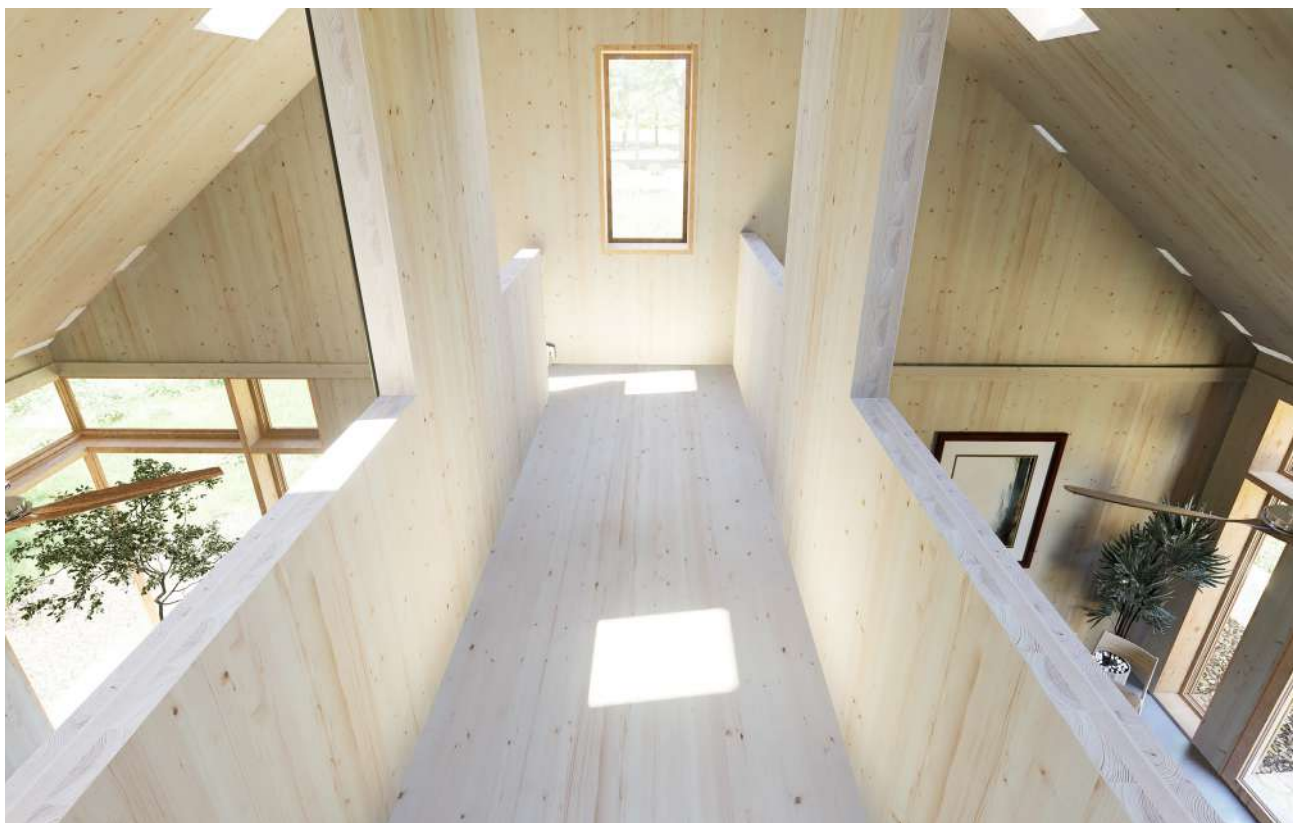
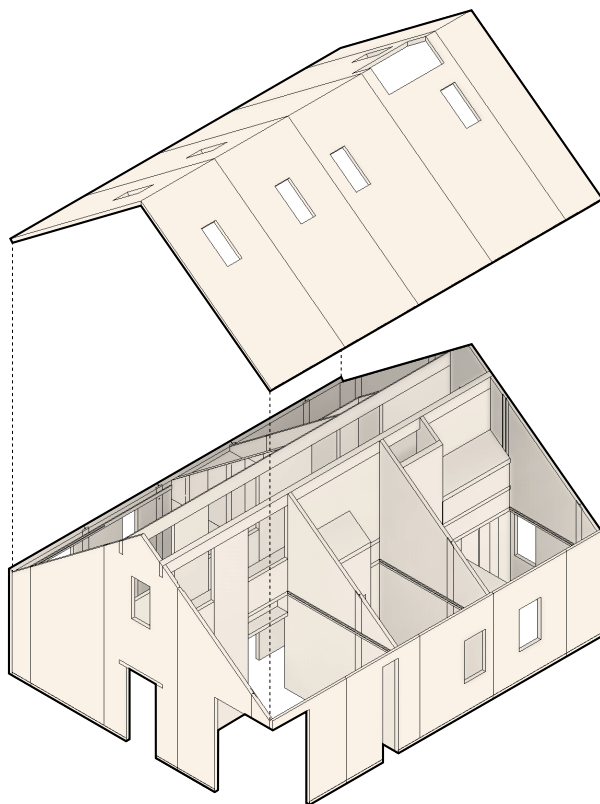
Mechanical Plan

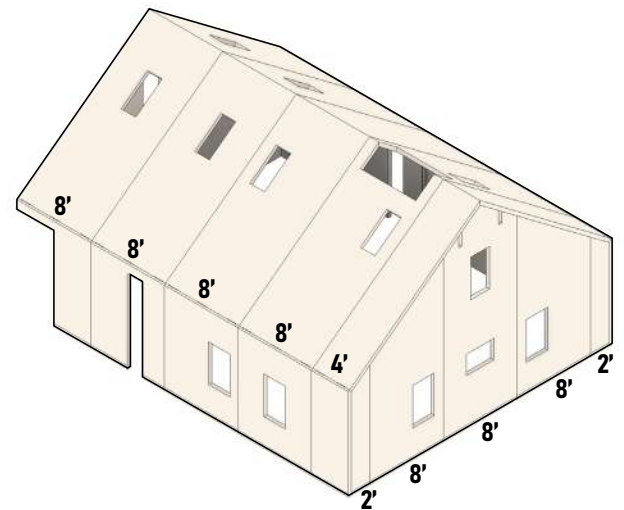
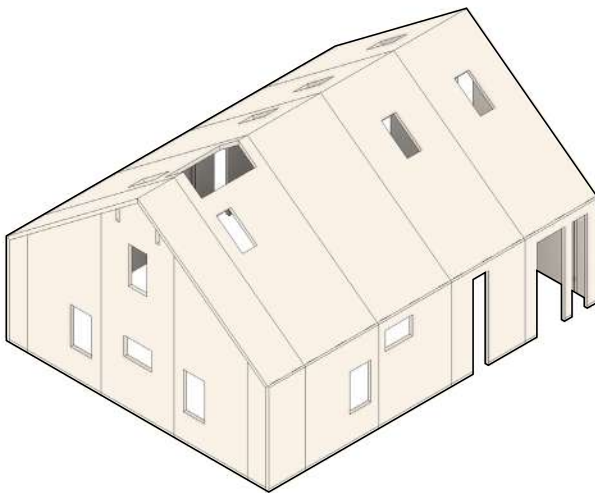
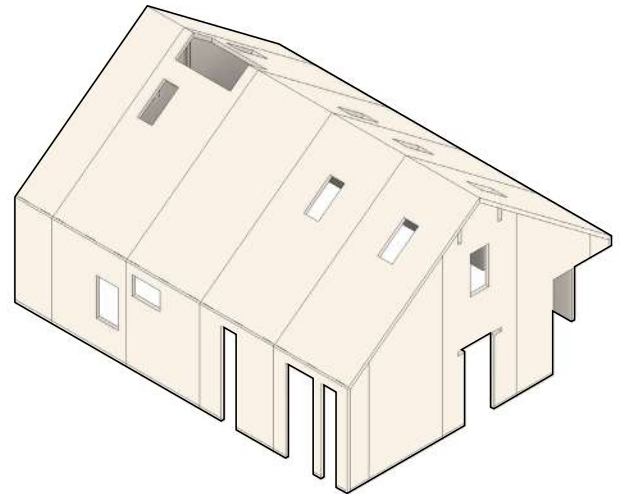
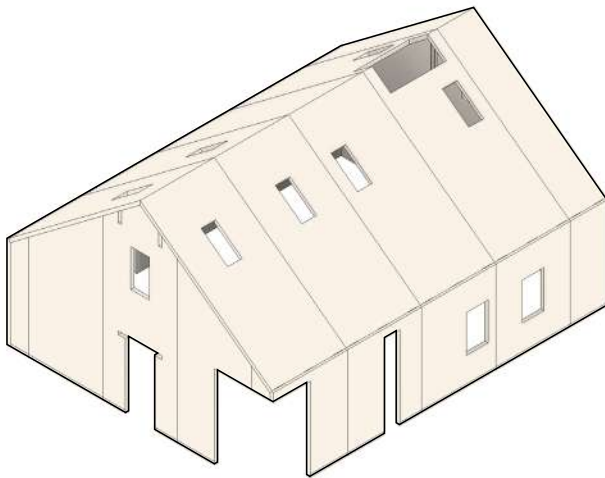


Electrical Integration Diagram.

CLT COMPOSITION

At the core of the project is the emphasis on utilizing an 8-foot-width Eastern White Pine CLT panel system to comprise the entire structural shell and interior of the design. The exterior panel organization follows a segmented format in line with the expandable system. Structurally, the roof panels are primarily held up by two sister beams that run the length of the house, and rest on the two central end-panels.





[Left] Overall Panel Composition

[Above] Exterior CLT Panel Composition



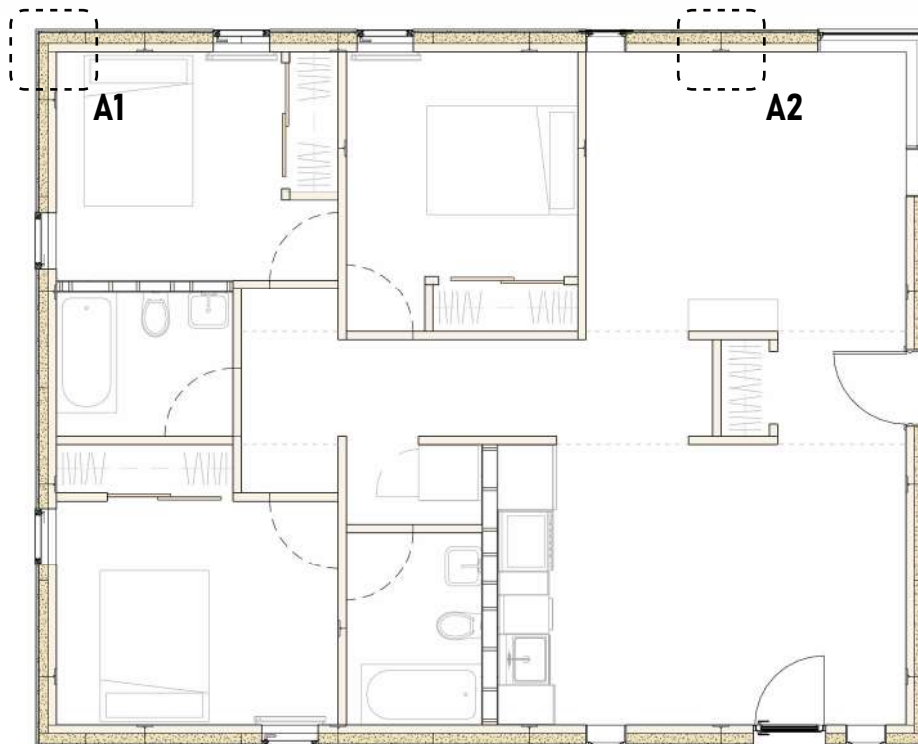


ASSEMBLY DETAILS

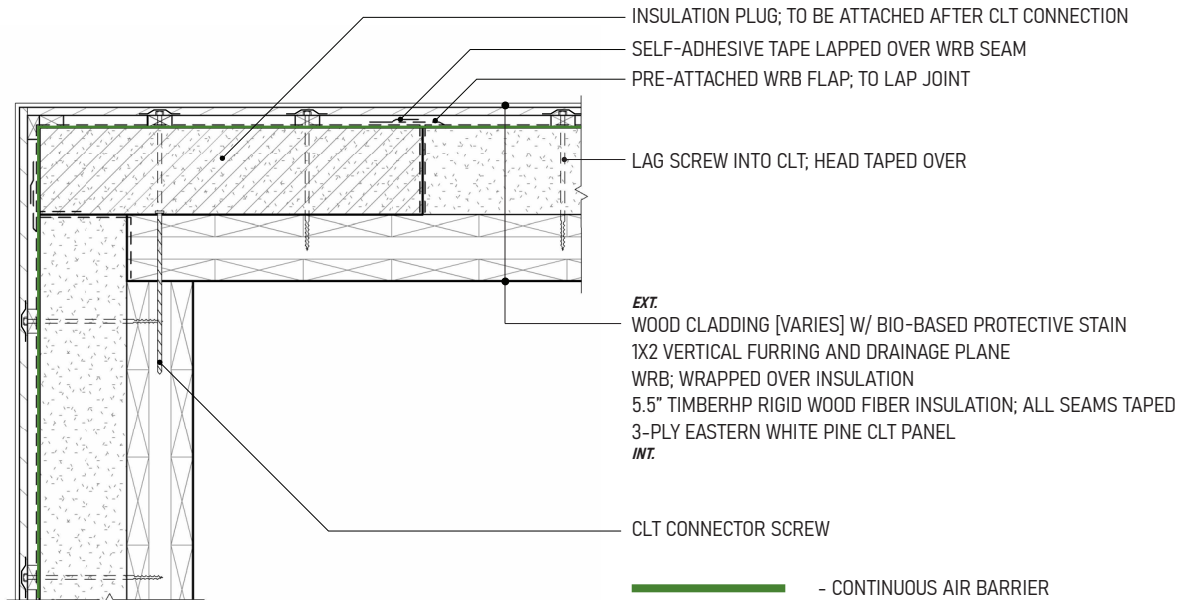
THE PANEL-TO-PANEL SYSTEM

As expressed in earlier sections, the system works on a panelized configuration for modular construction. With the entire shell of exterior and interior walls being comprised of CLT panels (with the exception of plumbing walls), the panels are connected by a system of vertical micro-CLT splines that nest within the profile of panel-to-panel junctions and are fastened to each. The splines—which are fabricated in the same way as regular CLT, but with much thinner board members—are idealized as being made from Eastern White Pine lumber as well, to match the finish-quality of the EWP CLT panels as best as possible to achieve a visually-seamless connection on the interior.

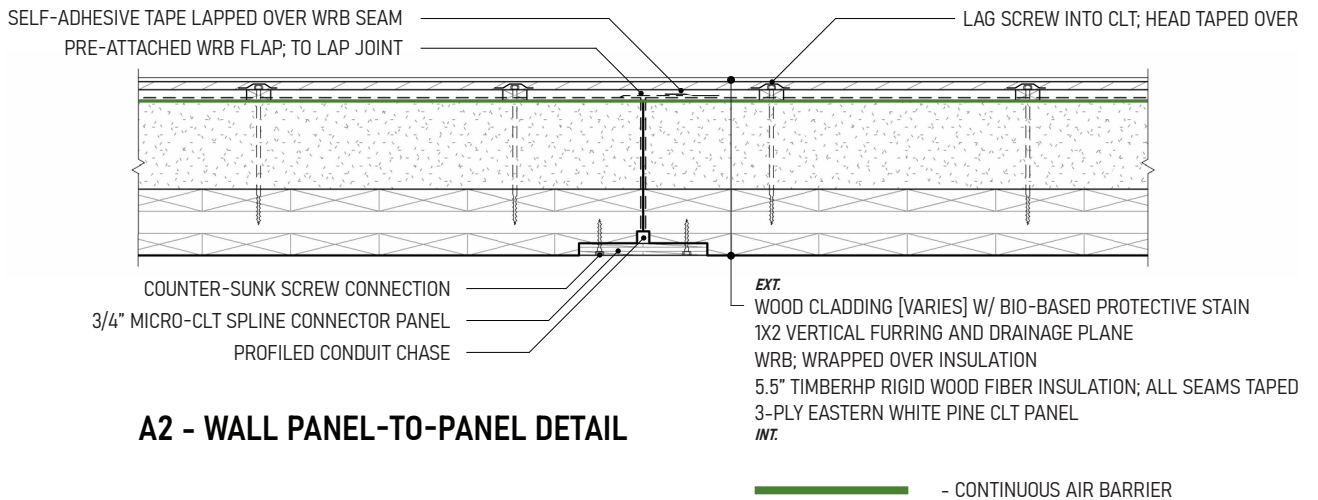
The following assembly details depict the enclosure conditions at the panel-to-panel interfaces of the exterior walls. The exterior wall panels are prefabricated to have the insulation, membranes, and vertical furring strips already attached. On site, the panels are fastened to one another via spline connections, with the exterior-facing seam between the panels being taped to seal the air and water barrier. At the corners of the house, a CLT panel is left exposed to deploy a simple screw-connection system and is then covered with the appropriate insulation after the fact. This insulation plug could then be removed, and the panels simply unscrewed in the event of disassembly.



*Ground Floor Plan of a 3-Bedroom
2-Bathroom Model*



A1 - WALL-TO-WALL CORNER DETAIL

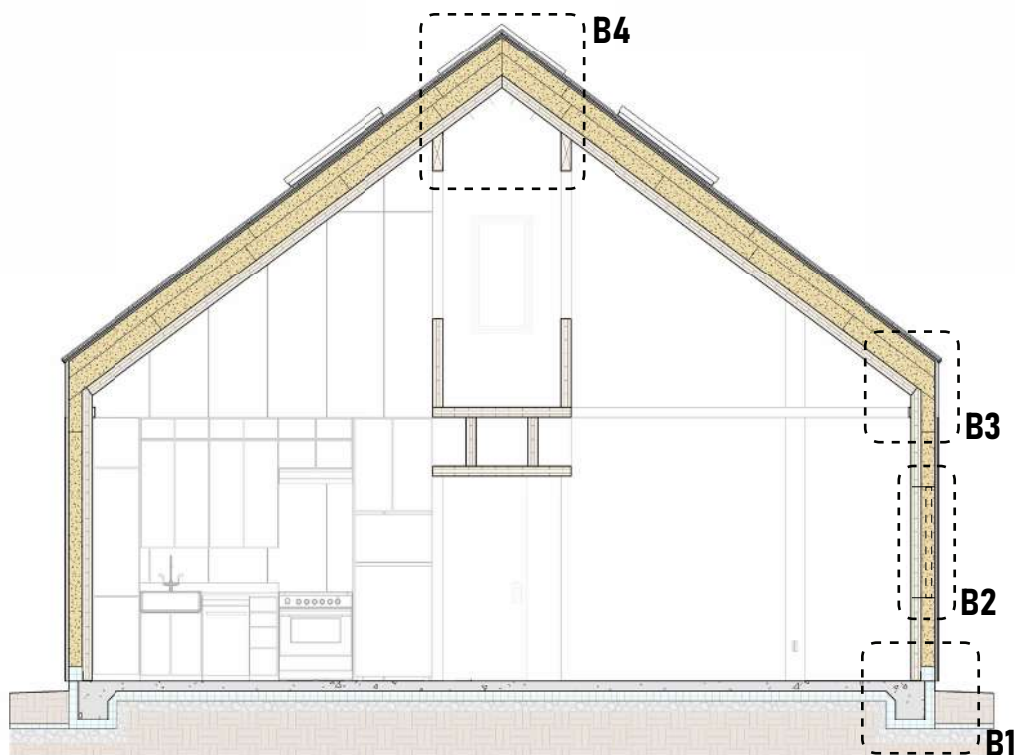


A2 - WALL PANEL-TO-PANEL DETAIL

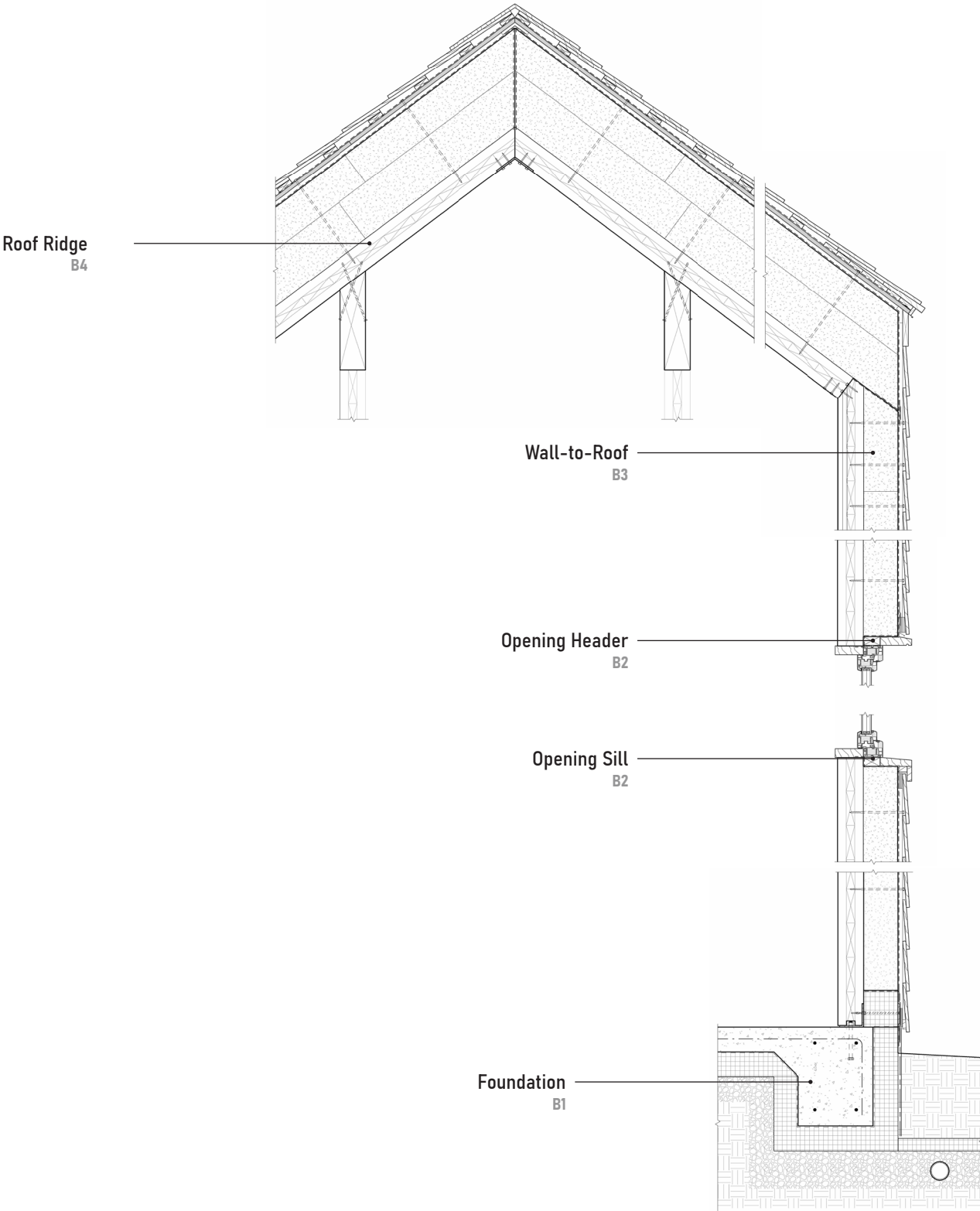
THE ENCLOSURE

The following details depict the general enclosure conditions of the assembly, which include the anticipated foundation, window openings, the wall-to-roof interface, and the roof ridge. The details express the intended connection methods, as well as a maintained continuous air barrier through the panelized envelope.

These details, which represent the study-condition BioMOD house design, utilize wood clapboard siding and wood roof shingles as the designated cladding elements. Depending on which cladding materials would be used in a given BioMOD house, the exterior assembly layers and connection methods may vary slightly.

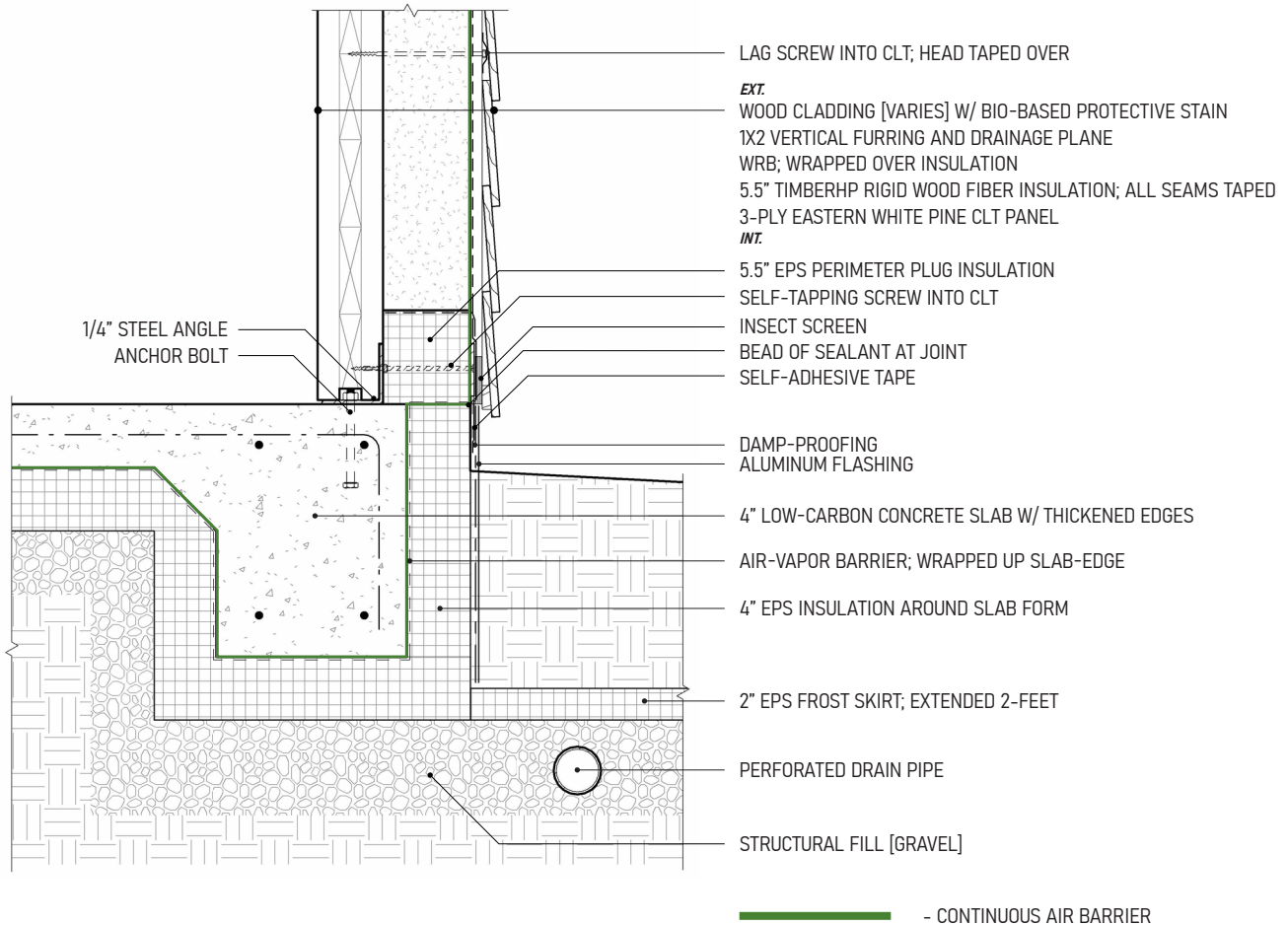


General Section Diagram



Enclosure Details Section

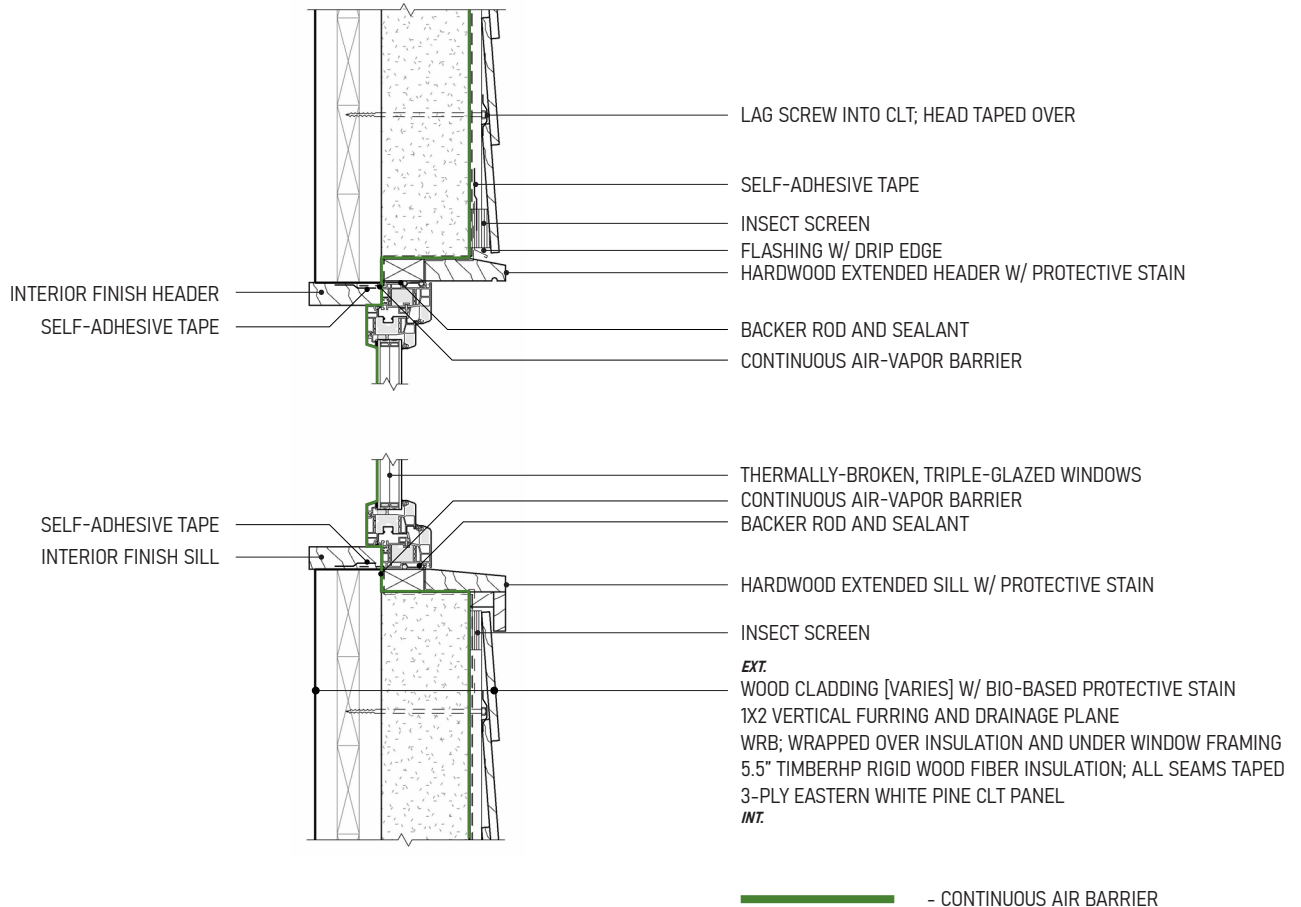
B1 - FOUNDATION DETAIL



Although a BioMOD house may be designed for several different foundation types, the designated foundation for representation is an insulated concrete slab. Requiring less excavation than all other in- or on-grade foundation types, a slab foundation is relatively faster and more affordable to install.

The CLT panel is mounted to the foundation by a steel angle connection, which also serves as a moisture barrier between the two materials. The base of the panel assembly is left exposed (much like the A1 detail) in order to connect the CLT to the steel angle, and is then plugged with EPS Insulation throughout the perimeter.

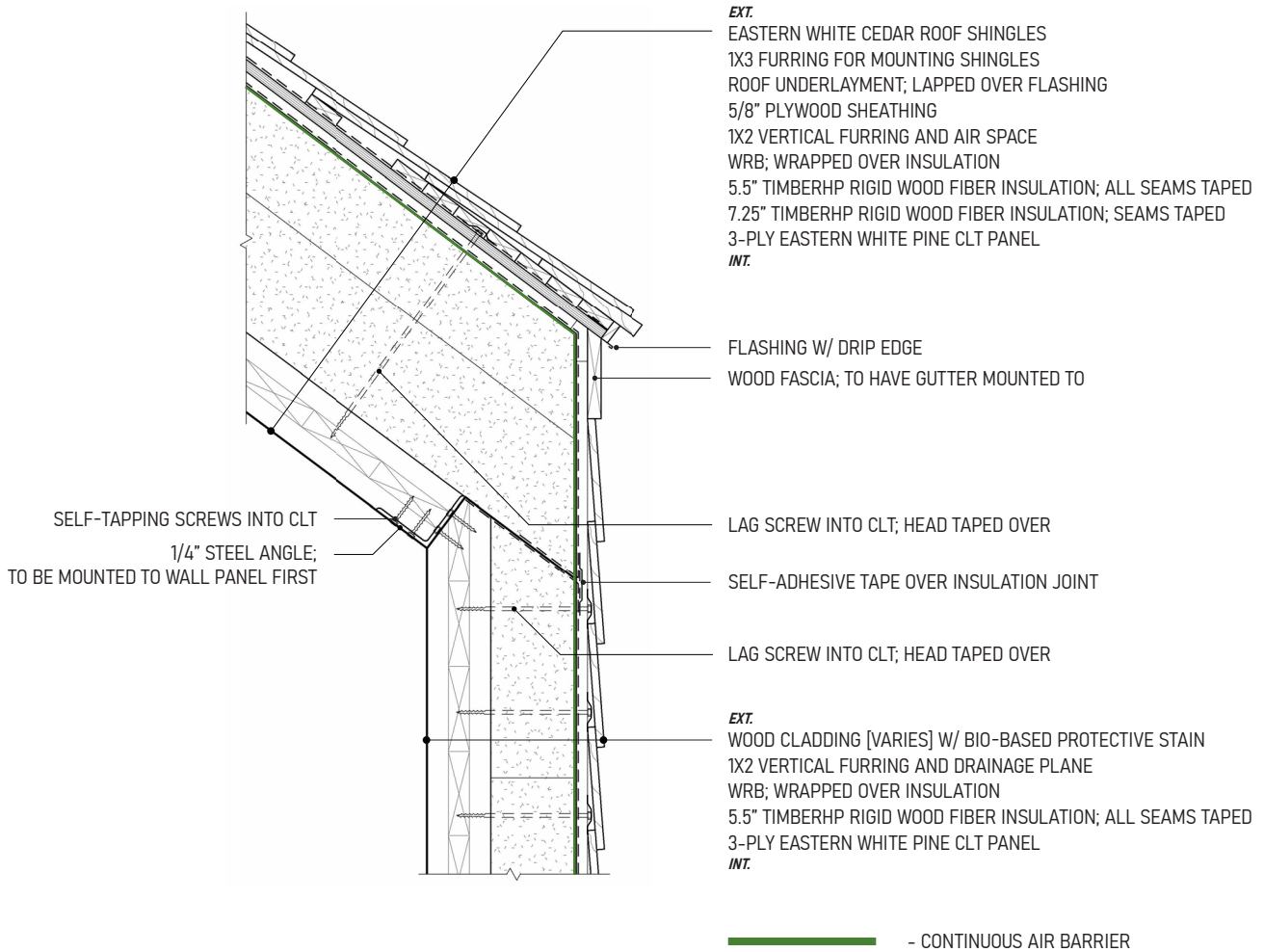
B2 - HEADER & SILL DETAIL



The idealized glazing and door systems throughout a BioMOD house's envelope would consist of high-performing, triple-glazed products that would greatly reduce heat losses related to opening penetrations in an otherwise solid wall.

A beneficial feature of a wall made from CLT is that the construction of openings do not require any additional framing, which aids to simplify the wall-to-opening interface, and reduce labor cost.

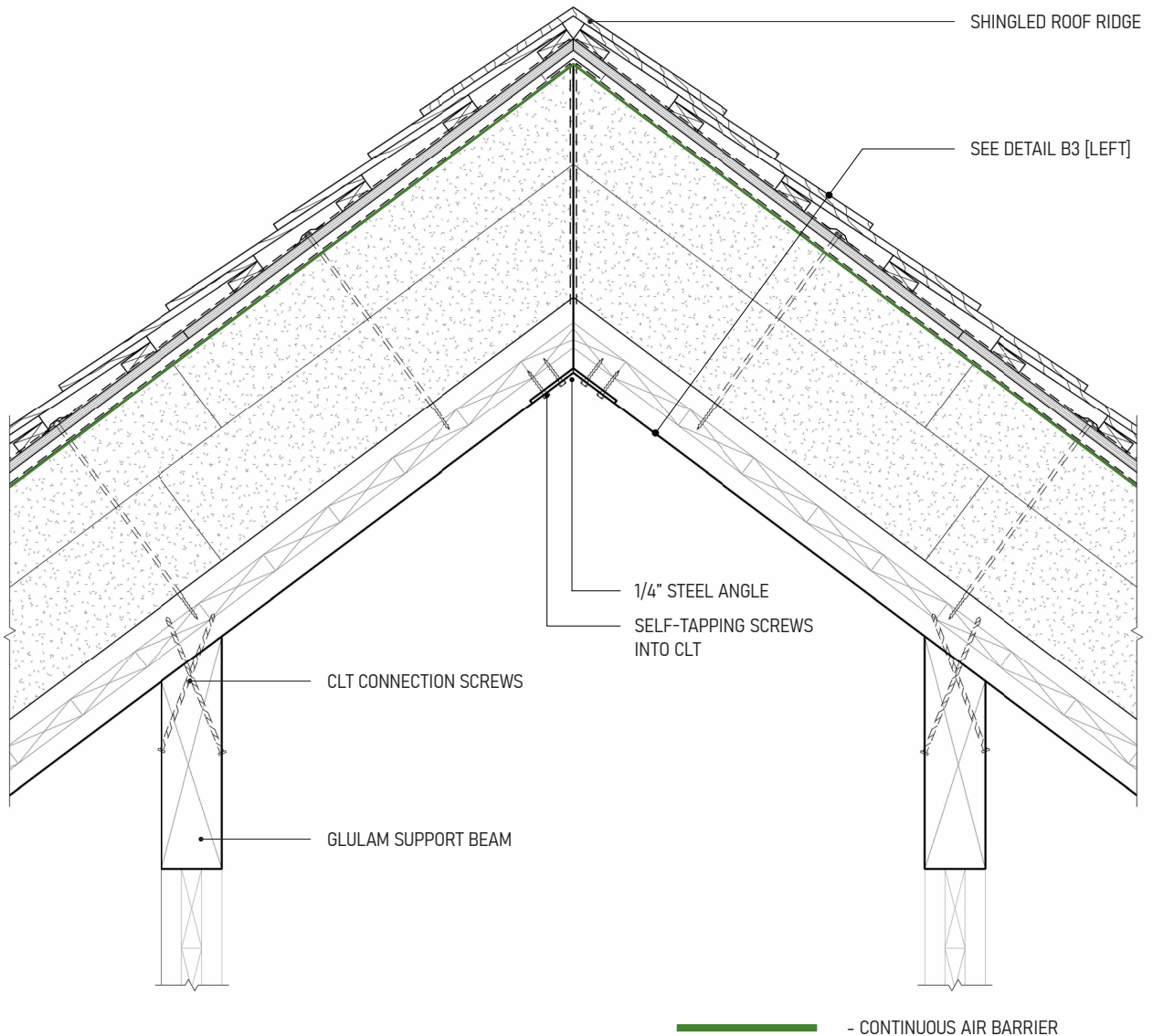
B3 - WALL-TO-ROOF DETAIL



The wall-to-roof interface depicts that, due to the insulation being pre-attached to the panels before reaching the site, all of the structural connections between the CLT must be made internally. The top of the wall CLT panels are profiled to have a simple steel angle attached to it as shown, and have the roof panel be dropped down on to it and fastened.

The rigid wood fiber insulation panels are profiled along with the CLT in order to create an assembly designed to have minimal to no roof overhang, as part of the architectural intent. Fascia blocking at the top of the clapboard siding is installed, which is where gutters for rain drainage would be mounted.

B4 - ROOF RIDGE DETAIL



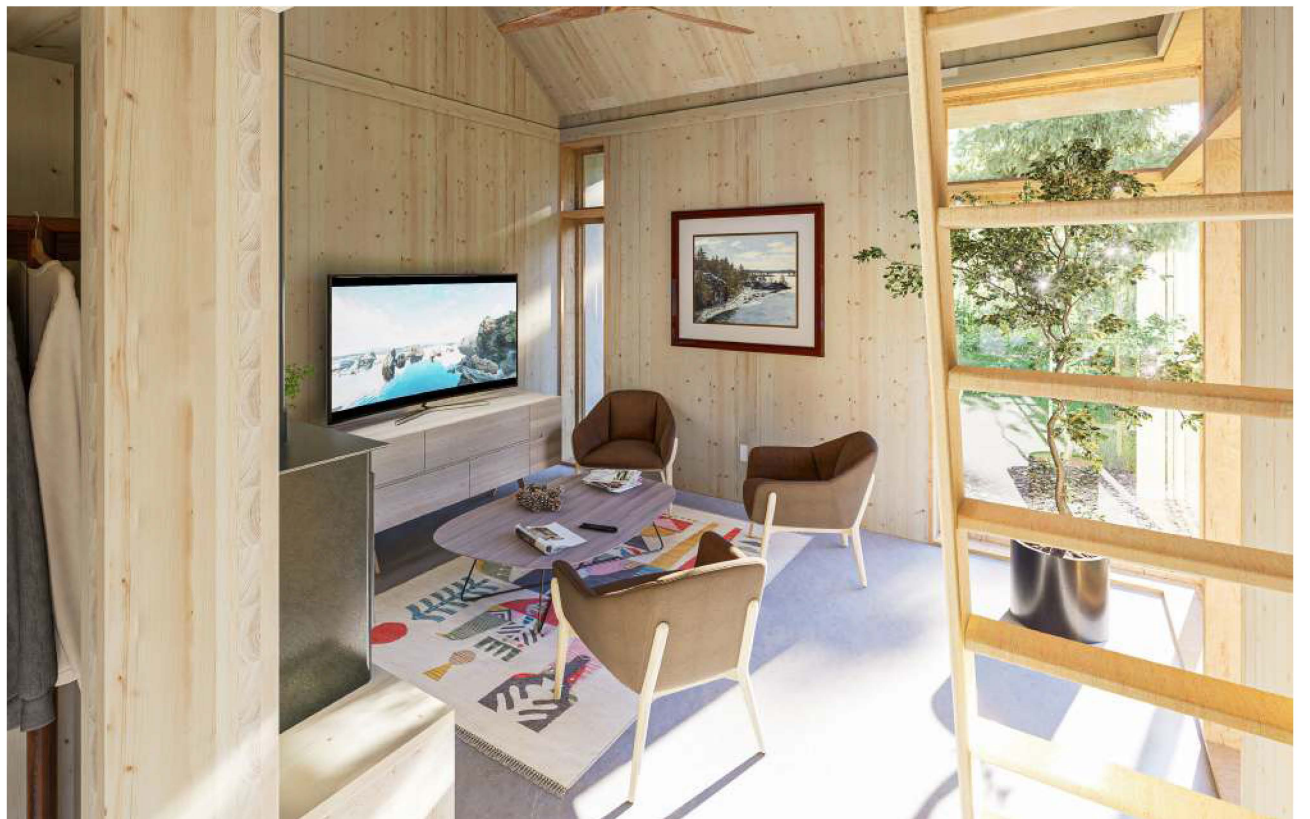
The primary support method for the roof panels are a pair of profiled glulam beams, which rest atop the load-bearing walls of the Circulation Core. The panels are dropped on to the beams, where they are fastened to each other with screws. At the ridge, the roof panels are connected with intermittent steel angle connections.

The seams of the two layers of rigid wood fiber insulation are staggered between layers as a best-practice approach in maintaining a continuous insulation layer, in tandem with the air barrier.











B3





PRODUCTION PROCESS

THE PRODUCTION CHAIN

MANUFACTURING CHAIN

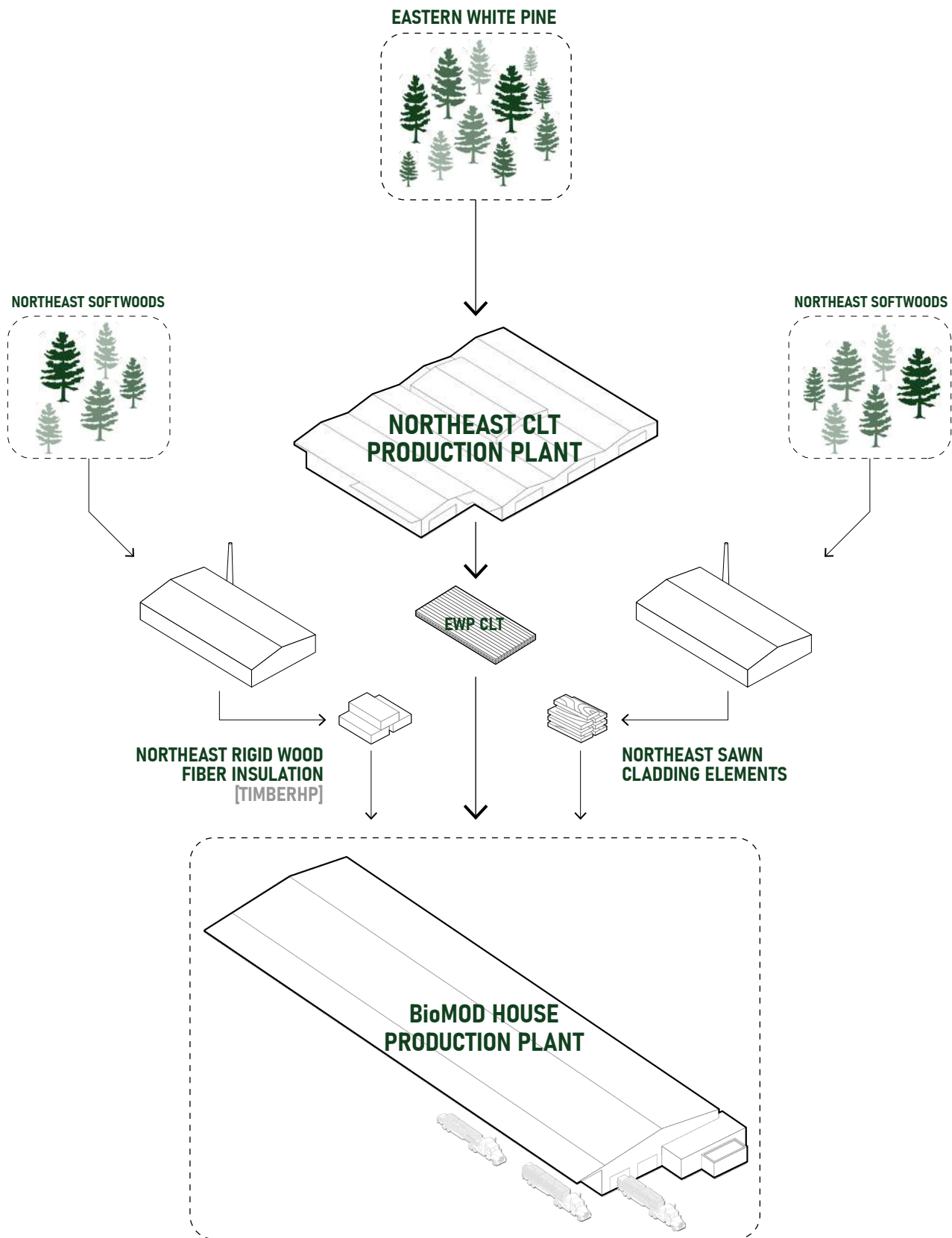
A major priority and supportive initiative of the BioMOD project is to emphasize the primary use of biogenic materials sourced from the forests of the Northeast to produce the modular homes. Within this criteria, the system is idealized to function with the production of Eastern White Pine CLT from a future CLT Manufacturing Plant located in the Northeast itself. Due to the nature of the single-family homes requiring relatively lower overall strength-performance requirements from the CLT they are constructed from, the possibility for smaller CLT production facilities could be feasible in this case—as relative parts would have shorter lengths, and simple vacuum presses may achieve sufficient bonding capability. This would aid in reducing the barrier of investment for a CLT production plant to open in the Northeast.

Alongside the EWP CLT, the remaining biogenic materials for the house assembly—the wood fiber insulation and exterior sheathing & cladding elements—would also be sourced locally in the Northeast to support local economy and forestry. In the case for sourcing the rigid wood fiber insulation, TimberHP by GoLab, based in Madison, Maine, is the only wood fiber insulation manufacturer in the United States—and it is local.

The sourced forest products would make their way to a designated BioMOD modular house production plant, where the prefabricated assembly panels and kit-of-parts modules would be made.



[Far Right] The Manufacturing Supply Chain



ECONOMY OF SCALE

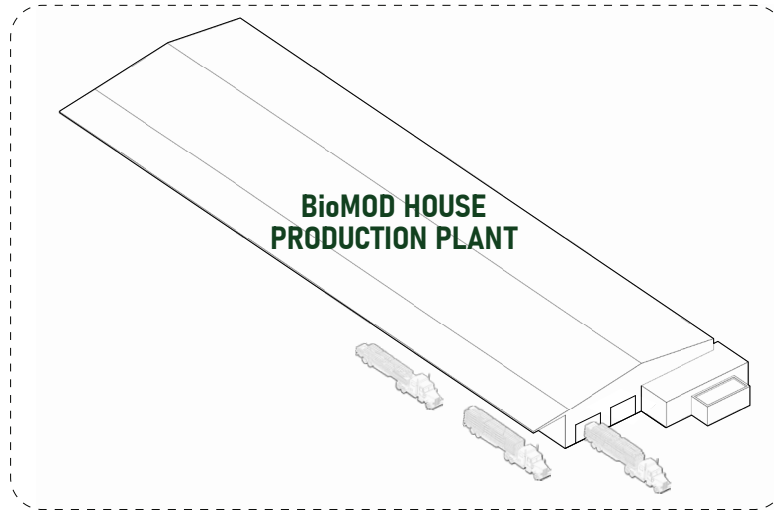
Despite being made from complex systems and components, consumer products such as smartphones and vehicles are made relatively affordable due to the high volume at which they are produced. The same method (while perhaps not at such an immense scale) is practiced by conventional modular home systems, as shown by the existence of modular house showcase lots. This method aids in lowering the unit cost of each individual house, which is a major contributor to how modular and manufactured homes achieve their affordability.

To remain competitive with conventional systems of building, this method of standardized production

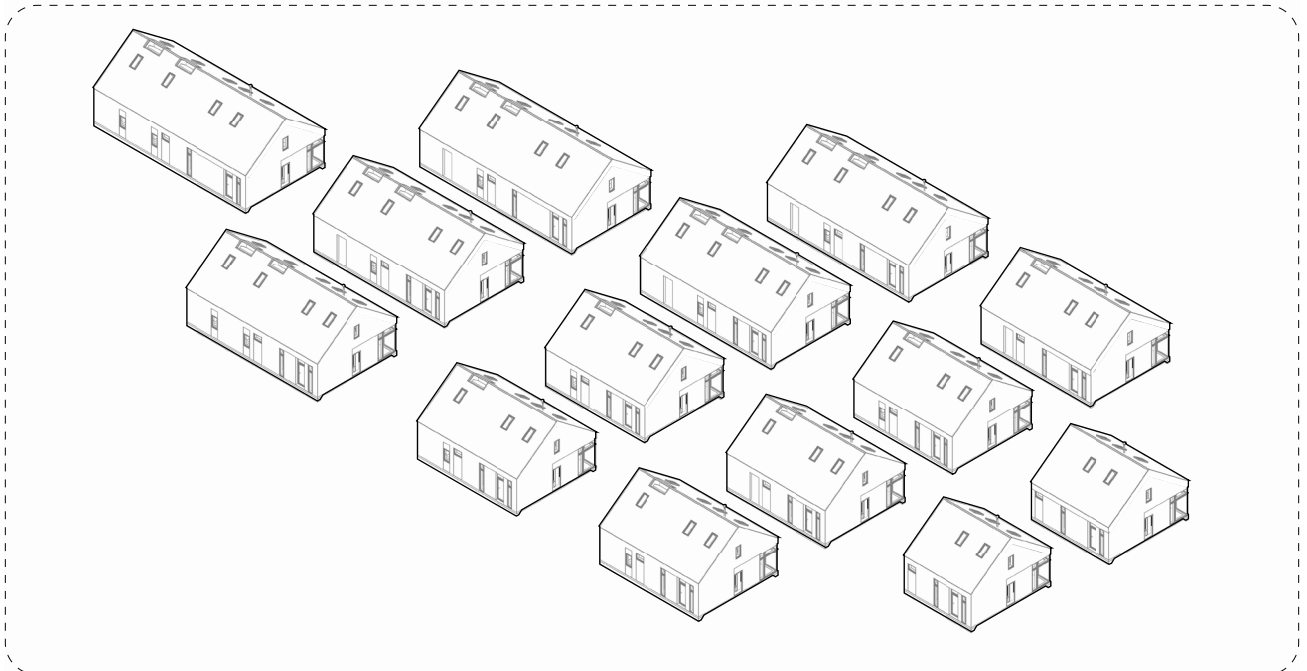
and mass-prefabrication is intended to be employed in the BioMOD system. Paired **only** with sustainable & ecological forestry practices with proper stand-rotation, the abundance of eastern white pine and other softwoods in the Northeast provides the opportunity for readily available material volumes that may allow for an economy of scale to take effect. With wood being a renewable resource, this system may be sustained in the long-run, which highlights a potential advantage of BioMOD's biogenic assembly comprised almost entirely of renewable-source material. In the case of conventional modular and manufactured houses, the source-materials for many of their assembly elements will eventually run out.



MASS-PREFABRICATION



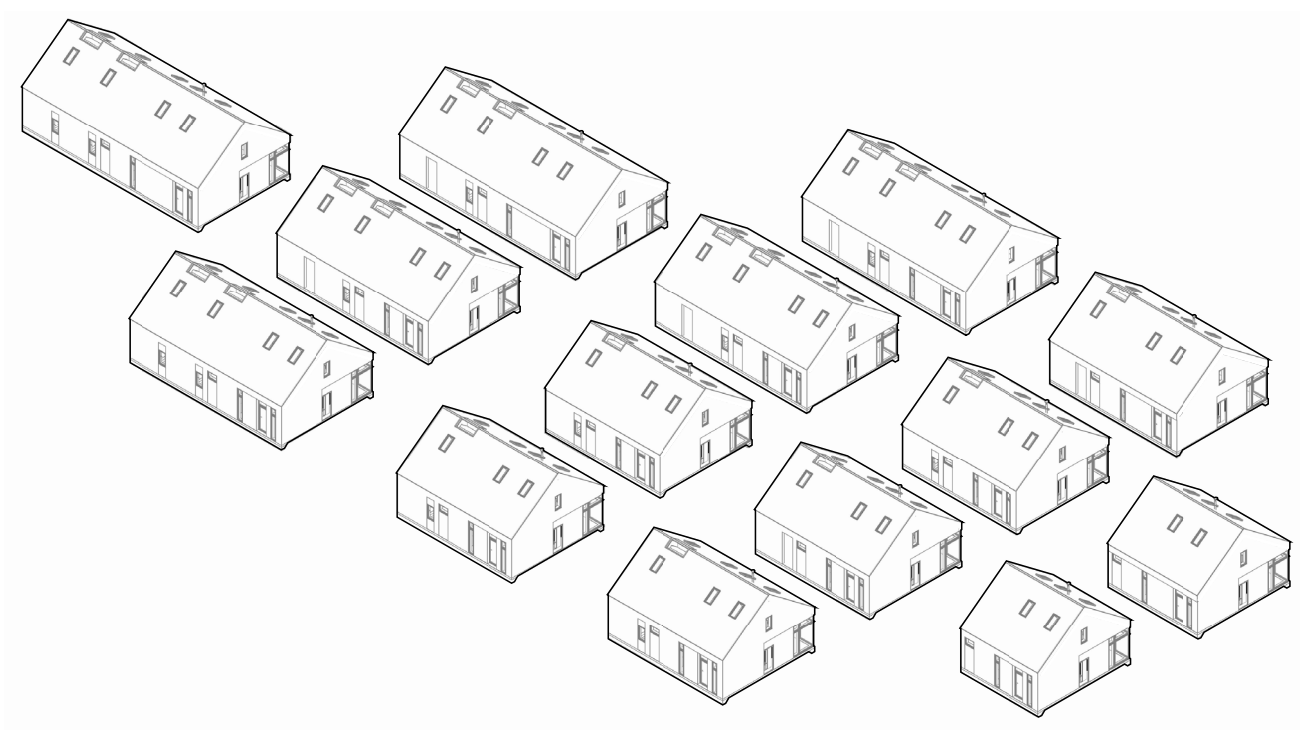
STANDARDIZED PRODUCTION

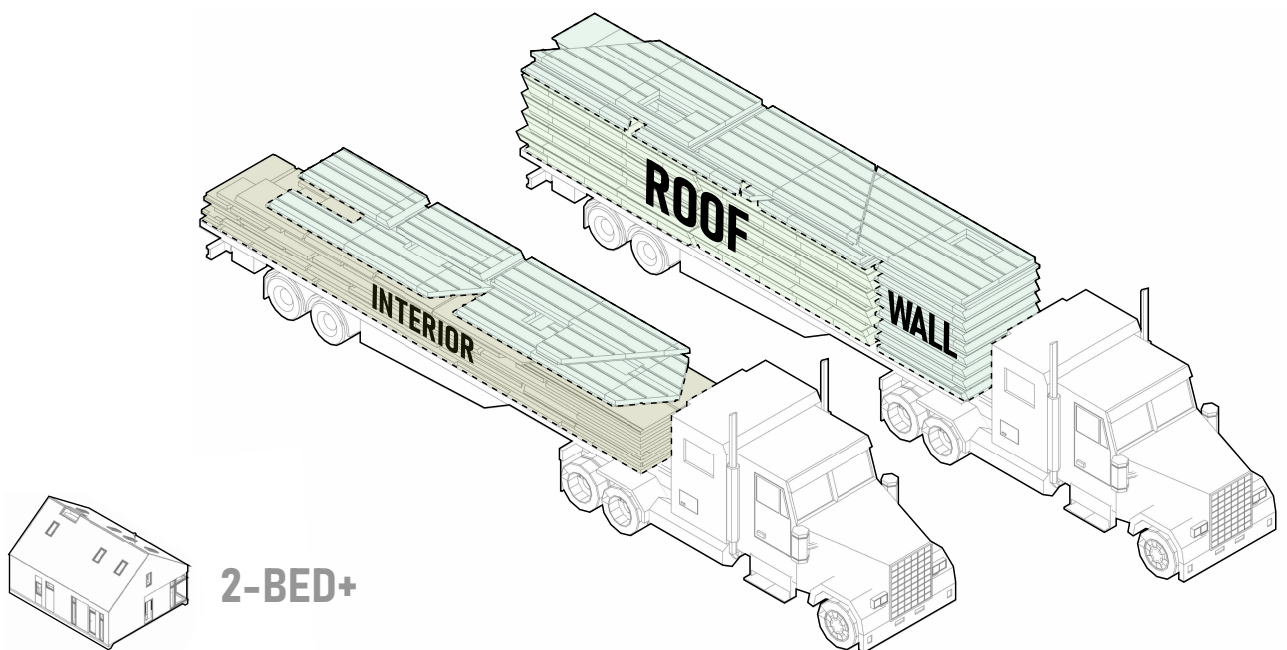
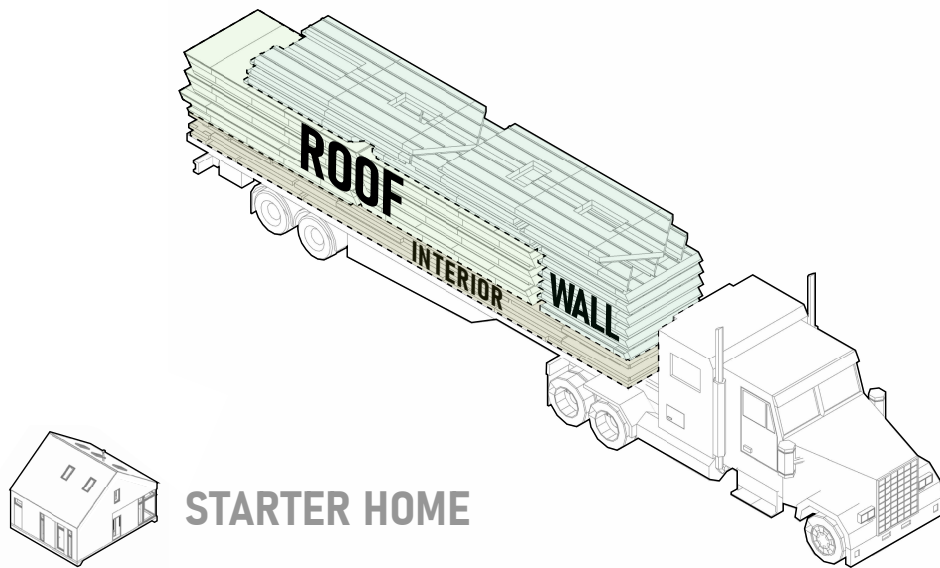


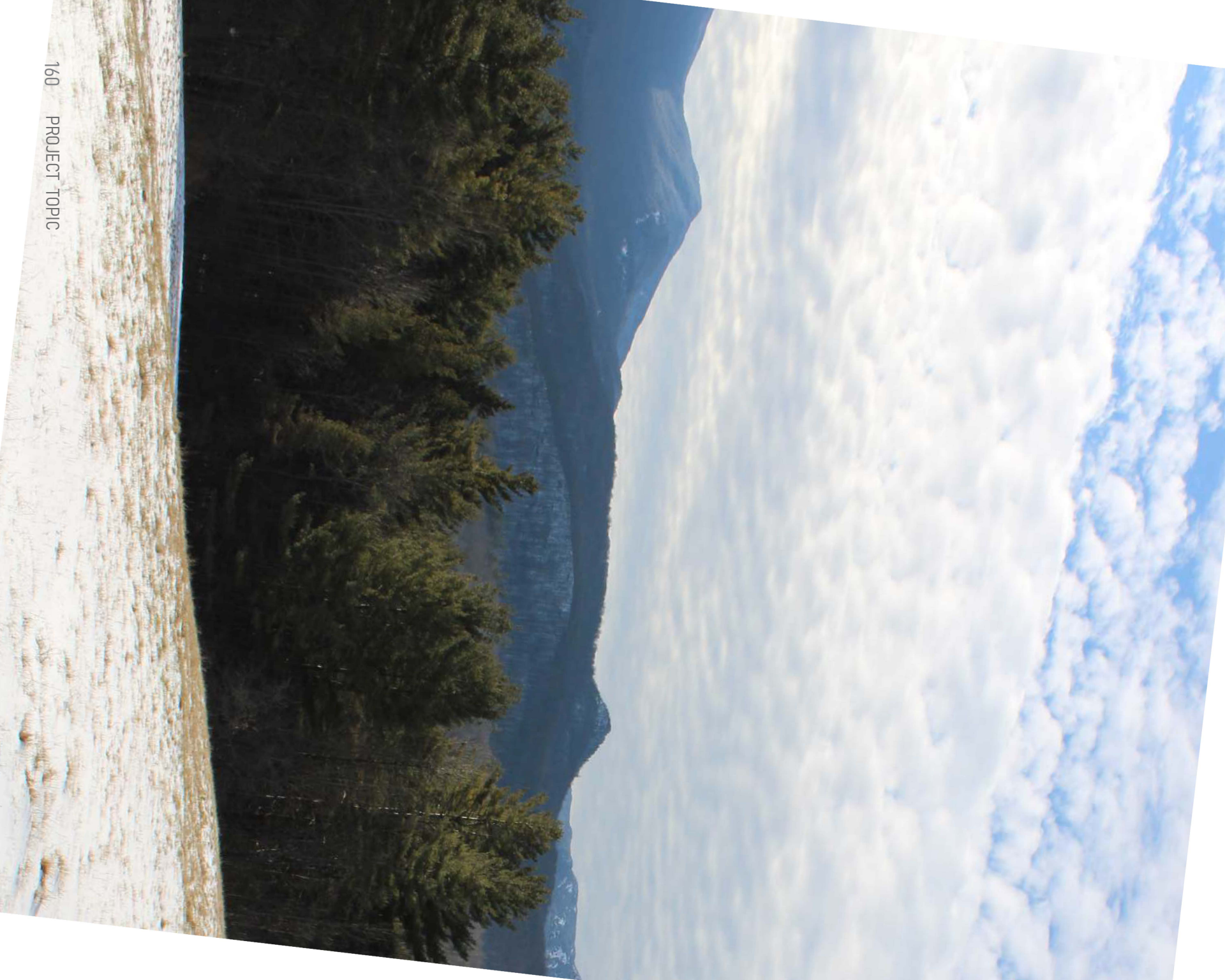
SHIPPING EFFICIENCY

When it comes to shipping a BioMOD house, the transportation of its panelized elements is designed for optimized efficiency to streamline logistics and minimize the embodied carbon emissions related to transport. Due to the design system's panelized format, and the maximum CLT panel width of 8-feet, the components can be flat-packed on a semi-truck trailer without any need for special wide-load accommodations. This, in turn, minimizes the cost of shipping a BioMOD house.

The panelized components of the design system's one-bedroom Starter Home can fit entirely on a single semi truck. Beyond this, the larger variations of the modular system, or a later-on expansion to the original home, would require a second truck to ship all its pieces.









ANALYSIS



C1





ANALYSIS INTRODUCTION

OVERVIEW

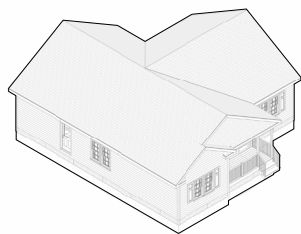
STRUCTURE OF ANALYSIS

The Analysis section of this project seeks to compare various aspects and qualities of the BioMOD mass timber modular system with typical modular construction systems, as well as standard light-wood-frame site-built construction systems.

Therefore, the following analyses will be comprised of three created BIM (Building Information Model) models to represent each of the three respective construction systems mentioned above. In terms of systematic order for analyses, the typical modular house will be at the start of each comparison, with the BioMOD mass timber house in the center, and the standard-constructed version of the BioMOD design situated last. The typical modular house and the BioMOD mass timber house represent a comparative analysis between the general conditions of current modular house characteristics with the proposed modular system of this project. The BioMOD mass timber house and its standard-constructed version represents a comparative analysis that targets the differential characteristics between biogenic mass timber construction and standard site-built light-wood-frame construction.

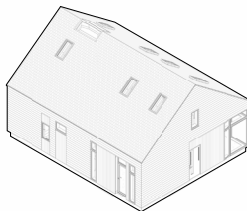
The three primary categories for comparative analysis in this project focus on the composition of construction materials in each system, embodied carbon through the performance of varying-structured life cycle assessments, and the general thermal performance of each construction system through analysis of thermal-resistance values. Additionally, as a simple qualitative assessment, the interior daylighting and aesthetic qualities of each system will be visualized through digital rendering imagery.

Through conducting these benchmark comparative analyses, the general qualities of each construction system may be revealed and compared with one another, aiding to reveal the research-backed benefits of a biogenic mass timber system for single-family residential construction.



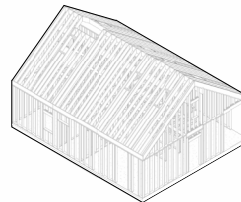
TYPICAL MODULAR HOUSE

VS



MASS TIMBER MODULAR HOUSE

VS



STANDARD-CONSTRUCTED HOUSE

PROJECT STRUCTURE

RESEARCH

CURRENT CONDITIONS -
RURAL HOUSING

FOREST SECTOR AND MASS
TIMBER TREE SPECIES

MASS TIMBER MODULAR
HOME CASE STUDIES

DESIGN

THE DESIGN SYSTEM

DETAILS

ANALYSIS

COMPARISONS TO
CONVENTIONAL MODULAR &
SITE-BUILT CONSTRUCTION
SYSTEMS

CONSTRUCTION COMPOSITION

LIFE CYCLE ASSESSMENTS

THERMAL PERFORMANCE

MODEL SELECTIONS

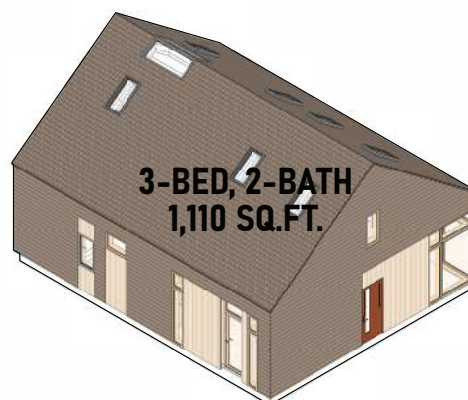
The criterion used to choose the size and condition for each of the three construction systems was determined through an extensive background analysis of the modular house models currently available from sampled manufacturers across the Northeast. Focusing on the single-floor modular house models, the square footage, number of bedrooms, number of bathrooms, and costs (when available) were recorded across all units to determine the average figure for each category.

From this information, the modular house model which most closely matched these averages amongst the assessed manufacturer models was selected to represent The Typical Modular House in this project's analysis section. In this case, the most appropriate modular house model available was a 1,592 sq.ft, 3-bedroom, 2-bathroom single-story modular home.

As for the BioMOD representative house selection, the standard 3-bedroom, 2-bathroom variation of the system was selected as the study condition, to best match the format of the typical modular house. The standard-constructed house is a light-wood-frame version of the BioMOD house design in essence, with only the materials directly tied to standard light-wood-frame construction assemblies being different from the mass timber house. The standard-constructed house serves as the control-variable of the study in the comparison between mass timber and conventional house construction.



THE TYPICAL MODULAR HOUSE



THE MASS TIMBER HOUSE

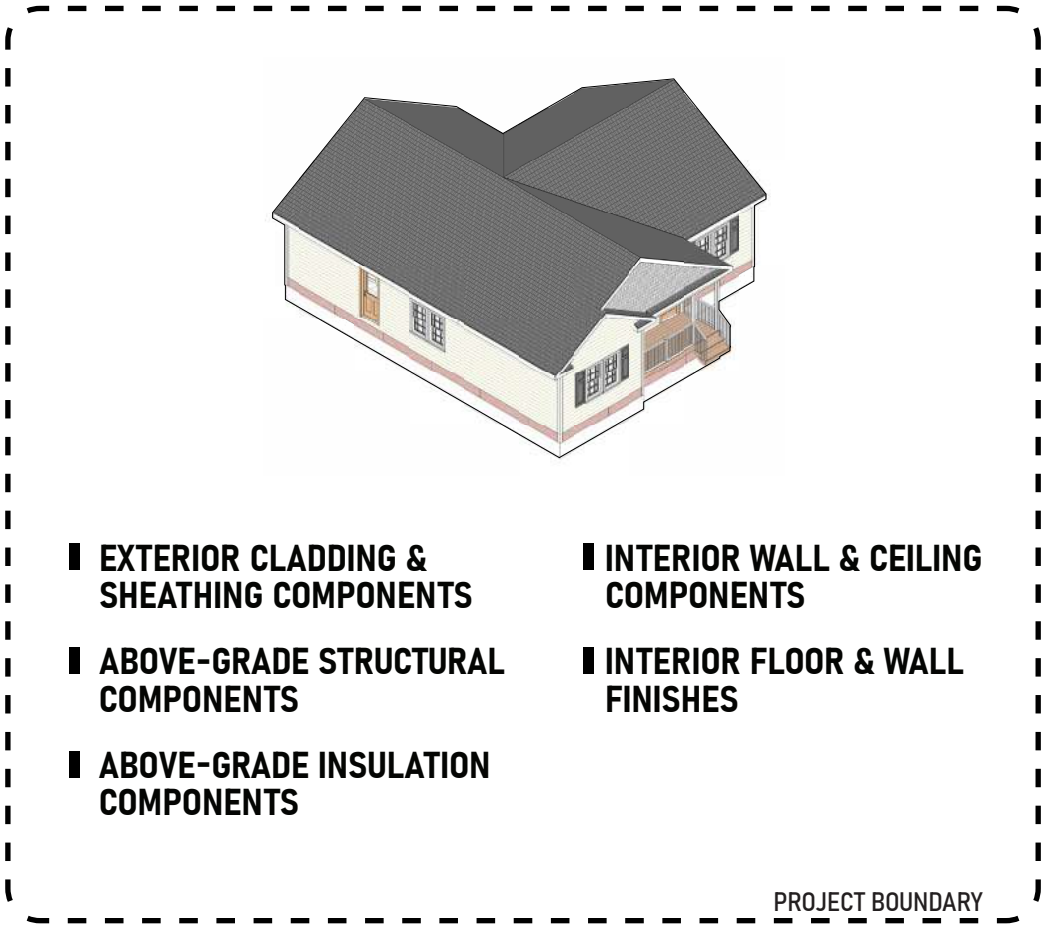


THE STANDARD-CONSTRUCTED HOUSE

PROJECT BOUNDARY

The project is intended to focus on the components of the construction systems that remain relatively consistent as part of the standards that define each respective construction system. In other words, the structural components above grade, as well as the typical cladding and finishes that comprise each system serve to display the general

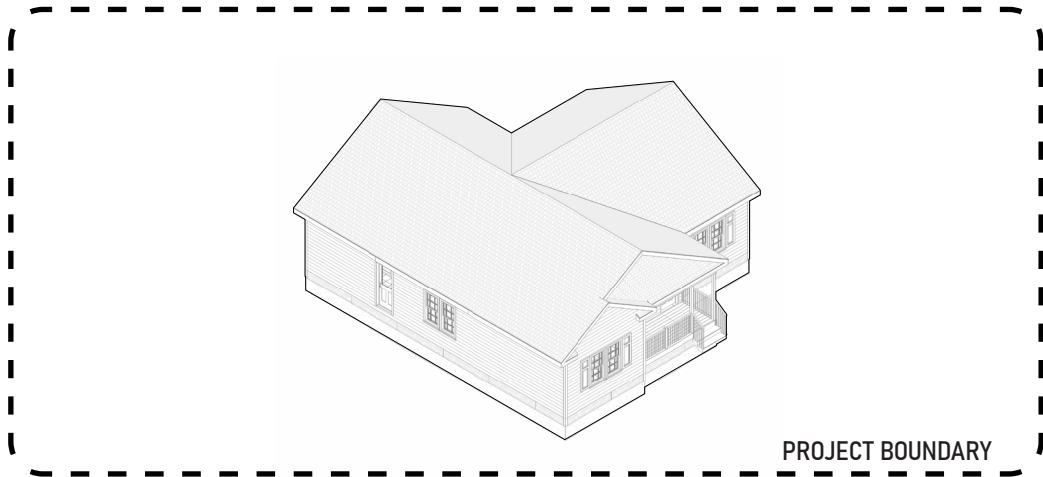
condition of each system's common characteristics. This helps to reduce the amount of variables, which allows for a generalized comparison of the systems themselves.



OUTSIDE OF PROJECT BOUNDARY

Of the aspects that remain outside of the project boundary, the two most significant components are the structural foundations and fasteners that would exist in the construction of each home. For the same reason that the other components listed below remain out-of-scope for the analyses, the foundations and fastener elements can vary greatly within a system, which makes it difficult

to justify a singular condition for each construction type. Additionally, foundations and fasteners are required for all construction types to some degree, and have a defined material designation (concrete and steel). By leaving these elements outside the scope, the analyses can be allowed to focus more precisely on the materials of each system that were designated above.



■ **STRUCTURAL FOUNDATIONS
(CONCRETE)**

■ **BELOW-GRADE INSULATION
COMPONENTS**

■ **STRUCTURAL FASTENERS
(STEEL)**

■ **EXTERIOR WEATHERPROOFING
MEMBRANES & SEALANTS**

■ **DOOR AND WINDOW
COMPONENTS**

■ **INTERIOR FURNITURE &
CASEWORK COMPONENTS**

■ **M.E.P. SYSTEMS COMPONENTS**

■ **STAIR & RAILING COMPONENTS**

CLIMATE ZONE DESIGNATION

As the construction compositions of each system are influenced by climate factors, as well as several sections of the analyses, a specific set of climate data had to be selected. Referring to IECC (International Energy Conservation Code) Climate Zones, the entirety of the Northeast contains areas that fall under the 4A, 5A, or 6A Climate Zones.

For the purpose of designating climate data that serves as an acceptable average condition of the Northeast climate, Concord, New Hampshire was chosen as the representative climate for the following analyses. Located at the relative center of the Northeast, Concord provides a good median climate, with some areas of the Northeast being warmer, and other areas being colder. Across all regions of the Northeast, however, the region is firmly a heating-dominated climate.

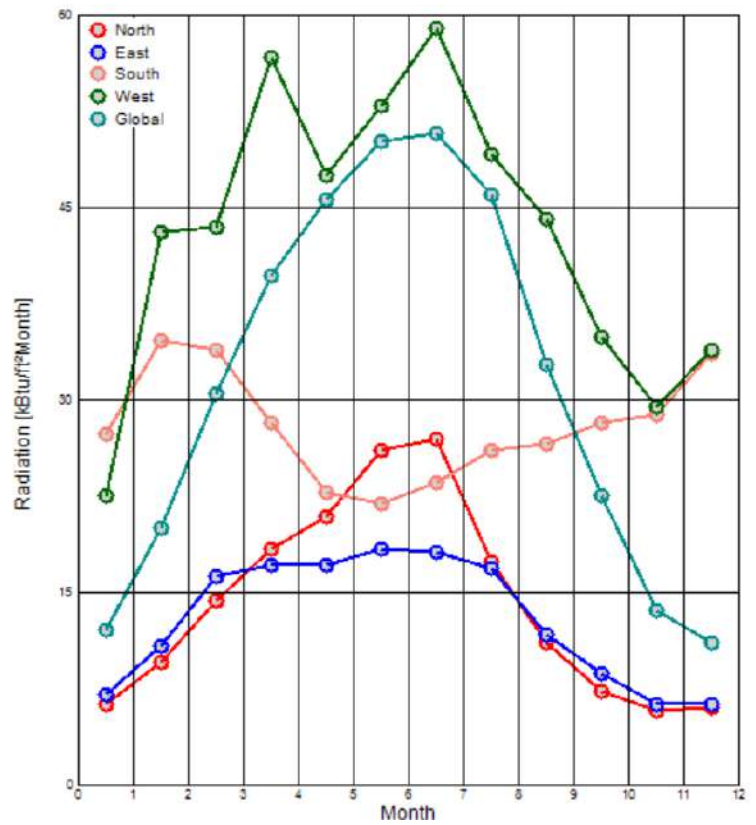
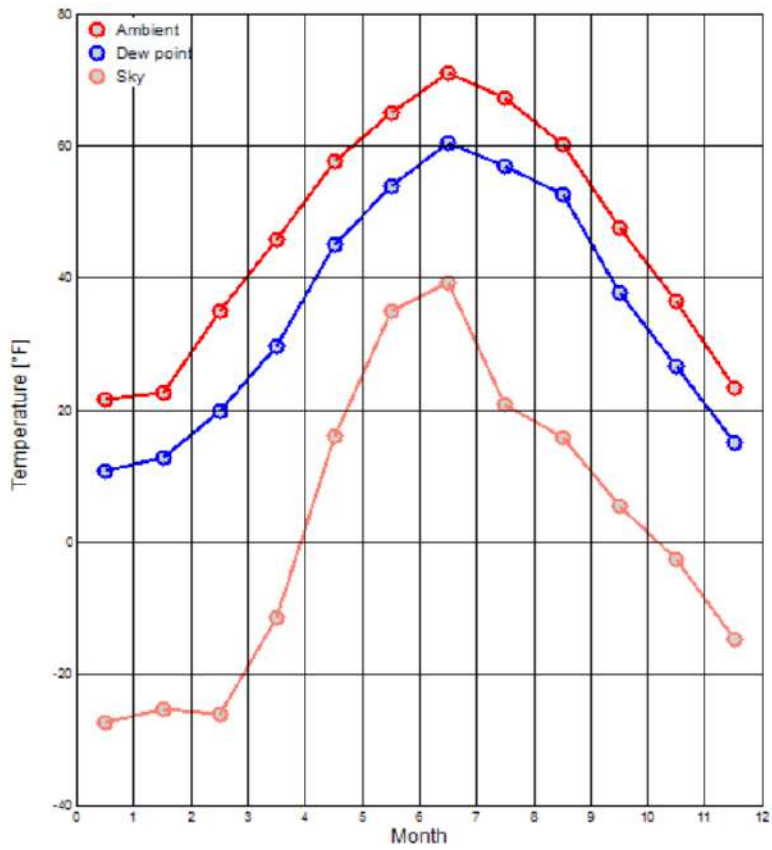
CLIMATE ZONE - 5A

HEATING DEGREE DAYS - 7,554

COOLING DEGREE DAYS - 328



Selected Climate Data Location



Annual Temperature and Solar Radiation
Data Graphs
Source: Wufi@Passive



C2



CONSTRUCTION COMPOSITIONS

OVERVIEW

ANALYSIS SUMMARY

The following analyses into the construction compositions of each system act to express the quantities and characteristics of the materials that comprise the three systems. Material quantities are expressed in various formats and organizations in order to view the characteristics of the results in as many angles as possible.

The quantitative metrics of each assembly system was justified as what exists on site, after construction has been completed. Entities were considered individually—or in other words, each loose part in the construction process. For instance, every singular shingle of roof cladding was treated as its own entity in quantification. This is done to best reflect the total number of parts that would require some degree of individual attention during on-site installation. The volumes of each material were recorded as their realized spatial value, which does not consider density. To address this, a specific quantification section on material mass was conducted.

Although the BioMOD house's panelized system would be intended to have the insulation and furring strips be pre-attached to the CLT panels before reaching the site, each layer was pulled apart and quantified individually in order to focus on the general condition of a mass timber construction system.

Beyond the physical quantities of materials, the renewability of each material source was also studied in order to provide information on the suggestive degree of environmental sustainability inherent within each system.

1. ASSEMBLY COMPOSITIONS

Visual breakdown and specification of the components that make up each construction system.

2. QUANTITIES - BY MATERIAL CLASS

Total volume and number of entities quantification based on the classification category of each material.

3. QUANTITIES - BY SUMMARIZED MATERIAL

Total volume and number of entities quantification by general material.

4. QUANTITIES - EXTERIOR SHELL ONLY

Total volume and number of entities quantification by specific material distinction, related to the building shell.

5. QUANTITIES - INTERIOR ONLY

Total volume and number of entities quantification by specific material distinction, related only to parts internal of the building shell.

6. QUANTITIES - CLT vs. STICK-FRAME

Focused entity quantification and comparison between a CLT building shell construction system and a light-wood-frame building shell construction system.

7. QUANTITIES - TOTAL MASS

Quantification of total mass [weight] of total materials, and the total mass [weight] of each construction system.

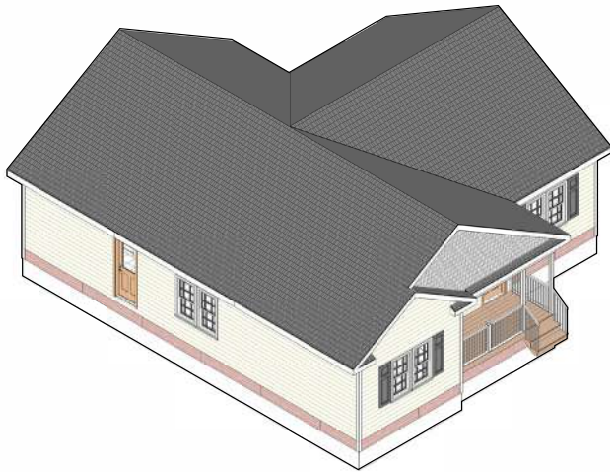
8. RENEWABILITY OF MATERIAL SOURCES

Analysis of renewable vs. non-renewable material source proportions in each construction system, by total volume.



ASSEMBLY COMPOSITIONS

THE TYPICAL MODULAR HOUSE



The Typical Modular house is a primarily prefabricated system of construction by which the occupiable areas of the home are shipped to site in a volumetric format, and the roof system is either pre-attached or comes separate. Originally laid flat, the roof of a typical modular house functions on a hinged system in which the rafters are tilted up to the proper angle and mounted in place with the addition of knee and bracing components.

The assembly materials of the typical modular house, in both its interior and exterior, mimic the conventionally-chosen materials for any typical new-construction house, regardless of modularity. Many of these materials are derived from non-renewable sources such as petroleum. The overall assembly showcases the many layers and finishes found in typical construction.

ASSEMBLY SPECIFICATIONS

ROOF CONSTRUCTION

- > 2x8 Fold-up Self-supporting Rafters @ 16" O.C. with 7/12 pitch.
- > 17" Blown-in Fiberglass Insulation (R-49)
- > 1/2" OSB Roof Sheathing (4' x 8')
- > Ply Dry Shingle Underlayment
- > Asphalt Architectural Shingles with Ridge Vent
- > Ventilated Vinyl Soffit with Vinyl Fascia Trim

WALL CONSTRUCTION

- > 2x6 Exterior Framing wall @ 16" O.C. with 5.5" Fiberglass Batt Cavity Insulation (R-21)
- > 7/16" OSB Wall Sheathing (4' x 8')
- > Exterior House Wrap (WRB)
- > Double 4 Vinyl Siding
- > Polypropylene Accent Shingle Siding
- > Vinyl Window Shutters and lineal Trim
- > 2x4 Interior Framing Wall @ 16" O.C.

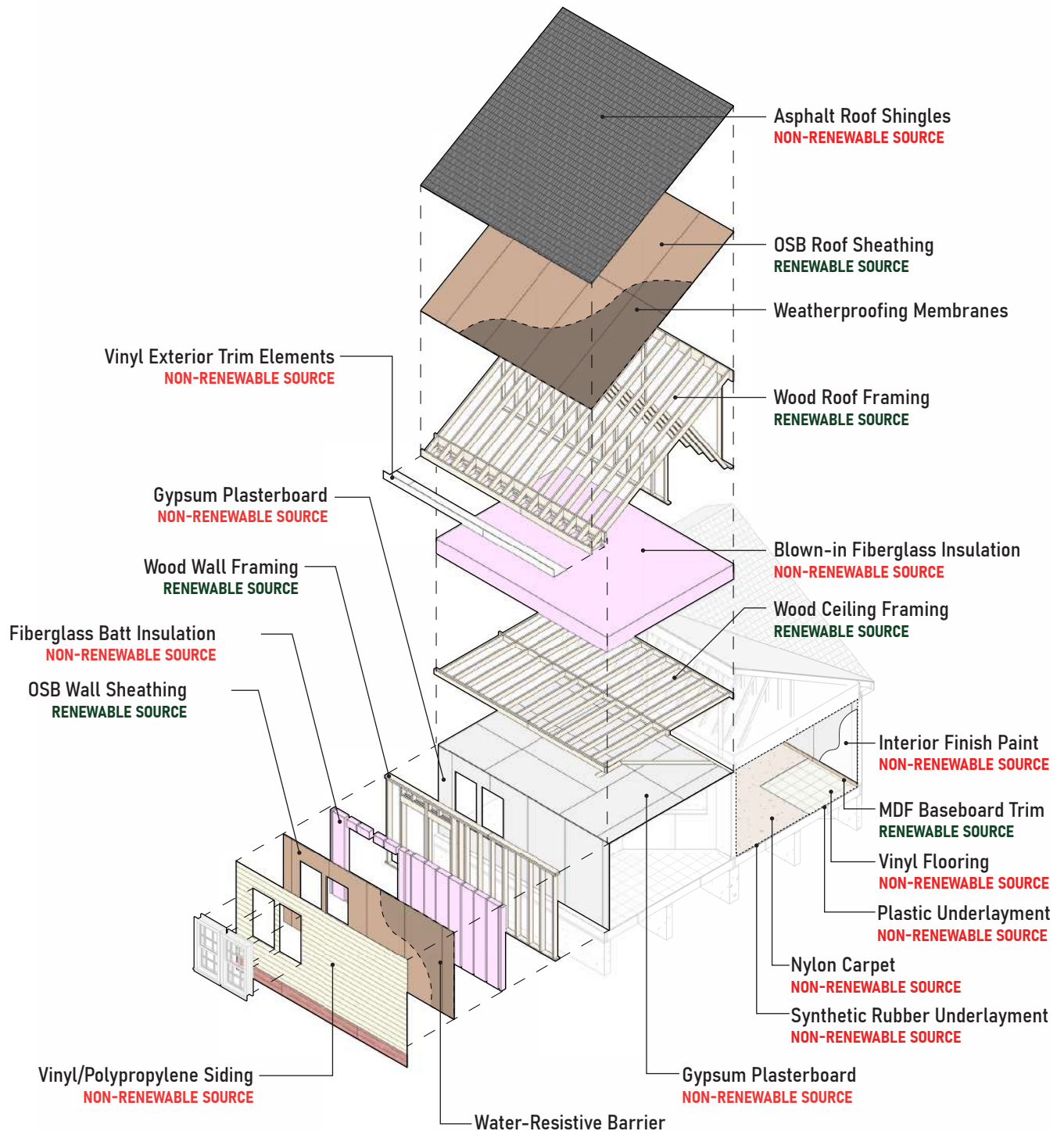
FLOOR & CEILING CONSTRUCTION

- > 2x10 Floor Joists @ 16" O.C. (Solid Block Bridging)
- > 9.25" Fiberglass Batt Insulation (R-30)
- > Double Perimeter 2x10 Band Joists
- > 3/4" OSB Floor Decking (4' x 8')
- > Microlam LVL Beam [where necessary]

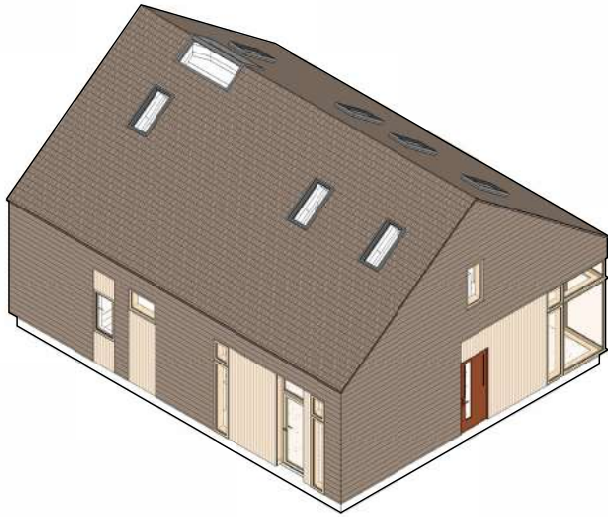
INTERIOR

- > 5/8" Gypsum Ceiling Plasterboard (4' x 8')
- > 1/2" Gypsum Wall Plasterboard (4' x 8')
- > 4"x1/2" MDF Baseboard Trim
- > Interior Finish Paint
- > 6-Pile Tufted Nylon Carpet with 1/4" Recycled Rubber Underlayment
- > 1/8" Vinyl Floor Tile (12"x12") with Plastic Moisture Barrier Underlayment

COMPOSITION OF THE TYPICAL MODULAR HOUSE



THE BioMOD HOUSE (MASS TIMBER HOUSE)



The BioMOD mass timber house is constructed almost entirely of biogenic materials derived from forest products in its panelized modular assembly. The construction system showcases greater simplicity in layers compared to the typical modular house—due in part to the mass-panel nature of the system, as well as the ability to omit many of the conventional interior material layers.

ASSEMBLY SPECIFICATIONS

ROOF CONSTRUCTION

- > 3-Ply Eastern White Pine CLT Roof Panel (8ft maximum width) with 3/4" MicroCLT Spline
- > 7.25" TimberHP Timberboard Rigid Wood Fiber Insulation Panel (R-26) (4' x 8')
- > 5.5" TimberHP Timberboard Rigid Wood Fiber Insulation Panel (R-20) (4' x 8') with exterior paraffin coating. All seams taped.
- > 1x2 Furring Strips @ 16" O.C.
- > 5/8" Plywood Roof Sheathing
- > Roofing Underlayment
- > 1x3 Furring Mounting Strips @ 12" O.C.
- > Eastern White Cedar Roof Shingles (6" Width)

WALL CONSTRUCTION

- > 3-Ply Eastern White Pine CLT Wall Panel (8ft maximum width) with 3/4" MicroCLT Spline
- > 5.5" TimberHP Timberboard Rigid Wood Fiber Insulation Panel (R-20) (4' x 8')
- > Exterior House Wrap (WRB)
- > 1x2 Vertical Furring Strips @ 16" O.C.
- > Stained Eastern White Cedar Clapboard Siding (8")
- > Stained Wood Accent Panel Siding (6")
- > 2x8 Plumbing Wall @ 16" O.C.

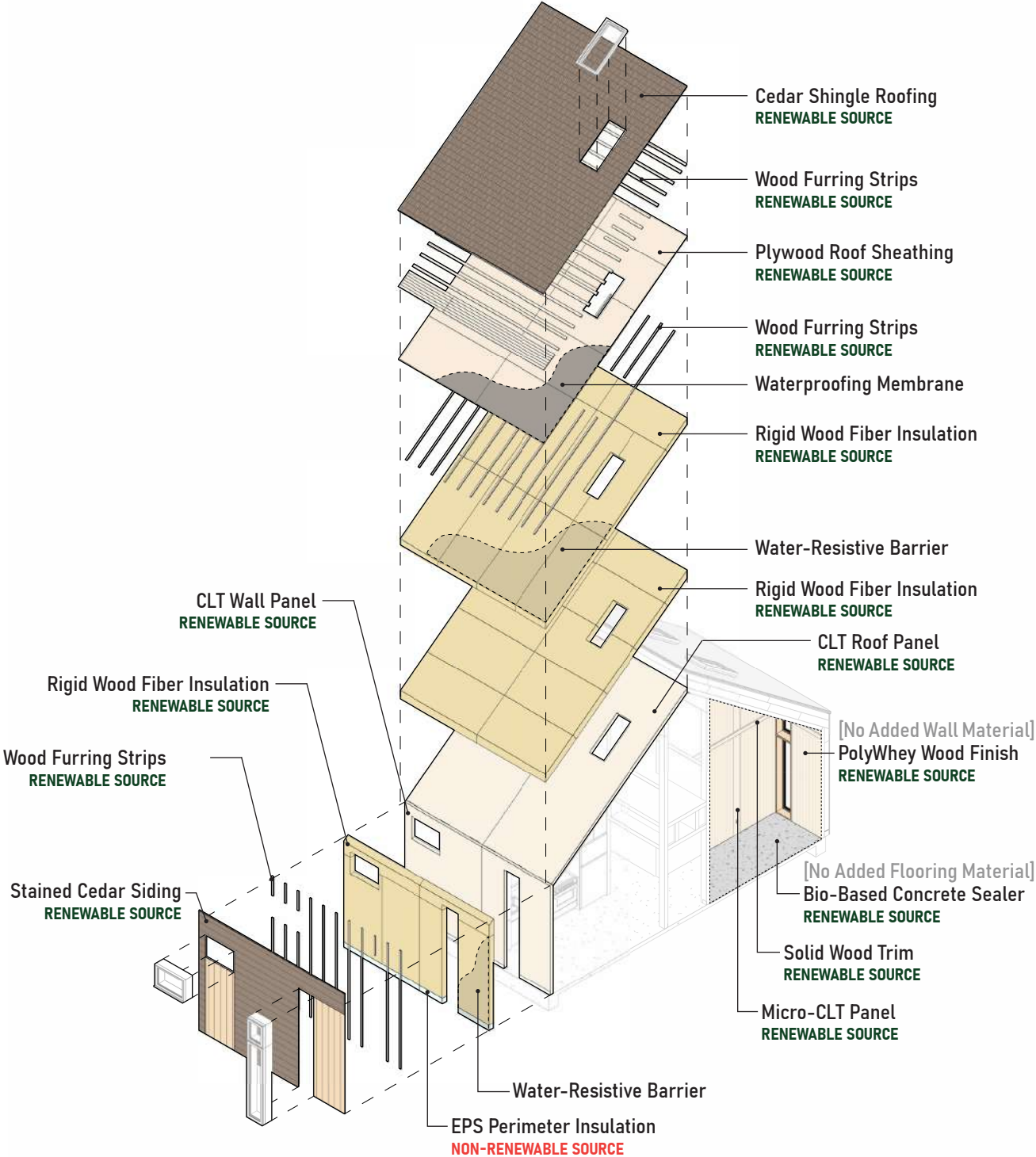
FLOOR & CEILING CONSTRUCTION

- > 3-Ply Eastern White Pine CLT Loft Floor Panel (8ft maximum width)
- > Exposed Concrete Slab

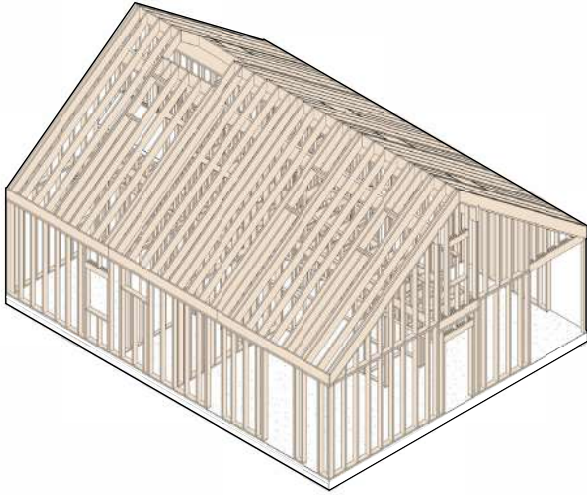
INTERIOR

- > 1/2" MicroCLT Wall Panel (2' x 8') on Plumbing Walls.
- > Clear PolyWhey Wood-Protecting Finish
- > Bio-Based Concrete Floor Sealer

COMPOSITION OF THE MASS TIMBER HOUSE



THE STANDARD-CONSTRUCTED HOUSE



The Standard-Constructed house represents a conventional site-built version of the BioMOD house design, and utilizes the typical materials used when a light-wood-frame structure is employed. The exterior cladding elements of the construction system, as well as the lack of ground floor finishes, remain identical to the mass timber house as these layers are independent from a differentiated structural and construction system.

As with the other two construction systems, the amount of insulation included in the model is justified to follow minimum Climate-5A requirements in the state of New Hampshire's energy codes.

ASSEMBLY SPECIFICATIONS

ROOF CONSTRUCTION

- > 2x12 Rafters @ 16" O.C. with 11.25" Fiberglass Batt Cavity Insulation (R-49). 9/12 pitch.
- > LVL Roof Support Beams
- > 1/2" OSB Nailbase Sheathing (4' x 8')
- > 2" XPS Rigid Insulation Board (R-10) (4' x 8')
- > 1/2" OSB Roof Sheathing (4' x 8')
- > Roofing Underlayment
- > 1x3 Furring Mounting Strips @ 12" O.C.
- > Eastern White Cedar Roof Shingles (6" Width)

WALL CONSTRUCTION

- > 2x6 Exterior Framing wall @ 16" O.C. with 5.5" Fiberglass Batt Cavity Insulation (R-21)
- > 1/2" OSB Wall Sheathing (4' x 8')
- > Exterior House Wrap (WRB)
- > 1x2 Vertical Furring Strips @ 16" O.C.
- > Stained Eastern White Cedar Clapboard Siding (8")
- > Stained Wood Accent Panel Siding (6")
- > 2x4 Interior Framing Wall @ 16" O.C.

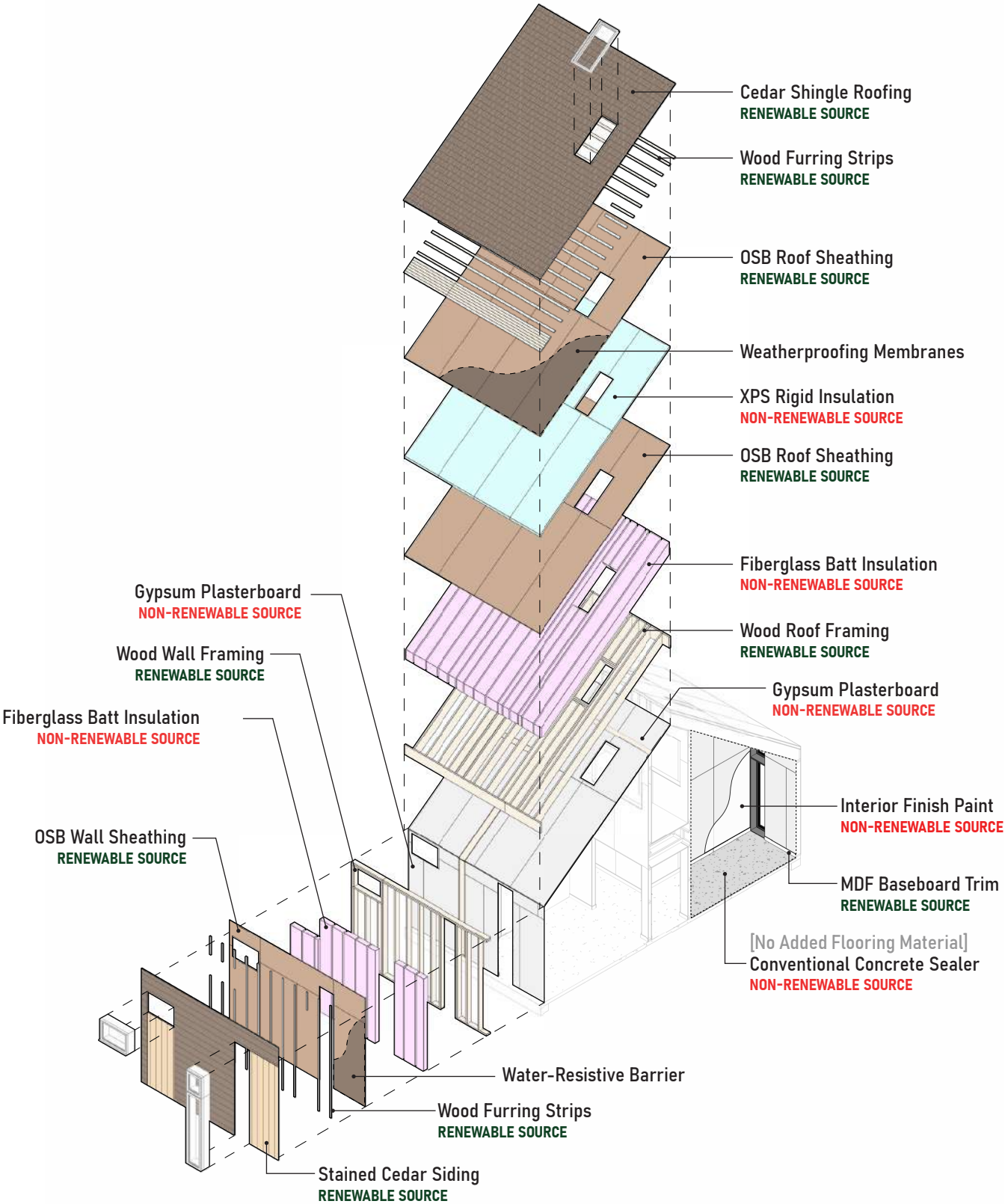
FLOOR & CEILING CONSTRUCTION

- > 2x10 Loft Floor Joists @ 16" O.C. (Solid Block Bridging)
- > 2x4 Framed Drop-Ceiling @ 12" O.C.
- > 3/4" Plywood Loft Floor Decking (4' x 8')
- > Exposed Concrete Slab

INTERIOR

- > 5/8" Gypsum Ceiling Plasterboard (4' x 8')
- > 1/2" Gypsum Wall Plasterboard (4' x 8')
- > 4"x1/2" MDF Baseboard Trim
- > Interior Finish Paint
- > 1/8" Vinyl Sheet Loft Floor with Plastic Moisture Barrier Underlayment
- > Polyurethane Concrete Sealer

COMPOSITION OF THE STANDARD-CONSTRUCTED HOUSE

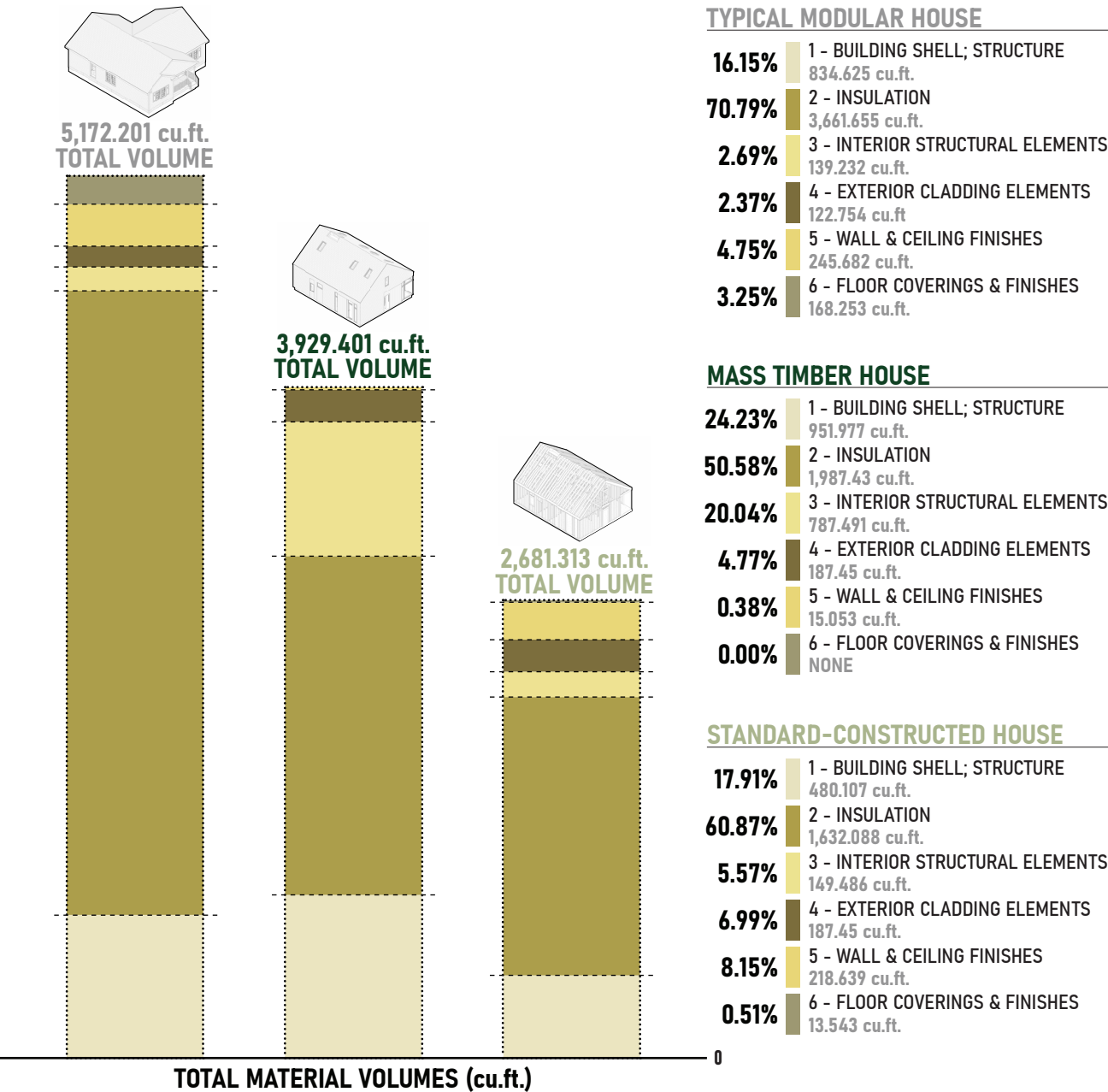


MATERIAL QUANTIFICATION

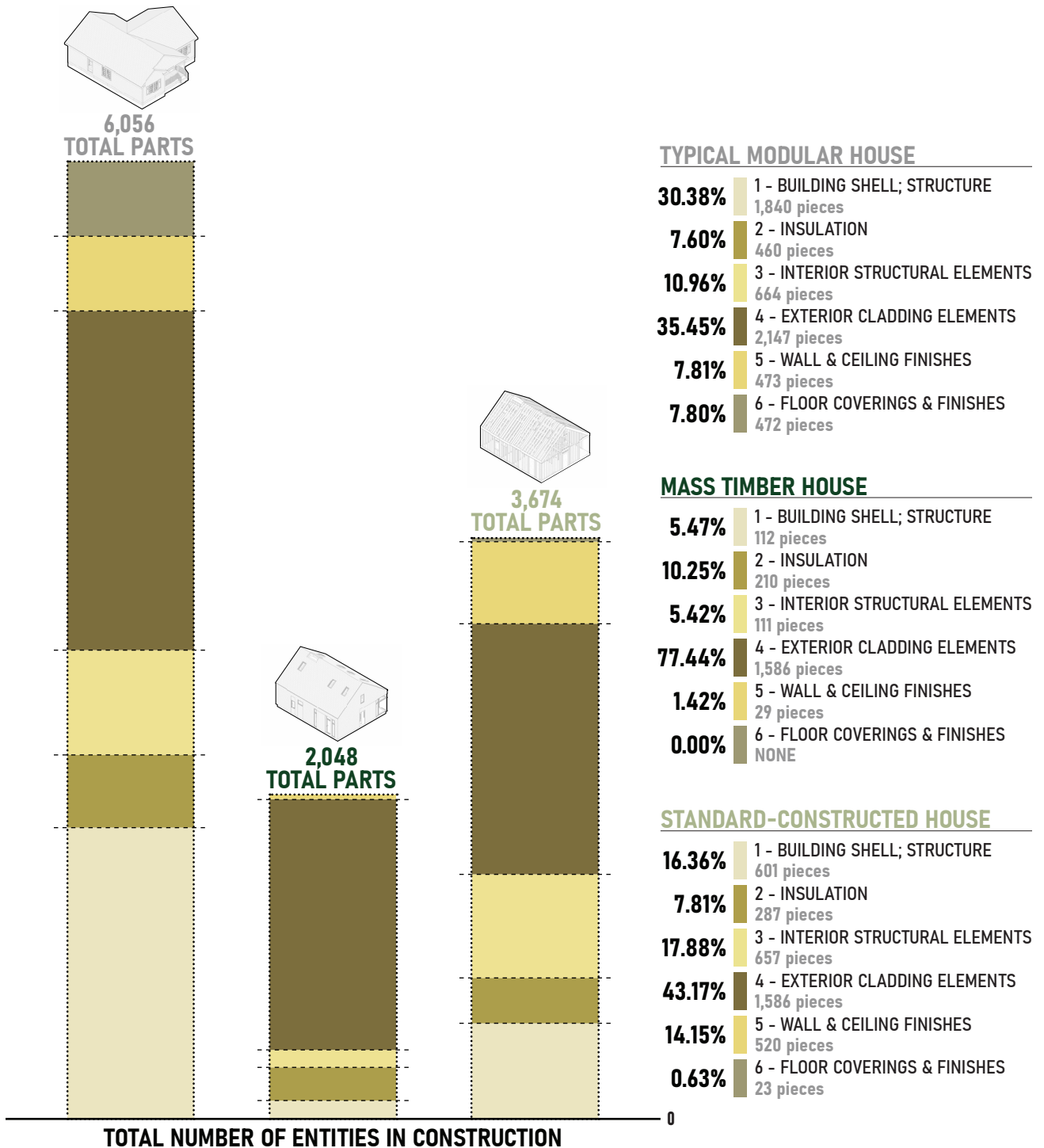
QUANTITIES BY MATERIAL CLASSIFICATION

Material quantities are organized by their classification category in construction. In terms of volume (irrespective to mass), the insulation materials of each system is the largest contributor

to total volume. With number of entities, the exterior cladding elements play a significant role—especially for the mass timber house’s total number of parts.



Cladding element quantities can differ greatly based on material selection. If this category was not considered, the polarity between the total number of entities between the mass timber house and the other two systems would be even more drastic.

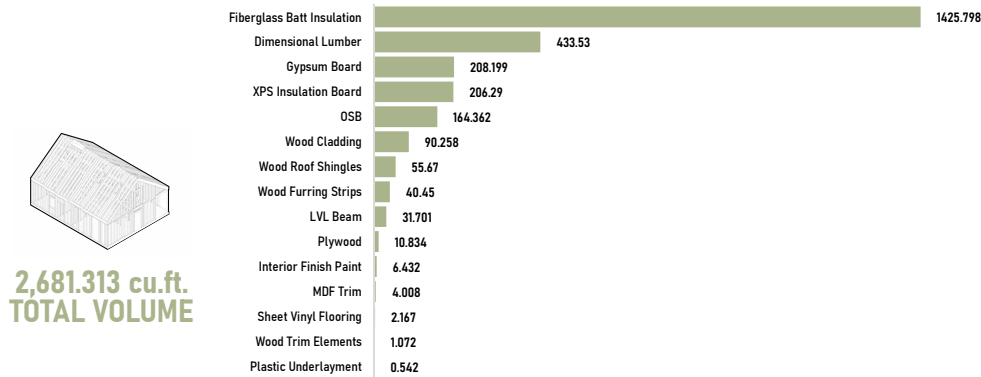
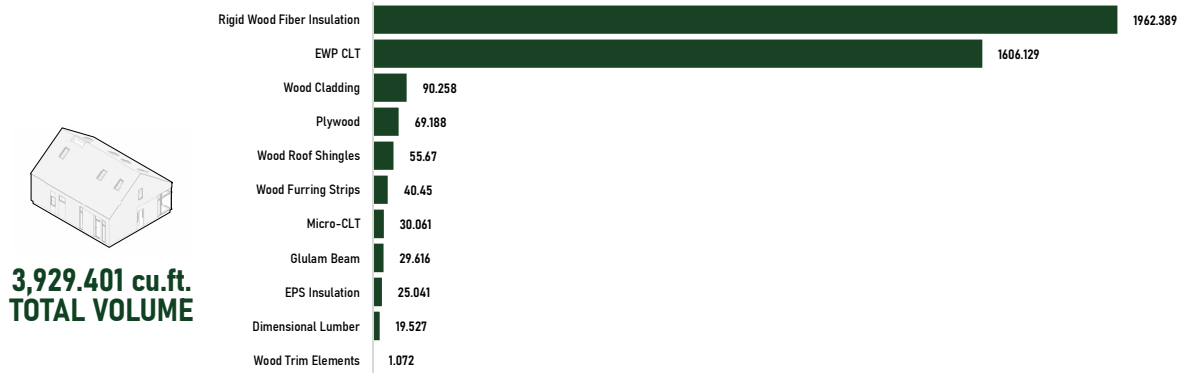
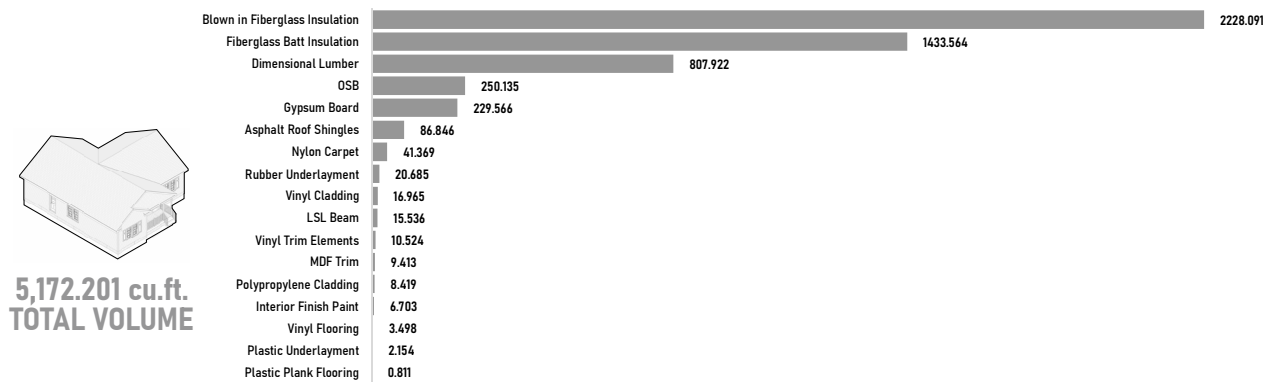


SUMMARIZED MATERIAL QUANTITIES

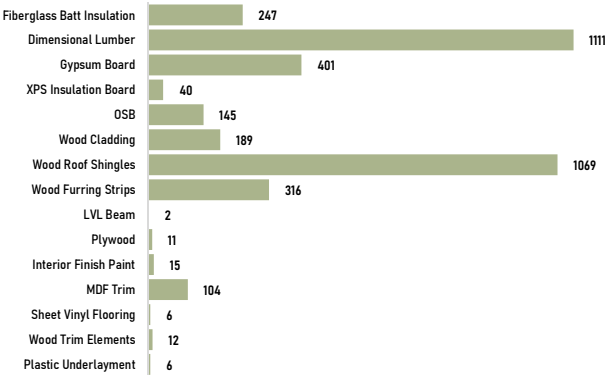
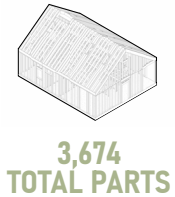
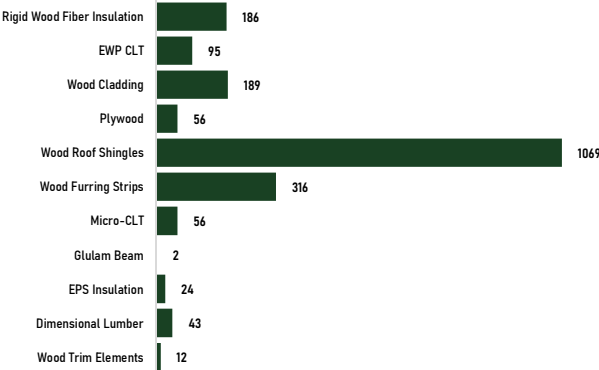
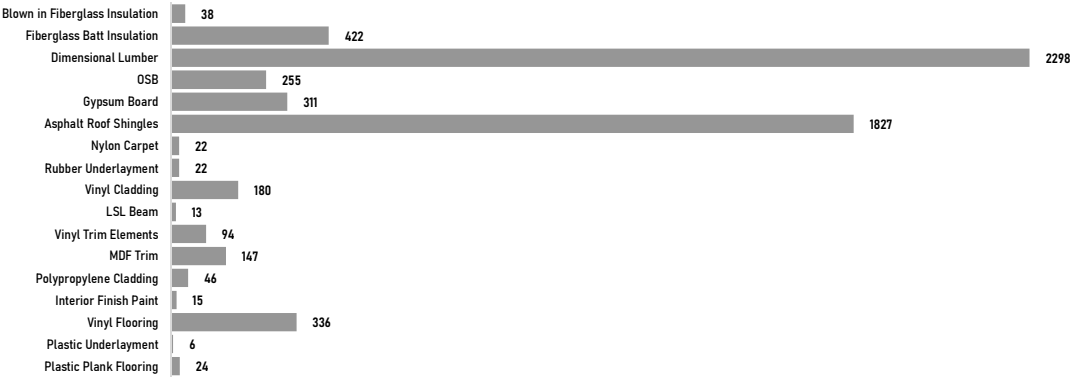
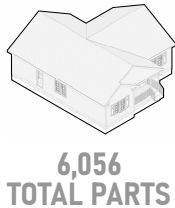
Materials are quantified and organized based on their general type of material across each entire construction system. The total volume of insulation is, again, a large contributor to each total.

In the Mass Timber House, the volume of the CLT is significant. However, in terms of number of entities, the total number of CLT panels is much lower than that of the respective dimensional lumber quantities in the other two systems.

TOTAL MATERIAL VOLUMES (cu.ft.)



TOTAL NUMBER OF ENTITIES IN CONSTRUCTION

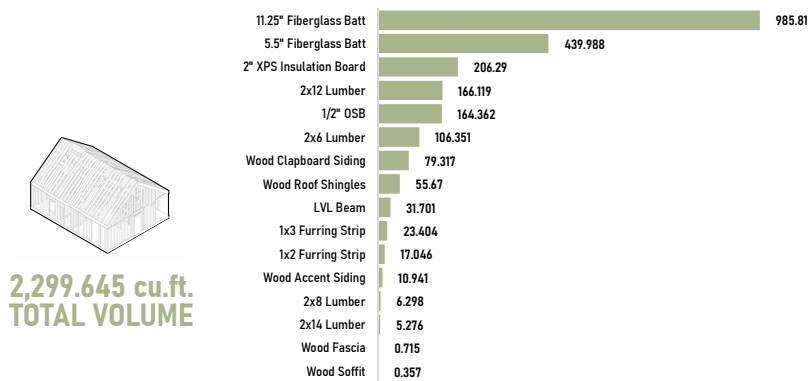
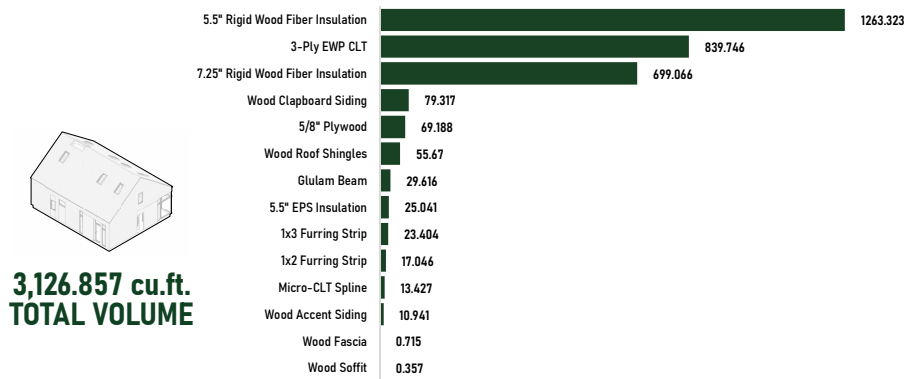
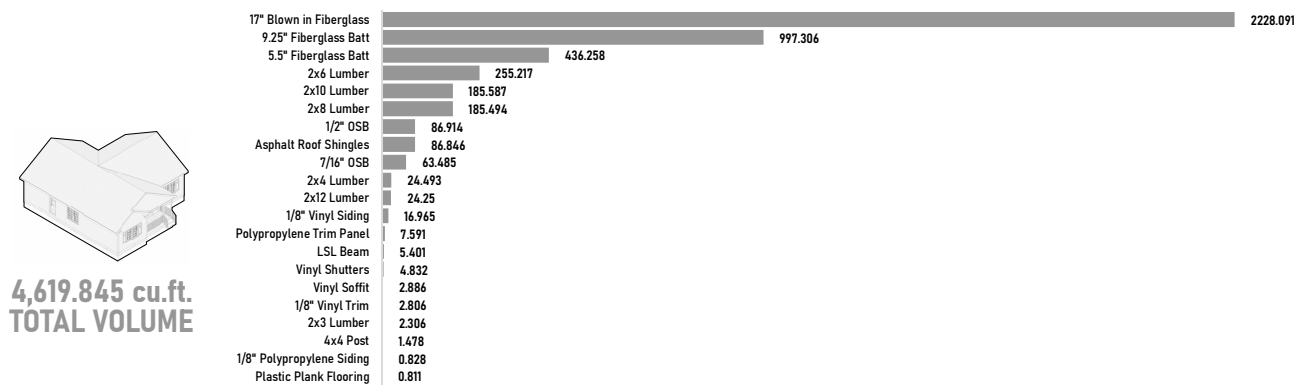


MATERIAL QUANTITIES - EXTERIOR SHELL

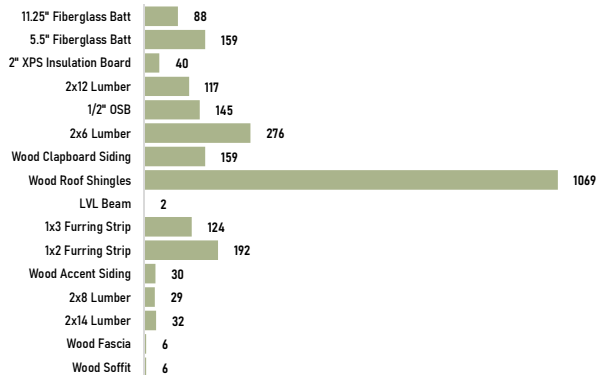
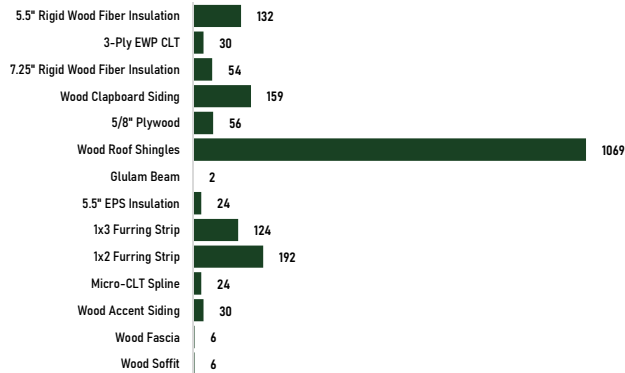
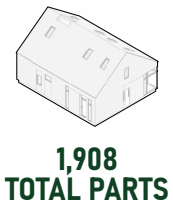
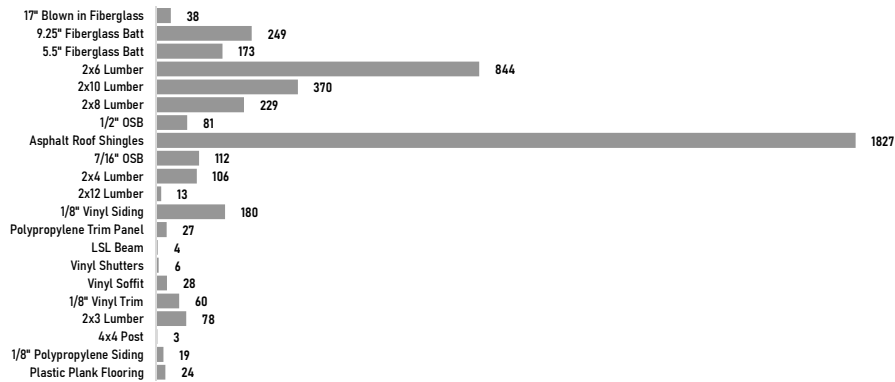
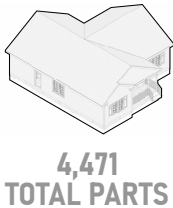
These metrics focus specifically on the material components that relate to the construction of each system’s building shell. The building shell specifically can be considered as a generally consistent condition of each construction system.

Similar trends exist as in previous graphs, with CLT having a considerable volume in the Mass Timber House, but far less number of pieces compared to the dimensional lumber of the other two systems.

TOTAL MATERIAL VOLUMES (cu.ft.): ENCLOSURE-RELATED



TOTAL NUMBER OF ENTITIES: ENCLOSURE-RELATED

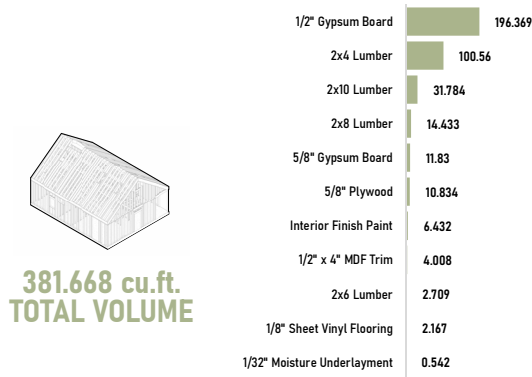
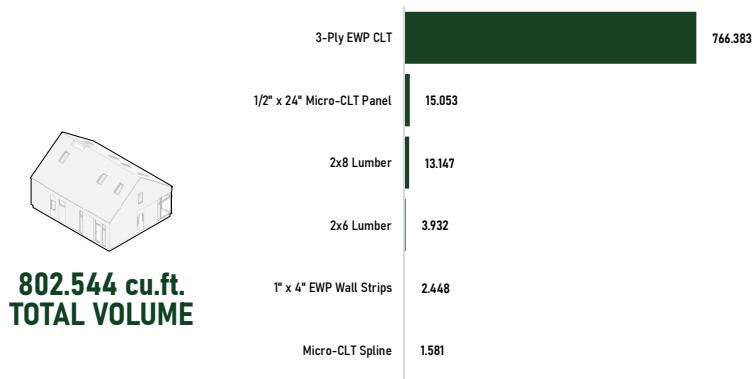
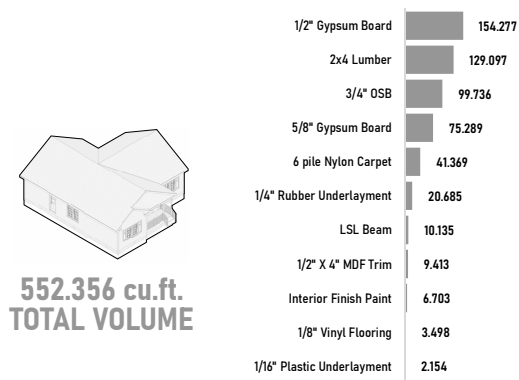


MATERIAL QUANTITIES - INTERIOR

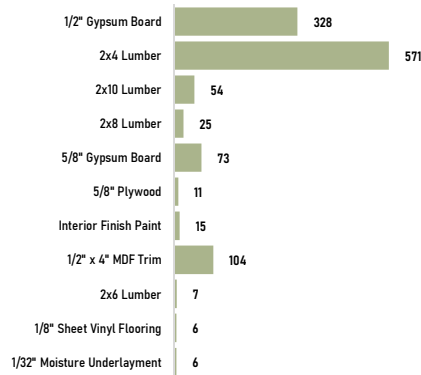
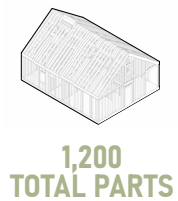
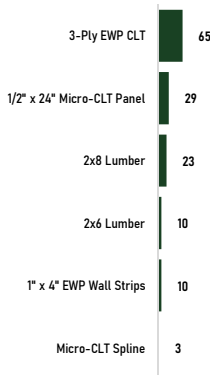
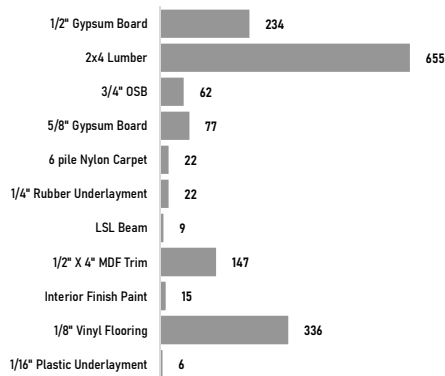
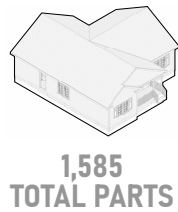
This section isolates the interior-related material entities into their own quantification; where its characteristics are much more variable, dependent on a specific interior design layout. The greatest

takeaway of these graphs is the sheer amount of volume in the Mass Timber House's CLT compared to all other materials. This may suggest that an optimal interior might benefit from utilizing CLT more sparingly, especially if not load-bearing.

TOTAL MATERIAL VOLUMES (cu.ft.): INTERNAL



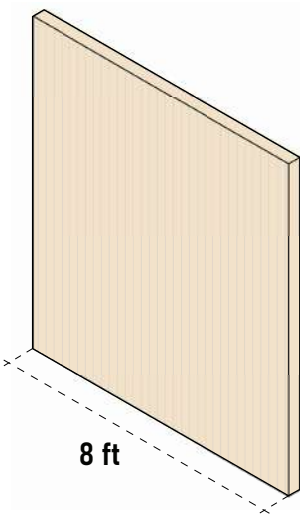
TOTAL NUMBER OF ENTITIES: INTERNAL



BUILDING SHELL - CLT vs. STICK-FRAME QUANTITIES

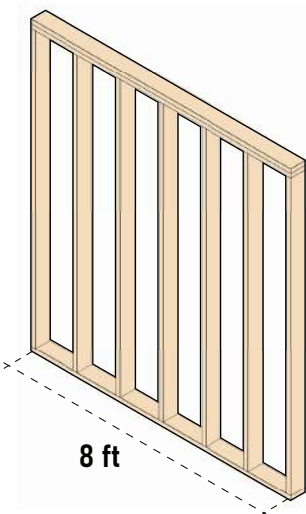
If we look specifically at the characteristic difference of number of pieces in a CLT system vs. a light-wood-frame system within a construction envelope, the general difference between total number of pieces involved in each system is explained. Focusing just on an 8-foot section of a solid wall, a light-wood-frame wall, with studs spaced 16" on center, would require about 10 members to be installed, whereas the CLT-created 8-foot section is just a single piece.

If an opening is introduced, The light-wood-frame wall jumps up to 22 pieces in order to properly frame an opening for a window, where, again, the CLT wall is still just a single piece. Additionally, the pieces of CLT left over from being cut out for window and door openings can be reused to make partitions, shelving, and doors such as in the BioMOD house.



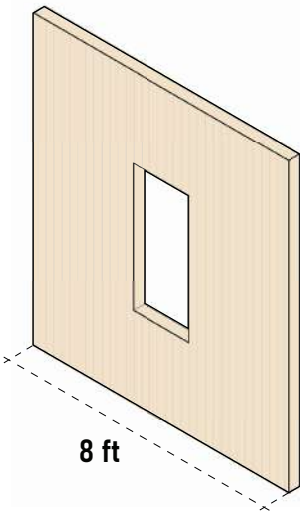
CLT SOLID WALL (8ft)

1 PIECE.



FRAMING WALL (8ft)

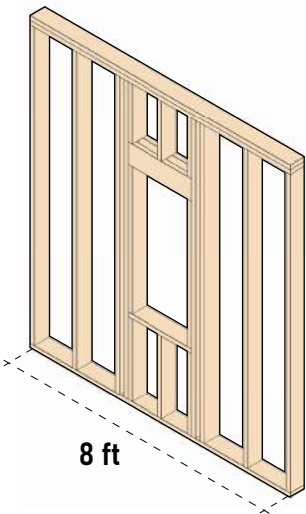
10 PIECES



CLT W/ OPENING (8ft)

1 PIECE.

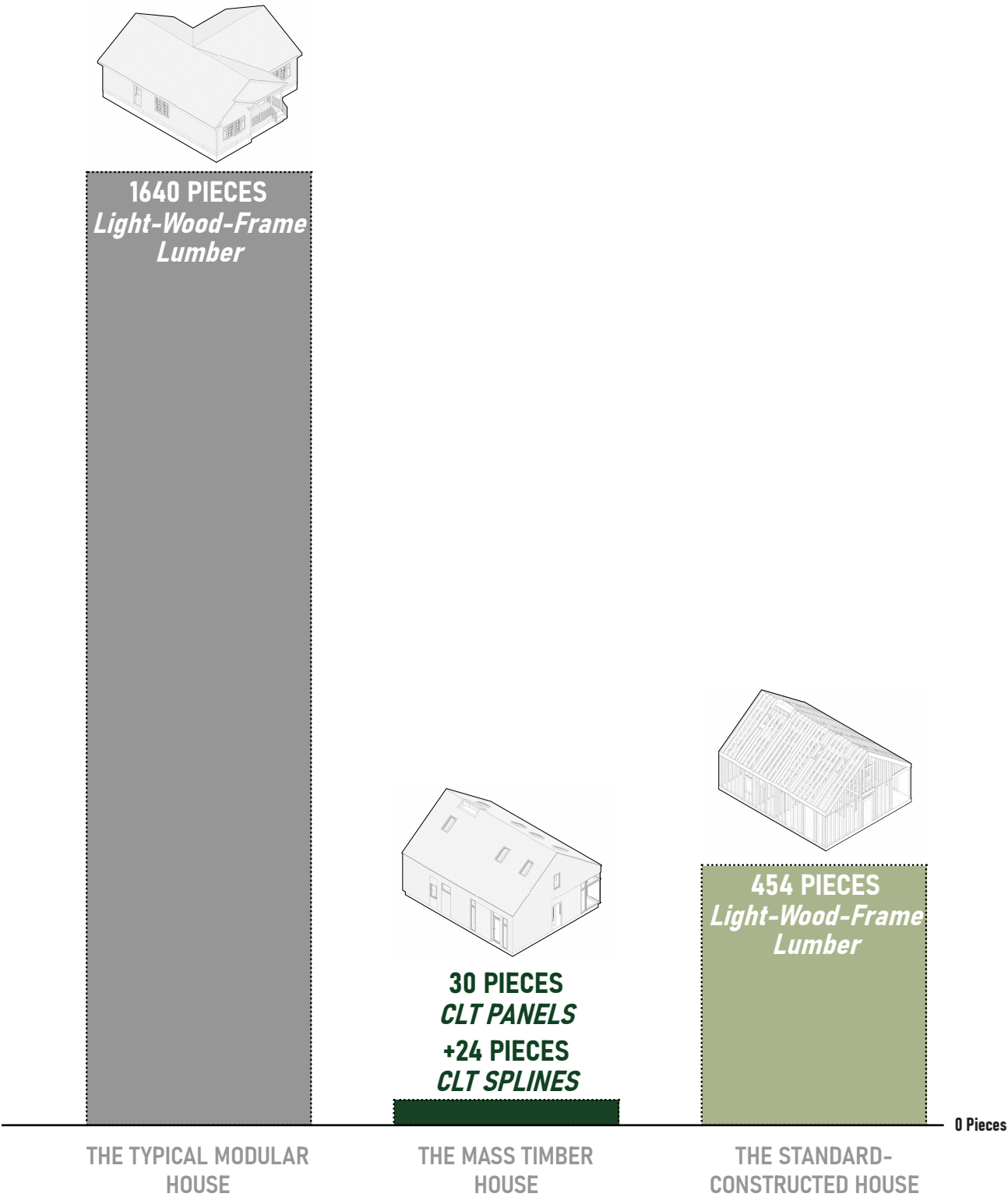
* NOTE: The resultant CLT pieces that are created from opening cut-outs can be reused for interior partition pieces, shelves, and even as doors. This is done in the BioMOD House.



FRAMING W/ OPENING (8ft)

22 PIECES

TOTAL NUMBER OF BUILDING SHELL LIGHT-WOOD-FRAMING OR CLT COMPONENTS

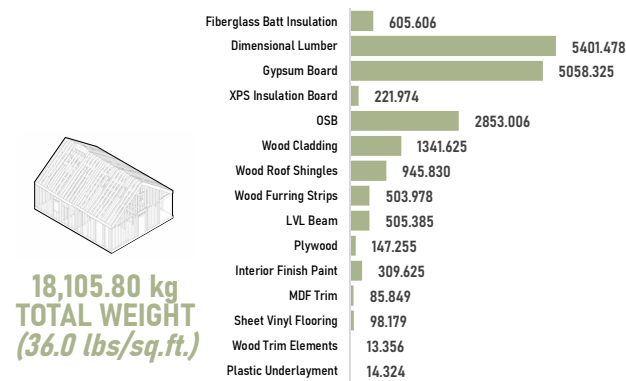
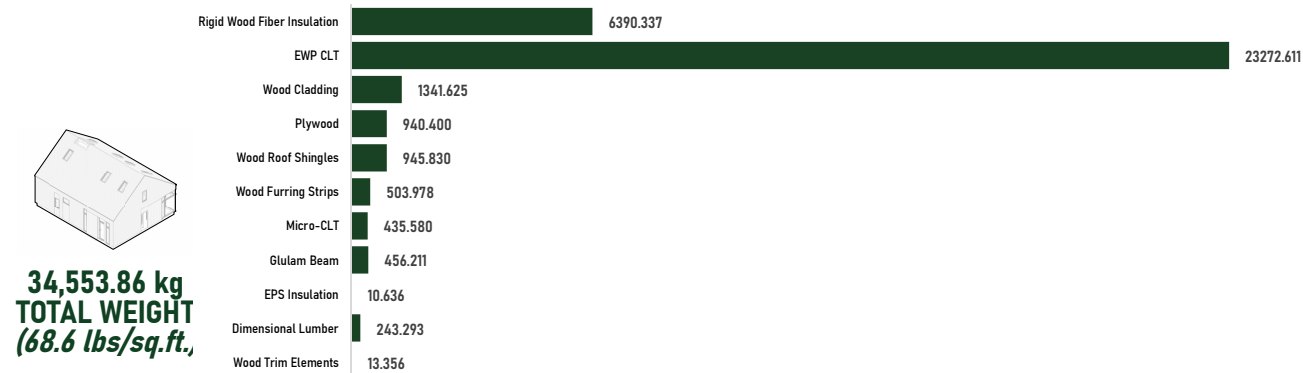
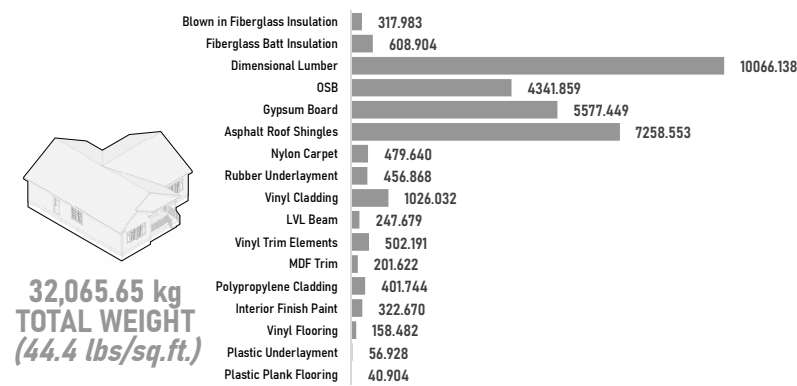


TOTAL MASS OF MATERIALS

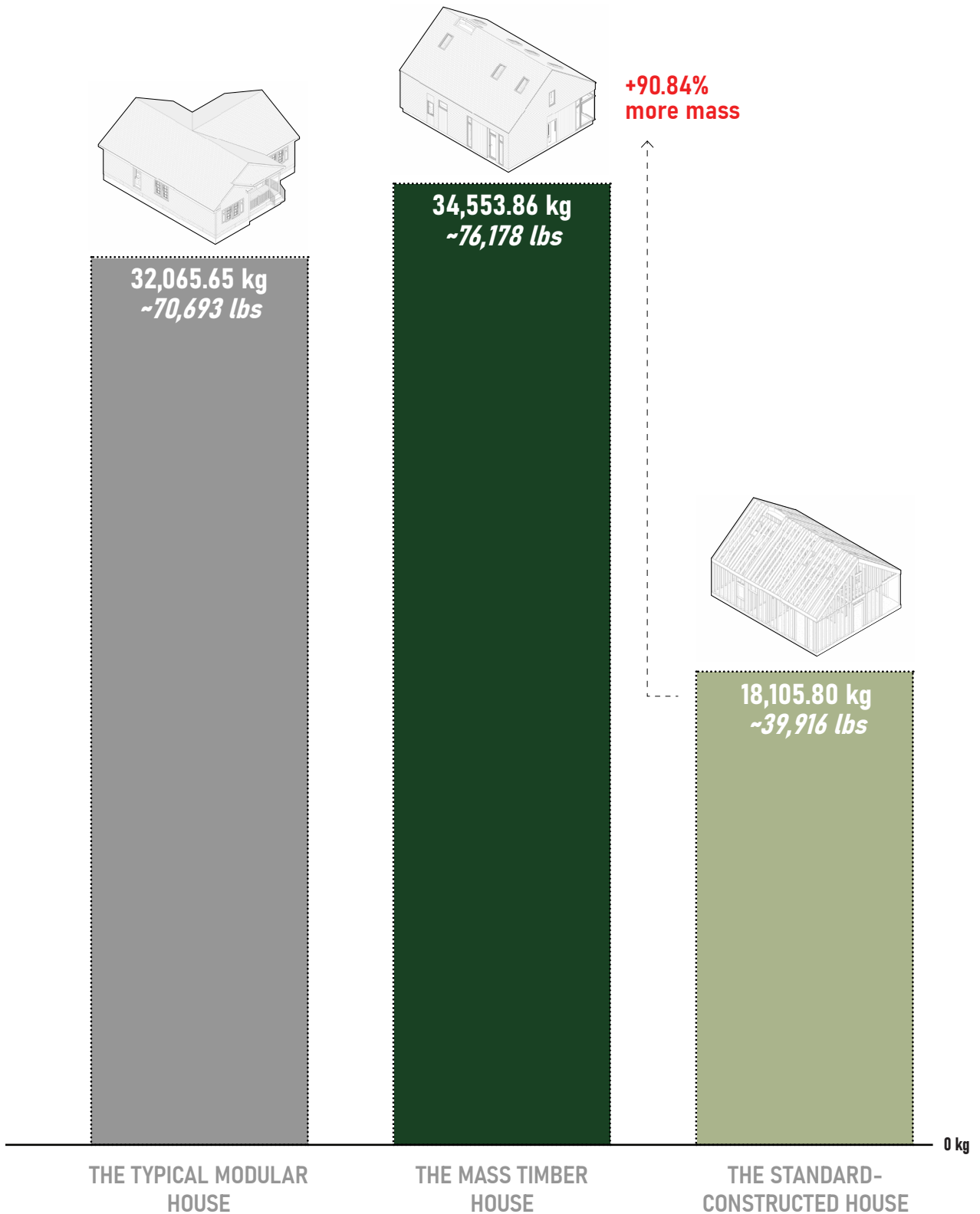
The total mass of a building, or relative weight, plays a role in the requirements of a structural foundation's intensity, amongst other things. The total mass of each of the three systems depict a

potential trade-off a building entirely out of CLT, which is that the mass timber house possesses a significant amount of weight. This would require a costlier foundation, or more concrete poured.

TOTAL MASS OF MATERIALS BY VOLUME (kg)



TOTAL MASS OF CONSTRUCTION COMPOSITIONS (kg)

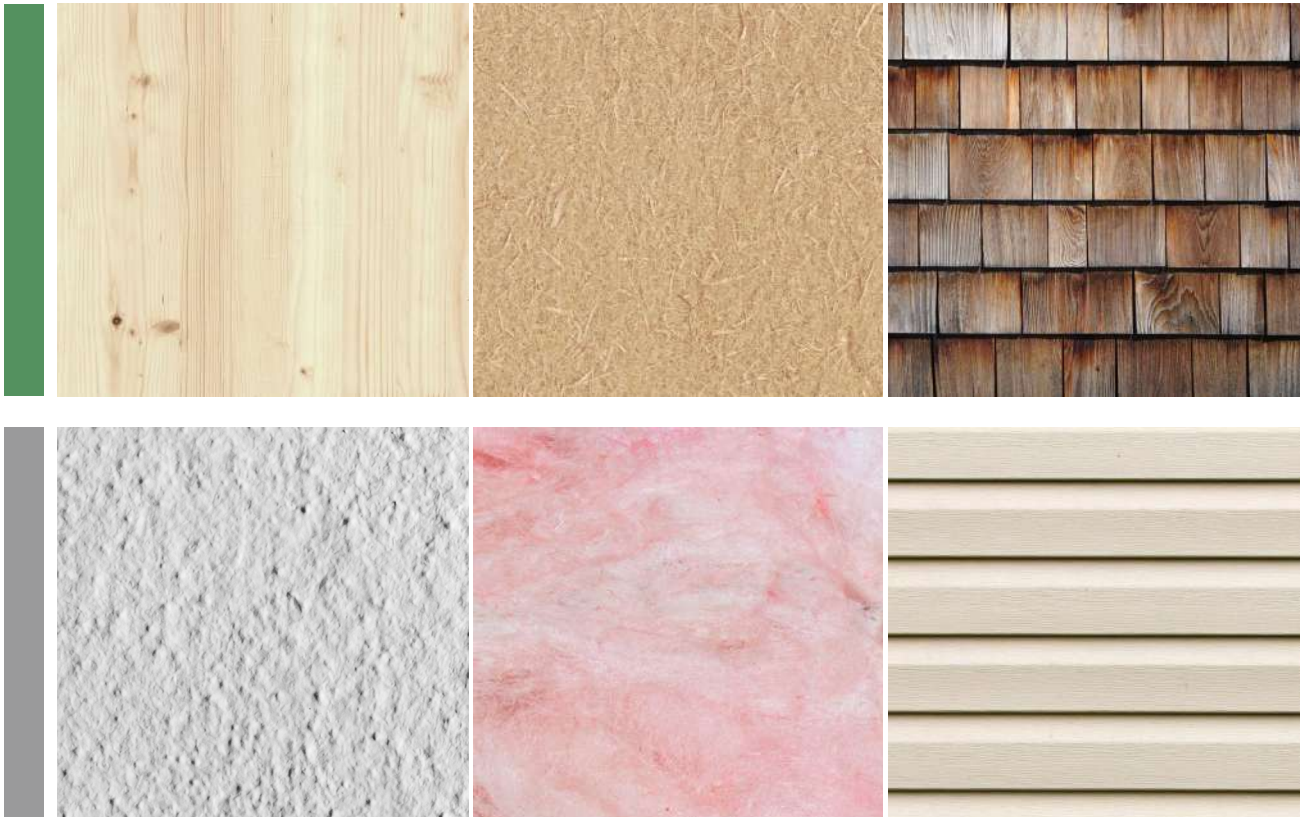


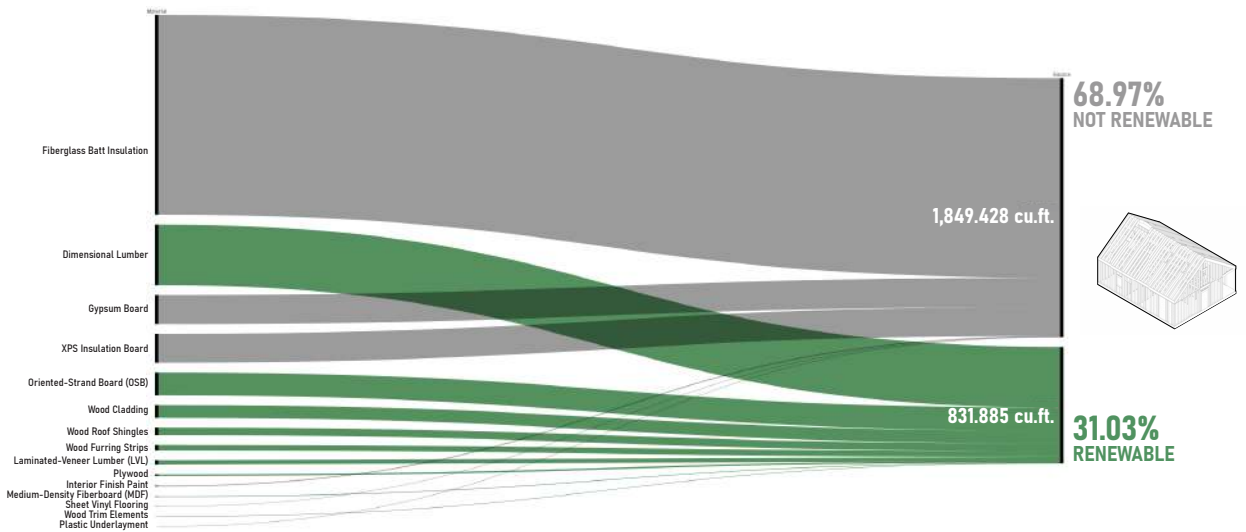
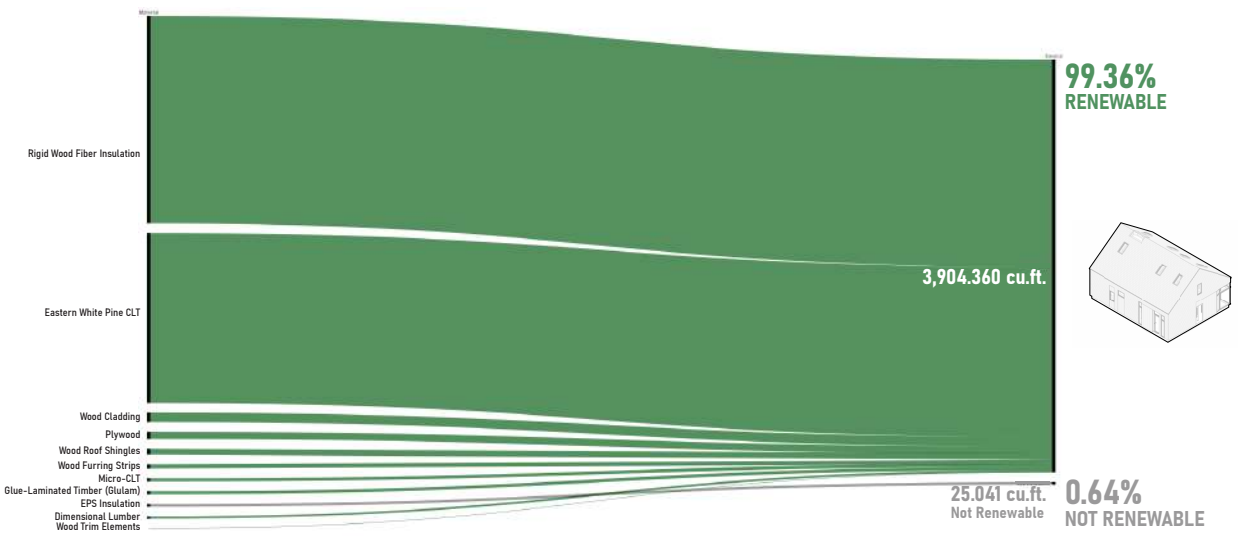
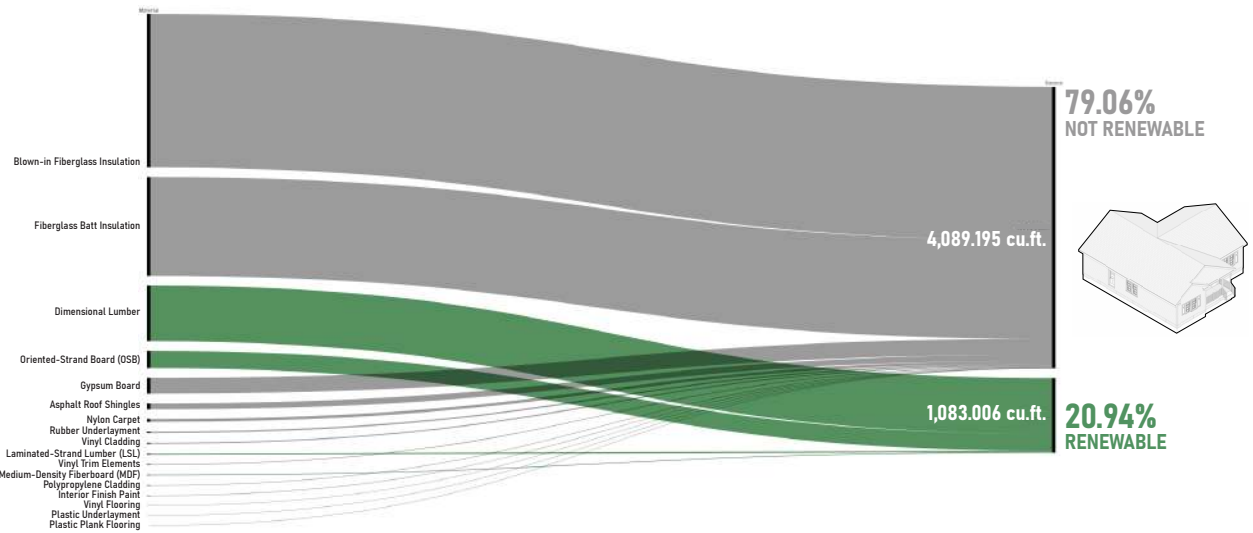
RENEWABILITY OF MATERIAL SOURCES

Quantifying the total proportion of renewability in the sources of each construction system's materials is important to analyze just how much of each house is comprised of materials that could be regenerated, as opposed to those which deplete resources for thousands to millions of years upon consumption. Furthermore, renewable-source materials are typically organic-composed and chemically unaltered in composition, which aids in posing fewer health risks to humans. Nonrenewable-source materials on the other hand, are created from either inorganic natural material that has been modified through energy-intensive processes, or from chemically-synthetic or petroleum-based products which contain

compounds that are adverse to human health. These material sources are also more likely to be sourced from foreign places.

Within the project boundary, the biogenic mass timber house is comprised of roughly 99% renewable-source materials, indicating its significant potential as a construction system that is sustainable. The typical modular house, on the other hand, is comprised of only 21% renewable-source materials, and the standard constructed home comprised of 31%. The rest of their materials contribute to relative resource-depletion on Earth.





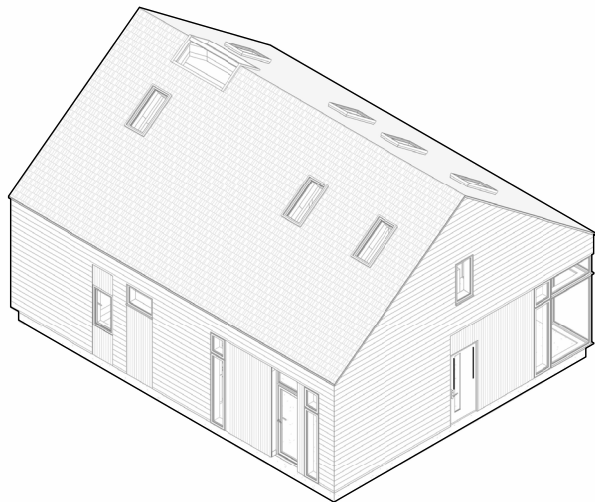
CONCLUSIVE RESULTS

QUALITIES OF A BIOGENIC MASS TIMBER HOUSE

This section of the comparative analyses introduced the construction compositions of each of the three systems for study, and explored the resultant quantities and characteristics of these assemblies through various metrics and lenses. Material volumes, mass, total number of parts, and source-renewability were observed as metrics for data compilation and visualization.

At the end of this section of analyses, it is evident that a biogenic mass timber-constructed house requires far less pieces of individual components, which would greatly save on labor. However, it contains a higher total of relative material volume as part of the material composition—which in

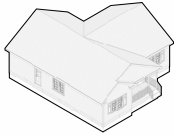
this case would put a larger demand on timber consumption for a single home. The construction system also includes more mass than a light-wood-frame constructed home, which would likely result in a more durable and resilient home, but also a need for a more intensive foundation. Lastly, a biogenic home, as a result of its use of wood fiber insulation, CLT, and generally reduced amount of material types required, possess a much higher proportion of renewable-source materials, which suggests it's superior sustainability.



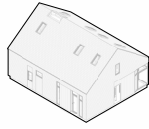
MORE RENEWABLE MATERIAL
LESS NUMBER OF PARTS
LESS MATERIAL LAYERS

MORE MASS [WEIGHT]

MORE MATERIAL VOLUME



VS



VS



THE TYPICAL MODULAR HOUSE

THE MASS TIMBER HOUSE

THE STANDARD CONSTRUCTED HOUSE

1,592 sq.ft.

1,110 sq.ft.

1,110 sq.ft.

Gross Square Footage

5,172 cu.ft.

3,929 cu.ft.

2,681 cu.ft.

Total Volume of Materials

6,056 parts

2,048 parts

3,674 parts

Total Number of On-Site Parts

3,909 parts

462 parts

2,088 parts

Total Number of On-Site Parts, **without** Exterior Cladding Elements

4,620 cu.ft.

3,127 cu.ft.

2,300 cu.ft.

Volume of Building Shell Materials

4,471 parts

1,908 parts

2,474 parts

Number of Building Shell Parts

552 cu.ft.

803 cu.ft.

382 cu.ft.

Volume of Interior Materials

1,585 parts

140 parts

1,200 parts

Number of Interior Parts

1,640 parts

LIGHT-WOOD-FRAMING

54 parts

CLT

454 parts

LIGHT-WOOD-FRAMING

Number of Framing or CLT Parts in Building Shell

70,693 lbs

76,178 lbs

39,916 lbs

Total Mass of Construction Systems

21 %

99%

31%

Total Renewable-Source Material Proportion



C3





LIFE CYCLE ASSESSMENTS

OVERVIEW

ANALYSIS SUMMARY

This section will explore the carbon footprint related to each construction system through a series of life-cycle assessments. The intent is to analyze each system's relative carbon-performance in various scenarios in order to depict an accurate and culminate result for the condition of each system's true carbon footprint.

Life cycle assessments rely on Environmental Product Declarations (EPD's), which are individual carbon assessments of specific products, provided by the product manufacturer and verified by a third party.

For this analysis, decisions on EPD selections to represent each material were prioritized in the following order:

- 1. Product Definition**
- 2. Industry-Average EPD's over specific products**
- 3. Country of Origin (Prioritize USA)**
- 4. EPD Year (Prioritize most-recent)**

Additionally, (and, although it is anticipated that CLT would be the more durable construction system compared to light-wood-frame,) the structural elements of each representative system are not appointed service-lives in the following life cycle assessments. This is done for the sake of simplicity, and out of consideration that both structural systems could theoretically last for centuries under proper conditions and protection.

1. CRADLE-TO-GATE (A1-A3) ASSESSMENT

Analysis of initial embodied carbon emissions of materials. Excludes biogenic-carbon consideration.

2. BIOGENIC CARBON ASSESSMENT (A1-A3)

Analysis of initial embodied carbon emissions of materials, including inherent biogenic carbon stored in each system.

3. CRADLE-TO-GRAVE (A1-C3) SUMMARY

Analysis of total embodied carbon emissions of the construction systems over time, including construction, material replacement, and service. Excludes biogenic-carbon consideration.

4. CRADLE-TO-GRAVE (A1-C3): YEAR 30

Analysis of total embodied carbon emissions of the construction systems after 30 years since initial construction. Excludes biogenic-carbon consideration.

5. CRADLE-TO-GRAVE (A1-C3): YEAR 60

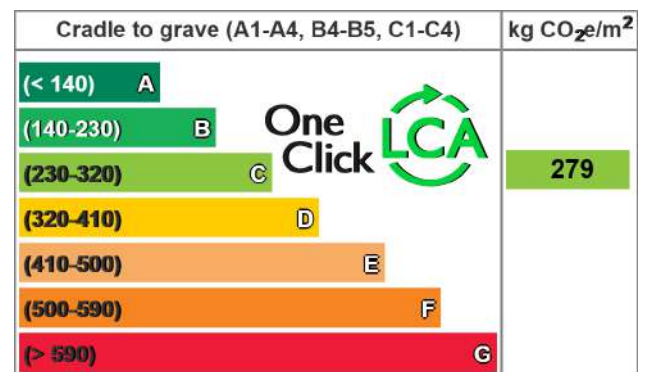
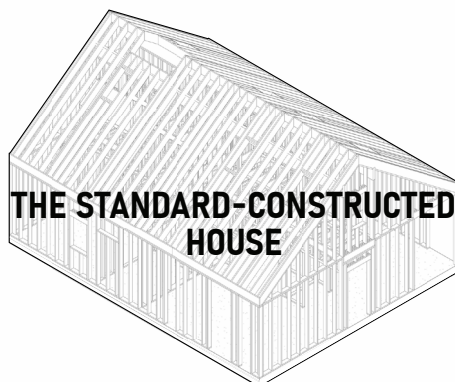
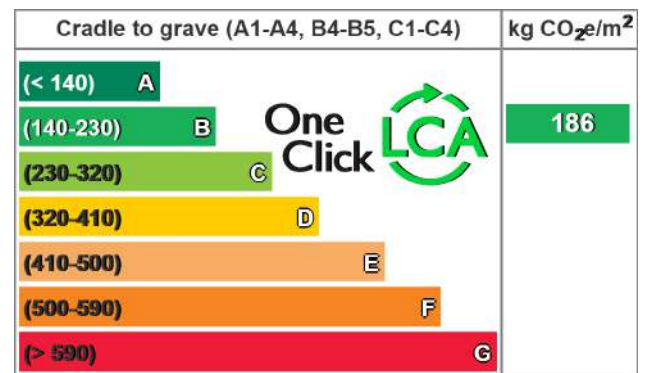
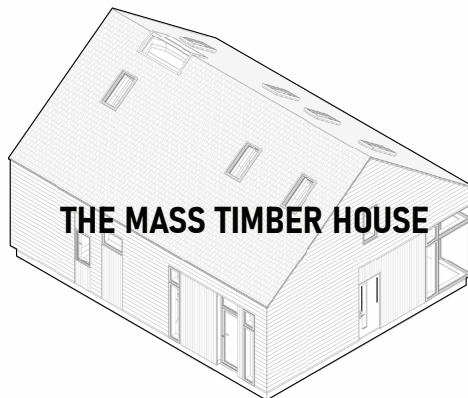
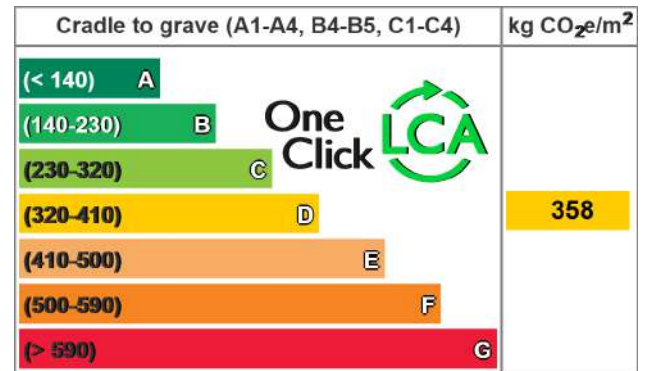
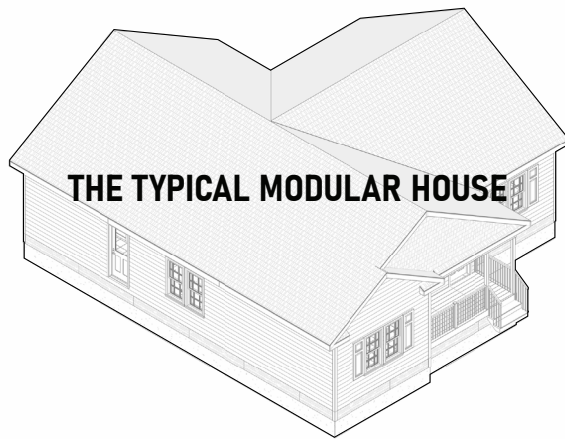
Analysis of total embodied carbon emissions of the construction systems after 60 years since initial construction. Excludes biogenic-carbon consideration.

6. CRADLE-TO-GRAVE (A1-C3): YEAR 100

Analysis of total embodied carbon emissions of the construction systems after 100 years since initial construction. Excludes biogenic-carbon consideration.

7. LONGTERM BIOGENIC CARBON

Analysis of total embodied carbon emissions of the construction systems after each of the study-years since initial construction, with biogenic-carbon consideration factored into the results.



Cradle-to-Grave Carbon Benchmark Score after 60 Years
Source: One Click LCA (2015)

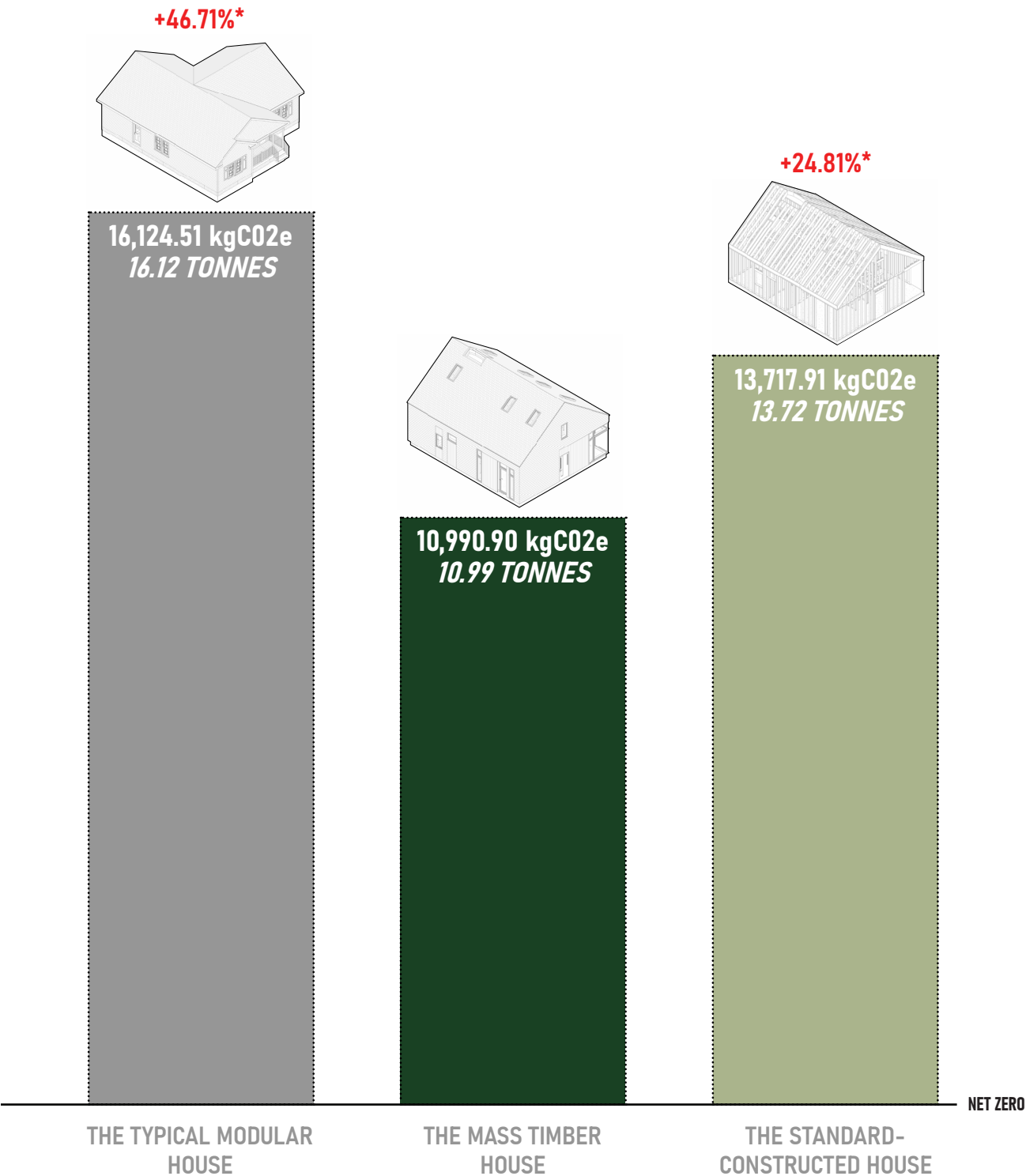
CRADLE-TO-GATE (A1-A3) ASSESSMENT

INITIAL CARBON OF MATERIALS

The cradle-to-gate assessment provides an analysis that isolates the immediate embodied carbon of materials from the rest of carbon related to construction, service, and repair throughout the homes' lives. While a cradle-to-gate assessment will often include A4-Transportation emissions, this analysis omitted that section. This is largely due to the lack of a specific site for the study, as well as the choice to prioritize generalized EPD's for materials instead of specific products where possible.

Without considering biogenic carbon for each of the construction types, the initial carbon emissions of the mass timber house is the lowest, and the initial carbon emissions of the typical modular house is the highest—at 46.71% more carbon emitted compared to the mass timber home. The standard-constructed house's initial emitted carbon is also higher than the mass timber house, indicating that the materials used by typical modular construction and standard construction have a larger inherent carbon footprint than a biogenic mass timber house.

CARBON EMISSION OF MATERIALS (EXCLUDING BIOGENIC CARBON)



* Percentage of Additional Carbon Emissions compared to the Mass Timber House

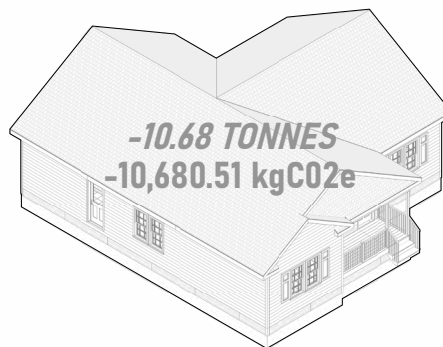
BIOGENIC CARBON CONSIDERATION

TOTAL CARBON SEQUESTRATION (A1-A3)

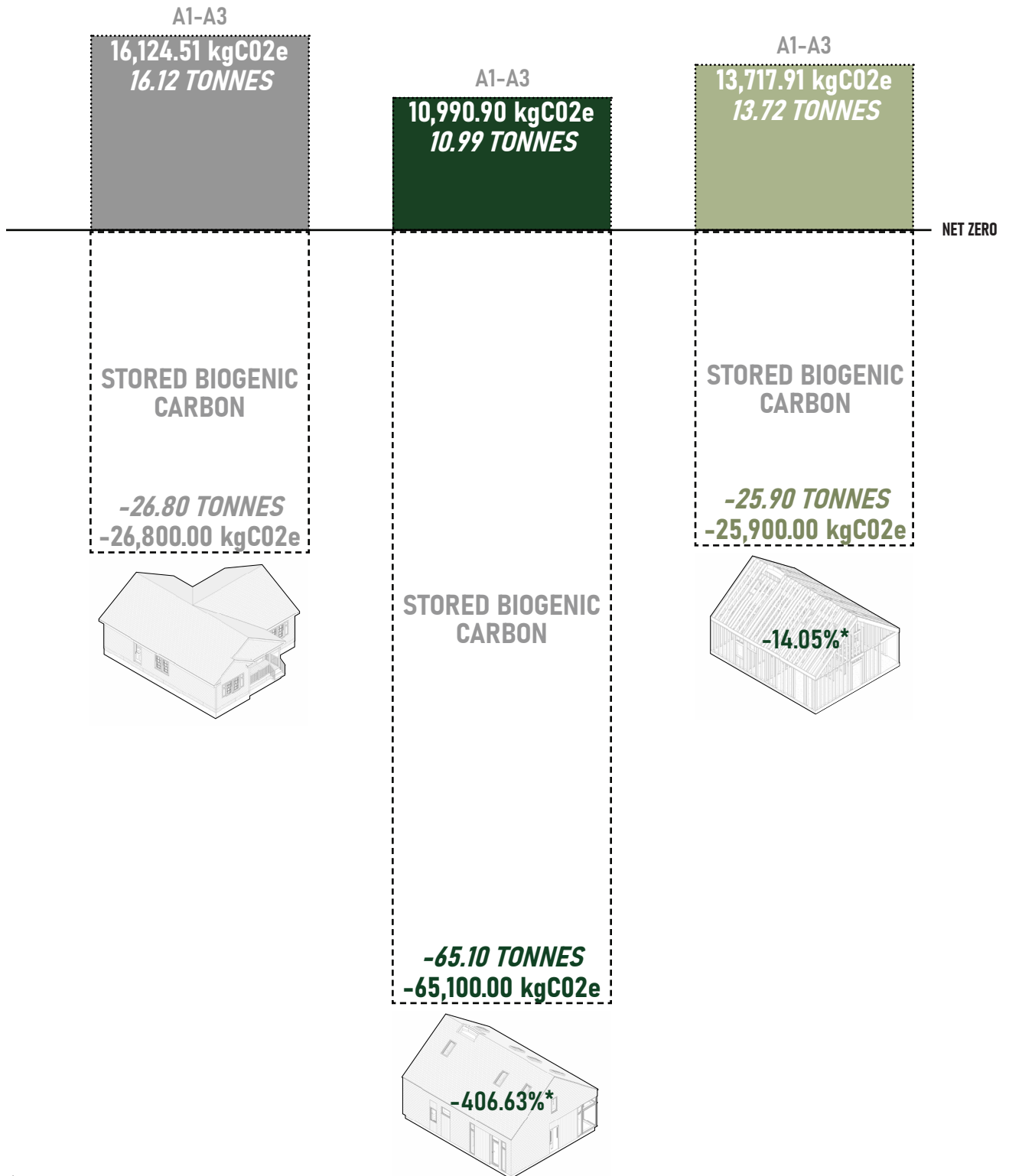
Biogenic carbon is the natural carbon content that is possessed within natural fiber-based materials, such as wood or straw. This is carbon that has been pulled from the atmosphere and held within the structure of a plant for the duration of its composition. In the case of trees, the sequestered carbon is stored in the wood, and remains there until decay. The purpose that biogenic carbon plays in regards to the construction materials of a building is that it represents the embodied amount of previous carbon pulled from the atmosphere that is now banked within a building to remain keeping this carbon sequestered. In short, it can delay the rate at which that carbon would be re-released into the atmosphere if it were left as a plant to naturally decay, which can be a great advantage in delaying or reversing climate change. However, no building lasts forever, and so the embodied biogenic carbon of a building will eventually return to the atmosphere at the end of the building's life. This emphasizes the importance of the durability and service-life of materials and the building stock as a whole.

In this cradle-to-gate analysis, the biogenic carbon embodied within the mass timber house is by far the greatest amount, at about 4-times (406.63%) more than the typical modular house. This, in turn, provides the greatest offset to the mass timber home's initial carbon emissions in the production of its materials, allowing it to achieve the greatest amount of net-negative carbon emission.

NET CARBON EMISSION



INITIAL CARBON EMISSION OF MATERIALS (INCLUDING BIOGENIC CARBON)



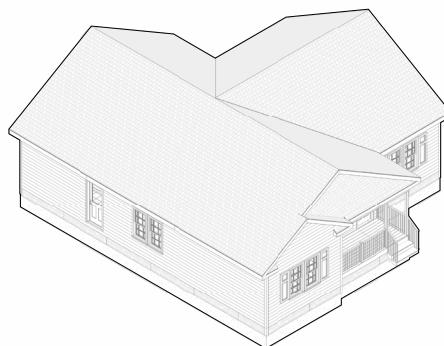
* Percentage of Additional Biogenic Carbon Offset compared to the Typical Modular House

CRADLE-TO-GRAVE: SUMMARY

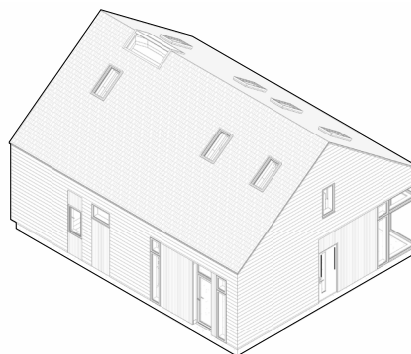
LONGTERM CARBON EMISSION

Beyond cradle-to-gate, a cradle-to-grave assessment provides a more accurate picture into the total realized carbon that is embodied in a building over the duration of its life; taking into account the service-life of materials and their need for replacement.

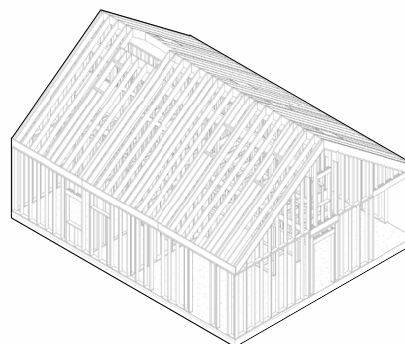
A cradle-to-grave assessment was calculated for three conditions in the analysis; after 30 years, after 60 years, and after 100 years since initial construction. The results indicate that the typical modular house emits significantly more carbon over time compared to the other two systems, with the mass timber house performance the best. Additionally, the difference of total emitted carbon between each year in the typical modular home is the most drastic, indicating a proportionally higher carbon footprint requirement each year. Conversely, the difference of carbon emitted between each year in the mass timber home is the least drastic, which suggests a lower amount of necessary material replacement over the course of 100 years.



THE TYPICAL MODULAR HOUSE



THE MASS TIMBER HOUSE

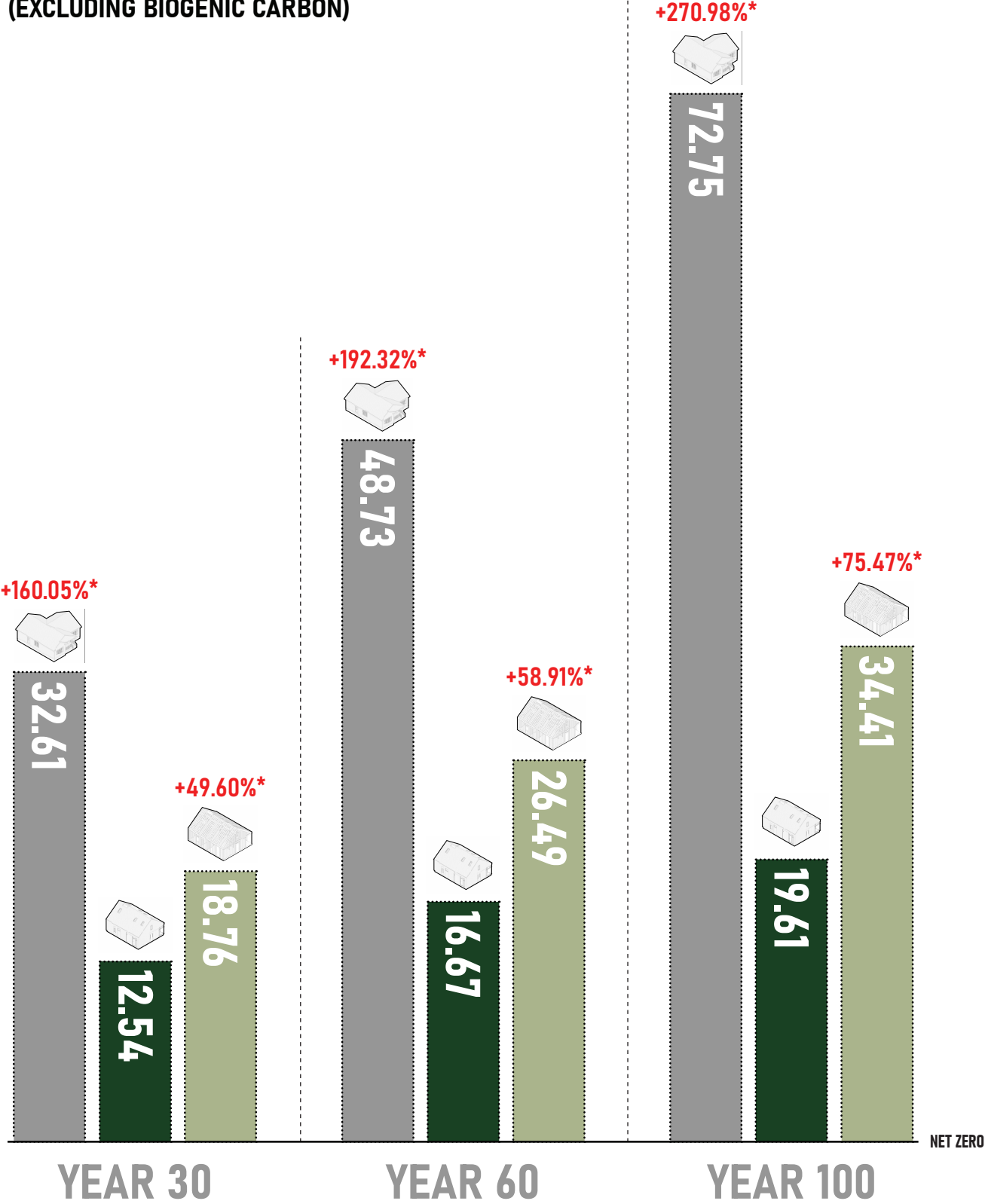


THE STANDARD-CONSTRUCTED HOUSE

NOTE: Biogenic Carbon is omitted from the Cradle-to-Grave Assessments.

Data Source: One Click LCA (2015). Helsinki: One Click LCA Ltd.

TOTAL CARBON EMISSION OVER TIME [TONNES CO2e]
(EXCLUDING BIOGENIC CARBON)



* Percentage of Additional Carbon Emissions compared to the Mass Timber House by respective Year

CRADLE-TO-GRAVE: YEAR 30

THE TYPICAL MODULAR HOUSE

After just 30 years, the typical modular house has already gone through numerous necessary material replacements due to the short-nature of their service lives. As such, the need for material replacement is now responsible for 28% of the home's total embodied carbon. The carbon contribution breakdown indicates that floor coverings & finishes were the largest contributor.



32.61 TONNES
TOTAL CARBON

NECESSARY MATERIAL REPLACEMENT

4 - EXTERIOR CLADDING ELEMENTS

Asphalt Roofing Shingles x1
2,084 sq. ft. | 20-year service life

5 - WALL & CEILING FINISHES

Interior Finish Paint x2
5,148 sq. ft. | 10-year service life

6 - FLOOR COVERINGS & FINISHES

Porch Composite-Plank Flooring x1
77 sq. ft. | 25-year service life

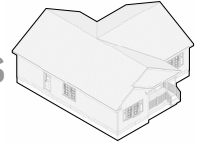
Interior Vinyl Flooring x1
335 sq. ft. | 25-year service life

Recycled Rubber Floor Underlayment x1
992 sq. ft. | 25-year service life

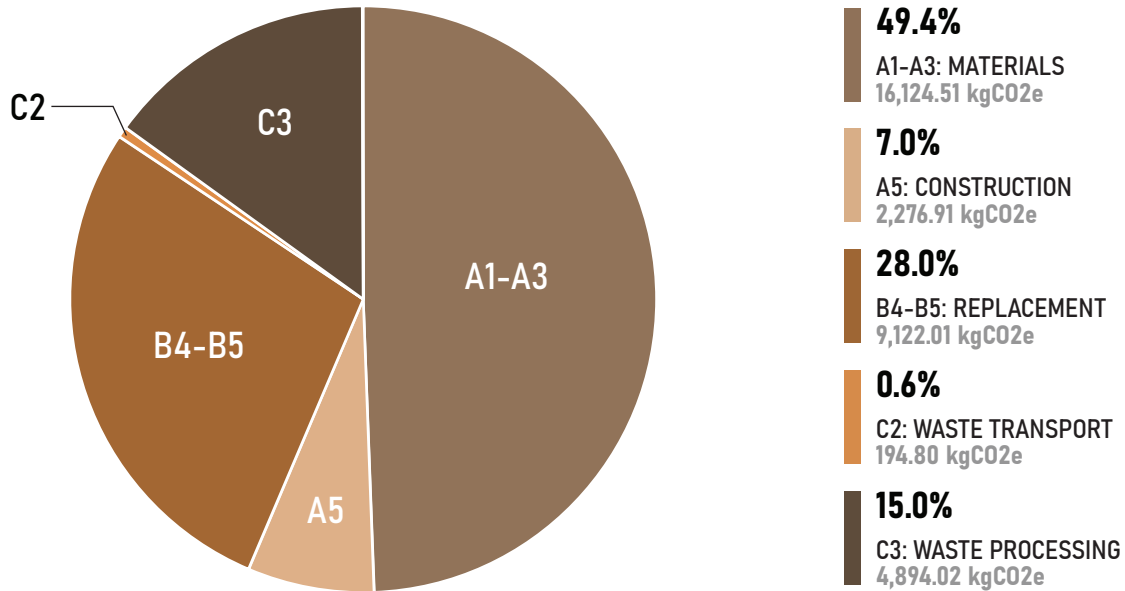
6-pile Nylon Carpet x1
992 sq. ft. | 15-year service life

NOTE: Material service life periods include the full duration of its final year. Replacement would occur the following year.

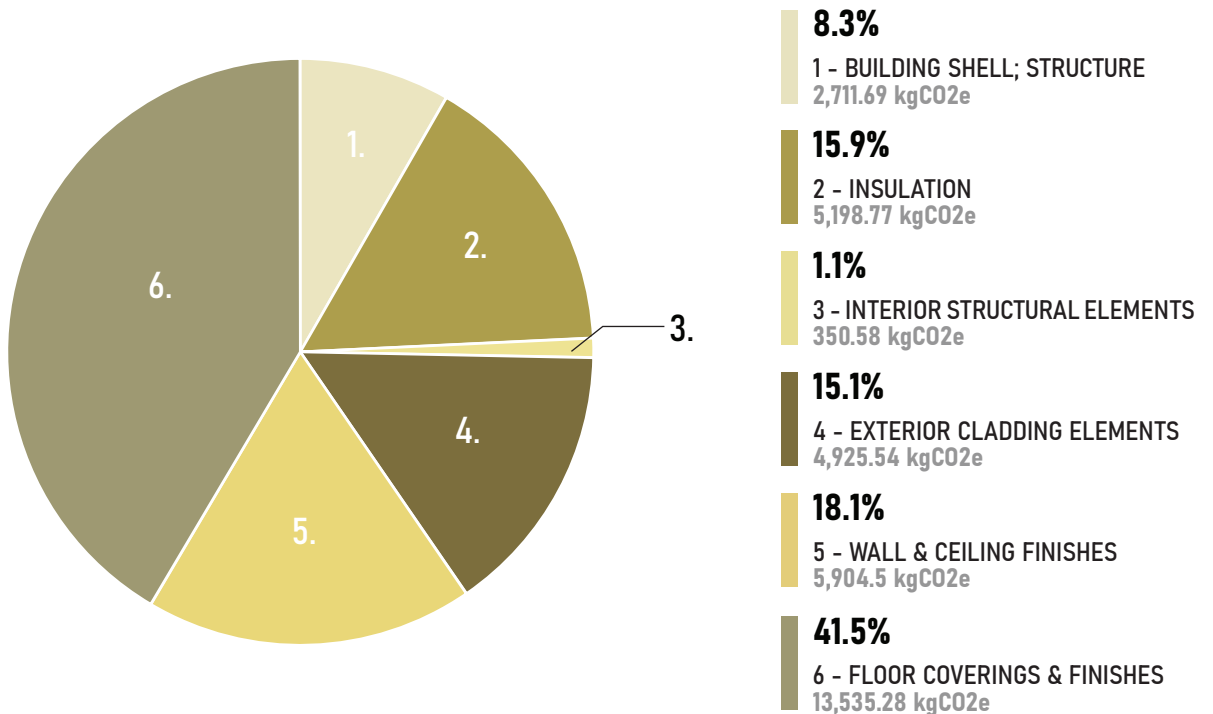
30 YEARS



CARBON CONTRIBUTION: LIFE-CYCLE STAGES



CARBON CONTRIBUTION: MATERIAL CLASSIFICATIONS



THE MASS TIMBER HOUSE

After 30 years, the mass timber house remains as it was when it was initially constructed, indicating no required replacement of materials under idealized conditions.

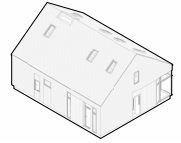


12.54 TONNES
TOTAL CARBON

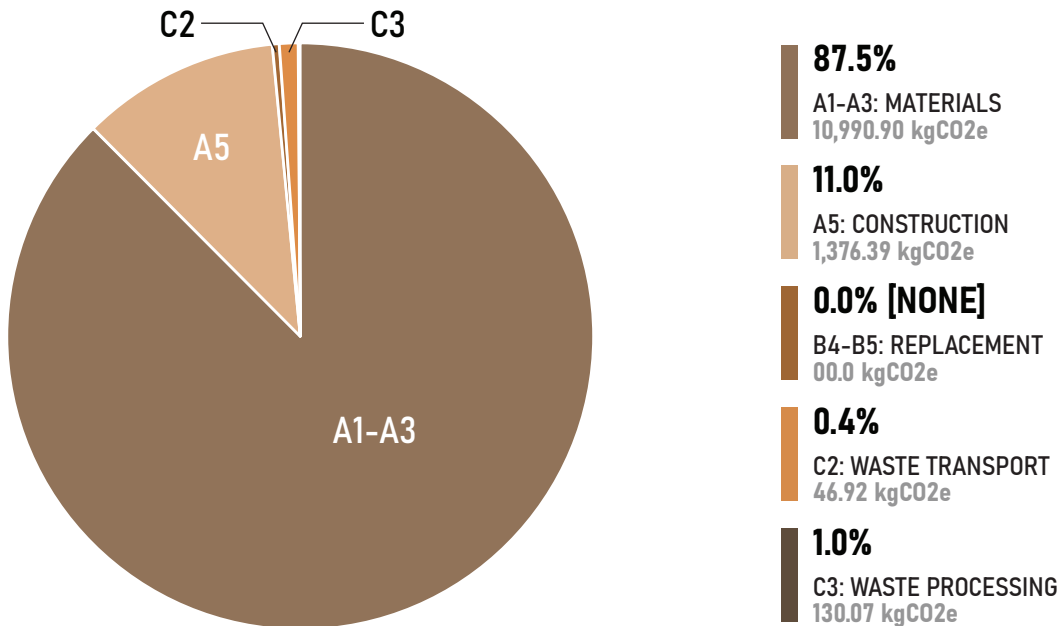
NECESSARY MATERIAL REPLACEMENT

NONE.

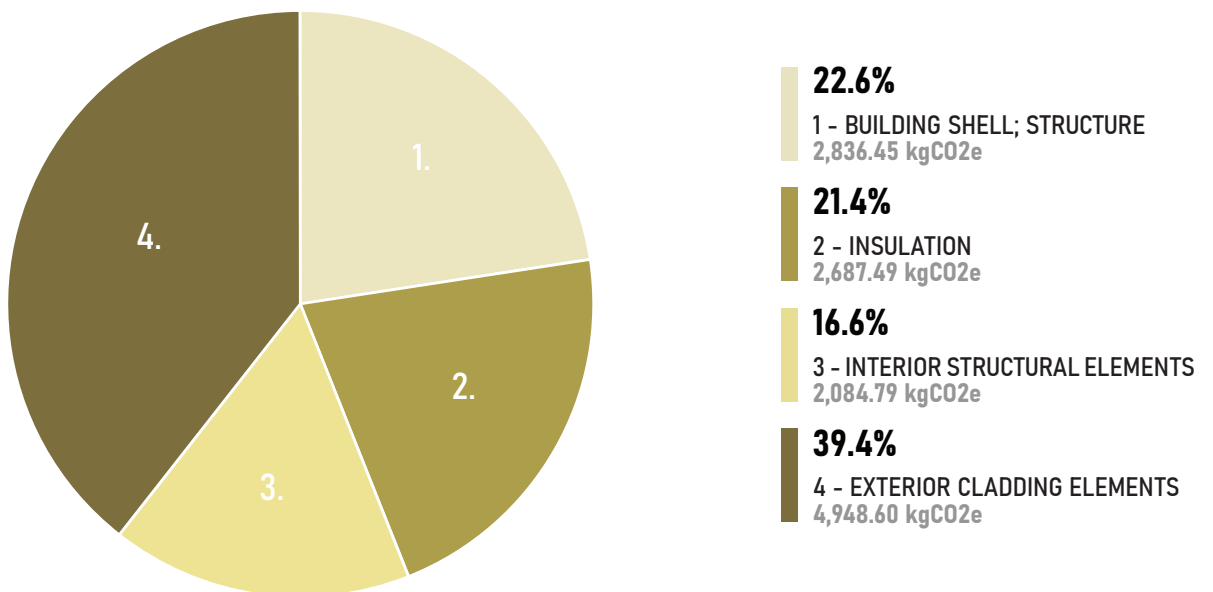
30 YEARS



CARBON CONTRIBUTION: LIFE-CYCLE STAGES



CARBON CONTRIBUTION: MATERIAL CLASSIFICATIONS



THE STANDARD-CONSTRUCTED HOUSE

The standard-constructed house undergoes a few material replacements after 30 years, making up 12.2% of the home's total embodied carbon. With the ground floor system being the same as the mass timber house, a simple exposed concrete floor, the need for floor coverings & finishes replacement is greatly reduced compared to the typical modular house.



18.76 TONNES
TOTAL CARBON

NECESSARY MATERIAL REPLACEMENT

5 - WALL & CEILING FINISHES

Interior Finish Paint x2
4,939 sq. ft. | 10-year service life

6 - FLOOR COVERINGS & FINISHES

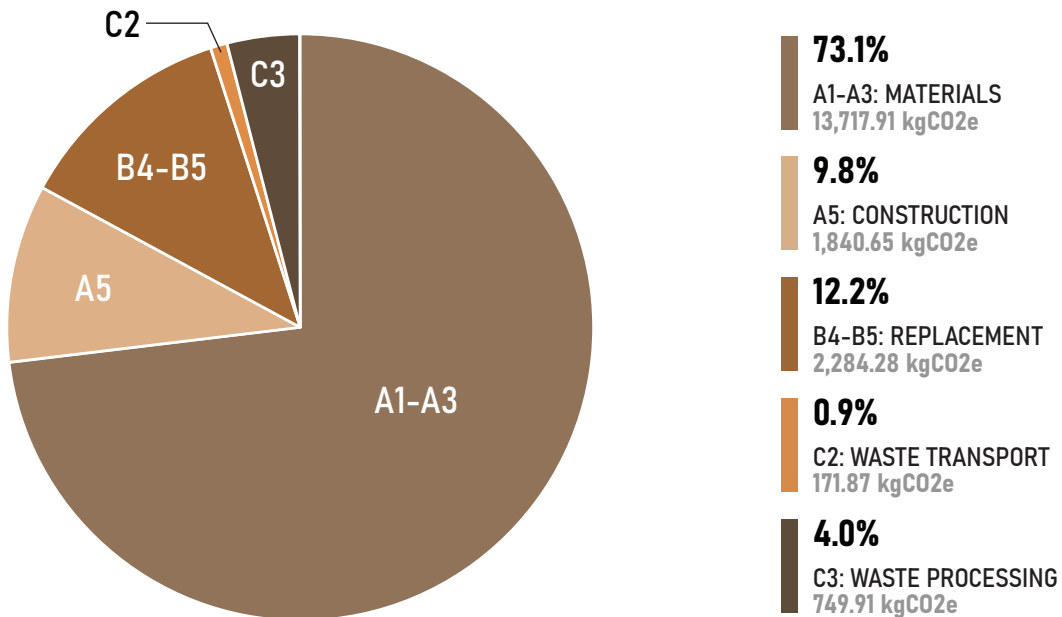
Interior Vinyl Flooring x1
2.17 cu. ft. | 25-year service life

NOTE: Material service life periods include the full duration of its final year. Replacement would occur the following year.

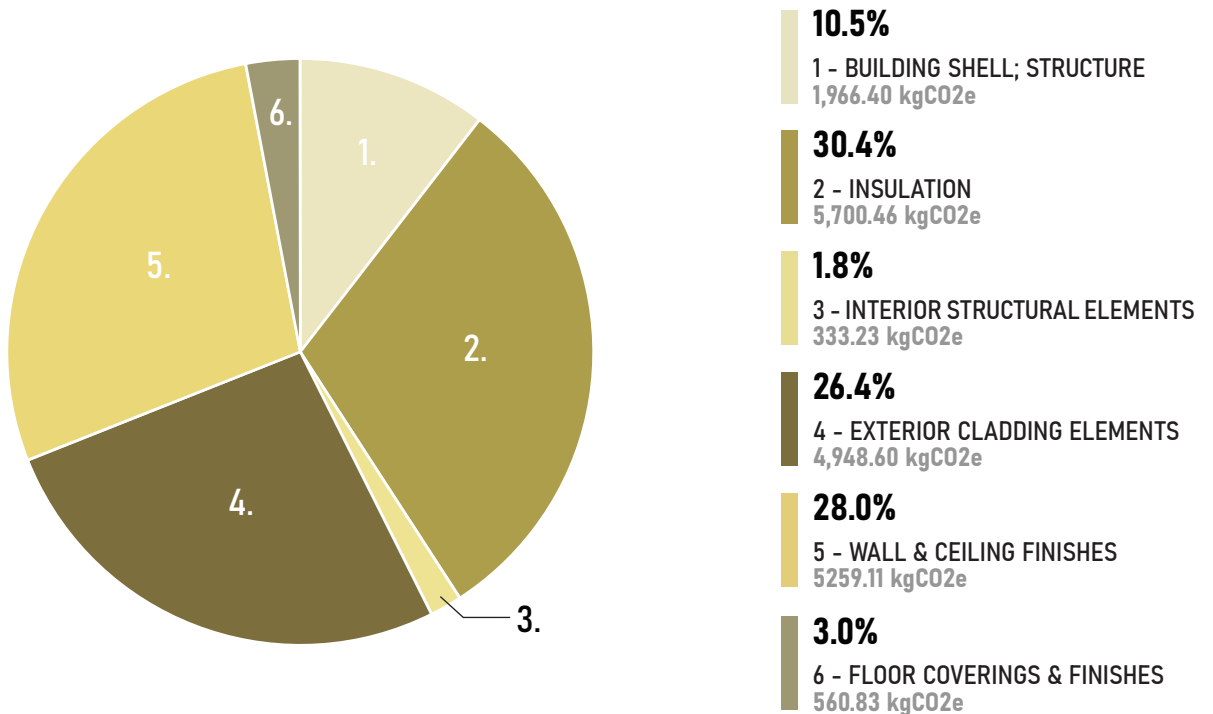
30 YEARS



CARBON CONTRIBUTION: LIFE-CYCLE STAGES



CARBON CONTRIBUTION: MATERIAL CLASSIFICATIONS



CRADLE-TO-GRAVE: YEAR 60

THE TYPICAL MODULAR HOUSE

After 60 years, many more materials are required to be replaced in the typical modular house—and in many cases, more than once. In the 30 years that have passed since the year-30 assessment, the total contribution of embodied carbon that the material replacement is responsible for has grown to over half of the home’s entire embodied carbon; now surpassing that of its initial materials.

The proportions of carbon contribution based on material classification has remained relatively the same, which indicates that floor coverings & finishes have the largest carbon footprint by nature.



48.73 TONNES
TOTAL CARBON

NECESSARY MATERIAL REPLACEMENT

4 - EXTERIOR CLADDING ELEMENTS

Asphalt Roofing Shingles x2
2,084 sq. ft. | 20-year service life

Vinyl Siding & Trim x1
1,628 sq. ft. | 30-year service life

Polypropylene Siding & Trim x1
866 sq. ft. | 30-year service life

5 - WALL & CEILING FINISHES

Interior Finish Paint x5
5,148 sq. ft. | 10-year service life

MDF Interior Base Trim x1
225 sq. ft. | 30-year service life

6 - FLOOR COVERINGS & FINISHES

Porch Composite-Plank Flooring x2
77 sq. ft. | 25-year service life

Plastic Floor Underlayment x1
413 sq. ft. | 30-year service life

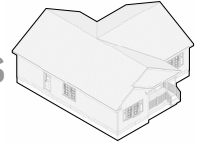
Interior Vinyl Flooring x2
335 sq. ft. | 25-year service life

Recycled Rubber Floor Underlayment x2
992 sq. ft. | 25-year service life

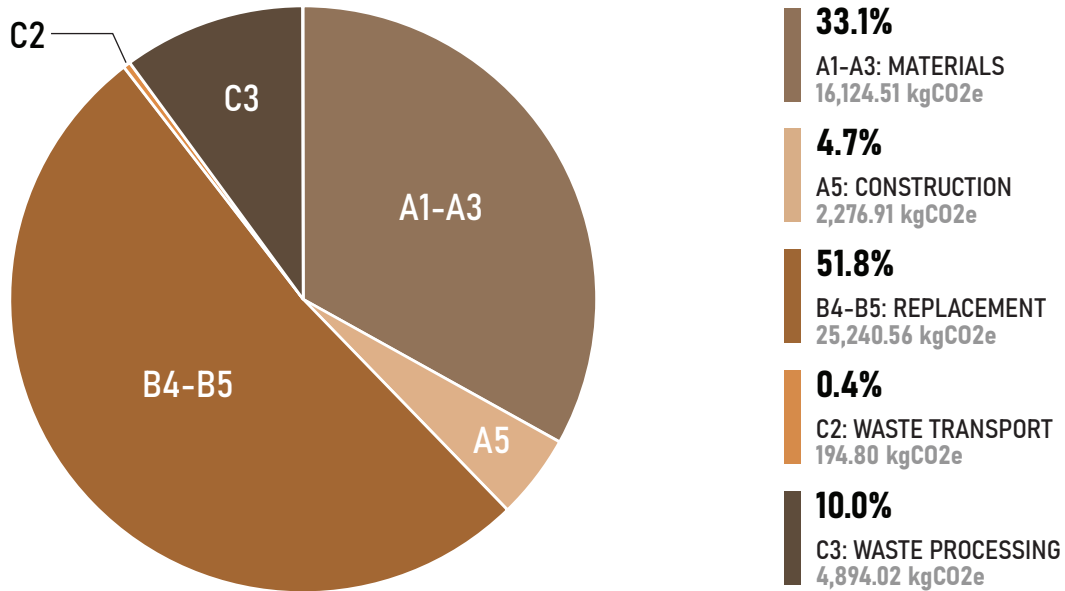
6-pile Nylon Carpet x3
992 sq. ft. | 15-year service life

NOTE: Material service life periods include the full duration of its final year. Replacement would occur the following year.

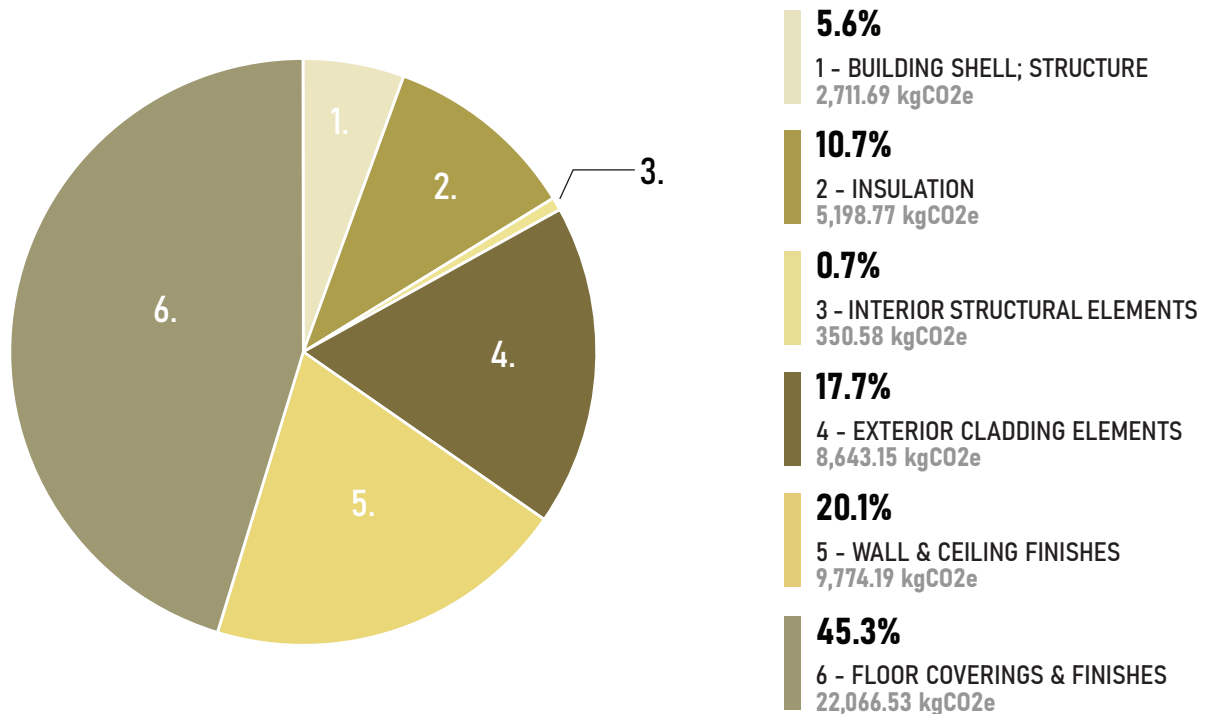
Data Source: One Click LCA (2015). Helsinki: One Click LCA Ltd.



CARBON CONTRIBUTION: LIFE-CYCLE STAGES



CARBON CONTRIBUTION: MATERIAL CLASSIFICATIONS



THE MASS TIMBER HOUSE

By year 60, all of the exterior cladding materials of the mass timber home have been replaced. Due to the home's greatly reduced presence of interior wall and floor finishes by design, the exterior cladding elements are the only category in need of replacement; keeping the overall carbon contribution of replacement to just 24.7% after 60 years. It is important to keep in mind that this percentage is the proportion of an already-smaller amount of total carbon emission compared to the other construction systems.



16.67 TONNES
TOTAL CARBON

NECESSARY MATERIAL REPLACEMENT

4 - EXTERIOR CLADDING ELEMENTS

Eastern White Cedar Roofing Shingles x1
1,336 sq. ft. | 35-year service life

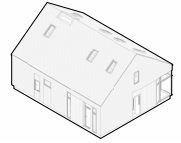
Solid Wood Trim x1
1.07 cu. ft. | 35-year service life

Eastern White Cedar Clapboard Siding x1
1,269 sq. ft. | 50-year service life

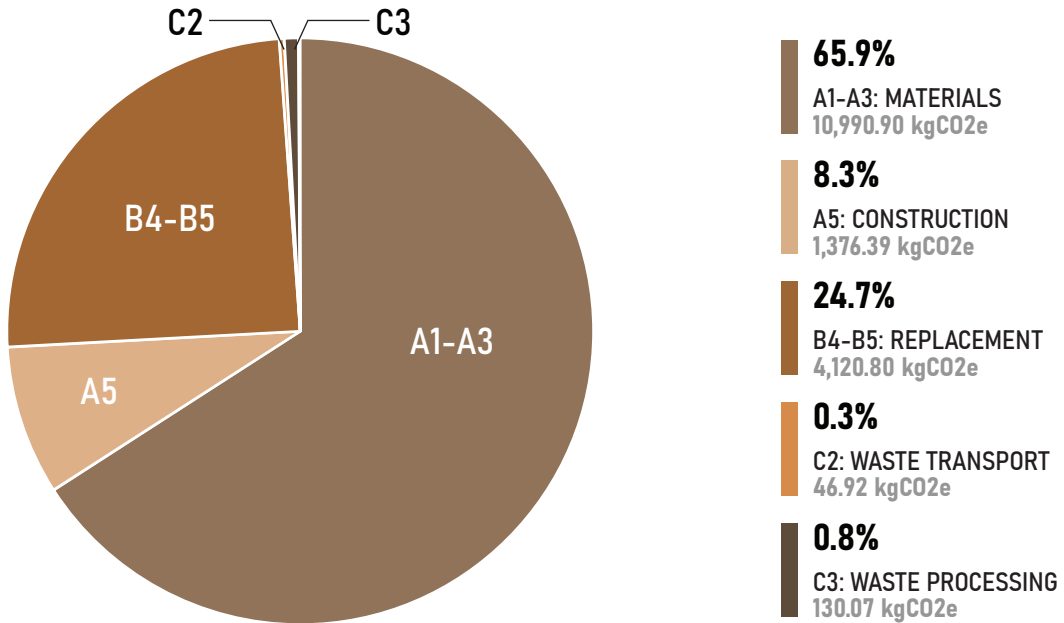
Cedar Shiplap Siding x1
175 sq. ft. | 50-year service life

NOTE: Material service life periods include the full duration of its final year. Replacement would occur the following year.

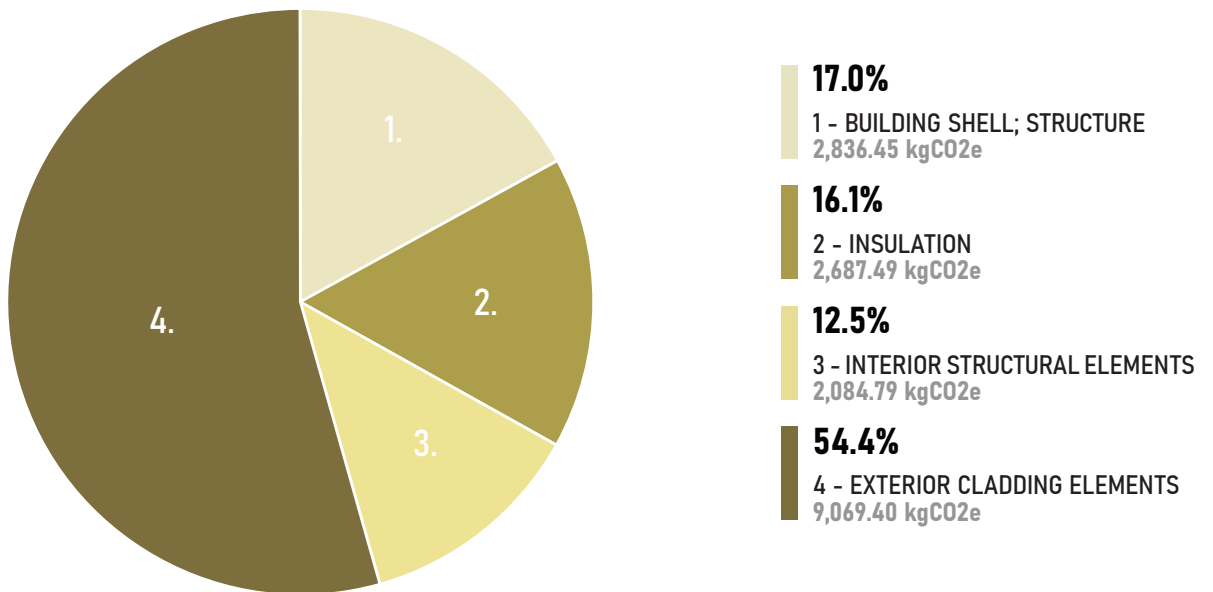
60 YEARS



CARBON CONTRIBUTION: LIFE-CYCLE STAGES



CARBON CONTRIBUTION: MATERIAL CLASSIFICATIONS



THE STANDARD-CONSTRUCTED HOUSE

Being identical to the mass timber house in its exterior cladding elements, these materials would be replaced all the same after 60 years for the standard-constructed house. Wall & ceiling finishes have also reached the end of their service lives. In total, the overall contribution of the embodied carbon related to material replacement remains at a smaller amount compared to the initial material carbon footprint.



26.49 TONNES
TOTAL CARBON

NECESSARY MATERIAL REPLACEMENT

4 - EXTERIOR CLADDING ELEMENTS

Eastern White Cedar Roofing Shingles x1
1,336 sq. ft. | 35-year service life

Solid Wood Trim x1
1.07 cu. ft. | 35-year service life

Eastern White Cedar Clapboard Siding x1
1,269 sq. ft. | 50-year service life

Cedar Shiplap Siding x1
175 sq. ft. | 50-year service life

5 - WALL & CEILING FINISHES

Interior Finish Paint x5
4,939 sq. ft. | 10-year service life

MDF Interior Base Trim x1
96 sq. ft. | 30-year service life

6 - FLOOR COVERINGS & FINISHES

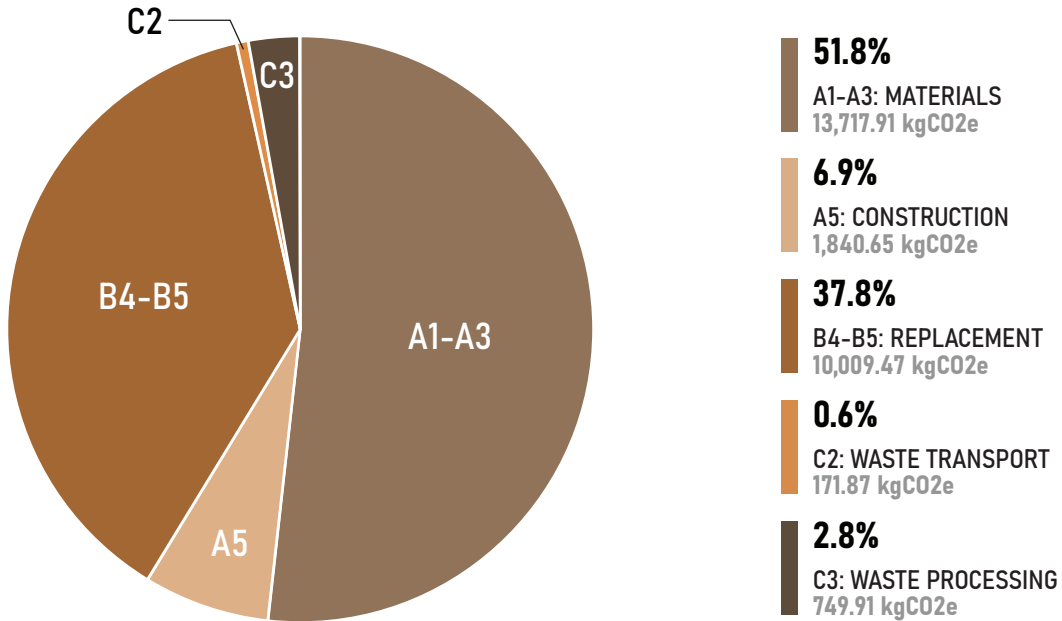
Interior Vinyl Flooring x2
2.17 cu. ft. | 25-year service life

Plastic Floor Underlayment x2
208 sq. ft. | 25-year service life

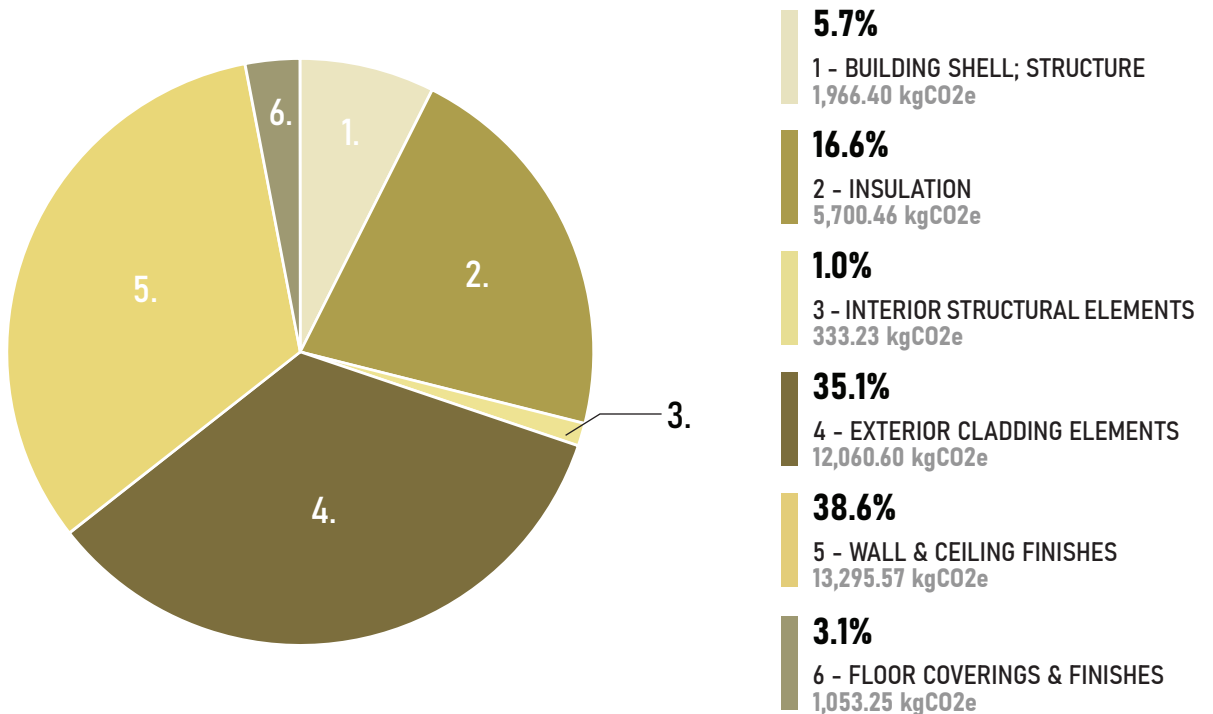
NOTE: Material service life periods include the full duration of its final year. Replacement would occur the following year.



CARBON CONTRIBUTION: LIFE-CYCLE STAGES



CARBON CONTRIBUTION: MATERIAL CLASSIFICATIONS



CRADLE-TO-GRAVE: YEAR 100

THE TYPICAL MODULAR HOUSE

After 100 years, the typical modular home has had countless material replacements, which would suggest a limited potential for the construction system to even last 100 years in general. At this point, the necessary material replacement dominates the overall embodied carbon of the house, at 67.7% total contribution of the 72.75 tonnes of CO₂ emitted.



72.75 TONNES
TOTAL CARBON

NECESSARY MATERIAL REPLACEMENT

4 - EXTERIOR CLADDING ELEMENTS

Asphalt Roofing Shingles x4
2,084 sq. ft. | 20-year service life

Vinyl Siding & Trim x3
1,628 sq. ft. | 30-year service life

Polypropylene Siding & Trim x3
866 sq. ft. | 30-year service life

5 - WALL & CEILING FINISHES

Interior Finish Paint x9
5,148 sq. ft. | 10-year service life

MDF Interior Base Trim x3
225 sq. ft. | 30-year service life

6 - FLOOR COVERINGS & FINISHES

Porch Composite-Plank Flooring x3
77 sq. ft. | 25-year service life

Plastic Floor Underlayment x3
413 sq. ft. | 30-year service life

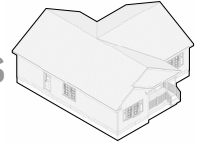
Interior Vinyl Flooring x3
335 sq. ft. | 25-year service life

Recycled Rubber Floor Underlayment x3
992 sq. ft. | 25-year service life

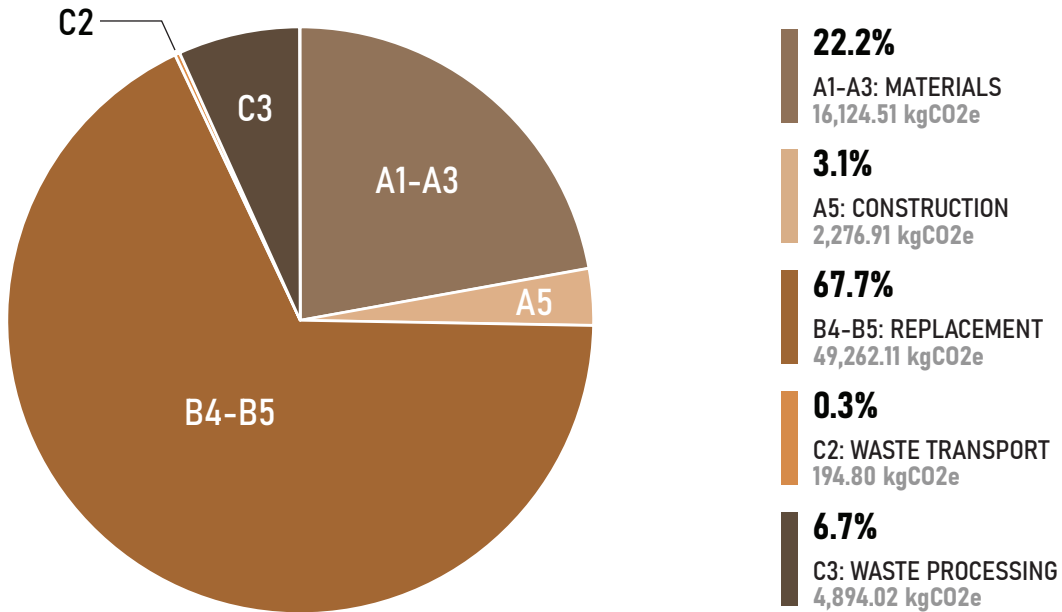
6-pile Nylon Carpet x6
992 sq. ft. | 15-year service life

NOTE: Material service life periods include the full duration of its final year. Replacement would occur the following year.

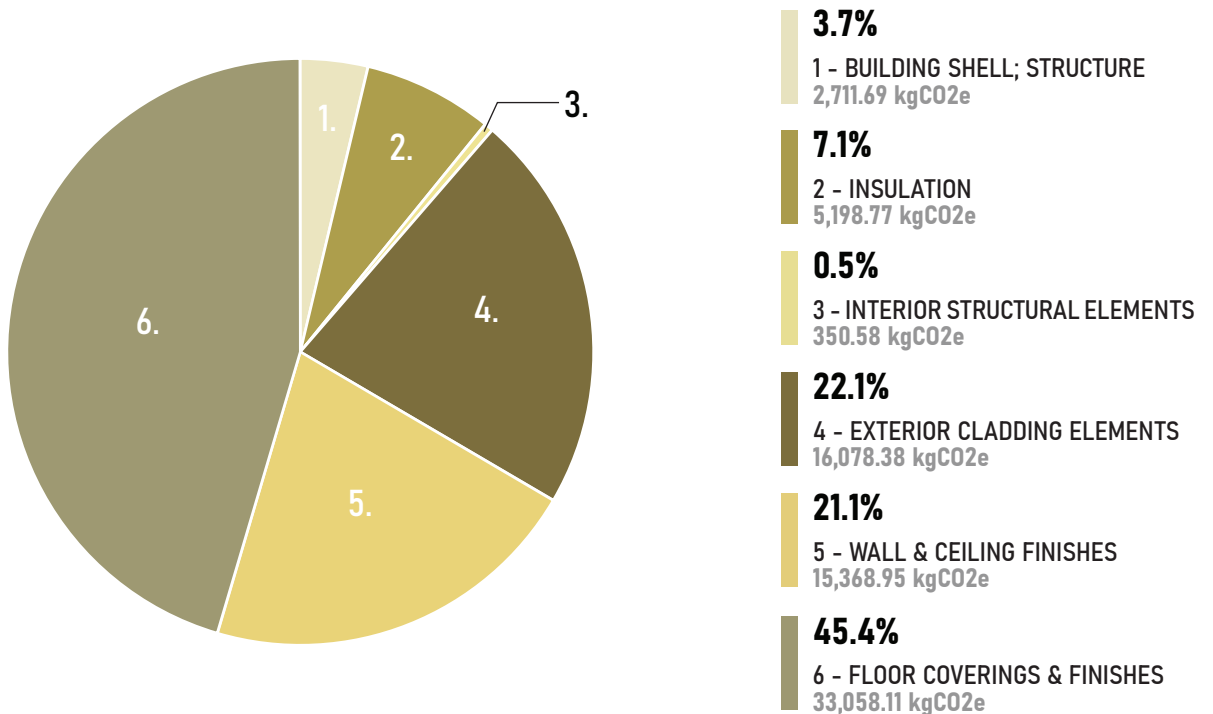
Data Source: One Click LCA (2015). Helsinki: One Click LCA Ltd.



CARBON CONTRIBUTION: LIFE-CYCLE STAGES



CARBON CONTRIBUTION: MATERIAL CLASSIFICATIONS



THE MASS TIMBER HOUSE

The mass timber house only experiences a couple material replacements in its exterior cladding elements after 100 years of life, with an overall material replacement contribution of just 36.2% of the 19.61 tonnes of CO₂ emitted. This indicates that the mass timber home could survive far longer than 100 years under proper conditions.



19.61 TONNES
TOTAL CARBON

NECESSARY MATERIAL REPLACEMENT

4 - EXTERIOR CLADDING ELEMENTS

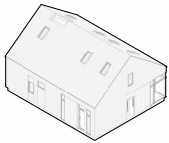
Eastern White Cedar Roofing Shingles x2
1,336 sq. ft. | 35-year service life

Solid Wood Trim x2
1.07 cu. ft. | 35-year service life

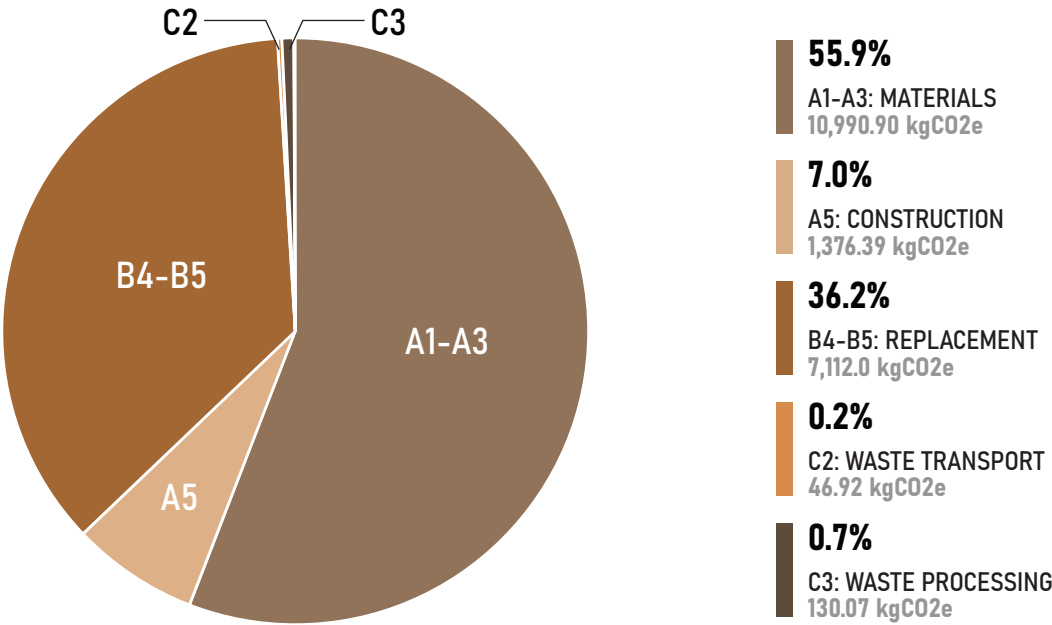
Eastern White Cedar Clapboard Siding x1
1,269 sq. ft. | 50-year service life

Cedar Shiplap Siding x1
175 sq. ft. | 50-year service life

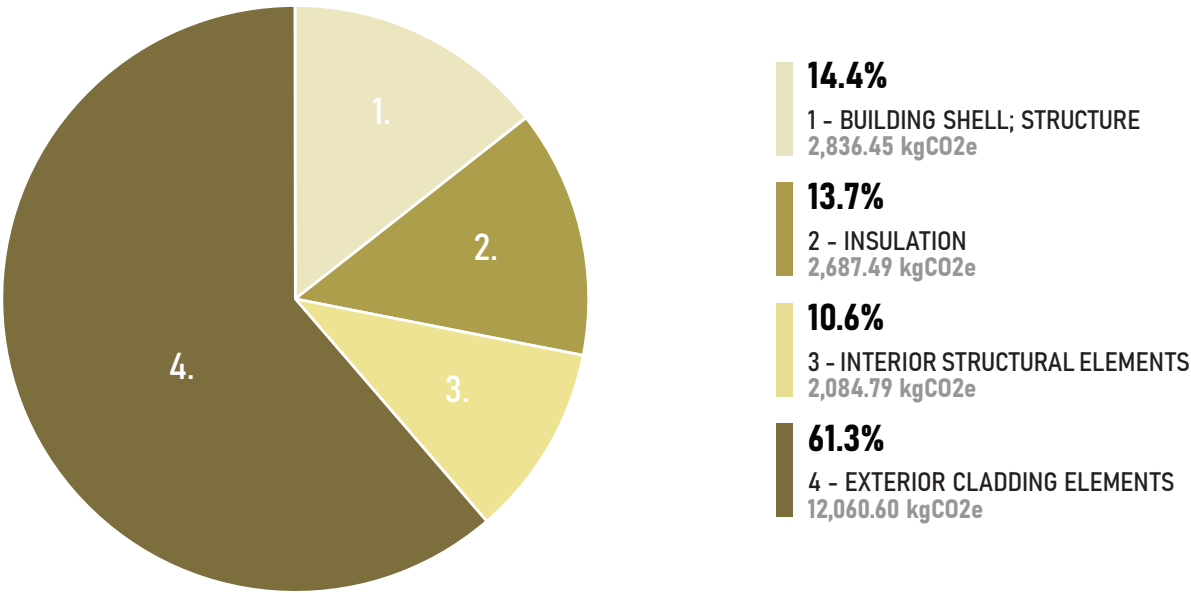
NOTE: Material service life periods include the full duration of its final year. Replacement would occur the following year.



CARBON CONTRIBUTION: LIFE-CYCLE STAGES



CARBON CONTRIBUTION: MATERIAL CLASSIFICATIONS



THE STANDARD-CONSTRUCTED HOUSE

After 100 years, the total contribution of embodied carbon from the necessary material replacement exceeds half of the home's overall emitted carbon. Exterior and interior elements have both been replaced multiple times in various amounts, with the home's wall & ceiling finishes being responsible for the most amount of carbon contribution in this case; at 38.6%. After 100 years, the total amount of emitted carbon is almost twice as much as its mass timber counterpart, at 34.41 tonnes CO₂.



34.41 TONNES
TOTAL CARBON

NECESSARY MATERIAL REPLACEMENT

4 - EXTERIOR CLADDING ELEMENTS

Eastern White Cedar Roofing Shingles x2
1,336 sq. ft. | 35-year service life

Solid Wood Trim x2
1.07 cu. ft. | 35-year service life

Eastern White Cedar Clapboard Siding x1
1,269 sq. ft. | 50-year service life

Cedar Shiplap Siding x1
175 sq. ft. | 50-year service life

5 - WALL & CEILING FINISHES

Interior Finish Paint x9
4,939 sq. ft. | 10-year service life

MDF Interior Base Trim x3
96 sq. ft. | 30-year service life

6 - FLOOR COVERINGS & FINISHES

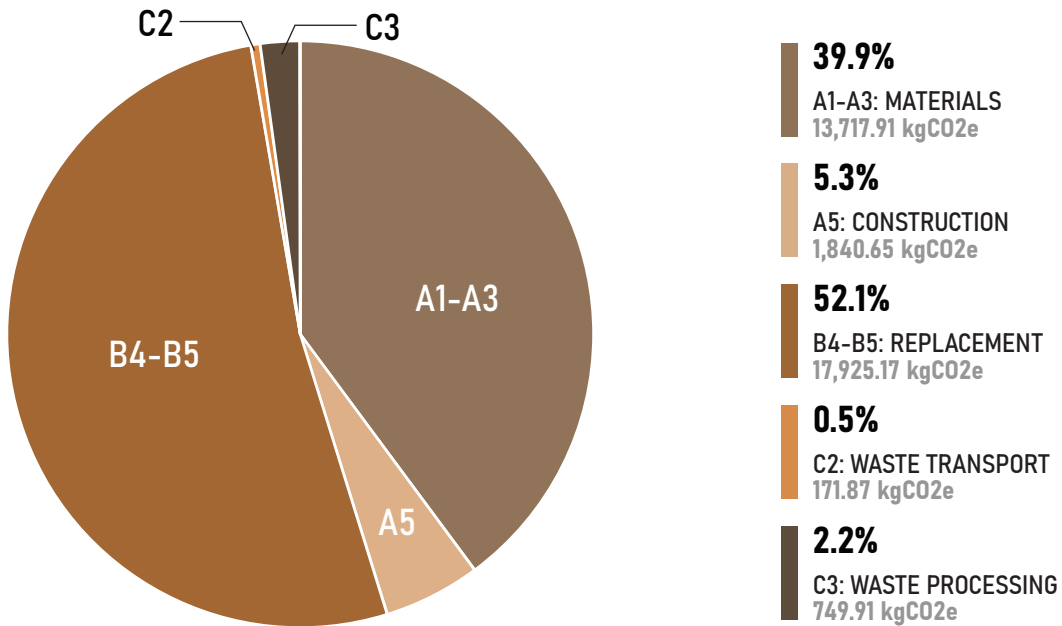
Interior Vinyl Flooring x3
2.17 cu. ft. | 25-year service life

Plastic Floor Underlayment x3
208 sq. ft. | 25-year service life

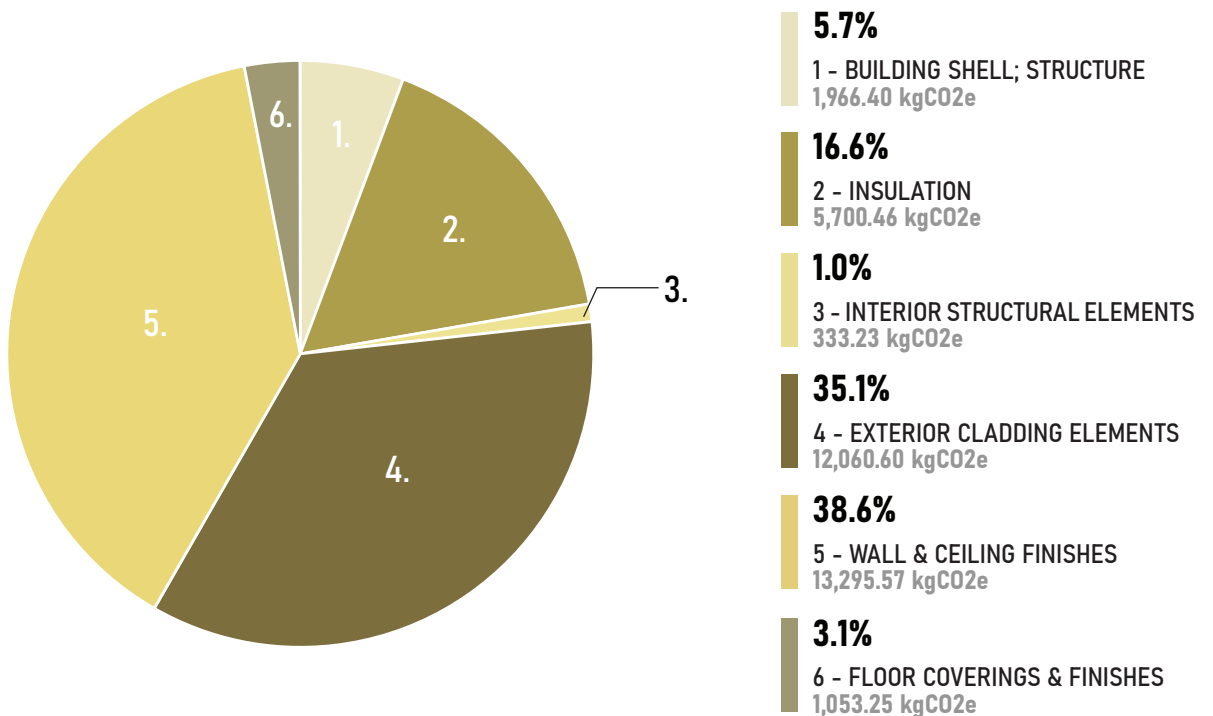
NOTE: Material service life periods include the full duration of its final year. Replacement would occur the following year.



CARBON CONTRIBUTION: LIFE-CYCLE STAGES



CARBON CONTRIBUTION: MATERIAL CLASSIFICATIONS



LONGTERM BIOGENIC CARBON EFFECT

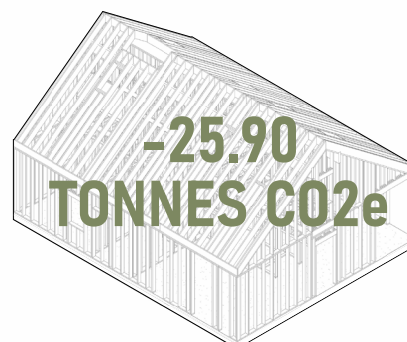
EFFECTIVENESS OF INITIAL BIOGENIC CARBON

Recalling the condition of biogenic carbon initially stored in each of the construction systems, these values were factored in to the results from the previous cradle-to-grave analyses.

While all three construction systems were considered to be net-negative in carbon emission at the start of their lives when considering each of their inherent biogenic carbon amounts, the typical modular home's total emitted carbon surpasses its biogenic carbon storage by year 30, and the standard-constructed house surpasses its own by year 60. Meanwhile, the mass timber home remains far below the net-negative carbon threshold even after 100 years. When considering the sequestering of carbon by biogenic materials, the results indicate the dramatic advantage that the mass timber house possesses in remaining a deterrent to climate change & global warming as opposed to a contributor to it.

After 100 years, the mass timber home's total net carbon has only increased from -54.11 tonnes to -45.49 tonnes of CO₂. What this suggests is that the mass timber construction system could quite possibly remain net-negative in overall carbon emission for another 400 years in perfect conditions. Meanwhile, the second-best contender, being the standard-constructed home, surpasses the net-zero carbon threshold after just 60 years.

INITIAL STORED BIOGENIC CARBON



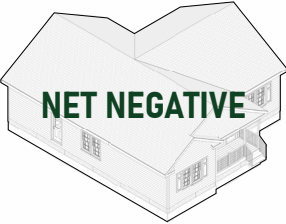
NET CARBON EMISSION OVER TIME (INCLUDING BIOGENIC CARBON)

YEAR 0

YEAR 30

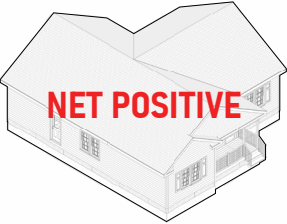
YEAR 60

YEAR 100



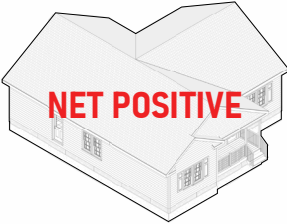
NET NEGATIVE

-10.68 TONNES CO₂e



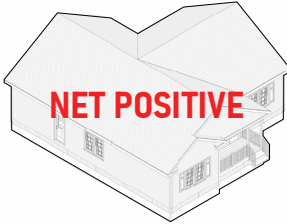
NET POSITIVE

+5.81 TONNES CO₂e



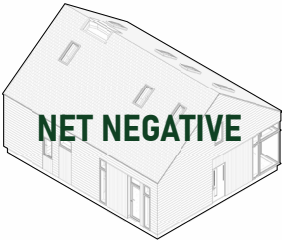
NET POSITIVE

+21.93 TONNES CO₂e



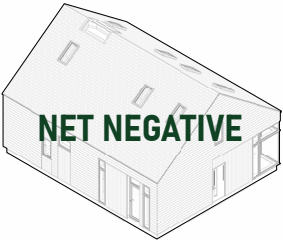
NET POSITIVE

+45.95 TONNES CO₂e



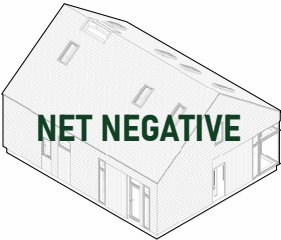
NET NEGATIVE

-54.11 TONNES CO₂e



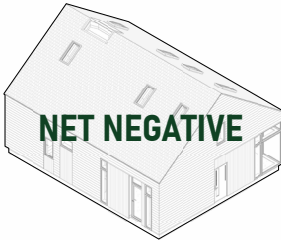
NET NEGATIVE

-52.56 TONNES CO₂e



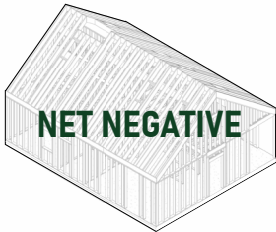
NET NEGATIVE

-48.43 TONNES CO₂e



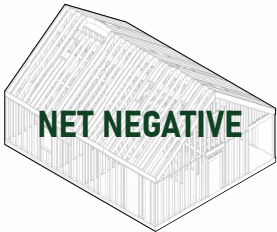
NET NEGATIVE

-45.49 TONNES CO₂e



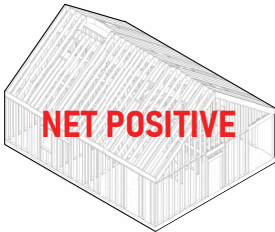
NET NEGATIVE

-12.18 TONNES CO₂e



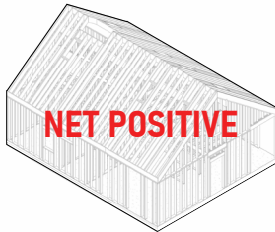
NET NEGATIVE

-7.14 TONNES CO₂e



NET POSITIVE

+0.59 TONNES CO₂e



NET POSITIVE

+8.51 TONNES CO₂e

** Values are a result of Initial Stored Biogenic Carbon factored in to Total Carbon Emissions by Year*

CONCLUSIVE RESULTS

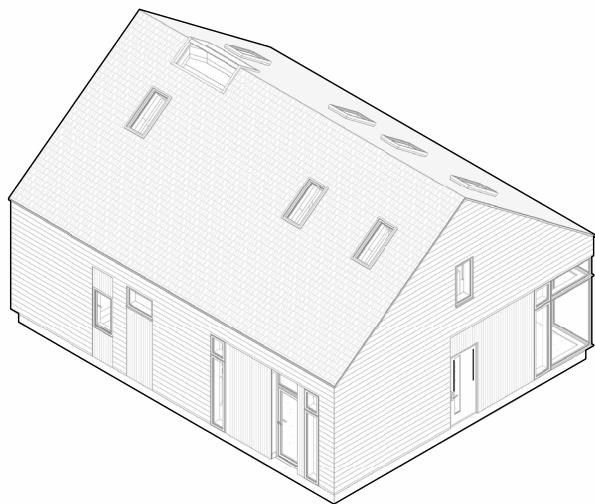
QUALITIES OF A BIOGENIC MASS TIMBER HOUSE

The characteristics of embodied and projected carbon emissions were explored in this section of the comparative analyses, which provides insight on the suggested degree at which each system contributes to global warming and environmental pressure.

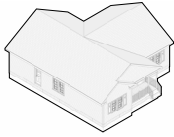
After conducting the various life cycle assessments, the evidence expressess that a biogenic mass timber house is significantly less carbon-intensive, and, when considering biogenic carbon, can effectively sequester cabon for a century or more. The lessened degree of material replacement—as well as the previously mentioned amount of mass of the construction system—suggests the greater

longevity in the overall lifespan of a mass timber home.

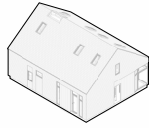
These studies also began to reveal the immense impact that the service-lives of materials play in the longrun for the overall carbon footprint of a construction system, which suggests the importance of longevity in material stocks. Both the typical modular house and standard-constructed house possessed carbon-intensive materials with short service-lives, which was a primary result of the interior finish materials of each system. This highlights the negative impact of the current conventional materials and finishes commonly associated with light-wood-frame construction.



LESS MATERIAL REPLACEMENT
LONGER LIFESPAN
CARBON-NEGATIVE FOR 100+ YEARS



VS



VS



THE TYPICAL MODULAR HOUSE

THE MASS TIMBER HOUSE

THE STANDARD CONSTRUCTED HOUSE

1,592 sq.ft.

1,110 sq.ft.

1,110 sq.ft.

Gross Square Footage

16.12 Tonnes CO₂e

10.99 Tonnes CO₂e

13.72 Tonnes CO₂e

Cradle-to-Gate (A1-A3)
Carbon Assessment

-26.80 Tonnes CO₂e

-65.10 Tonnes CO₂e

-25.90 Tonnes CO₂e

Initial Biogenic Carbon
Storage

32.61 Tonnes CO₂e

12.54 Tonnes CO₂e

18.76 Tonnes CO₂e

Cradle-to-Grave
Assessment, 30 Years

48.73 Tonnes CO₂e

16.67 Tonnes CO₂e

26.49 Tonnes CO₂e

Cradle-to-Grave
Assessment, 60 Years

72.75 Tonnes CO₂e

19.61 Tonnes CO₂e

34.41 Tonnes CO₂e

Cradle-to-Grave
Assessment, 100 Years

5.81 Tonnes CO₂e

-52.56 Tonnes CO₂e

-7.14 Tonnes CO₂e

Cradle-to-Grave with
Biogenic Carbon,
30 Years

21.93 Tonnes CO₂e

-48.43 Tonnes CO₂e

0.59 Tonnes CO₂e

Cradle-to-Grave with
Biogenic Carbon,
60 Years

45.95 Tonnes CO₂e

-45.49 Tonnes CO₂e

8.51 Tonnes CO₂e

Cradle-to-Grave with
Biogenic Carbon, 100
Years





THERMAL PERFORMANCE

OVERVIEW

ANALYSIS SUMMARY

As the last section of comparative analyses, the thermal analysis section provides a brief assessment into the characteristics and conditions of each construction system's efficiency in holding heat within its enclosure. The thermal performance of a home directly effects attributes such as occupant comfort, heating and cooling demands, and energy demands that translate to energy costs.

In this section, the study utilizes softwares such as THERM and WUFI®Passive to assess qualities such as heat transmission through each system's general enclosure assemblies, heating and energy demands, as well as realized thermal resistance values of the general assemblies. Air-tightness values, as well as industry R-values for materials had to be designated for each construction system, and was done in a manner to be best representative of an average condition for each.

1. THERMAL RESISTANCE VALUES

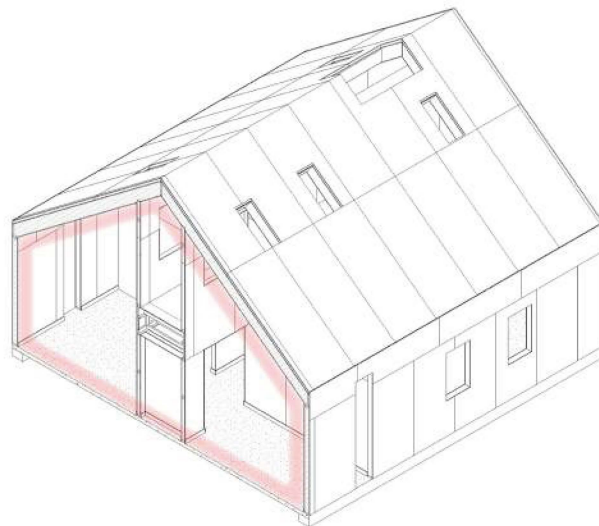
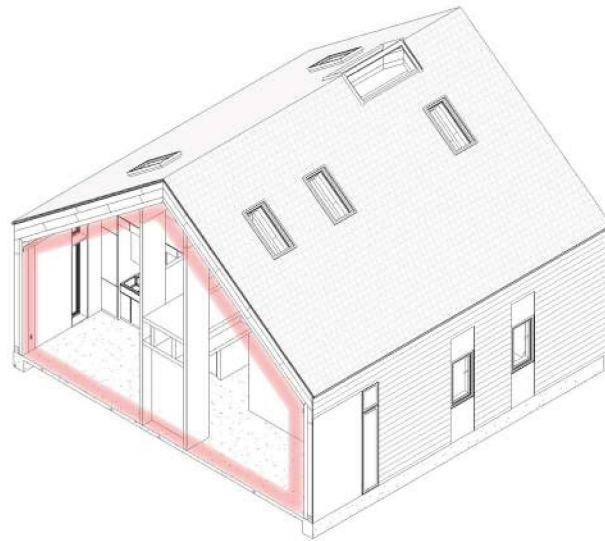
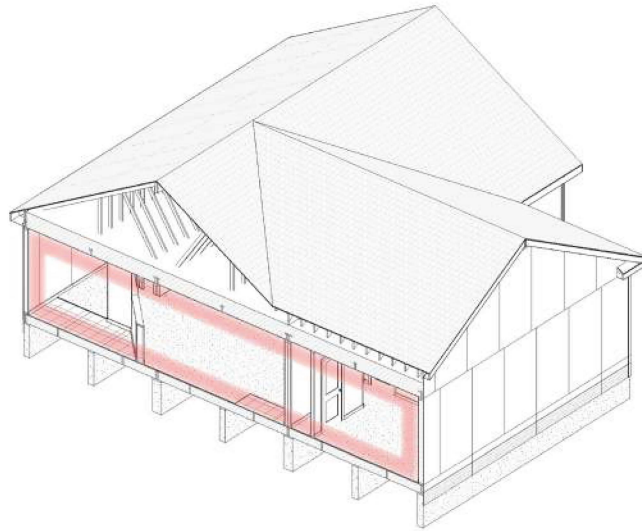
Analysis of the realized values for thermal ristance (R-value) across each system's general assembly conditions.

2. HEAT TRANSMISSION

Analysis of temperature gradients and the presence of thermal bridges across each system's general assembly conditions.

3. ENERGY ANALYSIS

Analysis of total heating & cooling demands and loads with each construction system, as well as energy demands.

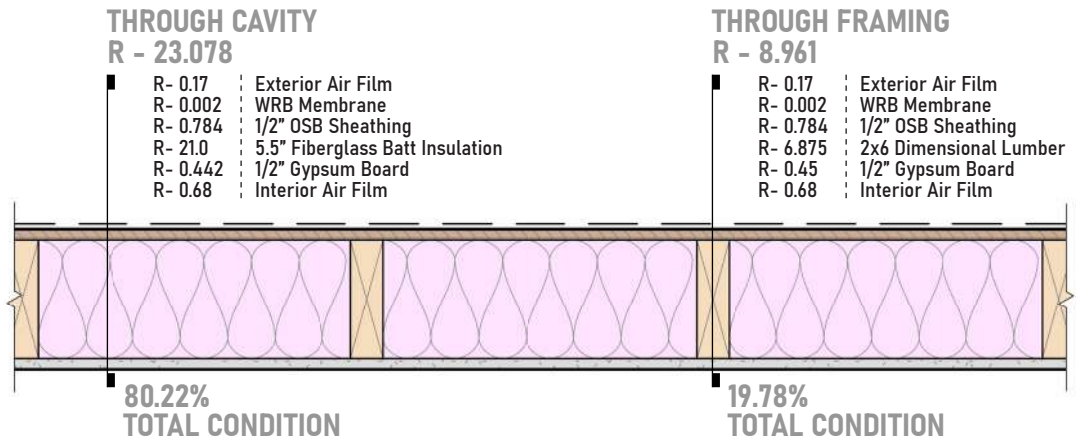
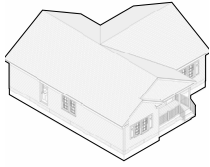


THERMAL RESISTANCE VALUES

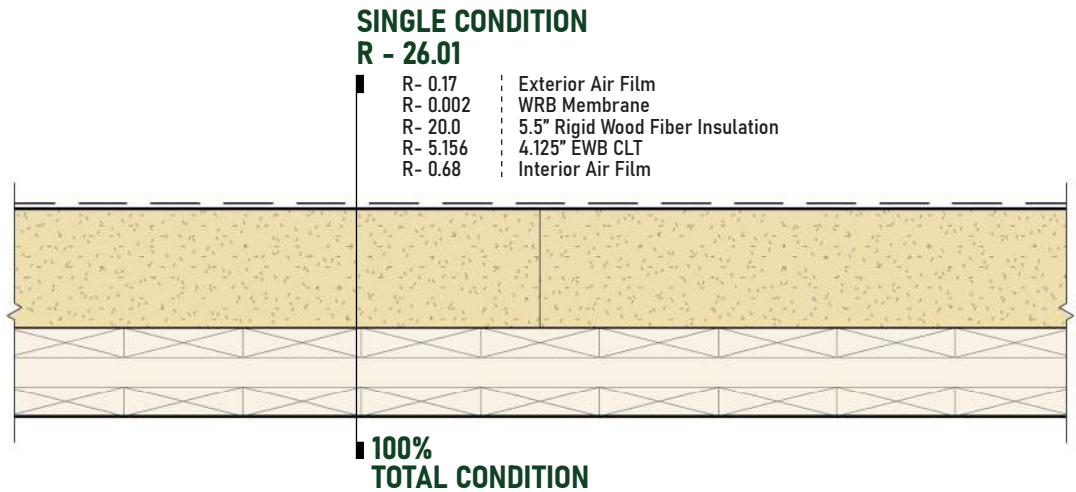
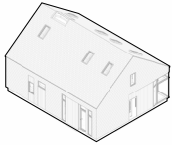
GENERAL-CONDITION WALL ASSEMBLIES

The thermal layers of the general wall and roof assemblies of each construction system was assessed to determine their true thermal resistance values, or R-values. In light-wood-frame constructed homes, the wood framing is situated within the same assembly layer of where the insulation is in a home. What this results in is a condition in which there is not any insulation-classified material between the interior and the outdoors wherever there is a framing element such as a stud in the exterior wall; unless additional insulation is installed outboard to the structure. What this results in is two different thermal-resistance value conditions within the same wall of a light-wood-frame constructed home, where the one value is taken through the cavity insulation, and the other taken through the wooden stud.

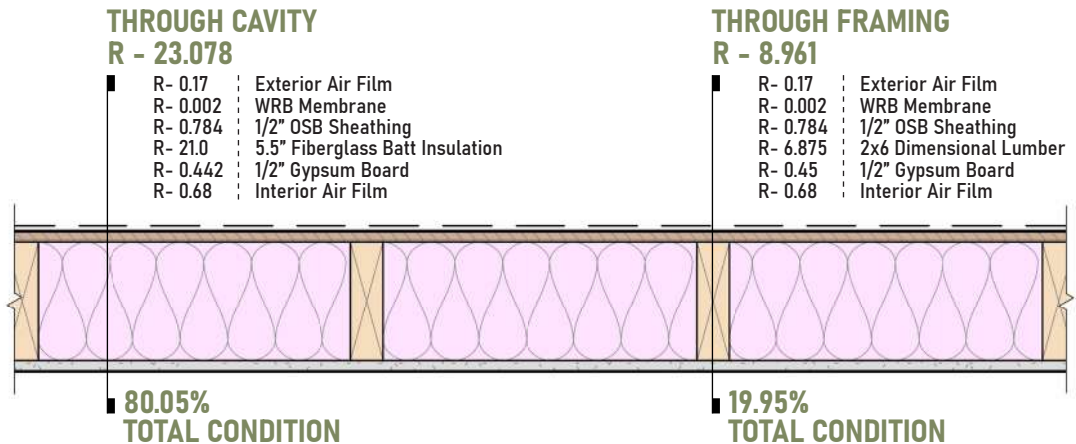
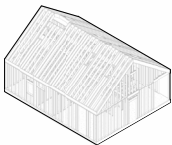
Referring to the two light-wood-frame construction systems, it can be seen how the true R-value of each assembly is actually lower than what they may be rated as, when considering the overall contribution of the two conditions to the whole wall or roof. The mass timber house assembly, on the other hand, only contains a single condition as a result of the solid panel system requiring that the insulation of the home be its own separate layer outboard to the structure.



R-20.29 REALIZED THERMAL RESISTANCE



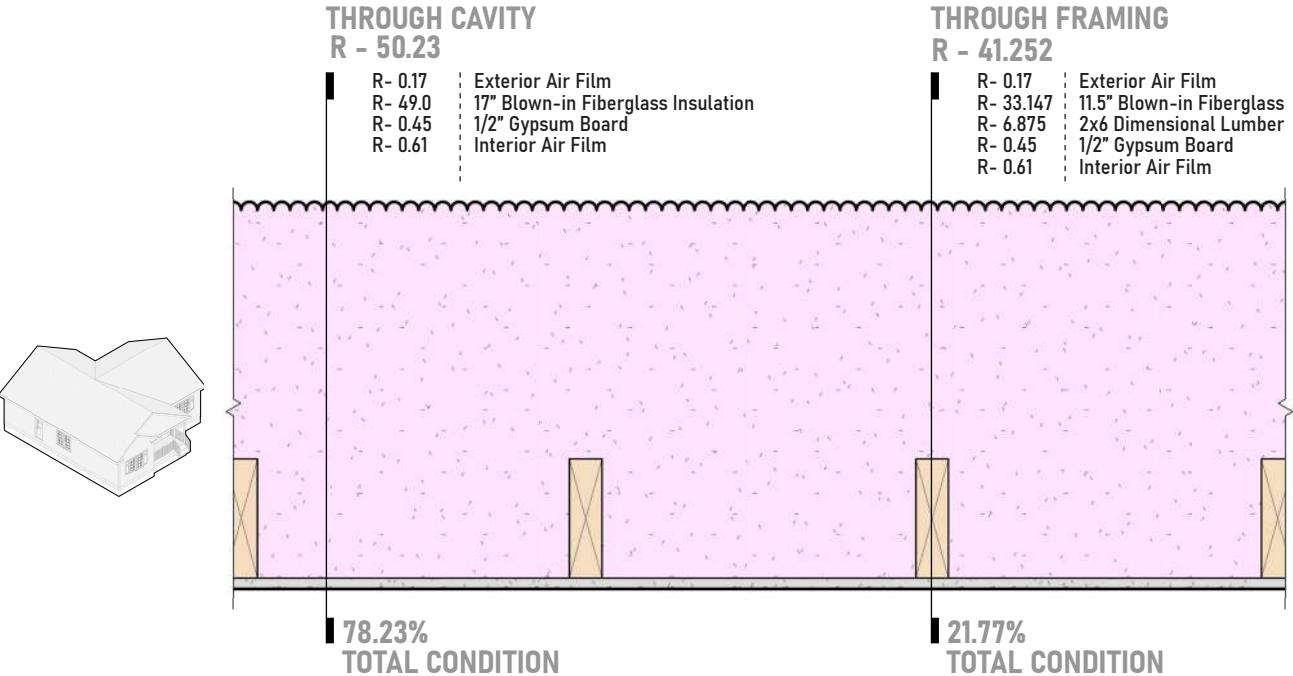
R-26.01 REALIZED THERMAL RESISTANCE



R-20.26 REALIZED THERMAL RESISTANCE

GENERAL-CONDITION ROOF ASSEMBLIES

Within the roof conditions, the same general trends of realized thermal performance remain, where the two light-wood-frame construction systems contain two thermal-resistance conditions within the general assembly, and the mass timber house contains only one as a result of the continuous panelized system. In the standard-constructed house, the addition of 2" XPS rigid insulation was required to meet the designated R-49 roof thermal resistance requirement. However, after weighted assessment, the true R-value is still projected to be lower than this amount.



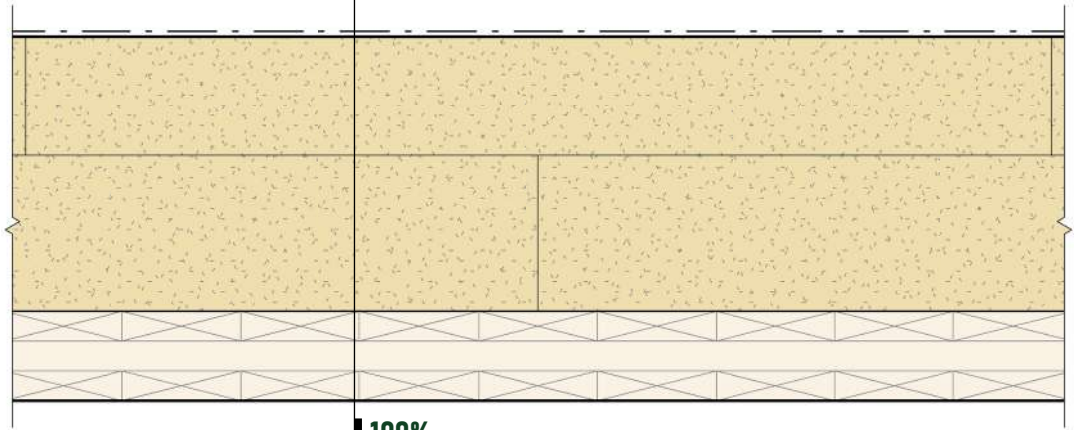
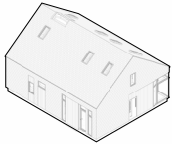
R-48.28 REALIZED THERMAL RESISTANCE

R-Values Source: Grondzik, Walter T., and Alison G. Kwok. *Mechanical and Electrical Equipment for Buildings*, John Wiley & Sons, Incorporated, 2019.

SINGLE CONDITION

R - 51.948

R- 0.17	Exterior Air Film
R- 0.002	WRB Membrane
R- 20.0	5.5" Rigid Wood Fiber Insulation
R- 26.0	7.25" Rigid Wood Fiber Insulation
R- 5.156	4.125" EWB CLT
R- 0.62	Interior Air Film



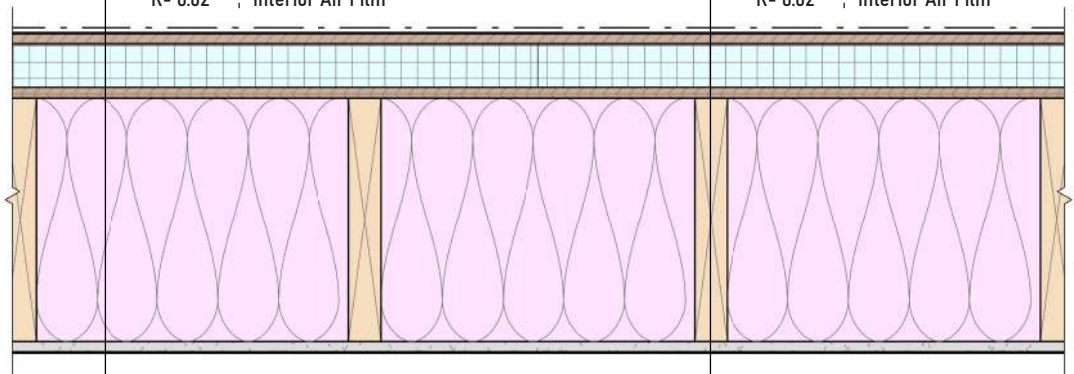
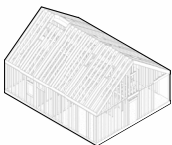
**100%
TOTAL CONDITION**

**R-51.95
REALIZED THERMAL RESISTANCE**

THROUGH CAVITY

R - 49.482

R- 0.17	Exterior Air Film
R- 0.002	Roof Underlayment
R- 0.62	1/2" OSB
R- 10.0	2" XPS Rigid Foam Board
R- 0.62	1/2" OSB
R- 37.0	11.25" Fiberglass Batt Insulation
R- 0.45	1/2" Gypsum Board
R- 0.62	Interior Air Film



**85.19%
TOTAL CONDITION**

THROUGH FRAMING

R - 26.545

R- 0.17	Exterior Air Film
R- 0.002	Roof Underlayment
R- 0.62	1/2" OSB
R- 10.0	2" XPS Rigid Foam Board
R- 0.62	1/2" OSB
R- 14.063	11.25" Fiberglass Batt Insulation
R- 0.45	1/2" Gypsum Board
R- 0.62	Interior Air Film

**14.81%
TOTAL CONDITION**

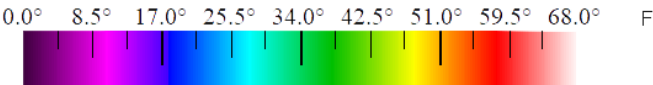
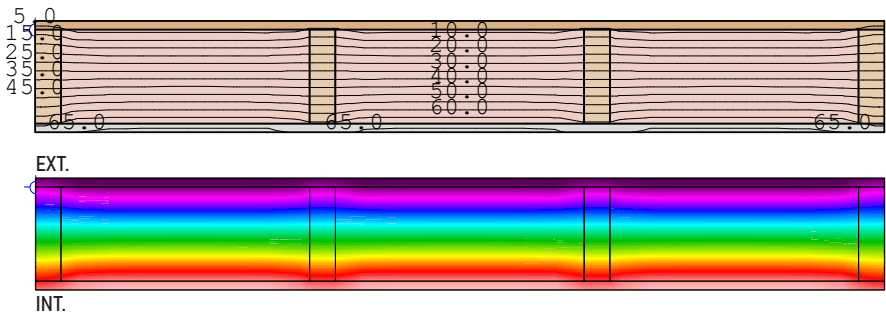
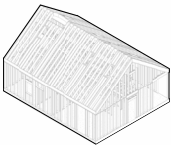
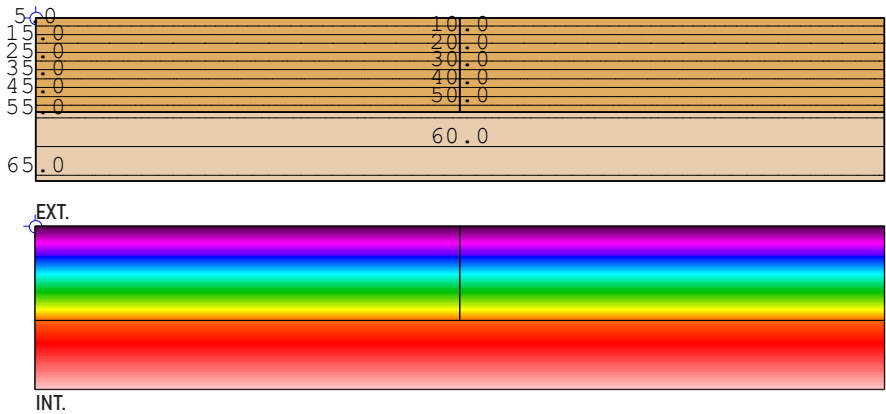
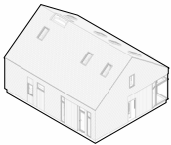
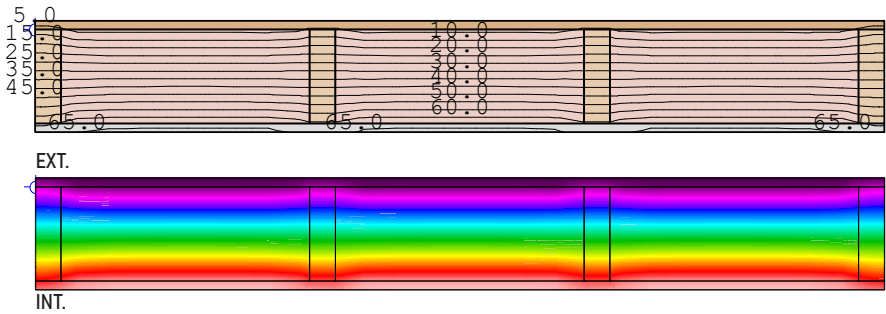
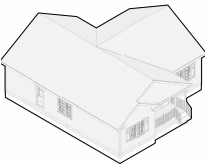
**R-46.09
REALIZED THERMAL RESISTANCE**

HEAT TRANSMISSION

TEMPERATURE ACROSS ASSEMBLIES

The next portion of the thermal analyses looks into the characteristics of heat flow across each construction system's general building assemblies. Utilizing THERM software, the systems are assessed of the temperature gradients across their assemblies, as well as for the existence of thermal bridges. The first analyses depict the temperature gradient across each construction assembly, from indoors to outdoors. A consistent gradient with no deviation is the ideal condition to have in a wall assembly, which would indicate that the assembly is thermally consistent with out thermal bridges.

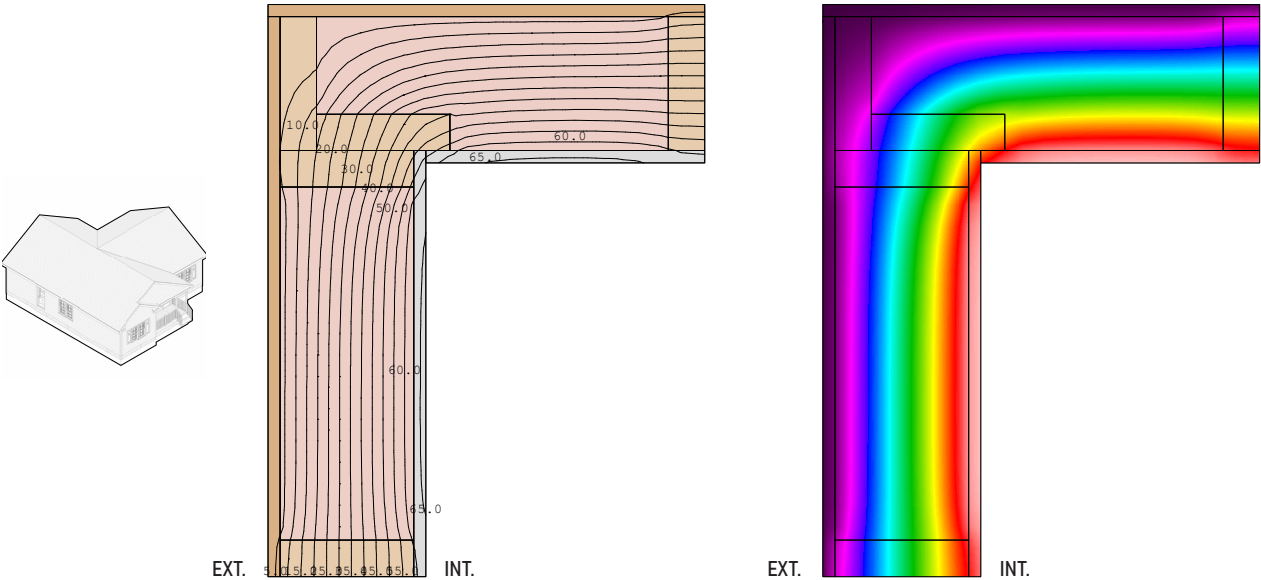
ASSEMBLY TEMPERATURE GRADIENT - GENERAL WALLS



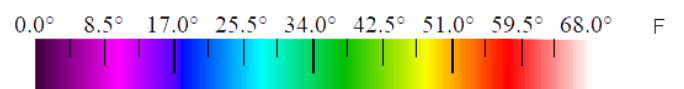
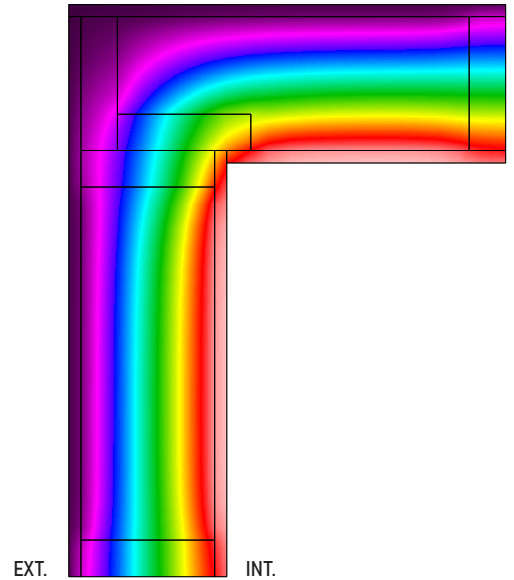
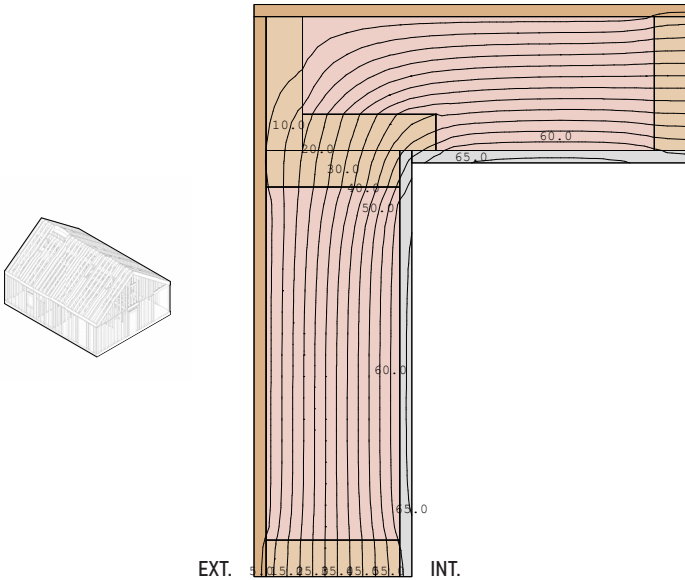
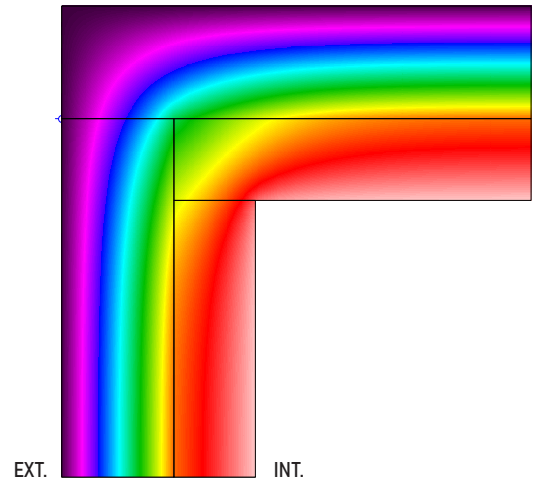
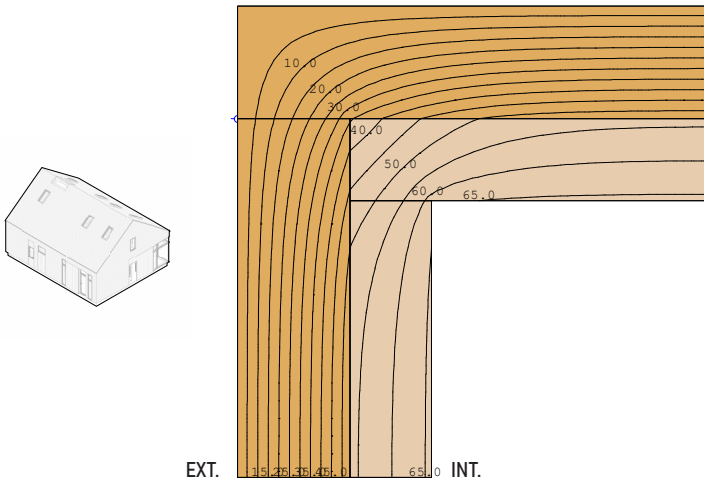
Data Source: THERM Finite Element Simulator, 7.8

ASSEMBLY TEMPERATURE GRADIENT : WALL CORNERS

As revealed in the previous general wall conditions, as well as these wall corner conditions, the two light-wood-frame construction systems have an inconsistent temperature gradient, where relative “thicknesses” of the color bars bulge wherever there is a framing element. This indicates a potential thermal bridge.

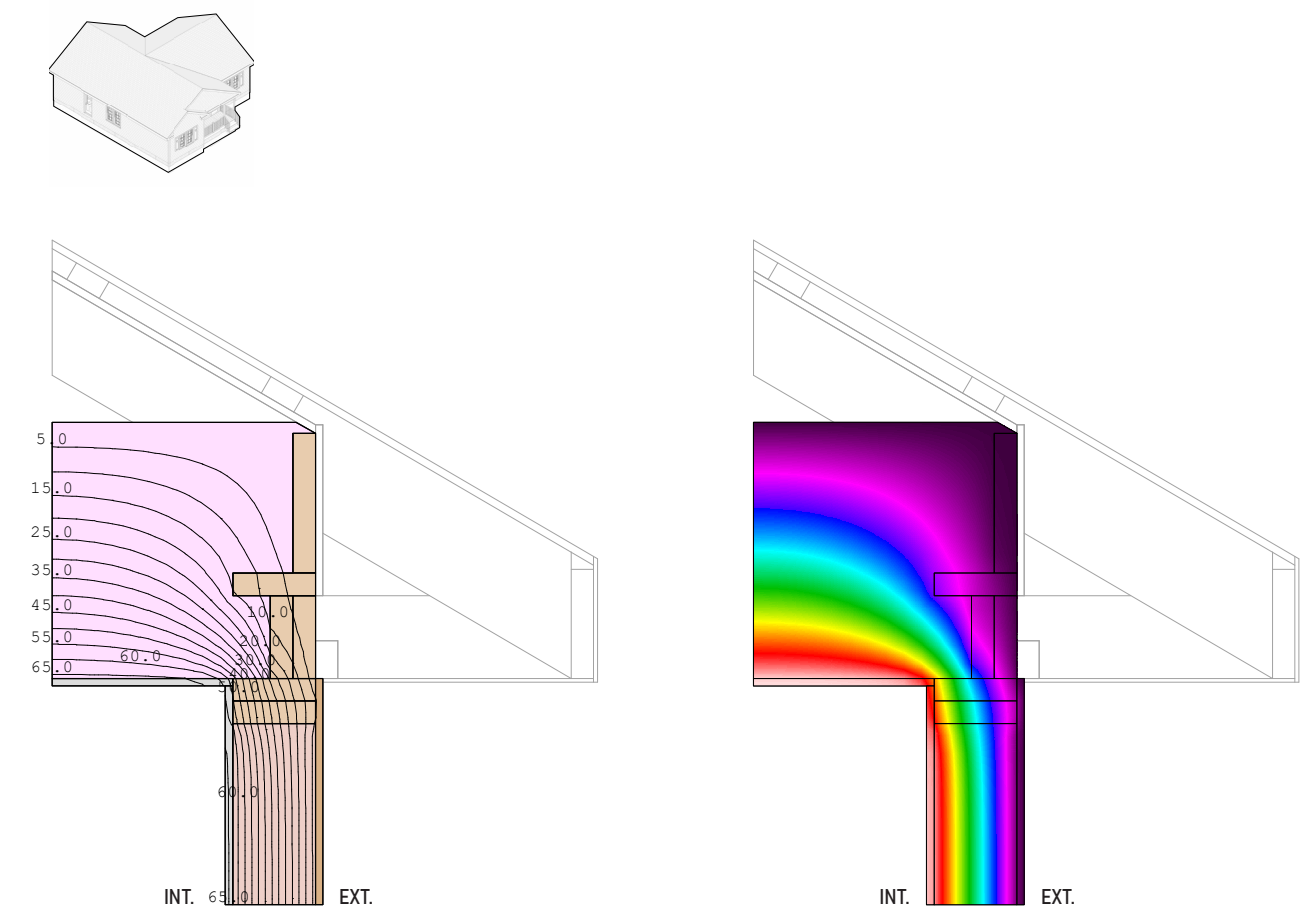


Data Source: THERM Finite Element Simulator, 7.8

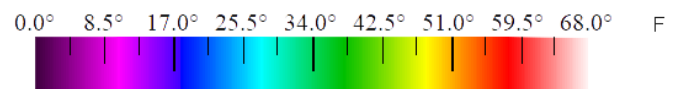
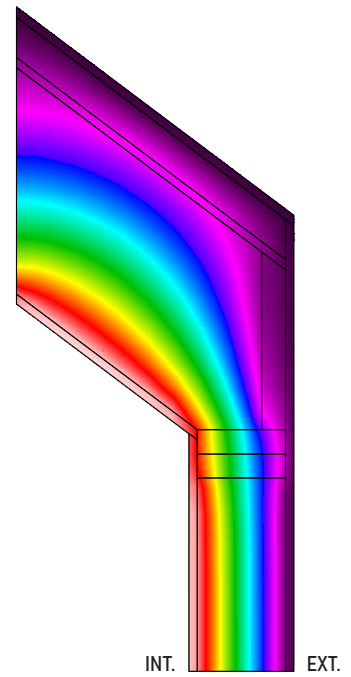
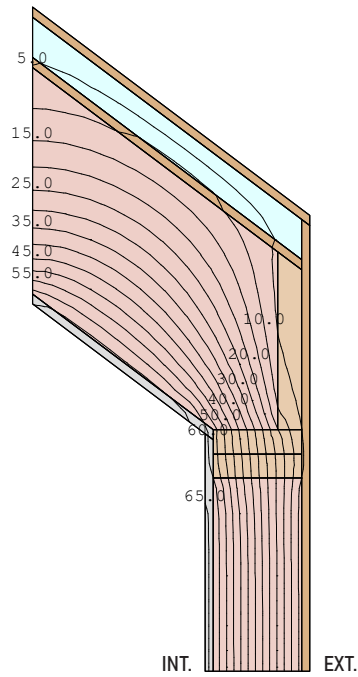
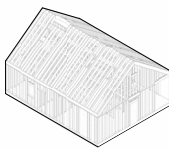
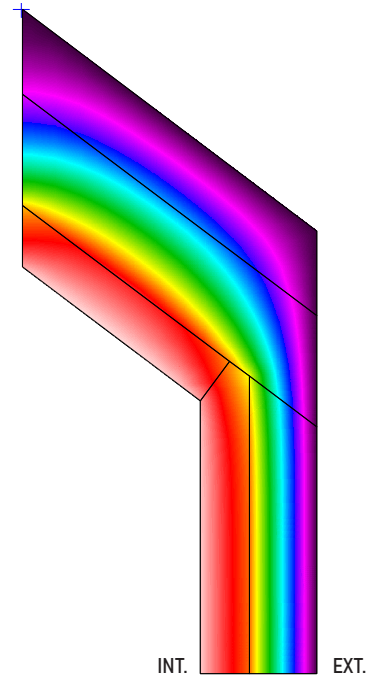
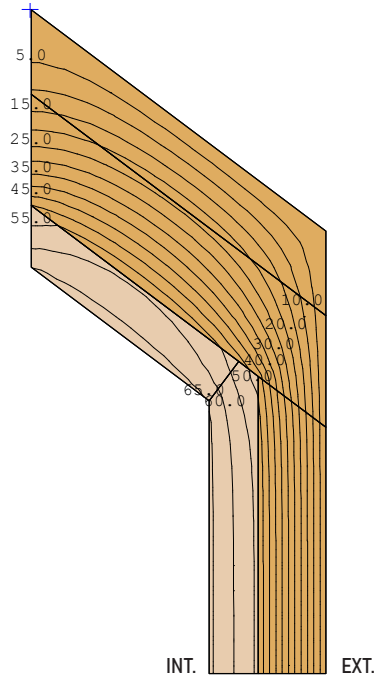
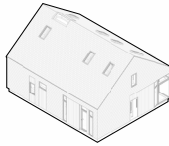


ASSEMBLY TEMPERATURE GRADIENT : WALL-TO-ROOF INTERFACE

In the Wall-to-Roof interfaces, the same relative conditions remain—where the two light-wood-frame assemblies have a relative anomaly in their temperature gradients at the framing location between the interior and exterior. The mass timber construction system remains consistent.



Data Source: THERM Finite Element Simulator, 7.8



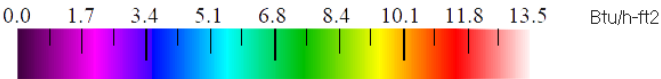
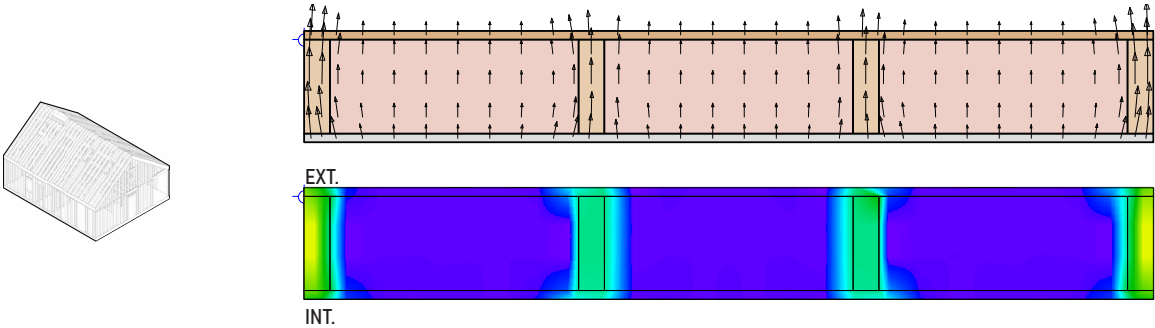
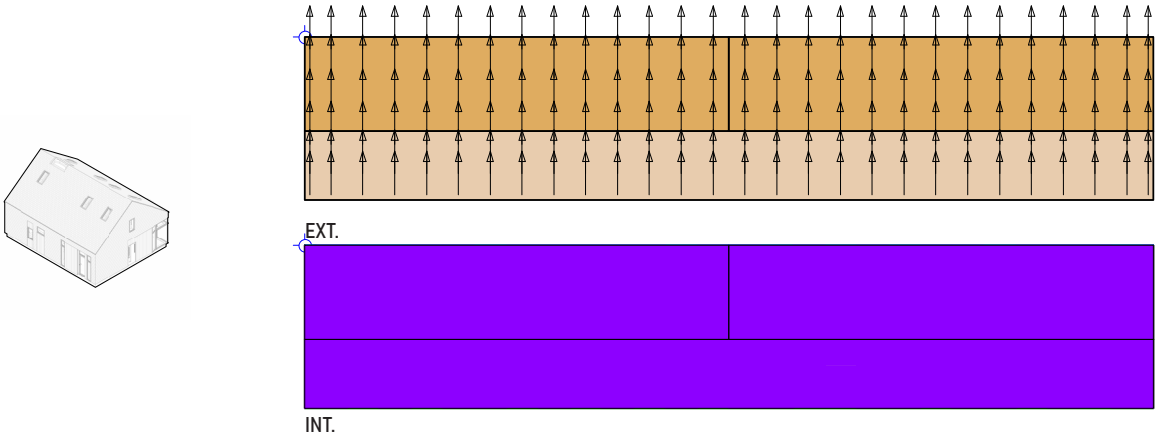
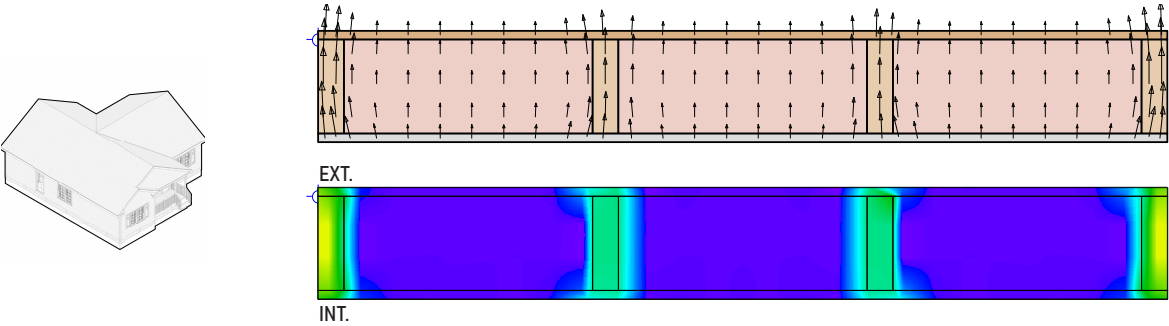
HEAT FLOW AND BRIDGING POTENTIAL

Thermal bridging in an assembly is when heat is actively transferred between the inside and outdoors through elements in the assembly that conduct heat, and are not thermally-buffered from the other assembly materials. Displayed here through heat-flux vectors and thermal imaging, the heat inside the two light-wood-frame construction systems is channeled from the interior to the exterior through the framing elements. This is a thermal bridge, and equates to the need to constantly heat a home in the winter for instance, in order to make up for the heat that is constantly being lost through this conduction.

As shown in the general wall assemblies, a direct thermal bridge exists through the framing elements of the two light-wood-frame construction systems. Meanwhile, there is no thermal bridge in the mass timber house's wall assembly.

* It is important to address, however, that all three construction assemblies would possess some degree of thermal bridging through steel fasteners within the exterior walls and roof if they were considered.

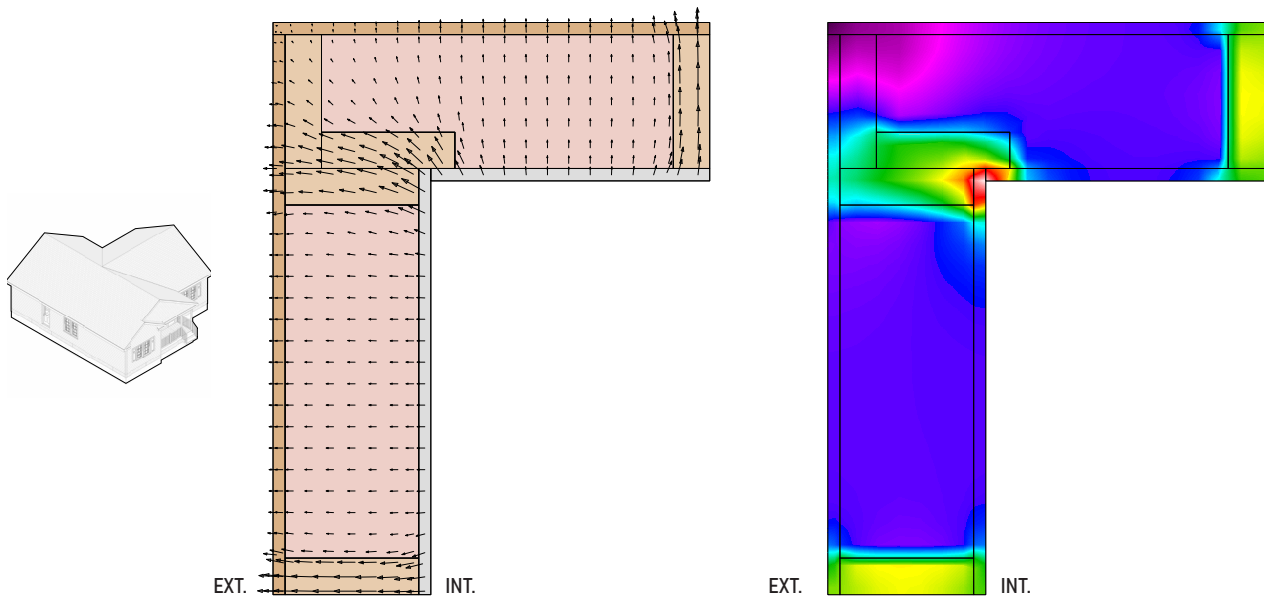
ASSEMBLY HEAT TRANSMISSION - GENERAL WALLS

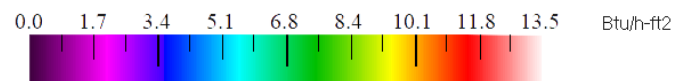
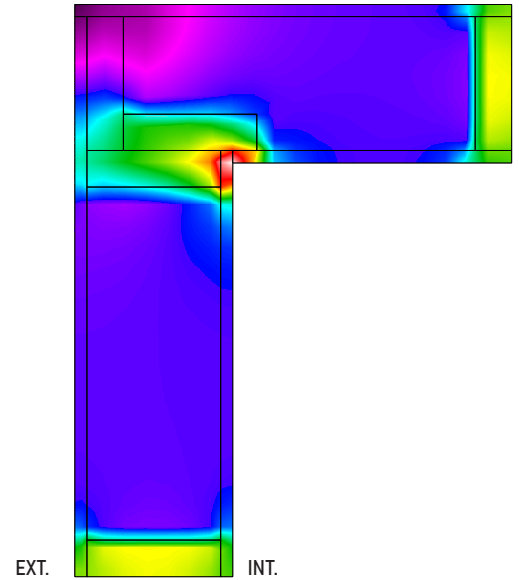
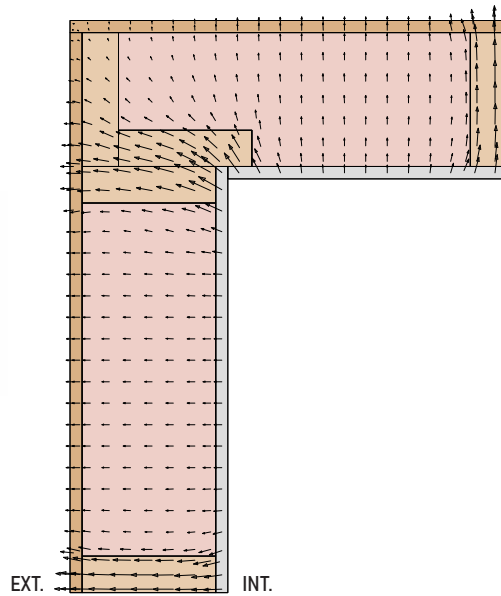
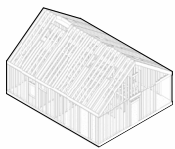
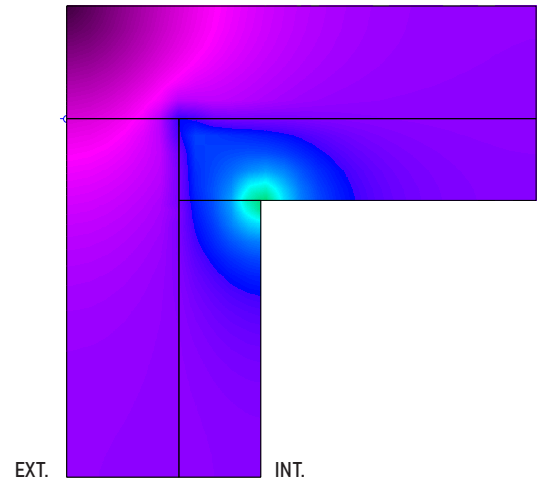
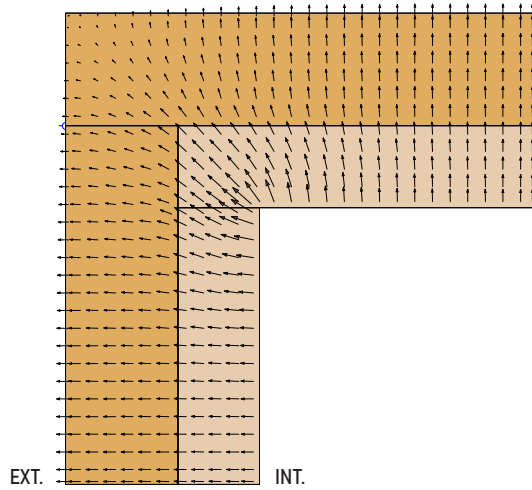
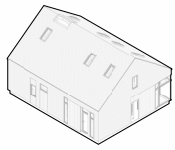


Data Source: THERM Finite Element Simulator, 7.8

ASSEMBLY HEAT TRANSMISSION : WALL CORNERS

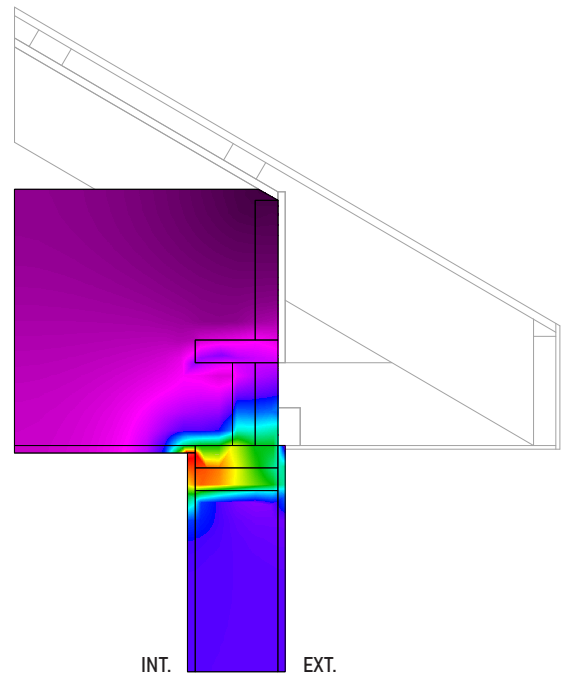
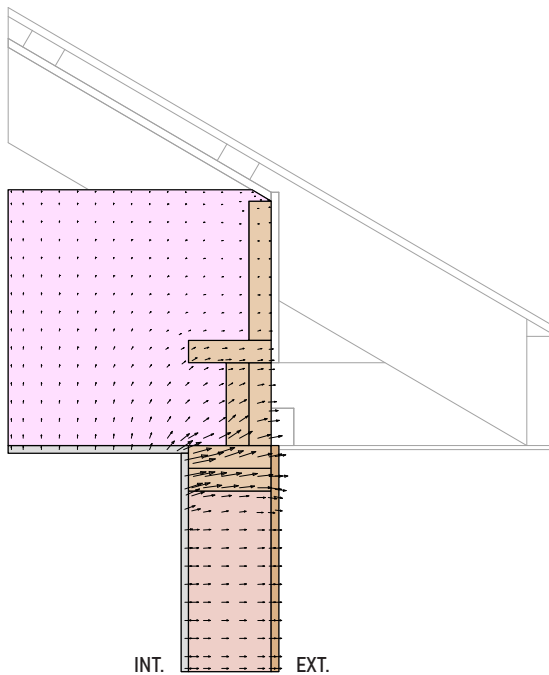
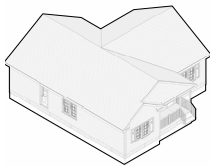
The corner conditions reveal a stronger degree of thermal bridging at the framing elements at the corner, within the two light-wood-frame construction systems. While some heat is also absorbed into the corner of the mass timber construction system, the heat flow is regulated before it reaches the exterior, thus not creating a thermal bridge.

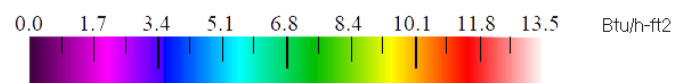
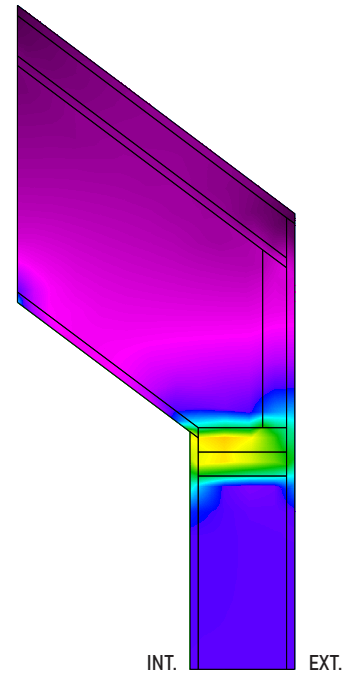
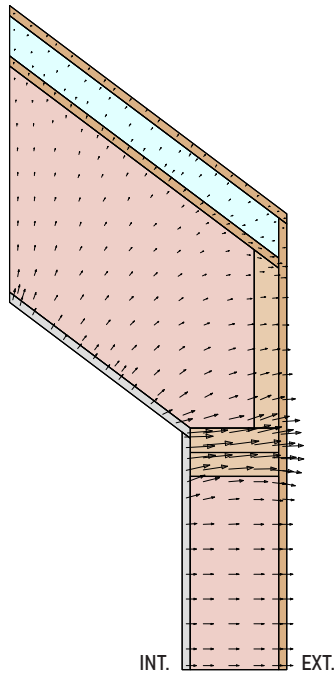
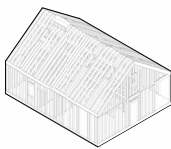
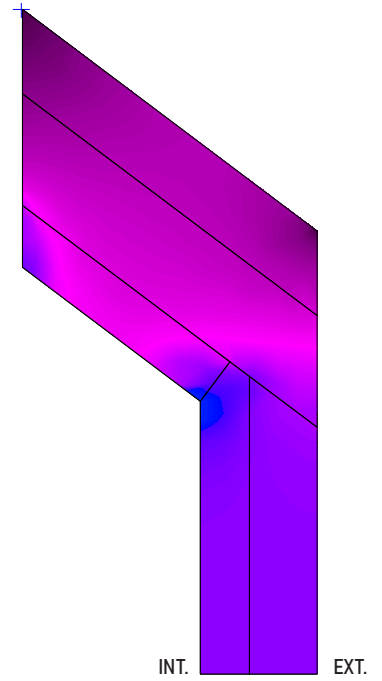
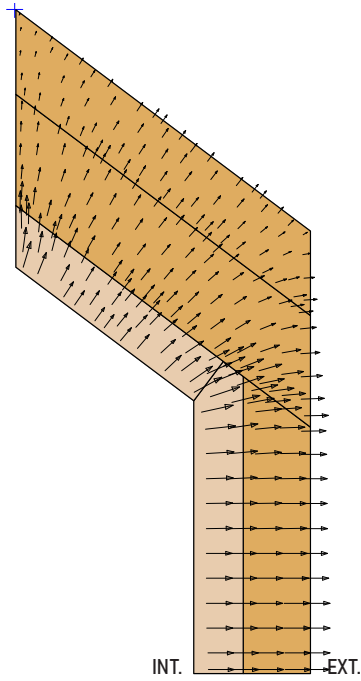
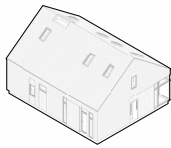




ASSEMBLY HEAT TRANSMISSION : WALL-TO-ROOF INTERFACE

Within the Wall-to-Roof interface, thermal bridges exist at this junction within the typical modular house and the standard-constructed house.





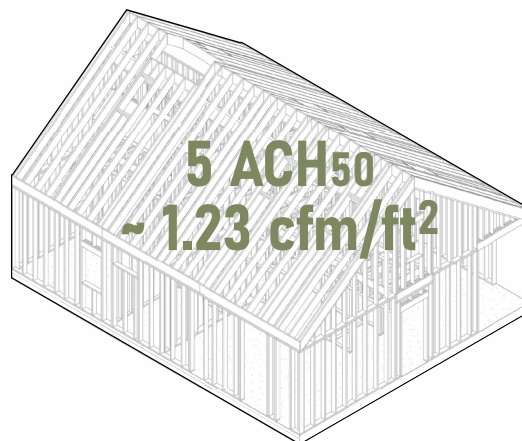
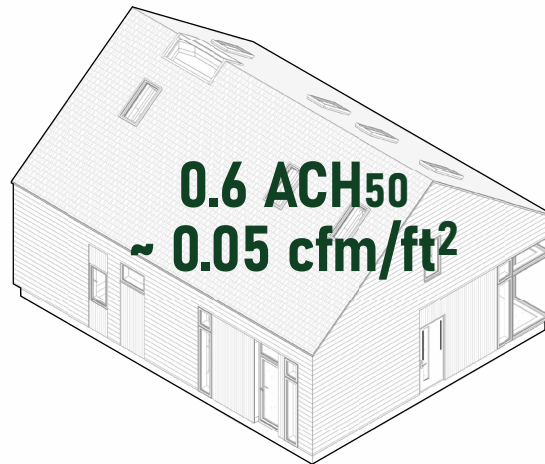
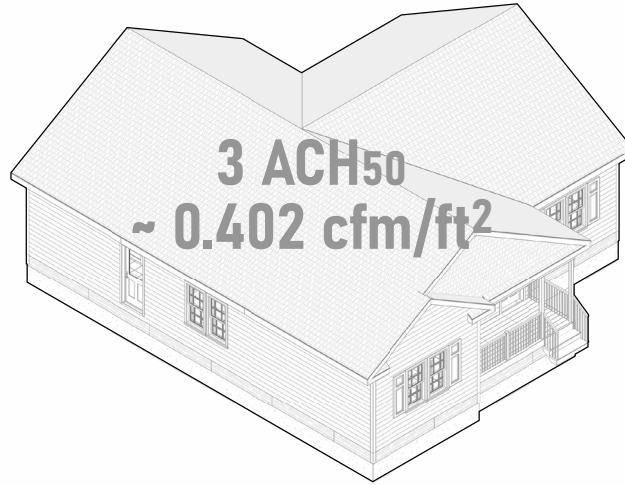
ENERGY ANALYSIS

OVERVIEW

As the last stage of thermal analysis, WUFI®Passive software was utilized to calculate metrics for each system's heating and cooling demands, as well as energy demand. This required that a specific air-tightness value be designated for each construction system. The industry explains that the average air-tightness of a newly constructed home is anywhere between 3 and 7 air changes per hour at 50 pascals. Considering that a modular home is fabricated in a controlled setting, the typical modular house was given the lowest end of this average. Since the standard-constructed home would be constructed in the field, it was given the average value of this range. As for the mass timber house, which is a panelized system with few seams and a continuous air barrier throughout the assembly to follow Passive House principles, it was given the maximum allowable Passive House airtightness of 0.6 ACH.

Within WUFI®Passive, all parameters besides the air-tightness, assembly materials, and thermal bridges were assigned with the same values and items to be constant across the three construction systems.

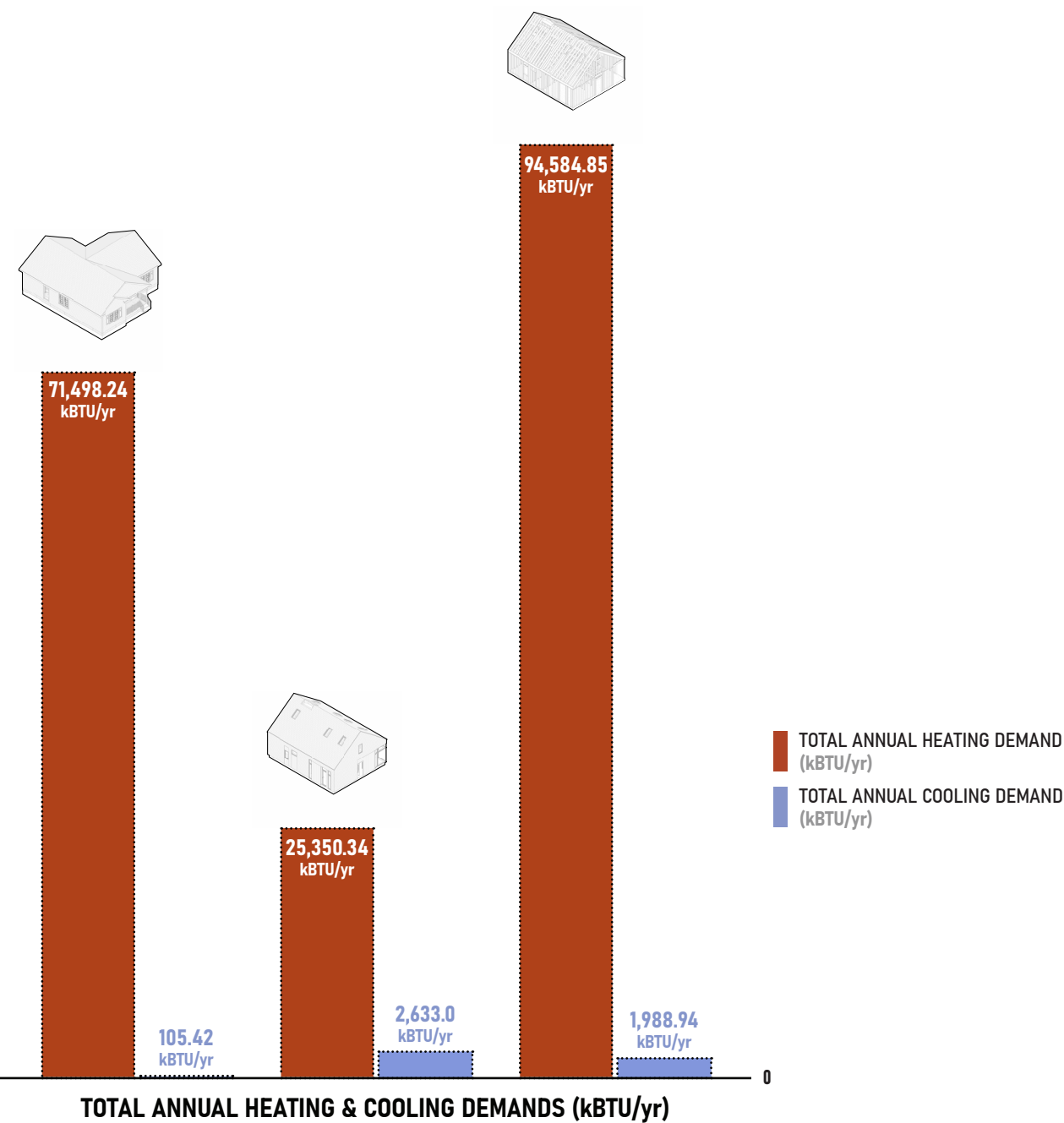
DESIGNATED AIR TIGHTNESS (ACH₅₀)



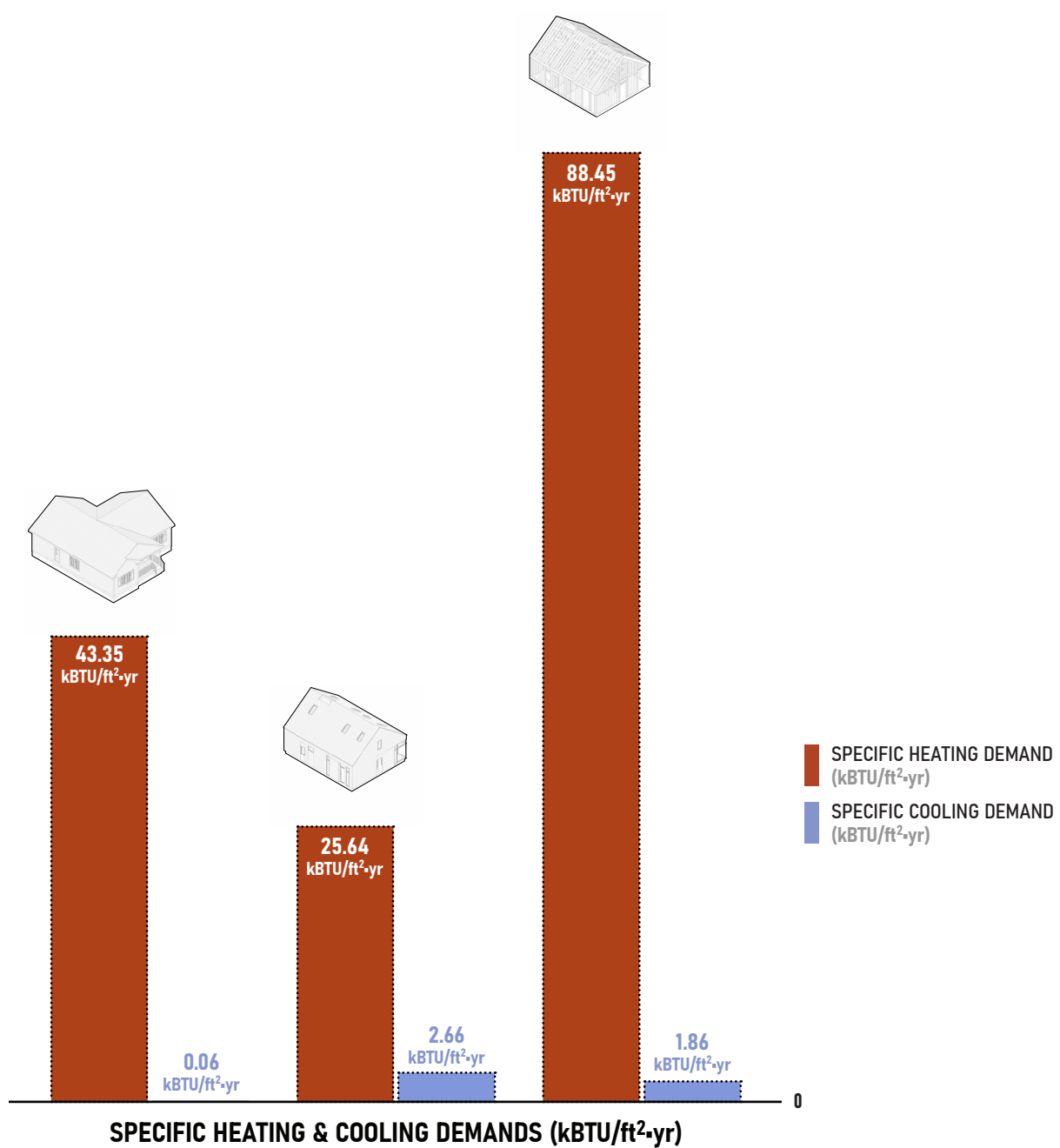
HEATING AND COOLING DEMAND

The following graphs depict the annual and specific heating and cooling demands of each of the construction systems. As the climate zone is widely a heating-dominated climate, the heating demands are much more significant than the

cooling demands. The specific heating and cooling demand considers the demand per square foot, which negates the penalty that the typical modular has for being of larger overall area. Either way, the standard-constructed house has the most demand.



Data Source: WUFI Passive 3.5, Fraunhofer IBP

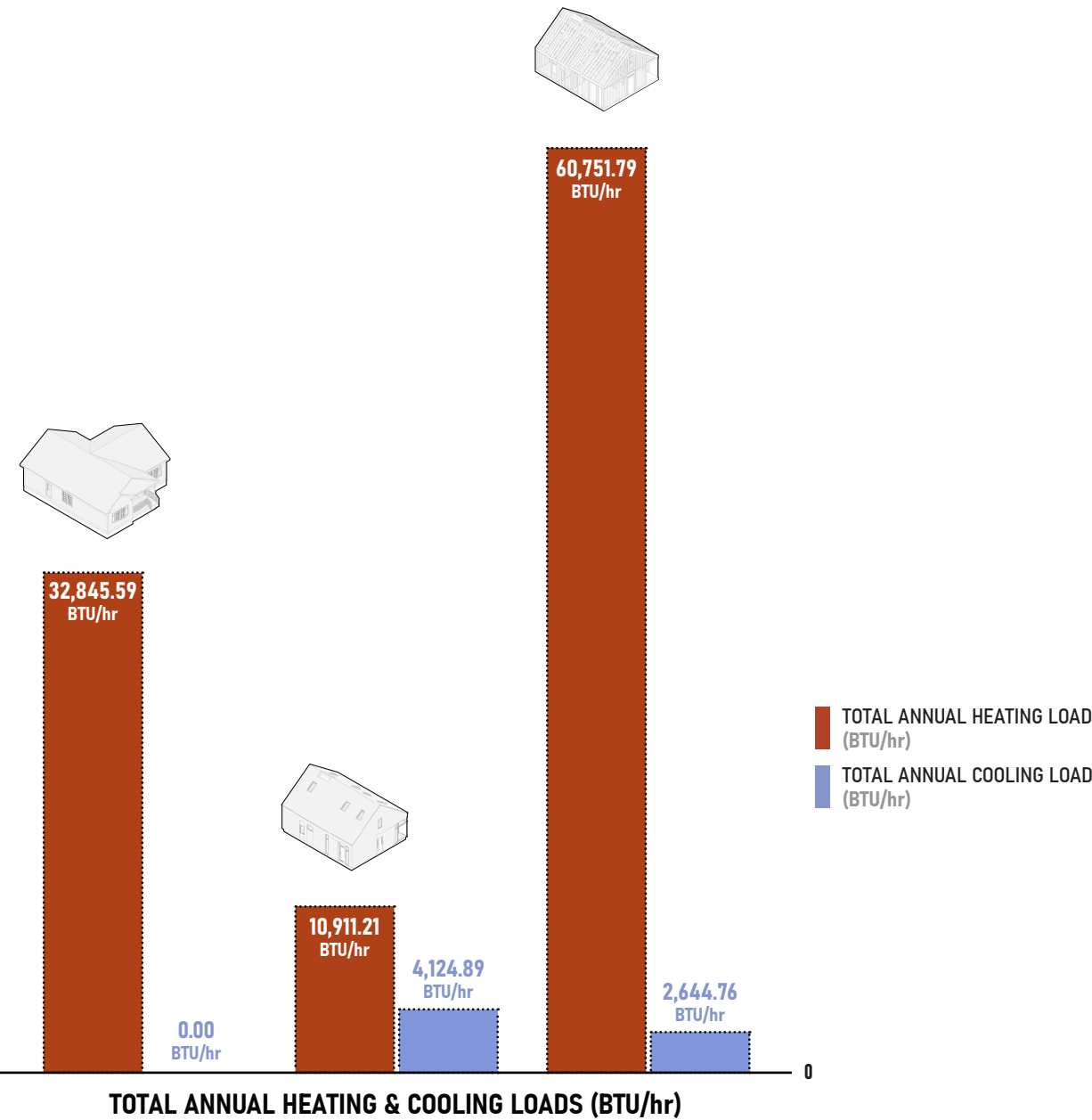


Data Source: WUFI Passive 3.5, Fraunhofer IBP

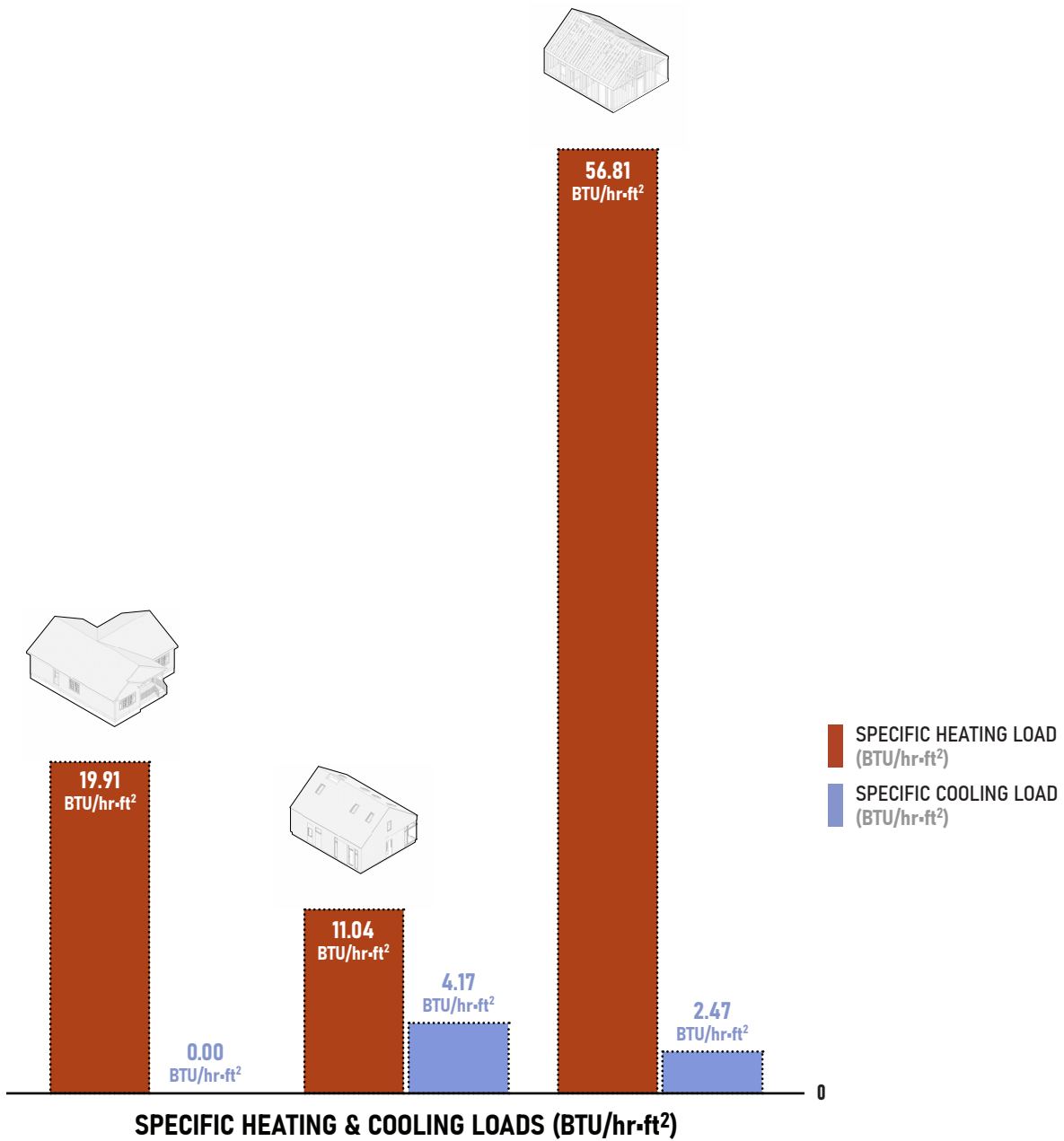
HEATING AND COOLING LOADS

In terms of annual and specific heating & cooling loads, the same trends seen in the annual demands exist. The mass timber house in both conditions possesses the least amount of overall demands and loads. However, in terms of cooling loads, it

does possess the largest cooling load—which is a result of its air-tightness combined with the amount of glazing in the design that would allow solar heat gain.



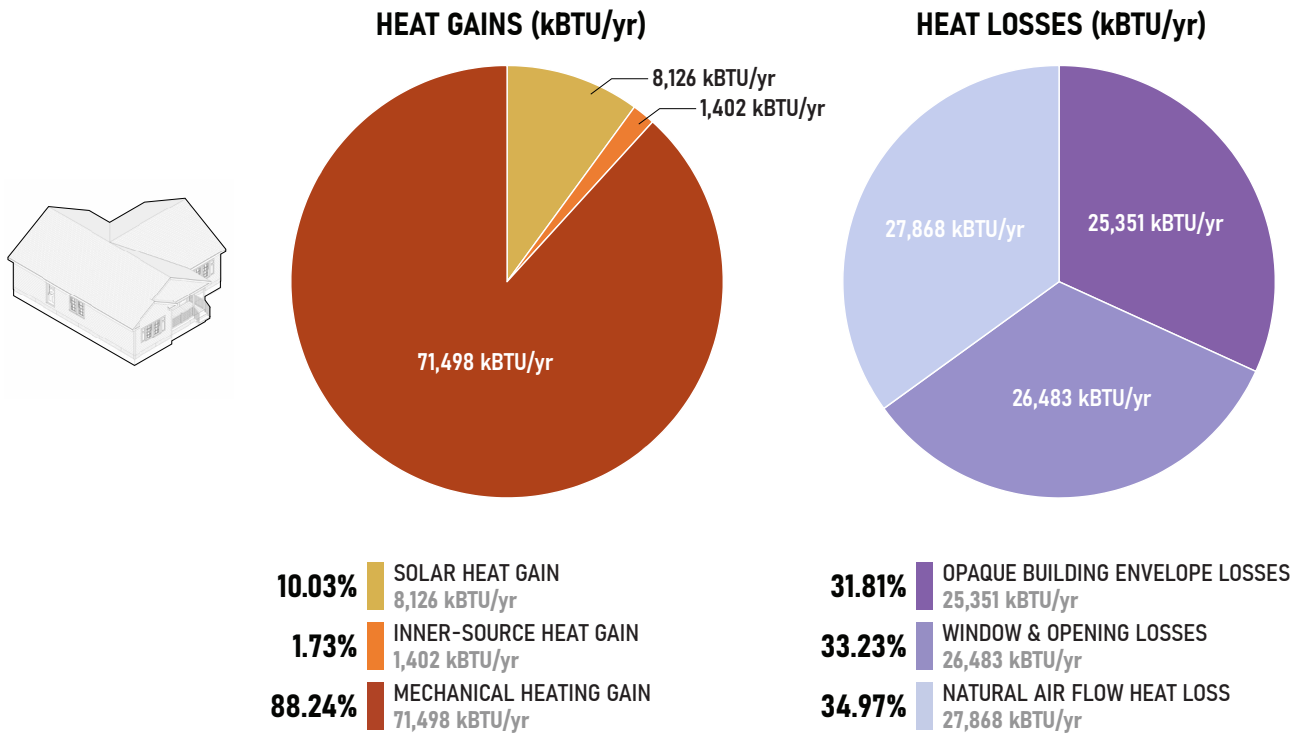
Data Source: WUFI Passive 3.5, Fraunhofer IBP



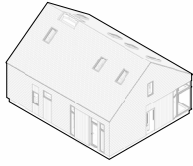
Data Source: WUFI Passive 3.5, Fraunhofer IBP

ANNUAL HEAT FLOW QUANTIFICATION

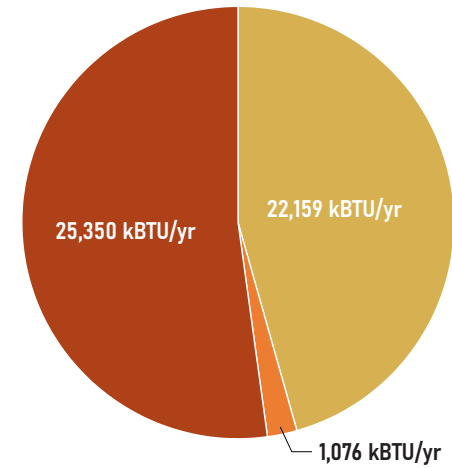
Analyzing the breakdown of annual heat gain and heat loss contribution in each construction system, it is shown how the degree of air-tightness of a construction system greatly influences the amount of heat loss related to air flow. The amount of glazing in the design, pair with the amount of air-tightness, influences the degree of solar heat gain.



Data Source: WUFI Passive 3.5, Fraunhofer IBP

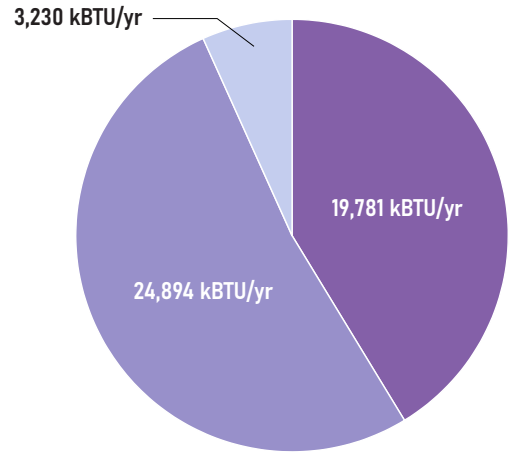


HEAT GAINS (kBTU/yr)

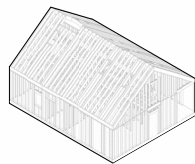


- 45.61%** SOLAR HEAT GAIN
22,159 kBTU/yr
- 2.21%** INNER-SOURCE HEAT GAIN
1,076 kBTU/yr
- 52.18%** MECHANICAL HEATING GAIN
25,350 kBTU/yr

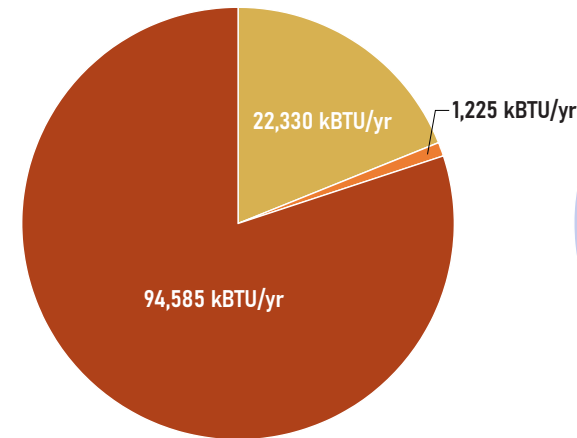
HEAT LOSSES (kBTU/yr)



- 41.29%** OPAQUE BUILDING ENVELOPE LOSSES
19,781 kBTU/yr
- 51.97%** WINDOW & OPENING LOSSES
24,894 kBTU/yr
- 6.74%** NATURAL AIR FLOW HEAT LOSS
3,230 kBTU/yr

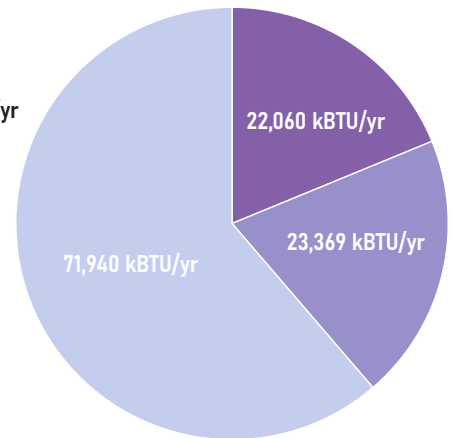


HEAT GAINS (kBTU/yr)



- 18.90%** SOLAR HEAT GAIN
22,330 kBTU/yr
- 1.04%** INNER-SOURCE HEAT GAIN
1,225 kBTU/yr
- 80.06%** MECHANICAL HEATING GAIN
94,585 kBTU/yr

HEAT LOSSES (kBTU/yr)



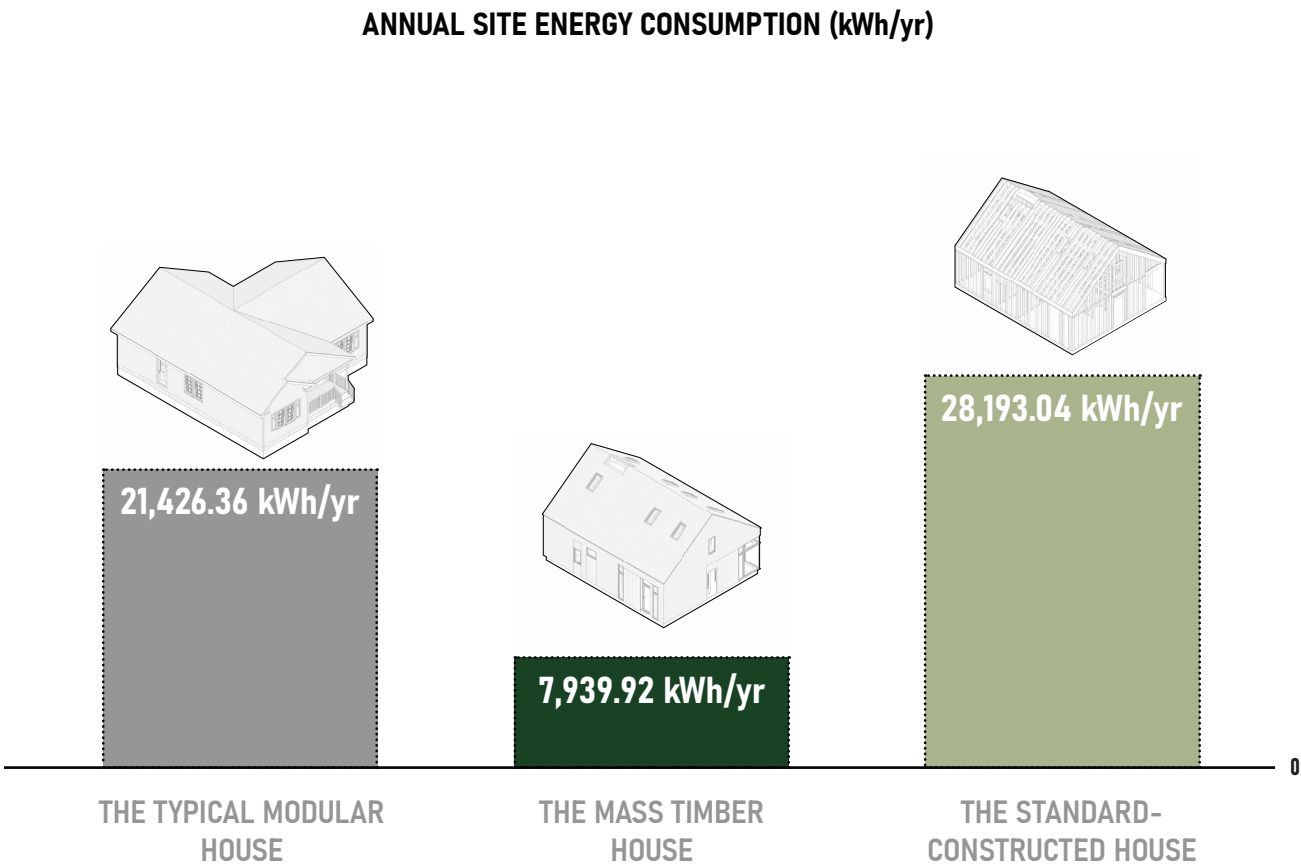
- 18.80%** OPAQUE BUILDING ENVELOPE LOSSES
22,060 kBTU/yr
- 19.91%** WINDOW & OPENING LOSSES
23,369 kBTU/yr
- 61.29%** NATURAL AIR FLOW HEAT LOSS
71,940 kBTU/yr

ANNUAL ENERGY CONSUMPTION

Annual energy consumption is a direct resultant of the amount of heating and cooling demands and loads that each construction system possesses, amongst other things. With this in mind, the efficiency ranks between the three systems in terms of energy consumption are the same as the trends within the annual heating and cooling demands and loads.

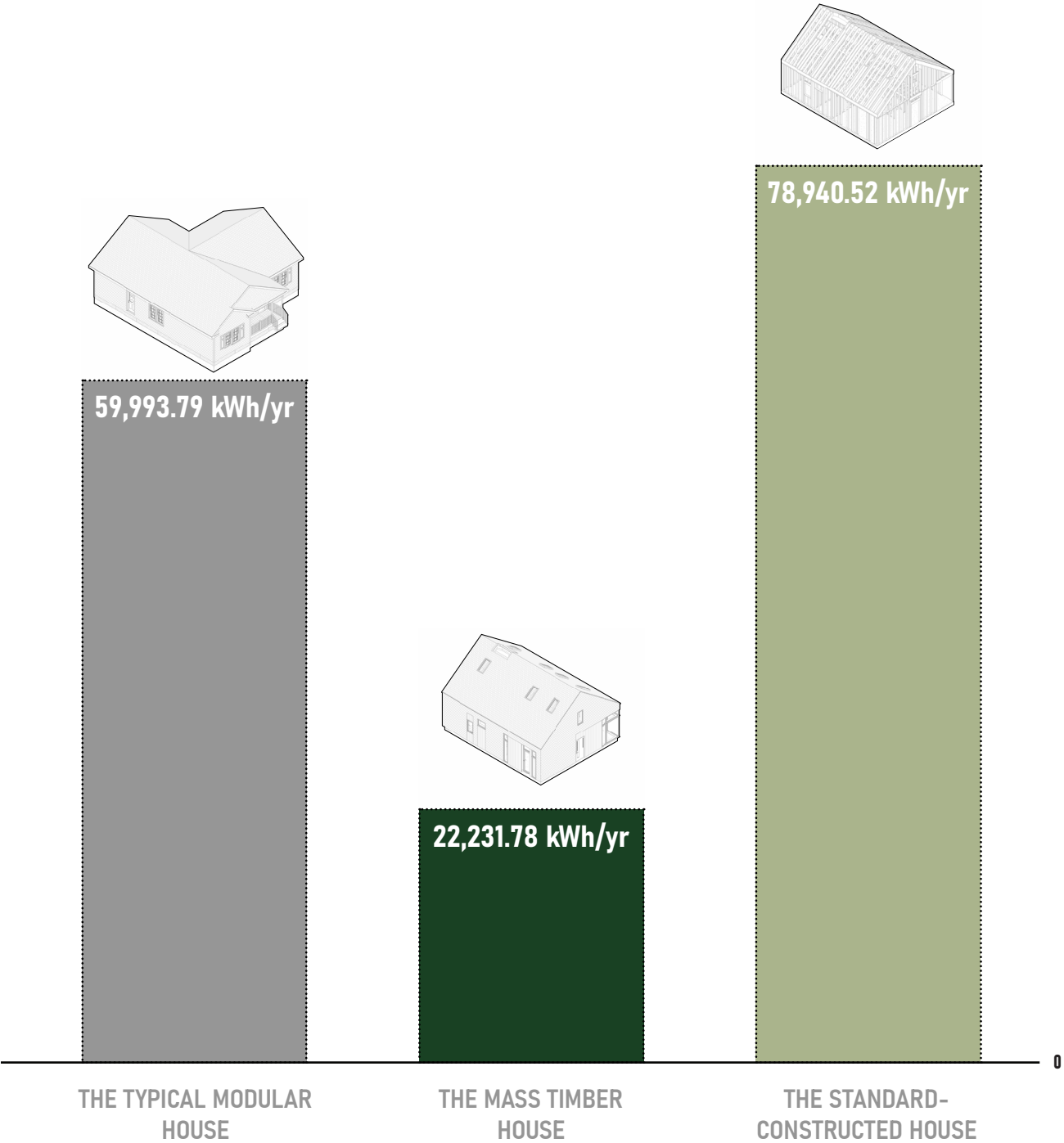
Site energy consumption is the direct energy that

is considered and represented within a homeowner's energy bill, while source energy relates to the total amount of energy involved in the process from resource to end-user. Focusing on the site energy, the typical modular house consumes roughly 3x the amount of energy for heating and cooling compared to the mass timber house. The standard-constructed house is roughly 4x the consumption rate of the mass timber house. This is a 4x higher energy bill paid each year.



Data Source: WUFI Passive 3.5, Fraunhofer IBP

ANNUAL SOURCE ENERGY CONSUMPTION (kWh/yr)



Data Source: WUFI Passive 3.5, Fraunhofer IBP

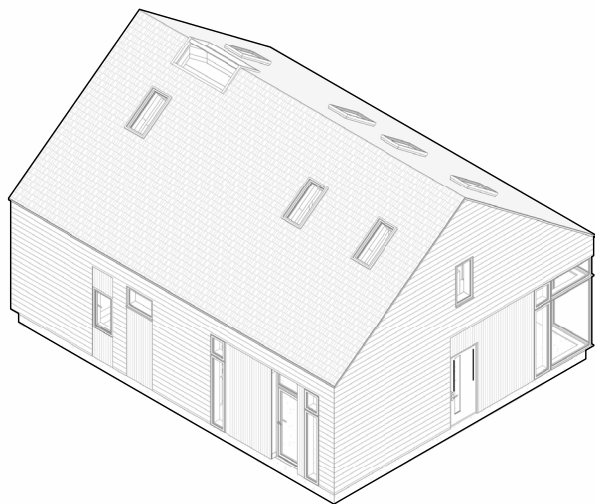
CONCLUSIVE RESULTS

QUALITIES OF A BIOGENIC MASS TIMBER HOUSE

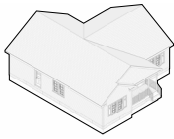
The characteristics of thermal performance and energy demands were observed in this section of the comparative analyses, which provides information by which to suggest the ongoing degrees of operational energy consumption rates in each construction assembly.

With a construction system that may easily achieve greater air-tightness compared to conventional systems, as well as its continuous rigid insulation outboard to the solid panel structure, the mass timber home achieves the lowest degree of required heating and energy demand in order to maintain proper thermal comfort within the dwelling. What this may ultimately allude to is that

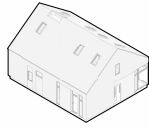
a mass timber construction system for single-family dwellings would require less money to be paid in the ongoing operational energy costs needed to heat a home for the duration of the house's lifetime. Over the longrun, the amount of money saved as a result of reduced ongoing energy costs could significantly add up to a point at where the overall cost invested between the mass timber house and the typical modular or standard constructed houses meet the same value. After which, the mass timber home officially requires less total investment.



- LESS HEAT LOSS
- LESS HEATING DEMAND
- LESS ENERGY DEMAND
- LOWER ENERGY COSTS



VS



VS



THE TYPICAL MODULAR HOUSE

THE MASS TIMBER HOUSE

THE STANDARD CONSTRUCTED HOUSE

1,592 sq.ft.	1,110 sq.ft.	1,110 sq.ft.	Gross Square Footage
R-20.29	R-26.01	R-20.26	R-Value of Opaque Wall Assemblies
R-48.28	R-51.95	R-46.09	R-Value of Opaque Roof Assemblies
6.0 Btu/hr-ft ²	NONE	6.0 Btu/hr-ft ²	Thermal Bridging in Opaque Walls
7.2 Btu/hr-ft ²	NONE	7.2 Btu/hr-ft ²	Thermal Bridging at Wall Corner Assemblies
9.6 Btu/hr-ft ²	NONE	9.0 Btu/hr-ft ²	Thermal Bridging at Wall-to-Roof Interface
3 ACH ₅₀	0.6 ACH ₅₀	5 ACH ₅₀	Construction Air Tightness
71,498 kBtu/yr	25,350 kBtu/yr	95,585 kBtu/yr	Annual Heating Demand
43.35 kBtu/ft ² -yr	25.64 kBtu/ft ² -yr	88.45 kBtu/ft ² -yr	Specific Heating Demand
32,846 Btu/hr	10,911 Btu/hr	60,752 Btu/hr	Annual Heating Load
19.91 Btu/hr-ft ²	11.04 Btu/hr-ft ²	56.81 Btu/hr-ft ²	Specific Heating Load
21,426 kWh/yr	7,940 kWh/yr	28,193 kWh/yr	Annual Site Energy Demand
59,994 kWh/yr	22,232 kWh/yr	78,941 kWh/yr	Annual Source Energy Demand

* Note: Some degree of thermal bridging would occur through the fasteners of each enclosure assembly if they were included within the project boundary.





CONCLUSION



D1



CONCLUSIONS

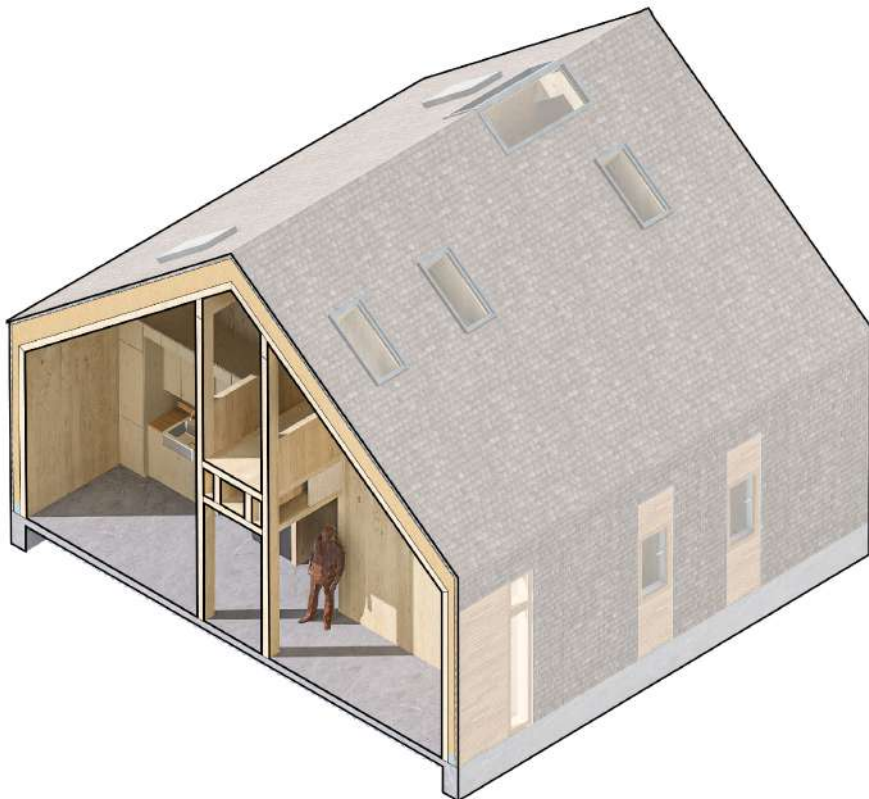
BENEFITS & TRADE-OFFS OF MASS TIMBER

TAKEAWAY

This project has looked into many different design aspects and analyses. After this study, it has been proven that a BioMOD mass timber modular house performs better in terms of renewability of materials, its carbon footprint, and thermal performance compared to standard construction systems. These are traits that would derive a construction system that achieves a greater degree of environmental sustainability, reduced ongoing cost related to operational energy demand, and longterm equity for a homeowner. Furthermore, its significantly fewer quantity of parts involved in construction would suggest an efficient on-site construction timeline, which would aid in reducing labor cost and potential error caused in

the field. With many benefits that especially see a return on investment in the longrun, for both the environment as well as homeowners, a mass timber house possesses a sufficient amount of beneficial attributes to be considered as a competitive model for housing in the Northeast.

Several tradeoffs of a mass timber system in single-family housing must also be considered. With the sheer use of volume in CLT, the construction system results in a heavier structure that would also demand more timber from the forest to produce. The initial investment of a home such as this would also likely be higher than the conventional systems that exist today. This is a housing system for the long-term.



MORE
LESS
LESS

RENEWABLE MATERIAL
NUMBER OF PARTS
MATERIAL LAYERS

LESS
LONGER
NEGATIVE

MATERIAL REPLACEMENT
LIFESPAN
CARBON FOR 100+ YEARS

LESS
LESS
LOWER

HEAT LOSS
ENERGY DEMAND
ENERGY COSTS

MORE

TOTAL MASS [WEIGHT]

MORE
MORE

MATERIAL VOLUME
INITIAL INVESTMENT

PROJECT CONCLUSION

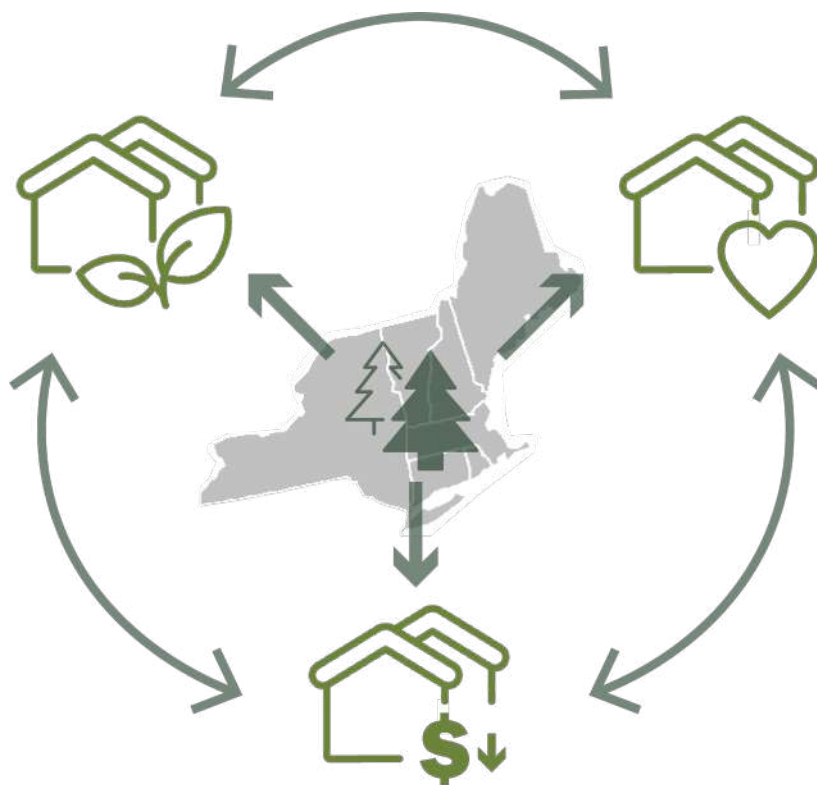
A MODEL FOR THE NORTHEAST

The BioMOD project set out to demonstrate the use of locally made mass timber for the Northeast, showcase the benefits of biophilic materials in construction, and support the rural housing & forest sector. Through the system's compact design, use of local forest products, and considerable performance that was proven through the comparative analyses, it can be determined that the project's initial objectives were addressed.

By prioritizing a biogenic material-comprised construction system that entails a solid-panel format with outboard insulation, a single-family home constructed in the northeastern United States can support local labor and industry in the

regional forest sector, and create a home that may serve to reduce the carbon impacts of housing construction and energy demands from the grid. Furthermore, a mass timber home such as this may achieve a multi-generational lifespan that can aid in the retention of community members, and see less waste due to vacancy or replacement in the housing sector.

The BioMOD panelized modular mass timber housing system is a housing model that could regenerate the health and equity of the Northeast's communities and environment alike—all of which would be thanks to sustainable harvesting of the Northern Forest's bounty, the eastern white pine.





FUTURE RESEARCH

AVENUES

This study focused on the development of a panelized modular mass timber housing system for single-family housing in the northeastern United States, which utilized eastern white pine in its CLT structure. From design and analysis, the study had revealed the various benefits and considerations with mass timber construction in this sector, but had also helped to identify general trends of the competitive characteristics of CLT-constructed single-family residences.

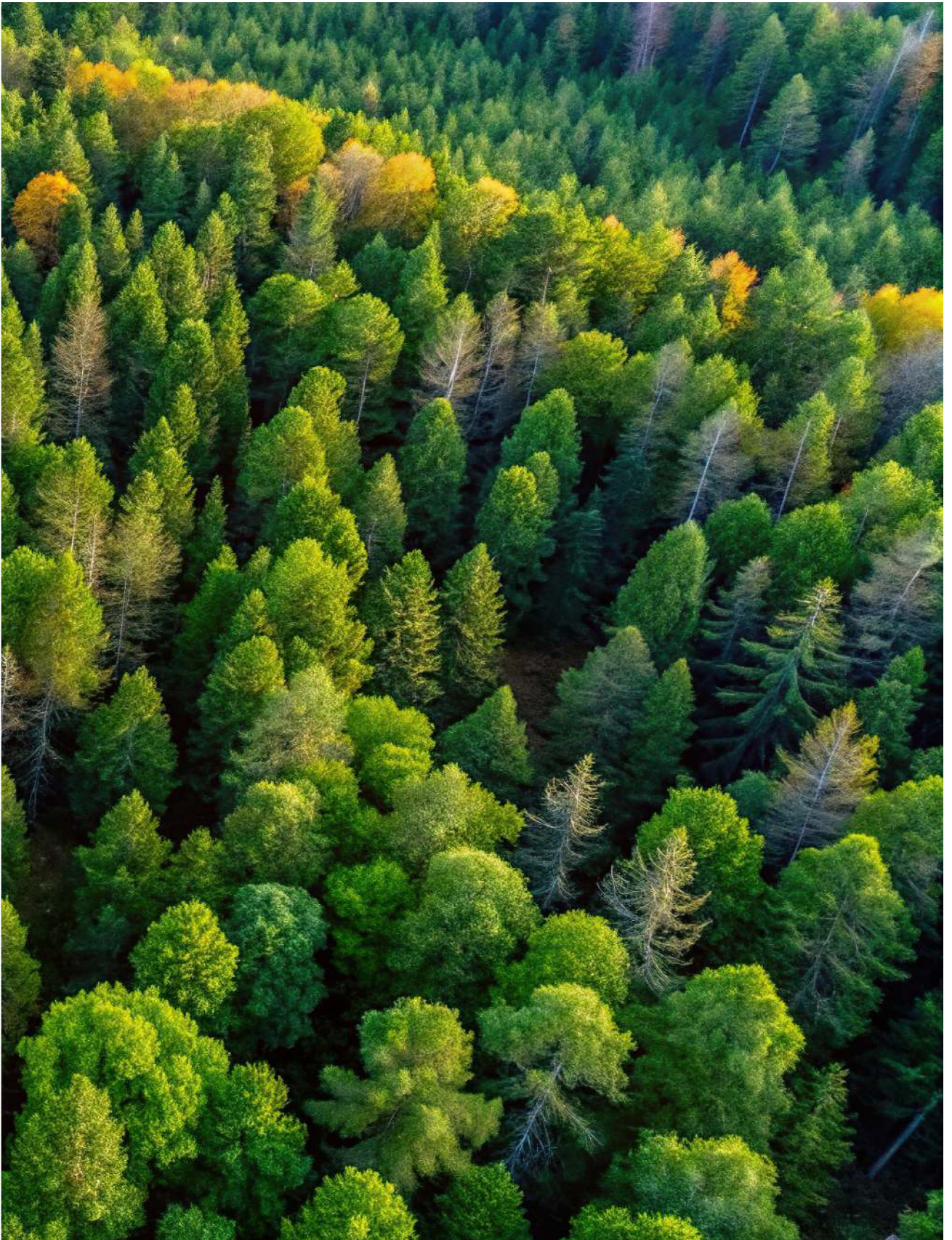
From this project, several avenues could be taken to further the research on this topic. The project boundary of the analyses could be expanded to include more aspects of the total construction elements that go into the making of a home, such as the foundation and fasteners. Including elements such as these would provide an even more accurate representation of the quantitative conditions of each of the construction systems studied. Furthermore, the design of multi-story single-family dwellings could be pursued.

Beyond the expansion of the general components existent in the study, future research could examine other tree species for use in applied mass timber products, as well as pursuing a deeper analysis into the current conditions of land ownership and supply chain functionality within the Northern forests. These would help to inform the true availability and viability of sawtimber choice and utilization.

Cost analysis and assessment is a vital factor of

concern in the realistic decision-making of industries and consumers alike. With more time and resources, the project could include an assessment into the true pricepoints of each construction system involved in the comparative analyses—both up front and over time. This would greatly assist in proving the competitiveness of a mass timber single-family housing.

Lastly, the BioMOD housing model, and the nature of this study could be explored in other forested regions throughout the world. With many paths for future research, the BioMOD project functions as a foundational gateway into considering mass timber application in modular single-family housing construction. This is a building sector where mass timber is only just getting started in its integration, with a promising future ahead.









D2





CREDITS



ACKNOWLEDGMENTS

PROJECT INFLUENCERS

The contents and achievements of this project were a result of several individuals who gave their guidance and assistance along the way. Although the project was physically produced personally, the end product could not have become what it has without the selfless sharing of insight and intuition by those who have helped me along the way.

I would like to thank:

Judith Sheine | Committee Chair. Professor, University of Oregon. Director of Design, TallWood Design Institute:

For her invaluable and consistent guidance throughout the entire creation of this project. Judith, as chair of my project, was the most heavily involved.

Uli Dangel | Committee. Professor, Department Director, University of Oregon:

For his assistance and valuable feedback during review phases.

Mikhail Gershfeld | Committee. Professor, California State Polytechnic University, Pomona:

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Dylan Wood | Dr. Ing., Assistant Professor, University of Oregon:

For his general suggestions and insight during weekly meetings.

Joe Short | Vice President, Northern Forest Center:

For sharing his knowledge on the current conditions of the northeastern forest sector, and viable avenues for mass timber in the region.

Nick Farmer | President, NotchSB:

For sharing insights into current practices of CLT utilization in the Northeast, willingness to share resources, as well as his interest and support for this project.

The last person to thank for this project is the individual who gave me her unwavering love and support throughout the making of this project. Without her selfless care, this project could not have gotten as far as it had in the timeframe that I was given. She is:

Hanna Gee

REFERENCES

ENDNOTES

- 1 Architecture 2030. (2022, March 15). *Why the Built Environment? We Must Eliminate All CO₂ Emissions from the Built Environment by 2040 to Meet 1.5°C Climate Targets*. <https://www.architecture2030.org/why-the-built-environment/>
- 2 Blanco, A., & Lindsay, J. (2024, December 12). "Nowhere to Hide:" Housing Costs Keep Climbing in All Corners of New England. Federal Reserve Bank of Boston. <https://www.bostonfed.org/news-and-events/news/2024/12/nowhere-to-hide-housing-costs-keep-climbing-in-all-corners-of-new-england-boston-fed-housing-crisis.aspx>
- 3 Jewell, K. (2003). *Manufactured Housing Appreciation: Stereotypes and Data*. Consumers Union. <https://www.consumersunion.org/mh>
- 4 Hodgson, A. T., Rudd, A. F., Beal, D., & Chandra, S. (2000). *Volatile organic compound concentrations and emission rates in new manufactured and site-built houses*. *Indoor Air*, 10(3), 178–192. <https://doi.org/10.1034/j.1600-0668.2000.010003178.x>
- 5 Northeast State Foresters Association. (2021). *Northeast Wood Markets Retention and New Market Recruitment Initiative*. <https://www.nefainfo.org>
- 6 Abidov, O., Alderman, D., Benedetti, D., Bumgardner, M., Eastin, I., Fernholz, K., Palacin, J., Wall, J. (2023). *UNECE/FAO Forest Products Annual Market Review, 2022–2022*. United Nations Economic Commission for Europe.
- 7 Northeast State Foresters Association. (2021). *Northeast Wood Markets Retention and New Market Recruitment Initiative*. <https://www.nefainfo.org>
- 8 Adhikari, S., Quesada, H., Bond, B., & Hammett, T. (2021). *Current Status of Hardwood Sawmills to Produce Structural Grade Hardwood Lumber*. *Mass Timber Construction Journal*, 4.
- 9 Adhikari, S., Quesada, H., Bond, B., & Hammett, T. (2020). *Potential of Hardwood Lumber in Cross Laminated Timber in North America, A CLT Manufacturer's Perspective*. *Mass Timber Construction Journal*, 3.
- 10 Northeast State Foresters Association. (2024, March 14). *Sourcing Eastern Hemlock CLT for Northeastern Mass Timber Building Construction*. <https://www.nefainfo.org>
- 11 Clouston, P. L., Kaboli, H., & Lawrence, S. (2020). *Feasibility of Two Northeastern Species in Three-Layer ANSI-Approved Cross-Laminated Timber*. *Journal of Materials in Civil Engineering*, 32. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003058](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003058)
- 12 Beaudoin, J. (2024). *A Novel Use for Eastern Hemlock*. *Northern Woodlands Magazine*. <https://www.northernwoodlands.org/articles>
- 13 Breneman, S., & McLain, R. (2019). *Fire Design of Mass Timber Members*. Woodworks Wood Products Council. <https://www.woodworks.org>
- 14 Goode, E., Heath, O., Jackson, V. (2018). *Creating Positive Spaces Using Biophilic Design*. Global Wellness Institute. <https://www.globalwellnessinstitute.org>

SELECTED ORGANIZATIONS

INFORMATION

Architecture 2030 | <https://architecture2030.org/>
United States Department of Housing and Urban Development | <https://www.hud.gov/>
Key Homes | <https://keymdoularhomes.com>
US National Park Service, National Register of Historic Places | <https://www.nps.gov/>
North East State Foresters Association | <https://www.nefainfo.org>
Northern Forest Center | <https://northernforest.org>
NotchSB | <https://www.notchsb.com>
WoodWorks Wood Products Council | <https://woodworks.org>
Global Wellness Institute | <https://globalwellnessinstitute.org>
International WELL Building Institute | <https://www.wellcertified.com>
Passive House Institute US (PHIUS) | <https://www.phius.org>

ANALYSIS TOOLS

Esri, *ArcGIS Online* | <https://www.arcgis.com>
USDA Forest Service, *EVALIDator Tool* | <https://apps.fs.usda.gov/fiadb-api/evaluator>
Autodesk, *Autodesk Revit 2025 software* | <https://www.autodesk.com/products/revit>
Microsoft, *Microsoft Excel* | <https://www.microsoft.com/en-us/microsoft-365/excel>
RAWGraphs, *RAWGraphs 2.0* | <https://app.rawgraphs.io/>
One Click LCA Ltd., *One Click LCA software* | <https://oneclicklcaapp.com/>
Lawrence Berkeley National Laboratory, *THERM 7.8 software* | <https://windows.lbl.gov>
Fraunhofer Institute for Building Physics, *WUFI@Passive software* | <https://wufi.de/en>

CASE STUDIES

Green Canopy NODE | <https://greencanopynode.com>
Tieton Cabin Company | <https://www.tietoncabinco.com>
Kalesnikoff | <https://kalesnikoff.com>
Polyhaus | <https://www.polyhaus.com>
atelierjones LLC | <https://atelierjones.com>
OPAL Shelter | <https://opalshelter.us>
OPAL | <https://www.opalarch.us>
NotchSB | <https://www.notchsb.com>

ANNOTATED BIBLIOGRAPHY

Adhikari, S., Quesada, H., Bond, B., & Hammett, T. (2020). Potential of Hardwood Lumber in Cross Laminated Timber in North America_A CLT Manufacturer's Perspective. *Mass Timber Construction Journal*, 3.

This journal article explores the feasibility of integrating hardwood lumber into CLT production in North America, analyzing the opportunities and challenges from the perspective of manufacturers. The authors discuss the technical properties of hardwoods, such as strength and aesthetic appeal, which make them a promising alternative to softwoods traditionally used in CLT. Key barriers are also brought up, including cost considerations, supply chain limitations, and the need for updated manufacturing processes and standards. Through qualitative insights gathered from industry stakeholders, the article highlights the potential for hardwood CLT to expand the mass timber market while diversifying material options.

Adhikari, S., Quesada, H., Bond, B., & Hammett, T. (2021). Current Status of Hardwood Sawmills to Produce Structural Grade Hardwood Lumber. *Mass Timber Construction Journal*, 4.

The article examines the capacity of hardwood sawmills to produce structural-grade hardwood lumber suitable for mass timber construction. The authors explore the technical and economic challenges these facilities face, including grading, drying, and machining hardwood to meet industry standards. The study highlights the potential for hardwood species to diversify mass timber applications while addressing gaps in the supply chain, such as the need for upgraded equipment and certifications. Additionally, it evaluates the market opportunities for integrating hardwood into CLT and other engineered wood products. The findings express the need for innovation and investment to support the hardwood sector's role in the growing mass timber industry. However, in conclusion, hardwood mills simply are not yet prepared to create CLT at any commercial scale.

Ahn, N., Bjarvin, C., Riggio, M., Muszynski, L., Schimleck, L., Pestana, C., Dadoo, A., & Puettmann, M. (2023). Envisioning Mass Timber Buildings for Circularity: Life Cycle Assessment of a Mass Timber Building with Different End-of-Life (EOL) and Post-EOL Options. *13th World Conference on Timber Engineering, WCTE 2023*, 6, 3581–3587. <https://doi.org/10.52202/069179-0466>

Assesses the environmental impact of mass timber buildings through LCA, focusing on circularity by examining various end-of-life (EOL) options like reuse, recycling, energy recovery, and disposal. Results indicate that reuse and recycling offer substantial environmental benefits over other options, supporting mass timber's potential in circular construction practices. The study underscores the role of sustainable EOL strategies in reducing environmental impacts and promoting a circular economy in the building sector.

Ahn, N., Dadoo, A., Riggio, M., Muszynski, L., Schimleck, L., & Puettmann, M. (2022). Circular economy in mass timber construction: State-of-the-art, gaps and pressing research needs. *Journal of Building Engineering*, 53. <https://doi.org/10.1016/j.jobbe.2022.104562>

Explores the role circular economy in mass timber construction, highlighting how CLT and other mass timber products could advance sustainable building practices. They identify current practices, challenges, and research needs in achieving material efficiency, waste reduction, and resource reuse in the lifecycle of timber structures. The study stresses gaps in LCA data and pressing needs for design standards to support circular economy goals in construction. This research underscores the potential of CLT in sustainable architecture.

Alderman, D., Duvall, P., Smith, R., & Bowe, S. (2007). Eastern white pine: Production, markets, and marketing of primary manufacturers. *Forest Products Journal*, 57(10). <https://research.fs.usda.gov/treesearch/12899>

The study analyzes supply chain dynamics, market demand, and challenges facing the industry, highlighting the importance of efficient marketing and production practices to enhance competitiveness. This work provides insights into the economic role of eastern white pine, emphasizing strategies that could support industry growth and sustainability.

Arceo, A., Tham, M., Guven, G., MacLean, H. L., & Saxe, S. (2021). Capturing variability in material intensity of single-family dwellings: A case study of Toronto, Canada. *Resources, Conservation and Recycling*, 175. <https://doi.org/10.1016/j.resconrec.2021.105885>

Investigates the variability in material intensity for single-family homes in Toronto, analyzing how differences in design, construction practices, and material choices impact resource use. Through a case study approach, the study highlights significant variability in material requirements, expressing the potential for resource conservation by optimizing material efficiency. This research offers valuable insights for sustainable building practices by identifying opportunities to reduce environmental impacts in residential construction.

Arkhangelskaya, Y., & Arkhangelskaya, E. (2020). Comparing the Economic Indicators of Sustainable Development in Wooden Housing. *IOP Conference Series: Materials Science and Engineering*, 753(8). <https://doi.org/10.1088/1757-899X/753/8/082022>

By comparing various economic metrics, the study assesses the viability of wood as a sustainable construction material, emphasizing its potential to reduce costs while supporting eco-friendly development. The findings suggest that wooden housing offers both economic and environmental benefits, reinforcing wood's role in sustainable building practices.

Ben-Alon, L., Loftness, V., Harries, K. A., & Cochran Hameen, E. (2021). Life Cycle Assessment (LCA) of Natural vs Conventional Building Assemblies. *Renewable and Sustainable Energy Reviews*, 144. <https://doi.org/10.1016/j.rser.2021.110951>

The study examines various material choices and construction methods, revealing that natural building assemblies typically demonstrate lower environmental impacts than conventional options. Results emphasize the potential for natural materials to enhance sustainability in construction, providing a foundation for greener building practices.

Brooks, M. M., & Mueller, J. T. (2020). Factors affecting mobile home prevalence in the United States: Poverty, natural amenities, and employment in natural resources. *Population, Space and Place*, 26(4). <https://doi.org/10.1002/psp.2311>

This study looks into the socioeconomic and geographic factors influencing the prevalence of mobile homes across the United States. They identify poverty levels, access to natural amenities, and employment in natural resource industries as key determinants. Using spatial and statistical analyses, the authors demonstrate that mobile homes are more common in areas with higher poverty rates and regions reliant on natural resource employment, often correlated with lower housing costs and economic vulnerability. The study also examines how proximity to natural amenities can make mobile home living attractive despite its association with economic hardship.

Gottlieb, S. C., Frederiksen, N., Molby, L. F., Fredslund, L., Primdahl, M. B., & Rasmussen, T. V. (2023). Roadmap for the transition to biogenic building materials: A socio-technical analysis of barriers and drivers in the Danish construction industry. *Journal of Cleaner Production*, 414. <https://doi.org/10.1016/j.jclepro.2023.137554>

Presents a socio-technical analysis of the Danish construction industry's transition to biogenic building materials, identifying key barriers and drivers. The study outlines economic, regulatory, and cultural factors that impact the adoption of sustainable materials, offering a roadmap to overcome these challenges. Findings emphasize that effective policy, industry collaboration, and public awareness are essential to advancing biogenic materials in construction, contributing to the industry's sustainability goals.

Gu, H., Liang, S., Pierobon, F., Puettmann, M., Ganguly, I., Chen, C., Pasternack, R., Wishnie, M., Jones, S., & Maples, I. (2021). Mass timber building life cycle assessment methodology for the U.S. regional case studies. *Sustainability (Switzerland)*, 13(24). <https://doi.org/10.3390/su132414034>

The paper develops an LCA methodology tailored for mass timber buildings in the U.S., applying it to regional case studies. This study identifies the environmental impacts of mass timber across different building stages, providing insights specific to the U.S. context. Results highlight the environmental benefits of mass timber compared to conventional materials, supporting its role in sustainable construction and contributing to improved LCA practices for regionally adapted building assessments.

Haftkhani, A. R., & Hematabadi, H. (2022). Effect of Layer Arrangement on Bending Strength of Cross-Laminated Timber (CLT) Manufactured from Poplar (*Populus deltoides* L.). *Buildings*, 12(5). <https://doi.org/10.3390/buildings12050608>

The study looks into how varying layer arrangements affect the bending strength of CLT panels made from eastern cottonwood, which is a type of poplar tree. The authors found that the orientation of layers significantly impacts mechanical performance, with panels featuring alternating orthogonal layers demonstrating superior bending strength. The research highlights poplar as a viable species for CLT production due to its fast growth, availability, and adequate mechanical properties. This paper is another example of proving the potential for alternatives to commonly used species like spruce, pine, and fir.

Hassler, C., McNeel, J. F., Denes, L., Norris, J., & Bencsik, B. (2022). Challenges Facing the Development and Market Introduction of Hardwood Cross-Laminated Timbers. *Forest Products Journal*, 72(4), 276–283. <https://doi.org/10.13073/FPJ-D-22-00048>

Examines the challenges and barriers to the development and commercialization of hardwood CLT, focusing on factors like technical, economic, and regulatory hurdles. The potential benefits of hardwood CLT include its environmental advantages and its role in reducing the carbon footprint of the construction industry. However, they highlight challenges such as limited availability of suitable hardwood species, the higher cost compared to softwood CLT, and regulatory standards that are not yet fully adapted for hardwood products. The paper also explores market perceptions and the industry's slow adaptation to hardwood CLT despite its advantages.

Hassler, C. C., Young, M., Denes, L., Bencsik, B., & McNeel, J. F. (2024). An Evaluation of Low-Grade Red Oak and Soft Maple as Raw Material for Cross-Laminated Timber Panel Production. *Forest Products Journal*, 72(4), 107–120. <https://doi.org/10.13073/FPJ-D-23-00058>

The paper evaluates the viability of using low-grade red oak and soft maple as raw materials for CLT production, focusing on their mechanical properties and structural performance. Results indicate that panels produced from these species meet or exceed minimum strength and stiffness requirements set by industry standards. Specifically, red oak panels demonstrated higher modulus of elasticity and tensile strength compared to soft maple, suggesting their superior suitability for load-bearing applications. Soft maple, while less robust, showed promise for non-structural or interior CLT components due to its workability and availability. These efforts help to express the potential for diversifying raw materials for CLT manufacturing, reducing reliance on traditional softwoods and adding value to underutilized hardwood species.

Hindman, D., & Mohamadzadeh, M. (2015). Mechanical Performance of Yellow-Poplar Cross Laminated Timber.

This is a report created from the testing done out of Virginia Tech University, looking into the strengths and potential for yellow poplar to be utilized in CLT. The mechanical testing proved that yellow poplar met the minimum requirements for CLT, with notable high amount of rolling shear capacity compared to conventional softwood CLTs. However, brittleness related to adhesive failure was examined in some of the tests, indicating the need for research that looks into improving available adhesives for hardwood CLT.

Jang, H., Ahn, Y., & Roh, S. (2022). Comparison of the Embodied Carbon Emissions and Direct Construction Costs for Modular and Conventional Residential Buildings in South Korea. *Buildings*, 12(1). <https://doi.org/10.3390/buildings12010051>

Quantifies the environmental impacts and financial implications associated with each building method, revealing that modular construction generally results in lower embodied carbon emissions without significantly increasing costs. The findings suggest that adopting modular building techniques could be a viable strategy for reducing environmental impacts in residential construction while maintaining economic feasibility.

Jellen, A. C., & Memari, A. M. (2022). Structural Design of a Single-Family Residential Dwelling Using Cross-Laminated Timber (CLT). *IntechOpen*. <https://doi.org/10.5772/intechopen.110790>

This study emphasizes the benefits of CLT, including its strength, sustainability, and ease of construction for single family homes. Through detailed analysis, the authors demonstrate the design process, structural considerations, and performance evaluations for CLT in residential applications. The findings advocate for CLT as a viable alternative to traditional materials, highlighting its potential to enhance sustainability and efficiency in residential construction.

Clouston, P. L., Kaboli, H., & Lawrence, S. (2020). Feasibility of Two Northeastern Species in Three-Layer ANSI-Approved Cross-Laminated Timber. *Journal of Materials in Civil Engineering*, 32. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003058](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003058)

Evaluates the mechanical properties and performance characteristics of Eastern Hemlock and Eastern White Pine, assessing their suitability for CLT applications. Results indicate that both species meet the required standards for strength and stability, suggesting their potential for use in CLT. This research contributes valuable insights into expanding the material options for CLT, promoting the use of local resources in the construction industry.

Karthik, S., Sharareh, K., & Behzad, R. (2020). Modular Construction vs. Traditional Construction: Advantages and Limitations: A Comparative Study. In M. Skibniewski & H. Miklos (Eds.), *Creative Construction e-Conference* (pp. 11–19). Periodica Polytechnica Budapest University of Technology and Economics. <https://doi.org/10.3311/cc2020-012>

Compares modular and traditional construction methods, focusing on their respective advantages and limitations. Results show that modular construction significantly reduces project timelines, waste, and on-site labor requirements while improving safety and quality due to controlled factory environments. However, it highlights challenges such as high initial costs, logistical complexities, and limitations in design flexibility. The authors emphasize modular construction's potential to mitigate construction delays and environmental impacts, making it an increasingly viable alternative to traditional methods, particularly for repetitive or scalable projects. It concludes that modular construction's adoption is limited by industry inertia and the need for specialized skills.

Kremer, P. D., Abbasnejad, B., Ahankoob, A., & Wakefield, R. (2024). An Assessment of the Quantifiable Effects for Expressed Timber Biophilic Treatments: A Case for Mass Timber Construction? *Mass Timber Construction Journal*, 7. <https://doi.org/10.55191/MTCJ.2024.3>

Explores how the integration of biophilic design principles, characterized by natural materials and aesthetics, impacts occupants' well-being and environmental performance. Through case studies and empirical analysis, the authors demonstrate that expressed timber not only enhances aesthetic appeal but also contributes positively to psychological and physiological outcomes for users. The findings advocate for the adoption of biophilic treatments in mass timber construction, positioning them as essential for promoting sustainable and health-oriented building practices.

Kuittinen, M., Organschi, A., & Ruff, A. (2022). *Carbon: A Field Manual for Building Designers*. Wiley.

This book is aimed at integrating carbon management into building design practices. The manual addresses the significance of carbon emissions throughout the life cycle of buildings, offering strategies for reducing carbon footprints through material selection, design optimization, and innovative construction methods. By combining theoretical insights with practical applications, the authors provide designers with essential tools to prioritize sustainability in their projects. This resource is instrumental in advancing carbon-conscious design and promoting a holistic approach to environmental responsibility in the architecture and construction industries.

Kurzinski, S., & Crovella, P. L. (2024). Investigating the Out-of-Plane Bending Stiffness Properties in Hybrid Species Diagonal-Cross-Laminated Timber Panels. *Applied Sciences (Switzerland)*, 14(7). <https://doi.org/10.3390/app14072718>

The study tests the out-of-plane bending stiffness of hybrid species diagonal-cross-laminated timber (DCLT) panels, utilizing black locust (a hardwood) as the exterior lamination layers, and eastern white pine (a softwood) as the interior diagonal-orientated layers. The authors analyze how incorporating hybrid species affects structural performance compared to conventional CLT, with their results indicating that hybrid species diagonal configurations can achieve stiffness levels comparable to or exceeding standard panels, depending on species selection and layer orientation. Additionally, the study highlights that these configurations optimize material utilization and enhance design flexibility without compromising mechanical integrity. The paper provides an example of usefulness for both black locust and eastern white pine in use for mass timber.

Lewis, P., Tsurumaki, M., & Lewis, D. J. (2022). *Manual of Biogenic House Sections*. ORO Editions.

This book is a compilation of comprehensive case studies of various architectural projects that have used biogenic material construction assemblies. The processes by which each biogenic material category is produced is represented throughout the chapters, with an Appendix that includes a reference table for carbon emission metrics related to specific materials found in construction.

Ma, Y., Si, R., Musah, M., Dai, Q., Xie, X., Wang, X., & Ross, R. J. (2021). Mechanical Property Evaluation of Hybrid Mixed-Species CLT Panels with Sugar Maple and White Spruce. *Journal of Materials in Civil Engineering*, 33(7). [https://doi.org/10.1061/\(asce\)mt.1943-5533.0003760](https://doi.org/10.1061/(asce)mt.1943-5533.0003760)

Investigates the mechanical properties of hybrid CLT panels made from sugar maple (a hardwood) and white spruce (a softwood). Researchers evaluated the bending, shear, and compressive strengths of these mixed-species panels, comparing them to those made from single-species panels. The results showed that panels combining sugar maple in the outer layers and white spruce in the core exhibited enhanced bending strength and stiffness due to the hardwood's higher density and strength. Additionally, the inclusion of white spruce improved the panels' overall cost-effectiveness and lightweight properties without significantly compromising structural performance. The research expresses the potential for using hybrid species in CLT production to optimize material properties while addressing resource availability and economic considerations.

Northeast State Foresters Association. (2021). Northeast Wood Markets Retention and New Market Recruitment Initiative. <https://www.nefainfo.org>

This report by the Northeast State Foresters Association (NSFA) outlines the initiative aimed at supporting and expanding wood markets in the northeastern United States. The initiative focuses on retaining existing wood markets while recruiting new ones, including those for mass timber, to bolster the region's timber industry. The document discusses challenges and opportunities related to market expansion, forest management practices, and the use of sustainable wood products like mass timber, which can play a role in reducing the carbon footprint of construction. Overall, the viability for mass timber production penetration in the local Northeastern market seems to be most viable in states like New York, Vermont, and New Hampshire.

O'Carroll, C., & Koskinen, A. (2017). Assessing the Wood Supply and Investment Potential for a New England Engineered Wood Products Mill. *Poyry Management Consulting*.

This report provides an in-depth analysis of the wood supply and investment potential for establishing an engineered wood products mill in New England, focusing on the feasibility of mass timber products like CLT. They assess regional wood resources, including timber availability, quality, and sustainability, and explore the economic and environmental benefits of developing a mill. They also discuss market demand for engineered wood products, potential risks, and investment opportunities. The report expresses a positive impact of local sourcing on reducing transportation emissions and costs, while also offering insight into the broader benefits of promoting sustainable forestry practices.

Palacio-Betancur, A., Hormozabad, S. J., Niman, C., Masterson, P., Sturlaugson, B., Brewer, J., Swetnam, B., Bryson, L. S., & Soto, M. G. (2023). Compressive Properties of Cross-Laminated Timber Panels Made of Hardwood Tree Species from the Appalachian Region. *Journal of Architectural Engineering*, 29(1). <https://doi.org/10.1061/jaeied.aeeng-1441>

The study evaluates the compressive properties of CLT panels constructed from red maple, sweetgum, and sycamore trees, which are all hardwoods. Results demonstrate that panels made from these hardwood species exhibit higher compressive strength and stiffness compared to panels from softwood species traditionally used in CLT production. The findings suggest hardwood-based CLT could diversify material sources for the mass timber industry, though further research is needed on large-scale production feasibility and environmental impacts.

Puettmann, M., Pierobon, F., Ganguly, I., Gu, H., Chen, C., Liang, S., Jones, S., Maples, I., & Wishnie, M. (2021). Comparative LCA's of conventional and mass timber buildings in regions with potential for mass timber penetration. *Sustainability (Switzerland)*, 13(24). <https://doi.org/10.3390/su132413987>

The study assesses the environmental impacts associated with both building types, focusing on factors such as material sourcing, construction processes, and end-of-life scenarios. Results indicate that mass timber buildings generally exhibit lower carbon footprints and resource consumption compared to conventional counterparts, highlighting the sustainability advantages of mass timber in construction. This research underscores the potential of mass timber to enhance environmental performance in the building sector and supports its integration as a mainstream construction material.

Rajanayagam, H., Beatinia, V., Poologanathan, K., & Nagaratnam, B. (2024). Comprehensive evaluation of flat pack modular building systems: Design, structural performance, and operational efficiency. *Journal of Building Engineering*, 95. <https://doi.org/10.1016/j.jobe.2024.110099>

Provides a thorough evaluation of flat pack modular building systems, focusing on their design optimization, structural integrity, and operational efficiency. The authors conducted experimental and computational analyses to assess the performance of these systems under varying load conditions. Key findings include a significant improvement in construction time and cost-efficiency compared to traditional methods, while maintaining structural reliability. The study highlights flat pack systems' sustainability benefits, such as reduced material waste and lower carbon emissions during manufacturing and assembly. Additionally, the research underscores the flexibility of modular systems in adapting to diverse architectural and functional requirements.

Rivera, J., & Swack, M. (2023). New York State Manufactured Home Communities Report. www.ruralhousing.org

This is a report that conducts an analysis of manufactured home communities (MHCs) in New York State, focusing on the challenges and opportunities faced by residents and owners. The authors highlight key issues such as affordability, infrastructure needs, and the regulatory environment surrounding MHCs. The report also examines the economic and social impacts of these communities on both local economies and the broader housing market. Key findings include the growing demand for affordable housing solutions and the need for better support systems for MHC residents.

Salama, T., Figgess, G., Elsharawy, M., & El-Sokkary, H. (2020). Financial modeling for modular and offsite construction. *International Journal of Engineering and Advanced Technology*, 10(2). <https://doi.org/10.35940/ijeat.b2085.1210220>

The research in this paper acts to develop a financial model to evaluate the cost-efficiency and profitability of modular and offsite construction methods compared to traditional approaches. The authors utilize case studies and sensitivity analyses to account for variables such as material costs, labor savings, project timelines, and quality control measures. Results indicate that modular construction significantly reduces overall project timelines and labor expenses, leading to cost savings of up to 20% in certain scenarios. However, initial setup costs and transportation logistics remain challenges that require strategic planning. The paper also highlights the environmental benefits, as reduced material waste and more efficient construction processes align with sustainable practices.

Snow, J., Herzog, B., & Edgar, R. (2021). Bonding Performance of the Ten Species in the Spruce-Pine-Fir (South) Lumber Grouping for Cross-laminated Timber. https://digitalcommons.library.umaine.edu/univ_publications

Examines the bonding performance of ten species within the Spruce-Pine-Fir (South) lumber grouping for potential use in CLT. The authors specifically evaluate how variations in wood density, grain characteristics, and adhesive interactions impact the strength and durability of bonds across species, such as loblolly pine, shortleaf pine, red spruce, eastern white pine, and the other SPF South species. Results indicate that denser species like loblolly pine exhibited superior bonding performance compared to less dense counterparts like eastern white pine. However, species with pronounced grain irregularities posed challenges for uniform adhesive application. The study expresses the importance of species selection and adhesive compatibility in optimizing CLT production. It is important to note that eastern white pine's bonding performance was still sufficient for CLT.

Wang, D., Zhang, M., Gong, M., & Chui, Y. H. (2024). Evaluation of Major Physical and Mechanical Properties of Trembling Aspen Lumber. *Materials*, 17(12). <https://doi.org/10.3390/ma17122952>

Examines the physical and mechanical properties of trembling aspen lumber, providing insights into its potential for structural applications, including CLT. The researchers tested density, moisture content, modulus of elasticity, and modulus of rupture across different grades of aspen lumber. Results showed that trembling aspen exhibits relatively low density and moderate mechanical strength compared to traditional structural species like spruce or pine. Overall, the results would suggest the species' suitability for non-load-bearing or secondary structural uses, while retaining potential for being used in CLT when combined with other species or adhesives.

Zhao, Y., Liu, L., & Yu, M. (2023). Comparison and analysis of carbon emissions of traditional, prefabricated, and green material buildings in materialization stage. *Journal of Cleaner Production*, 406. <https://doi.org/10.1016/j.jclepro.2023.137152>

The study employs LCA to quantify emissions associated with each building type, focusing on factors such as material sourcing, manufacturing processes, and transportation. Results indicate that green material buildings exhibit significantly lower carbon emissions compared to traditional and prefabricated structures, highlighting their environmental advantages. Their findings emphasize the importance of adopting sustainable building practices to minimize carbon footprints in construction, providing insights for policymakers and industry stakeholders to promote greener alternatives in the building sector.



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APPENDIX

APPENDIX 1 – CLT PERFORMANCE

EASTERN WHITE PINE CLT PERFORMANCE

Table 4. Long-span bending test results for eastern white pine

Strength direction	Specimen	Proportional limit (kN/m)	P_{max} (kN/m)	$\Delta_{at\ peak}$ (mm)	EI_{app} (10^9 N · mm ² /m)	$F_b S_{eff}$ (10^6 N · mm/m)
Major	WP-Major-1	94	121	85	772	60
	WP-Major-2	106	144	97	833	71
	WP-Major-3	91	104	71	701	51
	WP-Major-4	69	89	96	619	44
	Mean	90	114	87	731	57
	COV (%)	17.1	20.9	13.7	12.6	20.9
	Characteristic	—	—	—	731	37
Minor	WP-Minor-1	—	19	211	58	10
	WP-Minor-2	—	10	123	44	5
	Mean	—	14	167	51	7

Table 6. Short-span shear test results for eastern white pine

Specimen	P_{max} (kN/m)	$\Delta_{at\ peak}$ (mm)	V_{max} (kN/m)	$GA_{eff(LB)}$ (10^6 N/m)
WP-SS1	256	14	128	11.0
WP-SS2	287	20	144	9.6
WP-SS3	304	21	152	12.7
WP-SS4	265	17	133	12.8
WP-SS5	251	12	125	11.9
WP-SS6	298	15	149	10.2
WP-SS7	295	13	147	16.0
WP-SS8	276	13	138	15.0
WP-SS9	347	14	174	14.4
Mean	286	16	143	12.6
COV (%)	10.3	21.2	10.3	17.3
Characteristic	—	—	119	12.6

Table 2. Shear by compression loading test results

Species	Statistical value	Shear strength (MPa)
Eastern hemlock	Mean	3.6
	COV (%)	23
	Count	14
Eastern white pine	Mean	2.1
	COV (%)	19
	Count	14

Table 7. Combined bending stiffness EI_{eff} and shear stiffness GA_{eff} results

Species	EI_{eff} (10^9 N · mm ² /m)	GA_{eff} (10^6 N/m)
Eastern hemlock	823	19.5
Eastern white pine	700	23.6

Table 8. Adjusted ASD reference design values of ANSI/APA PRG 320 established CLT grades

CLT grade	CLT depth (mm)	Layers' thickness (mm)	$F_b S_{eff,0}$ (10^6 N · mm/m)	$EI_{eff,0}$ (10^9 N · mm ² /m)	$GA_{eff,0}$ (10^6 N/m)
E1	99	33	18	913	6.4
E2	99	33	15	810	7.3
E3	99	33	11	650	4.8
E4	99	33	18	913	7.3
V1	99	33	8	857	7.3
V2	99	33	8	753	6.3
V3	99	33	9	857	7.3

Table 9. Preliminary ASD reference design values of 3-ply eastern species CLT panels

CLT species	CLT depth (mm)	Layers' thickness (mm)	$F_b S_{eff,0}$ (10^6 N · mm/m)	$EI_{app,0}$ (10^9 N · mm ² /m)	$EI_{eff,0}$ (10^9 N · mm ² /m)	$GA_{eff,0}$ (10^6 N/m)
Eastern hemlock	99	33	21	846	823	19.5
Eastern white pine	99	33	15	731	700	23.6

SOURCE OF INFORMATION

Clouston, P. L., Kaboli, H., & Lawrence, S. (2020). Feasibility of Two Northeastern Species in Three-Layer ANSI-Approved Cross-Laminated Timber. *Journal of Materials in Civil Engineering*, 32. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003058](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003058)

APPENDIX 2 – SAWTIMBER TREE DATA

NET VOLUMES OF SAWTIMBER SPECIES ON TIMBERLAND (cu.ft.)

	New York	Vermont	New Hampshire	Maine	Massachusetts	Connecticut	Rhode Island	TOTAL
<i>Eastern White Pine</i>	3,033,676,385	981,236,993	2,221,257,748	2,588,671,290	2,288,845,846	419,860,284	185,478,548	11,719,027,094
<i>Eastern Hemlock</i>	2,054,495,338	867,157,946	815,325,626	1,384,103,499	592,041,818	171,144,938	4,886,604	5,889,155,769
<i>Balsam Fir</i>	132,211,149	138,872,027	126,360,278	625,882,042	1,526,191	0	0	1,024,851,687
<i>Red Spruce</i>	267,817,979	355,494,774	351,102,038	1,828,588,312	42,363,579	0	0	2,845,366,682
<i>Red Pine</i>	404,724,804	15,363,485	29,296,461	165,201,226	3,104,505	4,419,201	0	622,109,682
<i>Norway Spruce</i>	388,794,067	27,185,374	0	16,482,967	9,324,790	23,778,294	0	465,565,492
<i>White Spruce</i>	37,992,388	27,067,777	15,964,241	334,040,143	0	0	0	415,064,549
<i>Tamarack</i>	81,188,136	4,380,960	10,398,213	106,504,937	354,781	1,312,185	0	204,139,212
<i>Pitch Pine</i>	63,826,106	0	12,850,096	8,062,204	60,404,916	3,550,903	15,021,979	163,716,204
<i>Scotch Pine</i>	146,626,037	3,458,993	0	870,259	0	550,980	0	151,506,269
<i>Larch</i>	112,562,556	0	0	1,370,912	0	0	0	113,933,468
<i>Black Spruce</i>	3,807,458	0	0	104,651,221	0	0	0	108,458,679
<i>Hard Maple</i>	2,731,794,117	1,330,071,256	410,538,849	783,485,871	189,573,330	113,696,190	1,044,285	5,560,203,898
<i>Red Maple</i>	2,558,719,912	556,345,768	553,978,586	792,383,688	540,648,782	442,571,545	55,517,456	5,500,165,737
<i>Northern Red Oak</i>	1,911,408,633	244,589,295	887,489,779	613,372,955	732,105,944	540,026,868	135,528,261	5,064,521,735
<i>White Ash</i>	1,027,432,169	324,245,107	170,149,148	185,763,642	170,319,604	106,906,673	309,822	1,985,126,165
<i>Yellow Birch</i>	450,515,935	373,770,461	249,704,082	525,671,377	83,744,790	19,836,207	3,984,359	1,707,227,211
<i>Black Cherry</i>	1,065,685,298	59,989,407	18,637,433	8,628,207	112,274,394	36,680,607	251,267	1,302,146,613
<i>American Beech</i>	548,937,397	152,484,203	156,574,787	128,492,530	73,393,841	65,165,956	2,458,790	1,127,507,504
<i>Black Oak</i>	224,259,585	2,677,441	60,707,534	13,149,275	225,259,756	352,045,679	48,856,134	926,955,404
<i>Quaking Aspen</i>	368,246,202	52,780,336	59,035,470	242,076,620	24,962,292	1,748,433	1,240,477	750,089,830
<i>White Oak</i>	298,473,370	10,838,223	38,236,018	13,458,152	155,570,233	167,091,201	41,977,451	725,644,648
<i>Sweet Birch</i>	234,315,122	58,926,369	45,023,669	4,585,457	122,159,829	151,675,257	7,659,983	624,345,686
<i>Bigtooth Aspen</i>	214,261,316	53,572,483	44,507,121	233,690,036	56,710,854	15,341,665	6,245,642	624,329,117
<i>Silver Maple</i>	242,776,718	6,344,230	2,118,449	1,812,840	19,064,249	3,758,488	462,272	276,337,246
<i>Yellow Poplar</i>	114,792,793	0	0	0	7,558,624	82,512,516	4,193,159	209,057,092
<i>American Elm</i>	52,068,422	8,070,126	617,774	4,579,699	1,819,881	5,694,794	0	72,850,696
<i>Black Locust</i>	45,459,818	0	0	0	3,480,358	9,313,638	0	58,253,814
TOTAL SOFTWOOD	6,727,722,403	2,420,218,329	3,582,554,701	7,164,429,012	2,997,966,426	624,616,785	205,387,131	23,722,894,787
TOTAL HARDWOOD	12,089,146,807	3,234,704,705	2,697,318,699	3,551,150,349	2,518,646,761	2,114,065,717	309,729,358	26,514,762,396
TOTAL	18,816,869,210	5,654,923,034	6,279,873,400	10,715,579,361	5,516,613,187	2,738,682,502	515,116,489	50,237,657,183

SOURCE OF INFORMATION

USDA Forest Service, *EVAL/Dator Tool* | <https://apps.fs.usda.gov/fiadb-api/evalidator>

APPENDIX 3 – TYPICAL MODULAR HOUSE

SINGLE-STORY MODULAR HOME MEAN RESULTS

3 BEDROOMS	AVG. SF.	1,614 SF
2 BATHROOMS	AVG. BASE PRICE	\$239,059
	\$ / SF	\$148.12

AVERAGE SQUARE FOOTAGE DERIVED FROM THE MEAN OF 44 THREE-BEDROOM MODULAR HOMES FROM 8 DIFFERENT COMPANIES ACROSS THE NORTHEAST

AVERAGE BASE PRICE DERIVED FROM THE MEAN OF THE 12 OUT OF 44 HOMES THAT WERE TRANSPARENT ABOUT THEIR PRICE

SOURCES OF INFORMATION

- Clayton Homes, NY | <https://www.claytonhomesutica.com>
- Showcase Homes of Maine, ME | <https://showcasehomesofmaine.com>
- Unity Homes, NH | <https://unityhomes.com>
- Lakes Region Modular Homes, NH | <https://lakesregionmodularhomes.com>
- Key Modular Homes, NY | <https://keymodularhomes.com>
- Village Homes, VT | <https://village-homes.com>
- Plattsburgh Housing Outlet, NY | <https://www.plattsburghhousing.com>
- Southern Maine Modular | <https://southernmainemodular.com>

REPRESENTATIVE MODULAR HOUSE SELECTION



THE APPLETON MODEL
KEY MODULAR HOMES, NY

1,592 sq.ft.
3 Bedrooms, 2 Bathrooms



SOURCE OF INFORMATION

Key Modular Homes, NY | <https://keymodularhomes.com>

APPENDIX 4 – MATERIAL QUANTITIES

CONSTRUCTION COMPOSITION QUANTITIES – BY GENERAL MATERIAL

Material	Volume (cu.ft.)	Volume (cu.m)	# of Instances	Density (kg/m3)	Total Mass (kg)
Blown in Fiberglass Insulation	2228.091	63.092	38	5.04	317.983
Fiberglass Batt Insulation	1433.564	40.594	422	15	608.904
Dimensional Lumber	807.922	22.878	2298	440	10066.138
OSB	250.135	7.083	255	613	4341.859
Gypsum Board	229.566	6.501	311	858	5577.449
Asphalt Roof Shingles	86.846	2.459	1827	2951.613	7258.553
Nylon Carpet	41.369	1.171	22	409.449	479.640
Rubber Underlayment	20.685	0.586	22	780	456.868
Vinyl Cladding	16.965	0.480	180	2135.827	1026.032
LVL Beam	15.536	0.440	13	563	247.679
Vinyl Trim Elements	10.524	0.298	94	1685.185	502.191
MDF Trim	9.413	0.267	147	756.43	201.622
Polypropylene Cladding	8.419	0.238	46	1685.185	401.744
Interior Finish Paint	6.703	0.190	15	1700	322.670
Vinyl Flooring	3.498	0.099	336	1600	158.482
Plastic Underlayment	2.154	0.061	6	933.333	56.928
Plastic Plank Flooring	0.811	0.023	24	1781.176	40.904
TOTAL	5172.201	146.459	6056		32065.647

TYPICAL MODULAR HOUSE

Material	Volume (cu.ft.)	Volume (cu.m)	# of Instances	Density (kg/m3)	Total Mass (kg)
Rigid Wood Fiber Insulation	1962.389	55.568	186	115	6390.337
EWP CLT	1606.129	45.480	95	511.71	23272.611
Wood Cladding	90.258	2.556	189	524.934	1341.625
Plywood	69.188	1.959	56	480	940.400
Wood Roof Shingles	55.67	1.576	1069	600	945.830
Wood Furring Strips	40.45	1.145	316	440	503.978
Micro-CLT	30.061	0.851	56	511.71	435.580
Glulam Beam	29.616	0.839	2	544	456.211
EPS Insulation	25.041	0.709	24	15	10.636
Dimensional Lumber	19.527	0.553	43	440	243.293
Wood Trim Elements	1.072	0.030	12	440	13.356
TOTAL	3929.401	111.267	2048		34553.859

MASS TIMBER HOUSE

Material	Volume (cu.ft.)	Volume (cu.m)	# of Instances	Density (kg/m3)	Total Mass (kg)
Fiberglass Batt Insulation	1425.798	40.374	247	15	605.606
Dimensional Lumber	433.53	12.276	1111	440	5401.478
Gypsum Board	208.199	5.895	401	858	5058.325
XPS Insulation Board	206.29	5.841	40	38	221.974
OSB	164.362	4.654	145	613	2853.006
Wood Cladding	90.258	2.556	189	524.934	1341.625
Wood Roof Shingles	55.67	1.576	1069	600	945.830
Wood Furring Strips	40.45	1.145	316	440	503.978
LVL Beam	31.701	0.898	2	563	505.385
Plywood	10.834	0.307	11	480	147.255
Interior Finish Paint	6.432	0.182	15	1700	309.625
MDF Trim	4.008	0.113	104	756.43	85.849
Sheet Vinyl Flooring	2.167	0.061	6	1600	98.179
Wood Trim Elements	1.072	0.030	12	440	13.356
Plastic Underlayment	0.542	0.015	6	933.333	14.324
TOTAL	2681.313	75.926	3674		18105.797

STANDARD CONSTRUCTED HOUSE

CONSTRUCTION COMPOSITION QUANTITIES - BY SPECIFIC MATERIAL

TYPICAL MODULAR HOUSE

MASS TIMBER HOUSE

STANDARD CONSTRUCTED HOUSE

BUILDING SHELL			BUILDING SHELL			BUILDING SHELL		
Material	Volume (cu.ft.)	# of Instances	Material	Volume (cu.ft.)	# of Instances	Material	Volume (cu.ft.)	# of Instances
17" Blown in Fiberglass	2228.091	38	5.5" Rigid Wood Fiber Insulation	1263.323	132	11.25" Fiberglass Batt	985.81	88
9.25" Fiberglass Batt	997.306	249	3-Ply EWP CLT	839.746	30	5.5" Fiberglass Batt	439.988	159
5.5" Fiberglass Batt	436.258	173	7.25" Rigid Wood Fiber Insulation	699.066	54	2" XPS Insulation Board	206.29	40
2x6 Lumber	255.217	844	Wood Clapboard Siding	79.317	159	2x12 Lumber	166.119	117
2x10 Lumber	185.587	370	5/8" Plywood	69.188	56	1/2" OSB	164.362	145
2x8 Lumber	185.494	229	Wood Roof Shingles	55.67	1069	2x6 Lumber	106.351	276
1/2" OSB	86.914	81	Glulam Beam	29.616	2	Wood Clapboard Siding	79.317	159
Asphalt Roof Shingles	86.846	1827	5.5" EPS Insulation	25.041	24	Wood Roof Shingles	55.67	1069
7/16" OSB	63.485	112	1x3 Furring Strip	23.404	124	LVL Beam	31.701	2
2x4 Lumber	24.493	106	1x2 Furring Strip	17.046	192	1x3 Furring Strip	23.404	124
2x12 Lumber	24.25	13	Micro-CLT Spline	13.427	24	1x2 Furring Strip	17.046	192
1/8" Vinyl Siding	16.965	180	Wood Accent Siding	10.941	30	Wood Accent Siding	10.941	30
Polypropylene Trim Panel	7.591	27	Wood Fascia	0.715	6	2x8 Lumber	6.298	29
LSL Beam	5.401	4	Wood Soffit	0.357	6	2x14 Lumber	5.276	32
Vinyl Shutters	4.832	6		3126.857	1908	Wood Fascia	0.715	6
Vinyl Soffit	2.886	28				Wood Soffit	0.357	6
1/8" Vinyl Trim	2.806	60					2299.645	2474
2x3 Lumber	2.306	78						
4x4 Post	1.478	3						
Polypropylene Siding	0.828	19						
Plastic Plank Flooring	0.811	24						
	4619.845	4471						
INTERIOR			INTERIOR			INTERIOR		
Material	Volume (cu.ft.)	# of Instances	Material	Volume (cu.ft.)	# of Instances	Material	Volume (cu.ft.)	# of Instances
1/2" Gypsum Board	154.277	234	3-Ply EWP CLT	766.383	65	1/2" Gypsum Board	196.369	328
2x4 Lumber	129.097	655	1/2" x 24" Micro-CLT Panel	15.053	29	2x4 Lumber	100.56	571
3/4" OSB	99.736	62	2x8 Lumber	13.147	23	2x10 Lumber	31.784	54
5/8" Gypsum Board	75.289	77	2x6 Lumber	3.932	10	2x8 Lumber	14.433	25
6 pile Nylon Carpet	41.369	22	1" x 4" EWP Wall Strips	2.448	10	5/8" Gypsum Board	11.83	73
1/4" Rubber Underlayment	20.685	22	Micro-CLT Spline	1.581	3	5/8" Plywood	10.834	11
LSL Beam	10.135	9		802.544	140	Interior Finish Paint	6.432	15
1/2" X 4" MDF Trim	9.413	147				1/2" x 4" MDF Trim	4.008	104
Interior Finish Paint	6.703	15				2x6 Lumber	2.709	7
Vinyl Flooring	3.498	336				Sheet Vinyl Flooring	2.167	6
Plastic Underlayment	2.154	6				1/32" Moisture Underlayment	0.542	6
	552.356	1585					381.668	1200
TOTAL	5172.201	6056	TOTAL	3929.401	2048	TOTAL	2681.313	3674

CONSTRUCTION COMPOSITION QUANTITIES - BY CLASSIFICATION

VOLUME (cu.ft.)						
	Building Shell; Structure	Insulation	Interior Structural Elements	Exterior Cladding Elements	Wall & Ceiling Finishes	Floor Coverings & Finishes
Typical Modular House	834.625	3661.655	139.232	122.754	245.682	168.253
Mass Timber House	951.977	1987.43	787.491	187.45	15.053	0
Standard-Constructed House	480.107	1632.088	149.486	187.45	218.639	13.543
# of Instances						
	Building Shell; Structure	Insulation	Interior Structural Elements	Exterior Cladding Elements	Wall & Ceiling Finishes	Floor Coverings & Finishes
Typical Modular House	1840	460	664	2147	473	472
Mass Timber House	112	210	111	1586	29	0
Standard-Constructed House	601	287	657	1586	520	23

SOURCES OF INFORMATION

Building Information Model Data -
Autodesk, *Autodesk Revit 2025 software* | <https://www.autodesk.com/products/revit>

Material Density Data -
One Click LCA Ltd., *One Click LCA software* | <https://oneclicklcaapp.com/>

APPENDIX 5 – LIFE CYCLE ASSESSMENTS

Data Source: One Click LCA (2015). Helsinki: One Click LCA Ltd.

CRADLE-TO-GATE LCA DATA

Level(s) life-cycle assessment (EN15804 +A1): Construction Materials

TYPICAL MODULAR HOUSE

Construction	Resource	User input	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-fossil elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	Comments
	Polypropylene siding, industry average, 2.16 mm, 3.64 kg/m2 ... ?	33 sq ft	3.06E+01 See calculations	0.00E+00 See calculations	9.20E-07 See calculations	1.02E-01 See calculations	4.25E-02 See calculations	5.66E-03 See calculations	1.56E-04 See calculations	7.76E+02 See calculations	Ornamental Shutter Panels
	Polypropylene siding, industry average, 2.16 mm, 3.64 kg/m2 ... ?	79 sq ft	7.35E+01 See calculations	0.00E+00 See calculations	2.21E-06 See calculations	2.44E-01 See calculations	1.02E-01 See calculations	1.36E-02 See calculations	3.74E-04 See calculations	1.86E+03 See calculations	
	Polypropylene siding, industry average, 2.16 mm, 3.64 kg/m2 ... ?	754 sq ft	6.98E+02 See calculations	0.00E+00 See calculations	2.10E-05 See calculations	2.31E+00 See calculations	9.67E-01 See calculations	1.29E-01 See calculations	3.55E-03 See calculations	1.77E+04 See calculations	Exterior Trim and Cover elements
	Vinyl siding, industry average, 1.016 mm, 2.17 kg/m2 (Vinyl ... ?	1,628 sq ft	7.23E+02 See calculations	0.00E+00 See calculations	3.89E-05 See calculations	5.55E+00 See calculations	5.22E-01 See calculations	2.98E-01 See calculations	6.28E-03 See calculations	1.88E+04 See calculations	
	Softwood board, kiln dried, sawn, 440 kg/m3, 10% moisture co... ?	1 cu ft	2.49E+00 See calculations	3.38E+01 See calculations	2.84E-07 See calculations	1.12E-02 See calculations	3.70E-03 See calculations	9.77E-04 See calculations	4.19E-05 See calculations	3.43E+01 See calculations	4x4 Lumber
	Softwood board, kiln dried, sawn, 440 kg/m3, 10% moisture co... ?	2 cu ft	3.88E+00 See calculations	5.27E+01 See calculations	4.43E-07 See calculations	1.75E-02 See calculations	5.78E-03 See calculations	1.52E-03 See calculations	6.53E-05 See calculations	5.36E+01 See calculations	2x3 Lumber
	Softwood board, kiln dried, sawn, 440 kg/m3, 10% moisture co... ?	24 cu ft	4.08E+01 See calculations	5.54E+02 See calculations	4.65E-06 See calculations	1.84E-01 See calculations	6.08E-02 See calculations	1.60E-02 See calculations	6.87E-04 See calculations	5.63E+02 See calculations	2x12 Lumber
	Softwood board, kiln dried, sawn, 440 kg/m3, 10% moisture co... ?	24 cu ft	4.12E+01 See calculations	5.59E+02 See calculations	4.70E-06 See calculations	1.86E-01 See calculations	6.14E-02 See calculations	1.62E-02 See calculations	6.94E-04 See calculations	5.69E+02 See calculations	2x4 Lumber
	Softwood board, kiln dried, sawn, 440 kg/m3, 10% moisture co... ?	185 cu ft	3.12E+02 See calculations	4.24E+03 See calculations	3.56E-05 See calculations	1.41E+00 See calculations	4.65E-01 See calculations	1.23E-01 See calculations	5.25E-03 See calculations	4.31E+03 See calculations	2x8 Lumber
	Softwood board, kiln dried, sawn, 440 kg/m3, 10% moisture co... ?	185 cu ft	3.12E+02 See calculations	4.24E+03 See calculations	3.56E-05 See calculations	1.41E+00 See calculations	4.65E-01 See calculations	1.23E-01 See calculations	5.26E-03 See calculations	4.31E+03 See calculations	2x10 Lumber
	Softwood board, kiln dried, sawn, 440 kg/m3, 10% moisture co... ?	255 cu ft	4.29E+02 See calculations	5.83E+03 See calculations	4.90E-05 See calculations	1.94E+00 See calculations	6.40E-01 See calculations	1.69E-01 See calculations	7.23E-03 See calculations	5.93E+03 See calculations	2x6 Lumber
	Laminated veneer lumber (LVL), 563 kg/m3, 6% moisture conten... ?	5 cu ft	2.72E+01 See calculations	1.58E+02 See calculations	2.87E-06 See calculations	1.21E-01 See calculations	3.31E-02 See calculations	1.06E-02 See calculations	2.00E-04 See calculations	5.01E+02 See calculations	
		Total	1.61E+04	2.68E+04	1.21E-03	6.97E+01	2.41E+01	4.01E+00	3.02E-01	2.57E+05	

TYPICAL MODULAR HOUSE

Construction	Resource	User input	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	Comments
	Oriented strand board (OSB), 613 kg/m ³ , 3% moisture content ... ?	63 cu ft	3.95E+02 See calculations	1.85E+03 See calculations	5.04E-05 See calculations	2.57E+00 See calculations	7.64E-01 See calculations	1.44E-01 See calculations	3.67E-03 See calculations	7.49E+03 See calculations	7/16" OSB
	Oriented strand board (OSB), 613 kg/m ³ , 3% moisture content ... ?	89 cu ft	5.59E+02 See calculations	2.62E+03 See calculations	7.14E-05 See calculations	3.64E+00 See calculations	1.08E+00 See calculations	2.04E-01 See calculations	5.20E-03 See calculations	1.06E+04 See calculations	1/2" OSB
	Vinyl flooring planks, 3-5.5 mm, 127 x 1219.2 mm, 7.57 kg/m ² ... ?	77 sq ft	8.75E+01 See calculations	0.00E+00 See calculations	4.95E-07 See calculations	2.14E-01 See calculations	3.60E-02 See calculations	2.60E-02 See calculations	3.00E-04 See calculations	1.68E+03 See calculations	Representative Product EPD for Vinyl Plank Porcrt Flooring
	Asphalt roofing shingles, 6.2 mm, 18.3 kg/m ² , Windsor® (Mala... ?	2,084 sq ft	8.87E+02 See calculations	0.00E+00 See calculations	8.67E-07 See calculations	2.32E+00 See calculations	3.25E-01 See calculations	2.71E-01 See calculations	1.35E-02 See calculations	1.94E+04 See calculations	Representative Product EPD for Asphalt Shingles
	Softwood board, kiln dried, sawn, 440 kg/m ³ , 10% moisture co... ?	129 cu ft	2.17E+02 See calculations	2.95E+03 See calculations	2.48E-05 See calculations	9.80E-01 See calculations	3.24E-01 See calculations	8.53E-02 See calculations	3.66E-03 See calculations	3.00E+03 See calculations	2x4 Lumber
	Laminated veneer lumber (LVL), 563 kg/m ³ , 6% moisture conten... ?	10 cu ft	5.11E+01 See calculations	2.96E+02 See calculations	5.39E-06 See calculations	2.28E-01 See calculations	6.21E-02 See calculations	1.99E-02 See calculations	3.76E-04 See calculations	9.39E+02 See calculations	
	Luxury vinyl flooring tile, 5 mm, 8 kg/m ² , wear layer: 0.5 m... ?	335 sq ft	3.22E+02 See calculations	0.00E+00 See calculations	1.64E-04 See calculations	1.19E+00 See calculations	3.47E-01 See calculations	6.96E-02 See calculations	6.48E-03 See calculations	7.12E+03 See calculations	Interior Vinyl Flooring
	Oriented strand board (OSB), 613 kg/m ³ , 3% moisture content ... ?	99 cu ft	6.20E+02 See calculations	2.91E+03 See calculations	7.92E-05 See calculations	4.04E+00 See calculations	1.20E+00 See calculations	2.26E-01 See calculations	5.77E-03 See calculations	1.18E+04 See calculations	3/4" OSB
	Polyethylene vapour barrier membrane, 0.15 mm, 0.14 kg/m ² (O... ?	413 sq ft	1.51E+01 See calculations	0.00E+00 See calculations	5.53E-07 See calculations	5.06E-02 See calculations	1.80E-02 See calculations	7.69E-03 See calculations	1.52E-04 See calculations	4.38E+02 See calculations	
	Tufted carpet tile with nylon 6 pile material and bitumen ba... ?	992 sq ft	1.44E+03 See calculations	0.00E+00 See calculations	6.57E-05 See calculations	3.60E+00 See calculations	5.88E-01 See calculations	2.10E-01 See calculations	1.56E-02 See calculations	2.09E+04 See calculations	Interior Carpet
	Gypsum plaster board, regular, generic, 6.5-25 mm (0.25-0.98... ?	3,180 lbs	4.21E+02 See calculations	0.00E+00 See calculations	3.19E-05 See calculations	1.78E+00 See calculations	2.19E+00 See calculations	1.17E-01 See calculations	4.63E-03 See calculations	5.56E+03 See calculations	
	Gypsum plaster board, regular, generic, 6.5-25 mm (0.25-0.98... ?	8,145 lbs	1.08E+03 See calculations	0.00E+00 See calculations	8.16E-05 See calculations	4.55E+00 See calculations	5.60E+00 See calculations	2.98E-01 See calculations	1.19E-02 See calculations	1.42E+04 See calculations	
	Low VOC, high solids paint, 0.365 kg/m ² , 1.7 kg/l, Internati... ?	5,148 sq ft	1.07E+03 See calculations	0.00E+00 See calculations	3.89E-05 See calculations	4.38E+00 See calculations	8.42E-01 See calculations	3.95E-01 See calculations	2.39E-03 See calculations	1.60E+04 See calculations	Representative Product EPD for Interior Paint
		Total	1.61E+04	2.68E+04	1.21E-03	6.97E+01	2.41E+01	4.01E+00	3.02E-01	2.57E+05	

TYPICAL MODULAR HOUSE

Construction	Resource	User input	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	Comments
	MDF veneered wood trims, 14.41 kg/m2, Trim (Rulon Internatio... ?	225 sq ft	6.48E+02 See calculations	5.28E+02 See calculations	4.54E-05 See calculations	2.93E+00 See calculations	1.81E+00 See calculations	1.69E-01 See calculations	1.29E-03 See calculations	8.49E+03 See calculations	
	Recycled rubber floor underlayment, 12 mm, 9.36 kg/m2, 780 k... ?	992 sq ft	8.11E+02 See calculations	0.00E+00 See calculations	6.48E-05 See calculations	4.14E+00 See calculations	6.65E-01 See calculations	2.02E-01 See calculations	8.69E-03 See calculations	1.87E+04 See calculations	Representative Product EPD for Underlayment under carpets
	Glass wool insulation in bats or rolls, unfaced, L = 0.034 W... ?	1,293 sq ft	3.54E+03 See calculations	0.00E+00 See calculations	2.36E-04 See calculations	1.55E+01 See calculations	3.97E+00 See calculations	4.56E-01 See calculations	1.22E-01 See calculations	3.91E+04 See calculations	9.25" Fiberglass Batt Insulation
	Glass wool insulation in bats or rolls, unfaced, L = 0.037 W... ?	951 sq ft	5.53E+02 See calculations	0.00E+00 See calculations	3.64E-05 See calculations	2.45E+00 See calculations	6.18E-01 See calculations	7.05E-02 See calculations	1.90E-02 See calculations	6.03E+03 See calculations	5.5" Fiberglass Batt Insulation
	Glass wool insulation, blown-in, R = 1 m2K/W, 114 mm, 0.574 ... ?	2,228 cu ft	7.13E+02 See calculations	0.00E+00 See calculations	1.09E-05 See calculations	1.65E+00 See calculations	2.57E-01 See calculations	1.30E-01 See calculations	4.78E-02 See calculations	1.06E+04 See calculations	Representative Product EPD for Blown-In Fiberglass Insulation
		Total	1.61E+04	2.68E+04	1.21E-03	6.97E+01	2.41E+01	4.01E+00	3.02E-01	2.57E+05	

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MASS TIMBER HOUSE

Level(s) life-cycle assessment (EN15804 +A1): Construction Materials

Construction	Resource	User input	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP- elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	Comments
	Solid wood roofing shingles, biogenic CO2 not subtracted (fo... ?	1,336 sq ft	2.91E+03 See calculations	8.04E+03 See calculations	3.68E-04 See calculations	1.40E+01 See calculations	4.05E+00 See calculations	2.15E+00 See calculations	1.62E-02 See calculations	3.45E+04 See calculations	Substitutional Product EPD to comparatively represent Eastern White Cedar Shingles
	Cross- Laminated Timber (CLT) panels, 511.71 kg/m3, TerraLam... ?	13 cu ft	3.23E+01 See calculations	3.57E+02 See calculations	3.46E-06 See calculations	1.76E-01 See calculations	4.68E-02 See calculations	6.46E-03 See calculations	4.68E-04 See calculations	5.70E+02 See calculations	Substitutional Product EPD to comparatively represent Eastern White Pine Mirco- CLT Spline
	Cross- Laminated Timber (CLT) panels, 511.71 kg/m3, TerraLam... ?	839 cu ft	2.02E+03 See calculations	2.23E+04 See calculations	2.17E-04 See calculations	1.10E+01 See calculations	2.92E+00 See calculations	4.04E-01 See calculations	2.92E-02 See calculations	3.57E+04 See calculations	Substitutional Product EPD to comparatively represent Eastern White Pine CLT
	Softwood board, kiln dried, sawn, 440 kg/m3, 10% moisture co... ?	1 cu ft	1.80E+00 See calculations	2.45E+01 See calculations	2.06E-07 See calculations	8.14E-03 See calculations	2.69E-03 See calculations	7.09E-04 See calculations	3.04E-05 See calculations	2.49E+01 See calculations	Exterior Trim Elements
	Softwood board, kiln dried, sawn, 440 kg/m3, 10% moisture co... ?	17 cu ft	2.87E+01 See calculations	3.89E+02 See calculations	3.27E-06 See calculations	1.29E-01 See calculations	4.27E-02 See calculations	1.13E-02 See calculations	4.83E-04 See calculations	3.96E+02 See calculations	1x2 Furring Strip
	Softwood board, kiln dried, sawn, 440 kg/m3, 10% moisture co... ?	23 cu ft	3.94E+01 See calculations	5.35E+02 See calculations	4.49E-06 See calculations	1.78E-01 See calculations	5.87E-02 See calculations	1.55E-02 See calculations	6.63E-04 See calculations	5.44E+02 See calculations	1x3 Furring Strip
	Glue laminated timber (Glulam), 544 kg/m3, 12% (± 3%) moistu... ?	29 cu ft	1.28E+02 See calculations	7.92E+02 See calculations	1.90E-05 See calculations	7.44E-01 See calculations	2.09E-01 See calculations	3.51E-02 See calculations	1.80E-03 See calculations	1.81E+03 See calculations	
	Softwood plywood, uncoated, 480 kg/m3, 8% moisture content (... ?	69 cu ft	3.72E+02 See calculations	1.54E+03 See calculations	5.20E-05 See calculations	1.49E+00 See calculations	5.11E-01 See calculations	1.38E-01 See calculations	2.06E-03 See calculations	5.80E+03 See calculations	
	Stained solid softwood cladding, 10 kg/m2 (One Click LCA) ?	175 sq ft	1.34E+02 See calculations	2.42E+02 See calculations	1.18E-05 See calculations	1.06E+00 See calculations	2.37E-01 See calculations	5.46E-02 See calculations	2.24E-03 See calculations	1.75E+03 See calculations	Wood Shiplap Accent Siding
	Stained solid softwood cladding, 10	1,269 sq ft	9.73E+02 See calculations	1.75E+03 See calculations	8.57E-05 See calculations	7.69E+00 See calculations	1.72E+00 See calculations	3.96E-01 See calculations	1.62E-02 See calculations	1.27E+04 See calculations	White Cedar Clapboard or Bevel Siding
		Total	1.10E+04	6.51E+04	1.40E-03	5.22E+01	1.33E+01	4.02E+00	9.74E-02	1.66E+05	

MASS TIMBER HOUSE

Construction	Resource	User input	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	Comments
	kg/m2 (One Click LCA) ?										
	Cross-Laminated Timber (CLT) panels, 511.71 kg/m3, TerraLam... ?	1 cu ft	3.80E+00 See calculations	4.20E+01 See calculations	4.08E-07 See calculations	2.07E-02 See calculations	5.51E-03 See calculations	7.61E-04 See calculations	5.51E-05 See calculations	6.72E+01 See calculations	Substitutional Product EPD to comparatively represent Eastern White Pine Micro-CLT Spline
	Cross-Laminated Timber (CLT) panels, 511.71 kg/m3, TerraLam... ?	15 cu ft	3.62E+01 See calculations	4.00E+02 See calculations	3.88E-06 See calculations	1.97E-01 See calculations	5.24E-02 See calculations	7.25E-03 See calculations	5.24E-04 See calculations	6.39E+02 See calculations	Substitutional Product EPD to comparatively represent Eastern White Pine Micro-CLT Wall Panel
	Cross-Laminated Timber (CLT) panels, 511.71 kg/m3, TerraLam... ?	766 cu ft	1.84E+03 See calculations	2.04E+04 See calculations	1.98E-04 See calculations	1.00E+01 See calculations	2.67E+00 See calculations	3.69E-01 See calculations	2.67E-02 See calculations	3.26E+04 See calculations	Substitutional Product EPD to comparatively represent Eastern White Pine CLT
	Softwood board, kiln dried, sawn, 440 kg/m3, 10% moisture co... ?	2 cu ft	4.12E+00 See calculations	5.59E+01 See calculations	4.70E-07 See calculations	1.86E-02 See calculations	6.14E-03 See calculations	1.62E-03 See calculations	6.93E-05 See calculations	5.68E+01 See calculations	Milled Eastern White Pine Picture Frame Strips
	Softwood board, kiln dried, sawn, 440 kg/m3, 10% moisture co... ?	3 cu ft	5.71E+00 See calculations	7.75E+01 See calculations	6.51E-07 See calculations	2.58E-02 See calculations	8.50E-03 See calculations	2.24E-03 See calculations	9.61E-05 See calculations	7.88E+01 See calculations	2x6 Lumber
	Softwood board, kiln dried, sawn, 440 kg/m3, 10% moisture co... ?	13 cu ft	2.21E+01 See calculations	3.00E+02 See calculations	2.52E-06 See calculations	9.98E-02 See calculations	3.30E-02 See calculations	8.69E-03 See calculations	3.72E-04 See calculations	3.05E+02 See calculations	2x8 Lumber
	Wood fiber insulation panel, biogenic CO2 not subtracted (fo... ?	1,157 sq ft	7.11E+02 See calculations	2.33E+03 See calculations	1.27E-04 See calculations	1.56E+00 See calculations	2.15E-01 See calculations	1.24E-01 See calculations	3.85E-05 See calculations	1.13E+04 See calculations	Substitutional Product EPD to comparatively represent TimberBoard 7.25" Rigid Wood Fiber Insulation by TimberHP
	Wood fiber insulation panel, biogenic CO2 not subtracted (fo... ?	2,756 sq ft	1.69E+03 See calculations	5.54E+03 See calculations	3.02E-04 See calculations	3.73E+00 See calculations	5.12E-01 See calculations	2.95E-01 See calculations	9.17E-05 See calculations	2.70E+04 See calculations	Substitutional Product EPD to comparatively represent TimberBoard 5.5" Rigid Wood Fiber Insulation by TimberHP
	EPS insulation panels, white, L= 0.037 W/mK, R= 2.7 m2KW, 1... ?	54 sq ft	3.76E+01 See calculations	0.00E+00 See calculations	6.99E-07 See calculations	5.54E-02 See calculations	7.17E-03 See calculations	4.02E-03 See calculations	1.19E-05 See calculations	5.31E+02 See calculations	
		Total	1.10E+04	6.51E+04	1.40E-03	5.22E+01	1.33E+01	4.02E+00	9.74E-02	1.66E+05	

Level(s) life-cycle assessment (EN15804 +A1): Construction Materials

STANDARD CONSTRUCTED HOUSE

Construction	Resource	User input	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	Comments
	Solid wood roofing shingles, biogenic CO ₂ not subtracted (fo... ?	1,336 sq ft	2.91E+03 See calculations	8.04E+03 See calculations	3.68E-04 See calculations	1.40E+01 See calculations	4.05E+00 See calculations	2.15E+00 See calculations	1.62E-02 See calculations	3.45E+04 See calculations	Substitutional Product EPD to comparatively represent Eastern White Cedar Shingles
	Softwood board, kiln dried, sawn, 440 kg/m ³ , 10% moisture co... ?	1 cu ft	1.80E+00 See calculations	2.45E+01 See calculations	2.06E-07 See calculations	8.14E-03 See calculations	2.69E-03 See calculations	7.09E-04 See calculations	3.04E-05 See calculations	2.49E+01 See calculations	Exterior Trim Elements
	Softwood board, kiln dried, sawn, 440 kg/m ³ , 10% moisture co... ?	5 cu ft	8.88E+00 See calculations	1.21E+02 See calculations	1.01E-06 See calculations	4.01E-02 See calculations	1.32E-02 See calculations	3.49E-03 See calculations	1.49E-04 See calculations	1.23E+02 See calculations	2x14 Lumber
	Softwood board, kiln dried, sawn, 440 kg/m ³ , 10% moisture co... ?	6 cu ft	1.06E+01 See calculations	1.44E+02 See calculations	1.21E-06 See calculations	4.78E-02 See calculations	1.58E-02 See calculations	4.16E-03 See calculations	1.78E-04 See calculations	1.46E+02 See calculations	2x8 Lumber
	Softwood board, kiln dried, sawn, 440 kg/m ³ , 10% moisture co... ?	17 cu ft	2.87E+01 See calculations	3.89E+02 See calculations	3.27E-06 See calculations	1.29E-01 See calculations	4.27E-02 See calculations	1.13E-02 See calculations	4.83E-04 See calculations	3.96E+02 See calculations	1x2 Furring Strip
	Softwood board, kiln dried, sawn, 440 kg/m ³ , 10% moisture co... ?	23 cu ft	3.94E+01 See calculations	5.35E+02 See calculations	4.49E-06 See calculations	1.78E-01 See calculations	5.87E-02 See calculations	1.55E-02 See calculations	6.63E-04 See calculations	5.44E+02 See calculations	1x3 Furring Strip
	Softwood board, kiln dried, sawn, 440 kg/m ³ , 10% moisture co... ?	106 cu ft	1.79E+02 See calculations	2.43E+03 See calculations	2.04E-05 See calculations	8.08E-01 See calculations	2.67E-01 See calculations	7.03E-02 See calculations	3.01E-03 See calculations	2.47E+03 See calculations	2x6 Lumber
	Softwood board, kiln dried, sawn, 440 kg/m ³ , 10% moisture co... ?	116 cu ft	1.95E+02 See calculations	2.65E+03 See calculations	2.23E-05 See calculations	8.82E-01 See calculations	2.91E-01 See calculations	7.68E-02 See calculations	3.29E-03 See calculations	2.70E+03 See calculations	2x12 Lumber
	Laminated veneer lumber (LVL), 563 kg/m ³ , 6% moisture conten... ?	31 cu ft	1.60E+02 See calculations	9.26E+02 See calculations	1.69E-05 See calculations	7.13E-01 See calculations	1.94E-01 See calculations	6.21E-02 See calculations	1.18E-03 See calculations	2.94E+03 See calculations	
	Oriented strand board (OSB), 613 kg/m ³ , 3% moisture content ... ?	164 cu ft	1.02E+03 See calculations	4.79E+03 See calculations	1.31E-04 See calculations	6.65E+00 See calculations	1.98E+00 See calculations	3.73E-01 See calculations	9.51E-03 See calculations	1.94E+04 See calculations	
	Stained solid softwood cladding, 10 kg/m ² (One Click LCA) ?	175 sq ft	1.34E+02 See calculations	2.42E+02 See calculations	1.18E-05 See calculations	1.06E+00 See calculations	2.37E-01 See calculations	5.46E-02 See calculations	2.24E-03 See calculations	1.75E+03 See calculations	Wood Shiplap Accent Siding
	Stained solid softwood cladding, 10 kg/m ² (One Click LCA) ?	1,269 sq ft	9.73E+02 See calculations	1.75E+03 See calculations	8.57E-05 See calculations	7.69E+00 See calculations	1.72E+00 See calculations	3.96E-01 See calculations	1.62E-02 See calculations	1.27E+04 See calculations	Eastern White Cedar Clapboard or Bevel Siding
		Total	1.37E+04	2.59E+04	1.15E-03	6.56E+01	2.32E+01	4.96E+00	2.18E-01	1.86E+05	

STANDARD CONSTRUCTED HOUSE

Construction	Resource	User input	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	Comments
	Vinyl flooring, heterogeneous, 1.1-5.5 mm x 1.83-3.66 m, 1.... ?	2 cu ft	1.39E+02 See calculations	0.00E+00 See calculations	1.19E-07 See calculations	3.62E-01 See calculations	4.14E-02 See calculations	8.16E-02 See calculations	4.34E-04 See calculations	2.69E+03 See calculations	
	Softwood board, kiln dried, sawn, 440 kg/m ³ , 10% moisture co... ?	2 cu ft	4.56E+00 See calculations	6.19E+01 See calculations	5.20E-07 See calculations	2.06E-02 See calculations	6.79E-03 See calculations	1.79E-03 See calculations	7.67E-05 See calculations	6.29E+01 See calculations	2x6 Lumber
	Softwood board, kiln dried, sawn, 440 kg/m ³ , 10% moisture co... ?	14 cu ft	2.43E+01 See calculations	3.30E+02 See calculations	2.77E-06 See calculations	1.10E-01 See calculations	3.62E-02 See calculations	9.54E-03 See calculations	4.09E-04 See calculations	3.35E+02 See calculations	2x8 Lumber
	Softwood board, kiln dried, sawn, 440 kg/m ³ , 10% moisture co... ?	31 cu ft	5.35E+01 See calculations	7.26E+02 See calculations	6.10E-06 See calculations	2.41E-01 See calculations	7.97E-02 See calculations	2.10E-02 See calculations	9.00E-04 See calculations	7.38E+02 See calculations	2x10 Lumber
	Softwood board, kiln dried, sawn, 440 kg/m ³ , 10% moisture co... ?	100 cu ft	1.69E+02 See calculations	2.30E+03 See calculations	1.93E-05 See calculations	7.64E-01 See calculations	2.52E-01 See calculations	6.65E-02 See calculations	2.85E-03 See calculations	2.34E+03 See calculations	2x4 Lumber
	Polyethylene vapour barrier membrane, 0.15 mm, 0.14 kg/m ² (O... ?	208 sq ft	7.62E+00 See calculations	0.00E+00 See calculations	2.78E-07 See calculations	2.54E-02 See calculations	9.07E-03 See calculations	3.87E-03 See calculations	7.66E-05 See calculations	2.20E+02 See calculations	
	Softwood plywood, uncoated, 480 kg/m ³ , 8% moisture content (... ?	10 cu ft	5.83E+01 See calculations	2.41E+02 See calculations	8.15E-06 See calculations	2.34E-01 See calculations	8.00E-02 See calculations	2.15E-02 See calculations	3.22E-04 See calculations	9.08E+02 See calculations	
	Gypsum plaster board, regular, generic, 6.5-25 mm (0.25-0.98... ?	499 lbs	6.62E+01 See calculations	0.00E+00 See calculations	5.00E-06 See calculations	2.79E-01 See calculations	3.44E-01 See calculations	1.83E-02 See calculations	7.28E-04 See calculations	8.73E+02 See calculations	5/8" Gypsum Board
	Gypsum plaster board, regular, generic, 6.5-25 mm (0.25-0.98... ?	10,368 lbs	1.37E+03 See calculations	0.00E+00 See calculations	1.04E-04 See calculations	5.79E+00 See calculations	7.13E+00 See calculations	3.80E-01 See calculations	1.51E-02 See calculations	1.81E+04 See calculations	1/2" Gypsum Board
	Low VOC, high solids paint, 0.365 kg/m ² , 1.7 kg/l, Internati... ?	4,939 sq ft	1.03E+03 See calculations	0.00E+00 See calculations	3.73E-05 See calculations	4.20E+00 See calculations	8.08E-01 See calculations	3.79E-01 See calculations	2.29E-03 See calculations	1.53E+04 See calculations	Placeholder Product EPD for Typical Interior Paint
	MDF veneered wood trims, 14.41 kg/m ² , Trim (Rulon Internatio... ?	96 sq ft	2.76E+02 See calculations	2.25E+02 See calculations	1.93E-05 See calculations	1.25E+00 See calculations	7.69E-01 See calculations	7.21E-02 See calculations	5.50E-04 See calculations	3.61E+03 See calculations	Placeholder Product EPD for Interior Floor Trim
	Glass wool insulation in bats or rolls, unfaced, L = 0.034 W... ?	1,051 sq ft	3.50E+03 See calculations	0.00E+00 See calculations	2.34E-04 See calculations	1.53E+01 See calculations	3.92E+00 See calculations	4.50E-01 See calculations	1.21E-01 See calculations	3.87E+04 See calculations	11.25" Fiberglass Batt Insulation
	Glass wool insulation in bats or rolls, unfaced, L = 0.037 W... ?	959 sq ft	5.58E+02 See calculations	0.00E+00 See calculations	3.67E-05 See calculations	2.47E+00 See calculations	6.23E-01 See calculations	7.11E-02 See calculations	1.92E-02 See calculations	6.08E+03 See calculations	5.5" Fiberglass Batt Insulation
	XPS insulation panels, L=0.035 W/mK, R=2.85	1,237 sq ft	8.03E+02 See calculations	0.00E+00 See calculations	1.00E-05 See calculations	2.39E+00 See calculations	2.63E-01 See calculations	1.68E-01 See calculations	9.37E-04 See calculations	1.80E+04 See calculations	2" XPS Rigid Insulation Board
		Total	1.37E+04	2.59E+04	1.15E-03	6.56E+01	2.32E+01	4.96E+00	2.18E-01	1.86E+05	

CRADLE-TO-GRAVE: YEAR-30 LCA DATA

Level(s) life-cycle assessment (EN15804 +A1)

TYPICAL MODULAR HOUSE - YEAR 30

Section	Result category	Global warming kg CO2e	Biogenic carbon storage kg CO2e bio	Ozone Depletion kg CFC11e	Acidification kg SO2e	Eutrophication kg PO4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
A1-A3	Construction Materials	1.61E+04	2.68E+04	1.21E-03	6.97E+01	2.41E+01	4.01E+00	3.02E-01	2.57E+05
A4	Transportation to site								
A4	Transport to the building site								
A4-leg2	Transportation to site - leg 2								
A5	Construction/installation process	2.28E+03		1.67E-04	8.60E+00	3.12E+00	5.11E-01	2.22E-01	3.01E+04
A5a	Site operations & site waste handling								
A5b	Site waste transportation								
A5c	Construction site - material wastage - materials	1.78E+03		1.45E-04	7.92E+00	2.95E+00	4.81E-01	2.95E-02	2.83E+04
A5d	Construction site - material wastage - transport								
A5e	Construction site - material wastage - waste	5.00E+02	0.00E+00	2.16E-05	6.77E-01	1.66E-01	2.98E-02	1.92E-01	1.80E+03
A5m-waste	Construction site - material use on site - waste								
B1	Use phase								
B1-a	Refrigerant annual leakages								
B1-b	Refrigerant loss, equipment replacement								
B1-c	Refrigerant loss, equipment end of life								
B1-d	Carbonisation								
B1-e	Vegetation withdrawal of carbon								
B3	Repair	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3a	Repair - materials	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3b	Repair - transport								
B3c	Repair - waste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5	Material replacement and refurbishment	9.12E+03		4.84E-04	2.23E+01	3.96E+00	1.71E+00	1.81E-01	1.06E+05
B4-B5a	Material replacement - materials	5.69E+03		3.74E-04	2.02E+01	3.65E+00	1.57E+00	4.94E-02	9.97E+04
B4-B5b	Material replacement - transport								
B4-B5b-leg2	Material replacement - transport leg 2								
B4-B5c	Material replacement - waste	3.43E+03	0.00E+00	1.11E-04	2.08E+00	3.18E-01	1.37E-01	1.32E-01	6.17E+03
B6	Energy consumption								
B7	Water use								

TYPICAL MODULAR HOUSE - YEAR 30

Section	Result category	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP- elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
C1-C4	End of life	5.10E+03		2.01E-04	5.36E+00	1.19E+00	2.61E-01	1.42E+00	1.52E+04
C1	Deconstruction/demolition								
C2	Waste transport	1.95E+02		3.85E-05	8.89E-01	1.93E-01	1.20E-02	1.41E+00	5.58E+03
C3	Waste processing	4.89E+03		1.60E-04	4.37E+00	9.70E-01	2.46E-01	6.27E-03	9.45E+03
C4	Waste disposal	1.41E+01		2.53E-06	1.04E-01	2.22E-02	2.82E-03	9.80E-06	2.02E+02
D	External impacts (not included in totals)	-3.18E+04		-4.26E-03	-7.92E+01	-1.12E+01	-4.69E+00	-2.04E-01	-4.57E+05
D	Installed Materials - benefit	-2.59E+04	0.00E+00	-3.46E-03	-6.45E+01	-9.13E+00	-3.82E+00	-1.81E-01	-3.72E+05
A5- benefit	Construction site - material wastage - benefit	-4.20E+03	0.00E+00	-5.63E-04	-1.05E+01	-1.48E+00	-6.21E-01	-2.27E-02	-6.04E+04
A5m- benefit	Construction site - material use - benefit								
B3- benefit	Repair - benefit	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5- benefit	Material replacement - benefit	-1.73E+03	0.00E+00	-2.32E-04	-4.31E+00	-6.09E-01	-2.56E-01	-1.53E-04	-2.49E+04
D2	Exported energy (not included in totals)								

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Level(s) life-cycle assessment (EN15804 +A1)

MASS TIMBER HOUSE - YEAR 30

Section	Result category	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP- elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
A1-A3	Construction Materials	1.10E+04	6.51E+04	1.40E-03	5.22E+01	1.33E+01	4.02E+00	9.74E-02	1.66E+05
A4	Transportation to site								
A4	Transport to the building site								
A4-leg2	Transportation to site - leg 2								
A5	Construction/installation process	1.38E+03		1.70E-04	6.98E+00	1.83E+00	6.08E-01	6.19E-02	1.97E+04
A5a	Site operations & site waste handling								
A5b	Site waste transportation								
A5c	Construction site - material wastage - materials	1.35E+03		1.67E-04	6.77E+00	1.77E+00	6.02E-01	1.20E-02	1.93E+04
A5d	Construction site - material wastage - transport								
A5e	Construction site - material wastage - waste	2.79E+01	0.00E+00	3.02E-06	2.08E-01	6.55E-02	6.58E-03	4.99E-02	3.90E+02
A5m- waste	Construction site - material use on site - waste								
B1	Use phase								
B1-a	Refrigerant annual leakages								
B1-b	Refrigerant loss, equipment replacement								
B1-c	Refrigerant loss, equipment end of life								
B1-d	Carbonisation								
B1-e	Vegetation withdrawal of carbon								
B3	Repair	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3a	Repair - materials	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3b	Repair - transport								
B3c	Repair - waste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5	Material replacement and refurbishment								
B4-B5a	Material replacement - materials								
B4-B5b	Material replacement - transport								
B4-B5b- leg2	Material replacement - transport leg 2								
B4-B5c	Material replacement - waste								
B6	Energy consumption								
B7	Water use								

MASS TIMBER HOUSE - YEAR 30

Section	Result category	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP- elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
C1-C4	End of life	1.90E+02		2.04E-05	1.27E+00	3.91E-01	3.98E-02	3.40E-01	2.56E+03
C1	Deconstruction/demolition								
C2	Waste transport	4.69E+01		9.27E-06	2.15E-01	4.68E-02	2.76E-03	3.40E-01	1.34E+03
C3	Waste processing	1.30E+02		8.84E-06	9.62E-01	3.23E-01	3.44E-02	3.33E-04	1.04E+03
C4	Waste disposal	1.30E+01		2.34E-06	9.59E-02	2.05E-02	2.61E-03	9.07E-06	1.87E+02
D	External impacts (not included in totals)	-1.87E+04		-2.39E-03	-5.92E+01	-1.13E+01	-2.99E+00	-6.31E-02	-2.83E+05
D	Installed Materials - benefit	-1.62E+04	-4.35E+04	-2.07E-03	-5.20E+01	-1.00E+01	-2.60E+00	-5.81E-02	-2.46E+05
A5- benefit	Construction site - material wastage - benefit	-2.50E+03	-3.69E+03	-3.26E-04	-7.22E+00	-1.25E+00	-3.87E-01	-5.04E-03	-3.71E+04
A5m- benefit	Construction site - material use - benefit								
B3- benefit	Repair - benefit	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5- benefit	Material replacement - benefit								
D2	Exported energy (not included in totals)								

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Level(s) life-cycle assessment (EN15804 +A1)

STANDARD CONSTRUCTED HOUSE - YEAR 30

Section	Result category	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP- elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
A1-A3	Construction Materials	1.37E+04	2.59E+04	1.15E-03	6.56E+01	2.32E+01	4.96E+00	2.18E-01	1.86E+05
A4	Transportation to site								
A4	Transport to the building site								
A4-leg2	Transportation to site - leg 2								
A5	Construction/installation process	1.84E+03		1.75E-04	9.29E+00	3.29E+00	7.62E-01	1.99E-01	2.46E+04
A5a	Site operations & site waste handling								
A5b	Site waste transportation								
A5c	Construction site - material wastage - materials	1.75E+03		1.66E-04	8.86E+00	3.16E+00	7.48E-01	2.38E-02	2.35E+04
A5d	Construction site - material wastage - transport								
A5e	Construction site - material wastage - waste	8.70E+01	0.00E+00	8.34E-06	4.34E-01	1.30E-01	1.34E-02	1.75E-01	1.07E+03
A5m- waste	Construction site - material use on site - waste								
B1	Use phase								
B1-a	Refrigerant annual leakages								
B1-b	Refrigerant loss, equipment replacement								
B1-c	Refrigerant loss, equipment end of life								
B1-d	Carbonisation								
B1-e	Vegetation withdrawal of carbon								
B3	Repair	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3a	Repair - materials	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3b	Repair - transport								
B3c	Repair - waste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5	Material replacement and refurbishment	2.28E+03		7.78E-05	8.83E+00	1.67E+00	8.43E-01	1.34E-02	3.35E+04
B4-B5a	Material replacement - materials	2.20E+03		7.47E-05	8.77E+00	1.66E+00	8.40E-01	5.02E-03	3.34E+04
B4-B5b	Material replacement - transport								
B4-B5b- leg2	Material replacement - transport leg 2								
B4-B5c	Material replacement - waste	8.91E+01	0.00E+00	3.08E-06	6.08E-02	9.78E-03	3.68E-03	8.36E-03	1.86E+02
B6	Energy consumption								
B7	Water use								

STANDARD CONSTRUCTED HOUSE - YEAR 30

Section	Result category	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP- elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
C1-C4	End of life	9.26E+02		6.69E-05	2.86E+00	8.07E-01	9.49E-02	1.25E+00	7.73E+03
C1	Deconstruction/demolition								
C2	Waste transport	1.72E+02		3.39E-05	7.84E-01	1.71E-01	1.06E-02	1.24E+00	4.93E+03
C3	Waste processing	7.50E+02		3.23E-05	2.05E+00	6.30E-01	8.35E-02	1.67E-03	2.75E+03
C4	Waste disposal	4.01E+00		7.20E-07	2.95E-02	6.30E-03	8.02E-04	2.79E-06	5.73E+01
D	External impacts (not included in totals)	-2.73E+04		-3.66E-03	-6.81E+01	-9.65E+00	-4.03E+00	-1.95E-01	-3.92E+05
D	Installed Materials - benefit	-2.32E+04	0.00E+00	-3.11E-03	-5.78E+01	-8.20E+00	-3.43E+00	-1.74E-01	-3.33E+05
A5- benefit	Construction site - material wastage - benefit	-3.97E+03	0.00E+00	-5.33E-04	-9.91E+00	-1.40E+00	-5.87E-01	-2.18E-02	-5.71E+04
A5m- benefit	Construction site - material use - benefit								
B3- benefit	Repair - benefit	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5- benefit	Material replacement - benefit	-1.30E+02	0.00E+00	-1.74E-05	-3.23E-01	-4.57E-02	-1.92E-02	-1.15E-05	-1.87E+03
D2	Exported energy (not included in totals)								

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CRADLE-TO-GRAVE: YEAR-60 LCA DATA

Level(s) life-cycle assessment (EN15804 +A1)

TYPICAL MODULAR HOUSE - YEAR 60

Section	Result category	Global warming kg CO2e	Biogenic carbon storage kg CO2e bio	Ozone Depletion kg CFC11e	Acidification kg SO2e	Eutrophication kg PO4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
A1-A3	Construction Materials	1.61E+04	2.68E+04	1.21E-03	6.97E+01	2.41E+01	4.01E+00	3.02E-01	2.57E+05
A4	Transportation to site								
A4	Transport to the building site								
A4-leg2	Transportation to site - leg 2								
A5	Construction/installation process	2.28E+03		1.67E-04	8.60E+00	3.12E+00	5.11E-01	2.22E-01	3.01E+04
A5a	Site operations & site waste handling								
A5b	Site waste transportation								
A5c	Construction site - material wastage - materials	1.78E+03		1.45E-04	7.92E+00	2.95E+00	4.81E-01	2.95E-02	2.83E+04
A5d	Construction site - material wastage - transport								
A5e	Construction site - material wastage - waste	5.00E+02	0.00E+00	2.16E-05	6.77E-01	1.66E-01	2.98E-02	1.92E-01	1.80E+03
A5m-waste	Construction site - material use on site - waste								
B1	Use phase								
B1-a	Refrigerant annual leakages								
B1-b	Refrigerant loss, equipment replacement								
B1-c	Refrigerant loss, equipment end of life								
B1-d	Carbonisation								
B1-e	Vegetation withdrawal of carbon								
B3	Repair	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3a	Repair - materials	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3b	Repair - transport								
B3c	Repair - waste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5	Material replacement and refurbishment	2.52E+04		1.25E-03	6.51E+01	1.30E+01	4.73E+00	4.38E-01	3.01E+05
B4-B5a	Material replacement - materials	1.61E+04		9.61E-04	5.96E+01	1.22E+01	4.37E+00	1.29E-01	2.84E+05
B4-B5b	Material replacement - transport								
B4-B5b-leg2	Material replacement - transport leg 2								
B4-B5c	Material replacement - waste	9.16E+03	0.00E+00	2.94E-04	5.51E+00	8.44E-01	3.66E-01	3.09E-01	1.63E+04
B6	Energy consumption								
B7	Water use								

TYPICAL MODULAR HOUSE - YEAR 60

Section	Result category	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP- elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
C1-C4	End of life	5.10E+03		2.01E-04	5.36E+00	1.19E+00	2.61E-01	1.42E+00	1.52E+04
C1	Deconstruction/demolition								
C2	Waste transport	1.95E+02		3.85E-05	8.89E-01	1.93E-01	1.20E-02	1.41E+00	5.58E+03
C3	Waste processing	4.89E+03		1.60E-04	4.37E+00	9.70E-01	2.46E-01	6.27E-03	9.45E+03
C4	Waste disposal	1.41E+01		2.53E-06	1.04E-01	2.22E-02	2.82E-03	9.80E-06	2.02E+02
D	External impacts (not included in totals)	-3.66E+04		-4.90E-03	-9.12E+01	-1.29E+01	-5.40E+00	-2.04E-01	-5.26E+05
D	Installed Materials - benefit	-2.59E+04	0.00E+00	-3.46E-03	-6.45E+01	-9.13E+00	-3.82E+00	-1.81E-01	-3.72E+05
A5- benefit	Construction site - material wastage - benefit	-4.20E+03	0.00E+00	-5.63E-04	-1.05E+01	-1.48E+00	-6.21E-01	-2.27E-02	-6.04E+04
A5m- benefit	Construction site - material use - benefit								
B3- benefit	Repair - benefit	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5- benefit	Material replacement - benefit	-6.52E+03	0.00E+00	-8.74E-04	-1.62E+01	-2.29E+00	-9.63E-01	-5.75E-04	-9.37E+04
D2	Exported energy (not included in totals)								

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Level(s) life-cycle assessment (EN15804 +A1)

MASS TIMBER HOUSE - YEAR 60

Section	Result category	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
A1-A3	Construction Materials	1.10E+04	6.51E+04	1.40E-03	5.22E+01	1.33E+01	4.02E+00	9.74E-02	1.66E+05
A4	Transportation to site								
A4	Transport to the building site								
A4-leg2	Transportation to site - leg 2								
A5	Construction/installation process	1.38E+03		1.70E-04	6.98E+00	1.83E+00	6.08E-01	6.19E-02	1.97E+04
A5a	Site operations & site waste handling								
A5b	Site waste transportation								
A5c	Construction site - material wastage - materials	1.35E+03		1.67E-04	6.77E+00	1.77E+00	6.02E-01	1.20E-02	1.93E+04
A5d	Construction site - material wastage - transport								
A5e	Construction site - material wastage - waste	2.79E+01	0.00E+00	3.02E-06	2.08E-01	6.55E-02	6.58E-03	4.99E-02	3.90E+02
A5m-waste	Construction site - material use on site - waste								
B1	Use phase								
B1-a	Refrigerant annual leakages								
B1-b	Refrigerant loss, equipment replacement								
B1-c	Refrigerant loss, equipment end of life								
B1-d	Carbonisation								
B1-e	Vegetation withdrawal of carbon								
B3	Repair	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3a	Repair - materials	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3b	Repair - transport								
B3c	Repair - waste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5	Material replacement and refurbishment	4.12E+03		4.76E-04	2.36E+01	6.27E+00	2.62E+00	2.09E-01	5.04E+04
B4-B5a	Material replacement - materials	4.02E+03		4.65E-04	2.27E+01	6.01E+00	2.60E+00	3.47E-02	4.90E+04
B4-B5b	Material replacement - transport								
B4-B5b-leg2	Material replacement - transport leg 2								
B4-B5c	Material replacement - waste	1.05E+02	0.00E+00	1.08E-05	8.18E-01	2.64E-01	2.64E-02	1.74E-01	1.43E+03
B6	Energy consumption								
B7	Water use								

MASS TIMBER HOUSE - YEAR 60

Section	Result category	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP- elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
C1-C4	End of life	1.90E+02		2.04E-05	1.27E+00	3.91E-01	3.98E-02	3.40E-01	2.56E+03
C1	Deconstruction/demolition								
C2	Waste transport	4.69E+01		9.27E-06	2.15E-01	4.68E-02	2.76E-03	3.40E-01	1.34E+03
C3	Waste processing	1.30E+02		8.84E-06	9.62E-01	3.23E-01	3.44E-02	3.33E-04	1.04E+03
C4	Waste disposal	1.30E+01		2.34E-06	9.59E-02	2.05E-02	2.61E-03	9.07E-06	1.87E+02
D	External impacts (not included in totals)	-2.79E+04		-3.62E-03	-8.20E+01	-1.45E+01	-4.34E+00	-6.39E-02	-4.15E+05
D	Installed Materials - benefit	-1.62E+04	-4.35E+04	-2.07E-03	-5.20E+01	-1.00E+01	-2.60E+00	-5.81E-02	-2.46E+05
A5- benefit	Construction site - material wastage - benefit	-2.50E+03	-3.69E+03	-3.26E-04	-7.22E+00	-1.25E+00	-3.87E-01	-5.04E-03	-3.71E+04
A5m- benefit	Construction site - material use - benefit								
B3- benefit	Repair - benefit	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5- benefit	Material replacement - benefit	-9.16E+03	0.00E+00	-1.23E-03	-2.28E+01	-3.22E+00	-1.35E+00	-8.08E-04	-1.32E+05
D2	Exported energy (not included in totals)								

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Level(s) life-cycle assessment (EN15804 +A1)

STANDARD CONSTRUCTED HOUSE - YEAR 60

Section	Result category	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP- elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
A1-A3	Construction Materials	1.37E+04	2.59E+04	1.15E-03	6.56E+01	2.32E+01	4.96E+00	2.18E-01	1.86E+05
A4	Transportation to site								
A4	Transport to the building site								
A4-leg2	Transportation to site - leg 2								
A5	Construction/installation process	1.84E+03		1.75E-04	9.29E+00	3.29E+00	7.62E-01	1.99E-01	2.46E+04
A5a	Site operations & site waste handling								
A5b	Site waste transportation								
A5c	Construction site - material wastage - materials	1.75E+03		1.66E-04	8.86E+00	3.16E+00	7.48E-01	2.38E-02	2.35E+04
A5d	Construction site - material wastage - transport								
A5e	Construction site - material wastage - waste	8.70E+01	0.00E+00	8.34E-06	4.34E-01	1.30E-01	1.34E-02	1.75E-01	1.07E+03
A5m- waste	Construction site - material use on site - waste								
B1	Use phase								
B1-a	Refrigerant annual leakages								
B1-b	Refrigerant loss, equipment replacement								
B1-c	Refrigerant loss, equipment end of life								
B1-d	Carbonisation								
B1-e	Vegetation withdrawal of carbon								
B3	Repair	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3a	Repair - materials	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3b	Repair - transport								
B3c	Repair - waste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5	Material replacement and refurbishment	1.00E+04		6.89E-04	4.67E+01	1.12E+01	4.77E+00	2.46E-01	1.37E+05
B4-B5a	Material replacement - materials	9.72E+03		6.72E-04	4.58E+01	1.09E+01	4.73E+00	4.77E-02	1.35E+05
B4-B5b	Material replacement - transport								
B4-B5b- leg2	Material replacement - transport leg 2								
B4-B5c	Material replacement - waste	2.92E+02	0.00E+00	1.76E-05	9.65E-01	2.91E-01	3.46E-02	1.98E-01	1.86E+03
B6	Energy consumption								
B7	Water use								

STANDARD CONSTRUCTED HOUSE - YEAR 60

Section	Result category	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP- elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
C1-C4	End of life	9.26E+02		6.69E-05	2.86E+00	8.07E-01	9.49E-02	1.25E+00	7.73E+03
C1	Deconstruction/demolition								
C2	Waste transport	1.72E+02		3.39E-05	7.84E-01	1.71E-01	1.06E-02	1.24E+00	4.93E+03
C3	Waste processing	7.50E+02		3.23E-05	2.05E+00	6.30E-01	8.35E-02	1.67E-03	2.75E+03
C4	Waste disposal	4.01E+00		7.20E-07	2.95E-02	6.30E-03	8.02E-04	2.79E-06	5.73E+01
D	External impacts (not included in totals)	-3.68E+04		-4.93E-03	-9.17E+01	-1.30E+01	-5.43E+00	-1.96E-01	-5.29E+05
D	Installed Materials - benefit	-2.32E+04	0.00E+00	-3.11E-03	-5.78E+01	-8.20E+00	-3.43E+00	-1.74E-01	-3.33E+05
A5- benefit	Construction site - material wastage - benefit	-3.97E+03	0.00E+00	-5.33E-04	-9.91E+00	-1.40E+00	-5.87E-01	-2.18E-02	-5.71E+04
A5m- benefit	Construction site - material use - benefit								
B3- benefit	Repair - benefit	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5- benefit	Material replacement - benefit	-9.62E+03	0.00E+00	-1.29E-03	-2.39E+01	-3.38E+00	-1.42E+00	-8.49E-04	-1.38E+05
D2	Exported energy (not included in totals)								

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CRADLE-TO-GRAVE: YEAR-100 LCA DATA

Level(s) life-cycle assessment (EN15804 +A1)

TYPICAL MODULAR HOUSE - YEAR 100

Section	Result category	Global warming kg CO2e	Biogenic carbon storage kg CO2e bio	Ozone Depletion kg CFC11e	Acidification kg SO2e	Eutrophication kg PO4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
A1-A3	Construction Materials	1.61E+04	2.68E+04	1.21E-03	6.97E+01	2.41E+01	4.01E+00	3.02E-01	2.57E+05
A4	Transportation to site								
A4	Transport to the building site								
A4-leg2	Transportation to site - leg 2								
A5	Construction/installation process	2.28E+03		1.67E-04	8.60E+00	3.12E+00	5.11E-01	2.22E-01	3.01E+04
A5a	Site operations & site waste handling								
A5b	Site waste transportation								
A5c	Construction site - material wastage - materials	1.78E+03		1.45E-04	7.92E+00	2.95E+00	4.81E-01	2.95E-02	2.83E+04
A5d	Construction site - material wastage - transport								
A5e	Construction site - material wastage - waste	5.00E+02	0.00E+00	2.16E-05	6.77E-01	1.66E-01	2.98E-02	1.92E-01	1.80E+03
A5m-waste	Construction site - material use on site - waste								
B1	Use phase								
B1-a	Refrigerant annual leakages								
B1-b	Refrigerant loss, equipment replacement								
B1-c	Refrigerant loss, equipment end of life								
B1-d	Carbonisation								
B1-e	Vegetation withdrawal of carbon								
B3	Repair	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3a	Repair - materials	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3b	Repair - transport								
B3c	Repair - waste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5	Material replacement and refurbishment	4.93E+04		2.31E-03	1.31E+02	2.75E+01	9.35E+00	8.58E-01	6.04E+05
B4-B5a	Material replacement - materials	3.21E+04		1.76E-03	1.21E+02	2.59E+01	8.66E+00	2.51E-01	5.73E+05
B4-B5b	Material replacement - transport								
B4-B5b-leg2	Material replacement - transport leg 2								
B4-B5c	Material replacement - waste	1.72E+04	0.00E+00	5.52E-04	1.04E+01	1.61E+00	6.89E-01	6.07E-01	3.07E+04
B6	Energy consumption								
B7	Water use								

TYPICAL MODULAR HOUSE - YEAR 100

Section	Result category	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP- elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
C1-C4	End of life	5.10E+03		2.01E-04	5.36E+00	1.19E+00	2.61E-01	1.42E+00	1.52E+04
C1	Deconstruction/demolition								
C2	Waste transport	1.95E+02		3.85E-05	8.89E-01	1.93E-01	1.20E-02	1.41E+00	5.58E+03
C3	Waste processing	4.89E+03		1.60E-04	4.37E+00	9.70E-01	2.46E-01	6.27E-03	9.45E+03
C4	Waste disposal	1.41E+01		2.53E-06	1.04E-01	2.22E-02	2.82E-03	9.80E-06	2.02E+02
D	External impacts (not included in totals)	-4.44E+04		-5.95E-03	-1.11E+02	-1.57E+01	-6.56E+00	-2.05E-01	-6.39E+05
D	Installed Materials - benefit	-2.59E+04	0.00E+00	-3.46E-03	-6.45E+01	-9.13E+00	-3.82E+00	-1.81E-01	-3.72E+05
A5- benefit	Construction site - material wastage - benefit	-4.20E+03	0.00E+00	-5.63E-04	-1.05E+01	-1.48E+00	-6.21E-01	-2.27E-02	-6.04E+04
A5m- benefit	Construction site - material use - benefit								
B3- benefit	Repair - benefit	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5- benefit	Material replacement - benefit	-1.44E+04	0.00E+00	-1.92E-03	-3.57E+01	-5.05E+00	-2.12E+00	-1.27E-03	-2.06E+05
D2	Exported energy (not included in totals)								

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Section	Result category	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
A1-A3	Construction Materials	1.10E+04	6.51E+04	1.40E-03	5.22E+01	1.33E+01	4.02E+00	9.74E-02	1.66E+05
A4	Transportation to site								
A4	Transport to the building site								
A4-leg2	Transportation to site - leg 2								
A5	Construction/installation process	1.38E+03		1.70E-04	6.98E+00	1.83E+00	6.08E-01	6.19E-02	1.97E+04
A5a	Site operations & site waste handling								
A5b	Site waste transportation								
A5c	Construction site - material wastage - materials	1.35E+03		1.67E-04	6.77E+00	1.77E+00	6.02E-01	1.20E-02	1.93E+04
A5d	Construction site - material wastage - transport								
A5e	Construction site - material wastage - waste	2.79E+01	0.00E+00	3.02E-06	2.08E-01	6.55E-02	6.58E-03	4.99E-02	3.90E+02
A5m-waste	Construction site - material use on site - waste								
B1	Use phase								
B1-a	Refrigerant annual leakages								
B1-b	Refrigerant loss, equipment replacement								
B1-c	Refrigerant loss, equipment end of life								
B1-d	Carbonisation								
B1-e	Vegetation withdrawal of carbon								
B3	Repair	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3a	Repair - materials	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3b	Repair - transport								
B3c	Repair - waste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5	Material replacement and refurbishment	7.11E+03		8.52E-04	3.82E+01	1.05E+01	4.79E+00	3.62E-01	8.61E+04
B4-B5a	Material replacement - materials	6.93E+03		8.33E-04	3.67E+01	1.01E+01	4.75E+00	5.10E-02	8.35E+04
B4-B5b	Material replacement - transport								
B4-B5b-leg2	Material replacement - transport leg 2								
B4-B5c	Material replacement - waste	1.87E+02	0.00E+00	1.93E-05	1.46E+00	4.71E-01	4.71E-02	3.11E-01	2.56E+03
B6	Energy consumption								
B7	Water use								

MASS TIMBER HOUSE - YEAR 100

Section	Result category	Global warming kg CO2e	Biogenic carbon storage kg CO2e bio	Ozone Depletion kg CFC11e	Acidification kg SO2e	Eutrophication kg PO4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP- elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
C1-C4	End of life	1.90E+02		2.04E-05	1.27E+00	3.91E-01	3.98E-02	3.40E-01	2.56E+03
C1	Deconstruction/demolition								
C2	Waste transport	4.69E+01		9.27E-06	2.15E-01	4.68E-02	2.76E-03	3.40E-01	1.34E+03
C3	Waste processing	1.30E+02		8.84E-06	9.62E-01	3.23E-01	3.44E-02	3.33E-04	1.04E+03
C4	Waste disposal	1.30E+01		2.34E-06	9.59E-02	2.05E-02	2.61E-03	9.07E-06	1.87E+02
D	External impacts (not included in totals)	-3.52E+04		-4.60E-03	-1.00E+02	-1.71E+01	-5.41E+00	-6.46E-02	-5.19E+05
D	Installed Materials - benefit	-1.62E+04	-4.35E+04	-2.07E-03	-5.20E+01	-1.00E+01	-2.60E+00	-5.81E-02	-2.46E+05
A5- benefit	Construction site - material wastage - benefit	-2.50E+03	-3.69E+03	-3.26E-04	-7.22E+00	-1.25E+00	-3.87E-01	-5.04E-03	-3.71E+04
A5m- benefit	Construction site - material use - benefit								
B3- benefit	Repair - benefit	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5- benefit	Material replacement - benefit	-1.65E+04	0.00E+00	-2.20E-03	-4.09E+01	-5.79E+00	-2.43E+00	-1.45E-03	-2.37E+05
D2	Exported energy (not included in totals)								

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Level(s) life-cycle assessment (EN15804 +A1)

STANDARD CONSTRUCTED HOUSE - YEAR 100

Section	Result category	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP- elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
A1-A3	Construction Materials	1.37E+04	2.59E+04	1.15E-03	6.56E+01	2.32E+01	4.96E+00	2.18E-01	1.86E+05
A4	Transportation to site								
A4	Transport to the building site								
A4-leg2	Transportation to site - leg 2								
A5	Construction/installation process	1.84E+03		1.75E-04	9.29E+00	3.29E+00	7.62E-01	1.99E-01	2.46E+04
A5a	Site operations & site waste handling								
A5b	Site waste transportation								
A5c	Construction site - material wastage - materials	1.75E+03		1.66E-04	8.86E+00	3.16E+00	7.48E-01	2.38E-02	2.35E+04
A5d	Construction site - material wastage - transport								
A5e	Construction site - material wastage - waste	8.70E+01	0.00E+00	8.34E-06	4.34E-01	1.30E-01	1.34E-02	1.75E-01	1.07E+03
A5m- waste	Construction site - material use on site - waste								
B1	Use phase								
B1-a	Refrigerant annual leakages								
B1-b	Refrigerant loss, equipment replacement								
B1-c	Refrigerant loss, equipment end of life								
B1-d	Carbonisation								
B1-e	Vegetation withdrawal of carbon								
B3	Repair	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3a	Repair - materials	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3b	Repair - transport								
B3c	Repair - waste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5	Material replacement and refurbishment	1.79E+04		1.26E-03	8.12E+01	2.03E+01	8.69E+00	4.33E-01	2.44E+05
B4-B5a	Material replacement - materials	1.74E+04		1.23E-03	7.95E+01	1.98E+01	8.63E+00	7.48E-02	2.41E+05
B4-B5b	Material replacement - transport								
B4-B5b- leg2	Material replacement - transport leg 2								
B4-B5c	Material replacement - waste	4.80E+02	0.00E+00	3.03E-05	1.72E+00	5.22E-01	6.08E-02	3.58E-01	3.29E+03
B6	Energy consumption								
B7	Water use								

STANDARD CONSTRUCTED HOUSE - YEAR 100

Section	Result category	Global warming kg CO ₂ e	Biogenic carbon storage kg CO ₂ e bio	Ozone Depletion kg CFC11e	Acidification kg SO ₂ e	Eutrophication kg PO ₄ e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP- elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
C1-C4	End of life	9.26E+02		6.69E-05	2.86E+00	8.07E-01	9.49E-02	1.25E+00	7.73E+03
C1	Deconstruction/demolition								
C2	Waste transport	1.72E+02		3.39E-05	7.84E-01	1.71E-01	1.06E-02	1.24E+00	4.93E+03
C3	Waste processing	7.50E+02		3.23E-05	2.05E+00	6.30E-01	8.35E-02	1.67E-03	2.75E+03
C4	Waste disposal	4.01E+00		7.20E-07	2.95E-02	6.30E-03	8.02E-04	2.79E-06	5.73E+01
D	External impacts (not included in totals)	-4.46E+04		-5.98E-03	-1.11E+02	-1.57E+01	-6.59E+00	-1.97E-01	-6.41E+05
D	Installed Materials - benefit	-2.32E+04	0.00E+00	-3.11E-03	-5.78E+01	-8.20E+00	-3.43E+00	-1.74E-01	-3.33E+05
A5- benefit	Construction site - material wastage - benefit	-3.97E+03	0.00E+00	-5.33E-04	-9.91E+00	-1.40E+00	-5.87E-01	-2.18E-02	-5.71E+04
A5m- benefit	Construction site - material use - benefit								
B3- benefit	Repair - benefit	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B4-B5- benefit	Material replacement - benefit	-1.74E+04	0.00E+00	-2.34E-03	-4.34E+01	-6.14E+00	-2.57E+00	-1.54E-03	-2.51E+05
D2	Exported energy (not included in totals)								

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APPENDIX 6 – THERMAL ANALYSES

THERM – BOUNDARY CONDITION INPUTS

EXTERIOR BOUNDARY CONDITION

Exterior Winter

Model

Simplified

Convection/Linearized Radiation

Temperature

0

F

Film

5.988

Btu/h-ft2-F

INTERIOR BOUNDARY CONDITION

~Interior 68F

Model

Simplified

Convection/Linearized Radiation

Temperature

68

F

Film

1.46

Btu/h-ft2-F

THERM – MATERIAL INPUTS

BLOWN-IN FIBERGLASS INSULATION

Solid Properties

Conductivity

0.29

Btu-in/h-ft2-F

Emissivity

0.5

FIBERGLASS BATT INSULATION

Solid Properties

Conductivity

0.3

Btu-in/h-ft2-F

Emissivity

0.5

RIGID WOOD FIBER INSULATION

Solid Properties

Conductivity

0.3

Btu-in/h-ft2-F

Emissivity

0.5

XPS RIGID BOARD INSULATION

Solid Properties

Conductivity

0.18

Btu-in/h-ft2-F

Emissivity

0.5

OSB SHEATHING

Solid Properties

Conductivity

0.732

Btu-in/h-ft2-F

Emissivity

0.5

GYPSUM BOARD

Solid Properties

Conductivity

1.104

Btu-in/h-ft2-F

Emissivity

0.9

DIMENSIONAL LUMBER

Solid Properties

Conductivity

0.972

Btu-in/h-ft2-F

Emissivity

0.9

CLT PANEL

Solid Properties

Conductivity

0.972

Btu-in/h-ft2-F

Emissivity

0.9

SOURCE OF INFORMATION

Lawrence Berkeley National Laboratory, *THERM 7.8 software* | <https://windows.lbl.gov>

WUFI®PASSIVE - SHARED CLIMATE DATA INPUTS

WEATHER STATION-INFORMED DATA

NameConcord, New Hampshire

Parameters

Latitude [°]	43.2
Longitude [°]	-71.5
Altitude weather station [ft]	347.8
Time zone [Hours from UTC]	0
Altitude building [ft]	347.8
Daily temperature swing summer [°F]	24.3
Average wind speed [ft/s]	9.68

Ground

Ground thermal conductivity [Btu/hr ft °F]	1.1556
Ground heat capacity [Btu/lb °F]	0.2388
Ground density [lb/ft³]	124.8559
Depth below grade of groundwater [ft]	9.8425
Flow rate of groundwater [ft/d]	0.164

Space conditioning target data

Calculate from climate data

Heating degree-days, base 65°F [°F/days]	7554
Cooling degree-days, base 50°F [°F/days]	328
Electricity price, marginal, state average [\$ /kWh]	0.162625

ANNUAL CLIMATE DATA

Data: Concord, New Hampshire																
Setting	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Heating W. 1	Heating W. 2	Cooling W. 1	Cooling W. 2
Temperature [°F]																
Ambient	21.6	22.6	34.9	45.9	57.7	65.1	71.2	67.3	60.3	47.7	36.5	23.4	11.1	20.8	74.7	
Dew point	10.9	12.9	19.9	29.8	45.0	54.0	60.4	57.0	52.7	37.8	26.8	15.1				
Sky*	-27.4	-25.2	-26.1	-11.4	16.2	35.1	39.2	20.8	15.8	5.4	-2.7	-14.8				
Ground*																
Solar radiation [kBtu/ft²Month]													Solar radiation [Btu/hr ft²]			
North	6.3	9.5	14.3	18.4	20.9	26.0	26.9	17.4	11.1	7.3	5.7	6.0	10.5	6.0	34.9	
East	7.0	10.8	16.2	17.1	17.1	18.4	18.1	16.8	11.7	8.6	6.3	6.3	11.7	6.0	30.4	
South	27.3	34.6	33.9	28.2	22.8	21.9	23.5	26.0	26.6	28.2	28.8	33.6	48.2	18.4	38.7	
West	22.5	43.1	43.4	56.7	47.5	52.9	59.0	49.1	44.1	34.9	29.5	33.9	34.9	16.8	85.0	
Global	12.0	20.0	30.4	39.6	45.6	50.1	50.7	46.0	32.7	22.5	13.6	11.1	21.6	9.8	83.7	

SOURCE OF INFORMATION

Fraunhofer Institute for Building Physics, *WUFI®Passive software* | <https://wufi.de/en>

WUFI®PASSIVE - SHARED GENERAL DATA INPUTS

SOURCE ENERGY DATA

Selection Standard USA ▼		
Name	Source energy factor [Btu/Btu]	CO2 emission factor [g/kBtu]
Oil	1.1	0.31
Natural Gas	1.1	0.25
LPG	1.1	0.27
Hard Coal	1.1	0.44
Wood	0.2	0.05
Electricity Mix	2.8	0.68
Electricity from photovoltaics	0.7	0.25
Hard Coal CGS 70% CHP	0.8	0.24
Hard Coal CGS 35% CHP	1.1	0.32
Hard Coal HS 0% CHP	1.5	0.41
Gas CGS 70% CHP	0.7	-0.07
Gas CGS 35% CHP	1.1	0.13
Gas HS 0% CHP	1.5	0.32
Oil CGS 70% CHP	0.8	0.1
Oil CGS 35% CHP	1.1	0.25
Oil HS 0% CHP	1.5	0.41

GLAZING DESIGNATION

Assigned window type	
Name	Uw [Btu/hr ft² °F]
Glazing: Low-e, low-solar 3, Frame: Wood/Vinyl - Fixed	0.1737

SOURCE OF INFORMATION

Fraunhofer Institute for Building Physics, *WUFI®Passive software* | <https://wufi.de/en>

VENTILATION UTILIZATION PATTERN INPUT

Name	Operating days per week [d/week]	Operating weeks per year [week/a]	
Residential	7	52	New Delete Copy Insert New/Insert: after

Intermediate results

Supply air due to persons [cfm]	72
Total extract air demand [cfm]	94.17
Design air flow rate [cfm]	94.17
Average air flow rate [cfm]	53.68
Average air change rate [1/hr]	0.25

Additional data: Residential

Setting	Daily operation schedule [h]	Fraction of design air flow [-]
Maximum	0	1
Standard	8	0.77
Basic	8	0.54
Minimum	8	0.4

Pattern: Residential is used in:

Case 1, Zone 1, Ventilation/Rooms, Rooms ventilation (current zone)

Case 2, Zone 1, Ventilation/Rooms, Rooms ventilation

Case 3, Zone 1, Ventilation/Rooms, Rooms ventilation

MECHANICAL SYSTEM INPUT

Database relevant data		Assign from database		Remaining parameters	
Required data				Required data	
Sensible recovery efficiency [-]	1			Quantity	1
Humidity recovery efficiency [-]	1			HRV/ERV in conditioned space	☒
Electric efficiency [W/cfm]	1			No summer bypass feature (summer ventilation with HRV/ERV)	☒
Equipped with frost protection			☒	Defrost active	☐
Rooms ventilated by this unit				Temperature below which defrost must be used [°F]	
Z 1, R.1, Kitchen			☒	Optional data (if not defined default value will be calculated)	
Z 1, R.2, Bathroom			☒	Subsoil heat exchanger efficiency [-]	
Z 1, R.3, WC			☒		

SOURCE OF INFORMATION

Fraunhofer Institute for Building Physics, WUFI@Passive software | <https://wufi.de/en>

WUFI®PASSIVE - CONSTRUCTION SYSTEM INPUTS

TYPICAL MODULAR HOUSE

Parameters

Building category	Residential
Occupancy type	Residential
Building status	In planning
Type	New construction
Indoor temperature [°F]	68
Internal gains setting	Calculated
Internal heat gains [Btu/hr ft²]	0.113
Occupancy setting method	Design
Number of occupants	4
Number of units [-]	1
Number of floors	1

Zones

Nr.	Name	Floor area [ft²]	
1	Simulated zone	1649.376	New Delete

Additional parameters

Required data

Preferred minimum indoor temperature for night ventilation [°F]	68
Overheating temperature threshold [°F]	77
Fresh air per person [cfm]	18
Hot water tap-openings per person per day [-]	3
Hot water tap-opening utilization days per year [days/yr]	365
Air-tightness metric	Envelope airtightness at 50 Pa
Envelope airtightness at 50 Pa [cfm/ft²]	402
Non combustible materials	☐
Type of ventilation system	Balanced PH ventilation
Max. humidity ratio (if dehumidification) [lbw/lba]	0.012
Building wind exposure	Several sides exposed - moderate screening
Wind screening coefficient (e) [-]	0.07
Wind exposure factor (f) [-]	15
Wind shield factor [-]	0.05

Optional data (if not defined default value will be calculated)

DHW consumption (140°F) per person per day [gal/Person/day]	6.6
Average cold water temperature of the supply [°F]	50
Mechanical room temperature [°F]	68

Linear thermal bridges

Nr	Name	Linear thermal transmittance [Btu/hr ft² F]	Length [ft]	Attachment	
1	Wall Corner 1	0.0325	8	Ambient	New Delete Copy Insert New/Insert: after
2	Wall Corner 2	0.0325	8	Ambient	
3	Wall Corner 3	0.0325	8	Ambient	
4	Wall Corner 4	0.0325	8	Ambient	
5	Wall Corner 5	0.0325	8	Ambient	
6	Wall Corner 6	0.0325	8	Ambient	
7	Wall Corner 7	0.0325	8	Ambient	
8	Wall-Roof Edge 1	0.0412	45	Ambient	
9	Wall-Roof Edge 2	0.0412	8.5	Ambient	
10	Wall-Roof Edge 3	0.0412	10	Ambient	
11	Wall-Roof Edge 4	0.0412	26.5	Ambient	
12	Wall-Roof Edge 5	0.0412	13.6	Ambient	
13	Wall-Roof Edge 6	0.0412	13.6	Ambient	

SOURCE OF INFORMATION

Parameters	
Building category	Residential
Occupancy type	Residential
Building status	In planning
Type	New construction
Indoor temperature [°F]	68
Internal gains setting	Calculated
Internal heat gains [Btu/hr ft²]	0.188
Occupancy setting method	Design
Number of occupants	4
Number of units [-]	1
Number of floors	1

Zones			
Nr.	Name	Floor area [ft²]	
1	Simulated zone	988.75	New Delete

Additional parameters	
Required data	
Preferred minimum indoor temperature for night ventilation [°F]	68
Overheating temperature threshold [°F]	77
Fresh air per person [cfm]	18
Hot water tap-openings per person per day [-]	3
Hot water tap-opening utilization days per year [days/yr]	365
Air-tightness metric	Envelope airtightness at 50 Pa
Envelope airtightness at 50 Pa [cfm/ft²]	0.05
Non combustible materials	☐
Type of ventilation system	Balanced PH ventilation
Max. humidity ratio (if dehumidification) [lbw/lba]	0.012
Building wind exposure	Several sides exposed - moderate screening
Wind screening coefficient (e) [-]	0.07
Wind exposure factor (f) [-]	15
Wind shield factor [-]	0.05
Optional data (if not defined default value will be calculated)	
DHW consumption (140°F) per person per day [gal/Person/day]	6.6
Average cold water temperature of the supply [°F]	50
Mechanical room temperature [°F]	68

Linear thermal bridges					
Nr	Name	Linear thermal transmittance [Btu/hr ft² F]	Length [ft]	Attachment	
1	Wall Corner 1	0.0261	9	Ambient	New
2	Wall Corner 2	0.0261	9	Ambient	Delete
3	Wall Corner 3	0.0261	9	Ambient	Copy
4	Wall Corner 4	0.0261	9	Ambient	Insert
5	Wall-Roof Edge 1	0.0319	36	Ambient	New/Insert:
6	Wall-Roof Edge 2	0.0319	36	Ambient	after

SOURCE OF INFORMATION

Fraunhofer Institute for Building Physics, *WUFI@Passive software* | <https://wufi.de/en>

STANDARD CONSTRUCTED HOUSE

Parameters

Building category	Residential
Occupancy type	Residential
Building status	In planning
Type	New construction
Indoor temperature [°F]	68
Internal gains setting	Calculated
Internal heat gains [Btu/hr ft²]	0.174
Occupancy setting method	Design
Number of occupants	4
Number of units [-]	1
Number of floors	1

Zones

Nr.	Name	Floor area [ft²]	
1	Simulated zone	1069.439	New Delete

Additional parameters

Required data

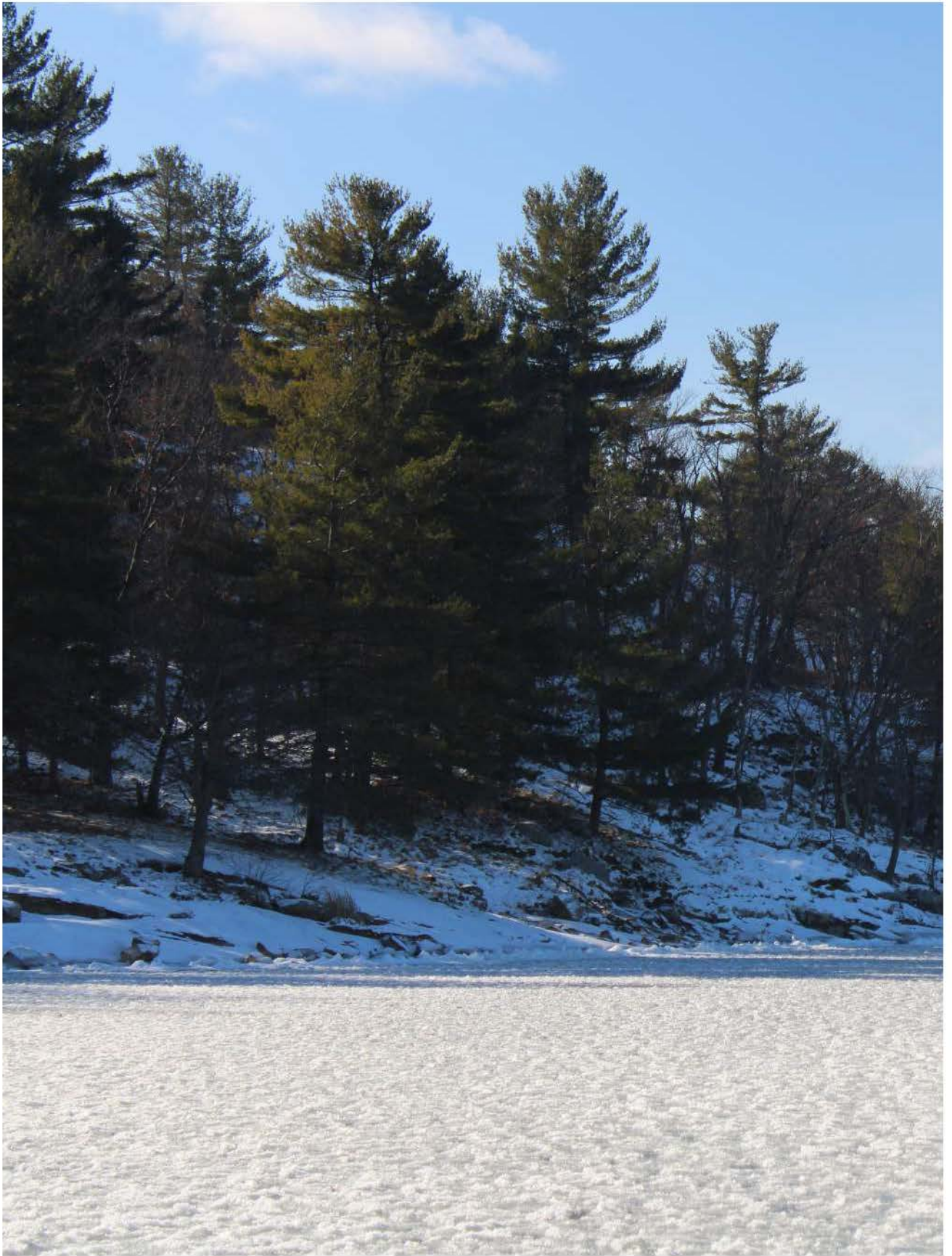
Preferred minimum indoor temperature for night ventilation [°F]	68
Overheating temperature threshold [°F]	77
Fresh air per person [cfm]	18
Hot water tap-openings per person per day [-]	3
Hot water tap-opening utilization days per year [days/yr]	365
Air-tightness metric	Envelope airtightness at 50 Pa
Envelope airtightness at 50 Pa [cfm/ft²]	1.23
Non combustible materials	☐
Type of ventilation system	Balanced PH ventilation
Max. humidity ratio (if dehumidification) [lbw/lba]	0.012
Building wind exposure	Several sides exposed - moderate screening
Wind screening coefficient (e) [-]	0.07
Wind exposure factor (f) [-]	15
Wind shield factor [-]	0.05

Optional data (if not defined default value will be calculated)

DHW consumption (140°F) per person per day [gal/Person/day]	6.6
Average cold water temperature of the supply [°F]	50
Mechanical room temperature [°F]	68

Linear thermal bridges

Nr	Name	Linear thermal transmittance [Btu/hr ft² °F]	Length [ft]	Attachment	
1	Wall Corner 1	0.0325	9	Ambient	New
2	Wall Corner 2	0.0325	9	Ambient	Delete
3	Wall Corner 3	0.0325	9	Ambient	Copy
4	Wall Corner 4	0.0325	9	Ambient	Insert
5	Wall-Roof Edge 1	0.0369	36.3	Ambient	New/Insert:
6	Wall-Roof Edge 2	0.0369	36.3	Ambient	after







037

