The Woods, the Neighborhood, & the City

Michael S Ennen

A thesis
submitted in partial fulfillment of the
requirements for the degree of

Master of Architecture

University of Washington
2018

Committee:
Kimo Griggs
Susan Jones

Program Authorized to Offer Degree:

Architecture

University of Washington

Abstract

The Woods, the Neighborhood, & the City

Michael S Ennen

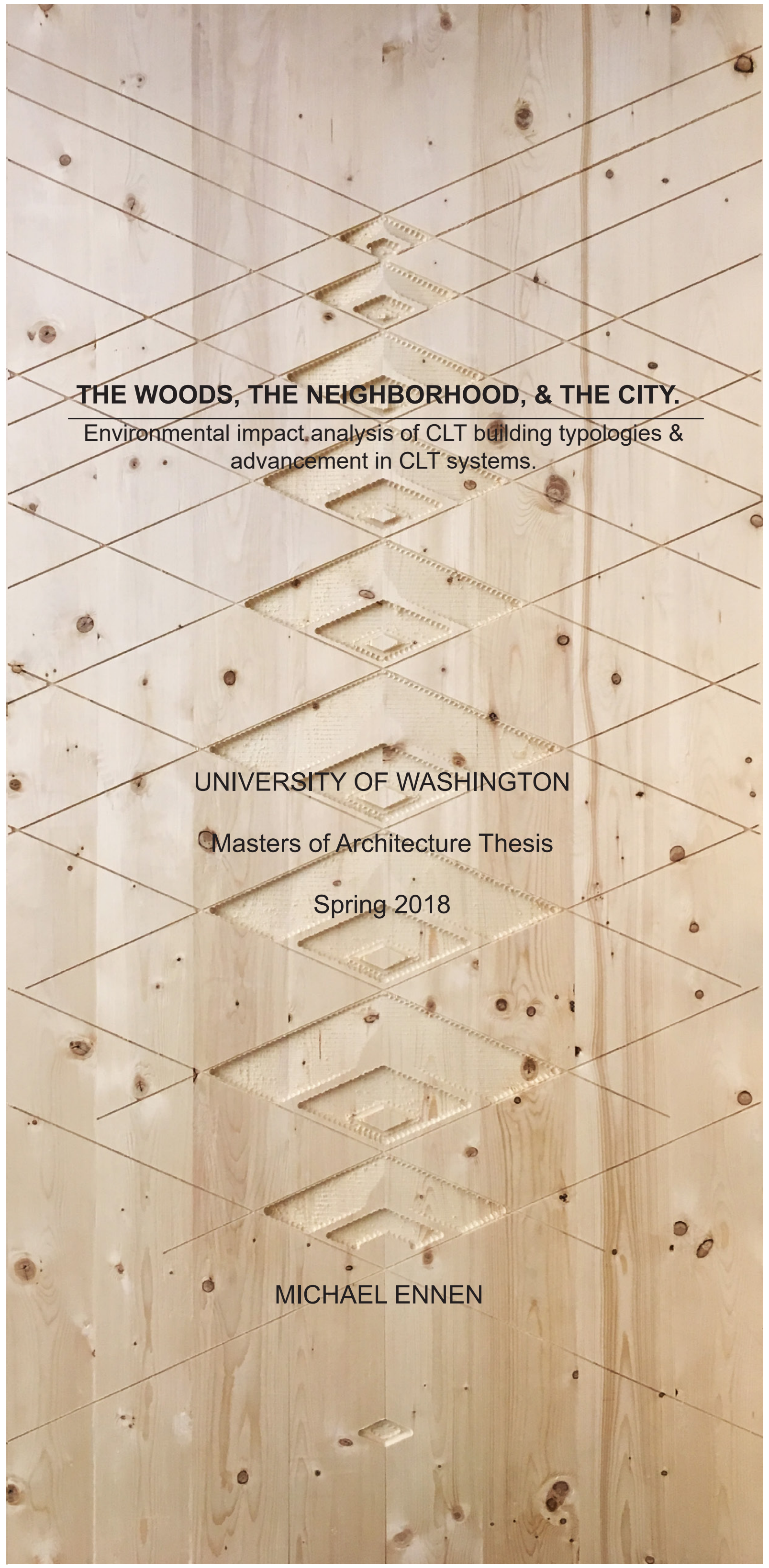
Chair of the Supervisory Committee:

Kimo Griggs

Susan Jones

Department of Architecture

This project explores design and analysis of three building scales, a cabin, a single-family residence, and an urban co-housing building. A modular gird creates a scalable relationship to each housing typology. LCA tools were used to understand each building scale and the difference between two construction methods: Typical construction vs. Cross Laminated Timber. The objective of this research is to look towards analysis and new technologies to quantify how to design and build into the future.



THE WOODS, THE NEIGHBORHOOD, & THE CITY.

Environmental impact analysis of CLT building typologies & advancement in CLT systems.

UNIVERSITY OF WASHINGTON

Masters of Architecture Thesis

Spring 2018

MICHAEL ENNEN

CONTENTS

1

INTRODUCTION

In the 21st century our world is confronted with overwhelming challenges including housing population growth (projected to hit 100 Million people nationally by 2050 "US Census bureau statista 2017"), and the looming state of climate change.[1] "Emissions of C02 from fossil fuel combustion, with contribution from cement manufacturing, are responsible for more than 75% of the increase in atmospheric C02 concentration since pre-industrial times" (IPCC Fourth Assessment report 2013).[2] The industrial revolution sparked 150-years of combustion of fossil fuels that released carbon dioxide into the earth's atmosphere to construct the society we live in today. This fuel was stored for millions of years and has now disturbed the flux ratio resulting in climate change. Our atmospheric carbon pool levels are at 829(PgC) petagrams/carbon and increasing by 4PgC/yr.[3] This has thrown off the natural net carbon flux from atmosphere to forest, soils and bodies of water. Carbon dioxide is the number one contributor to heat trapping of all the various greenhouse gases. (Carbon dioxide (C02), Methane (CH4), Nitrous Oxide (N20), HFCs, CFCs, & Sulfur hexafluoride).

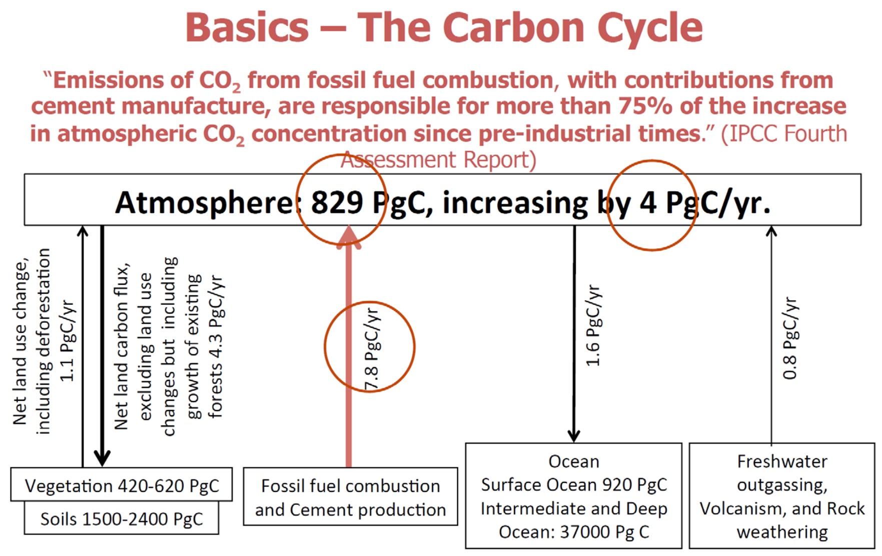
For our society to build and house our growing population we will need approximately 131 billion ft2 of new building space and 82 billion ft2 of replacement of existing space to accommodate 2000-2030 growth projections.[4] This amount of construction could likely be a major contributor in the increase of the atmospheric carbon emissions pool. Our current process of manufacturing building materials uses an excessive amount of fossil fuels to render raw materials into structural elements. Concrete and steel have been our primary means of constructing our Built Environment for the last century and continue to play a major role in everyday construction. Fossil fuel combustion and cement production releases 7.8 PgC/yr (IPPC Fifth Assessment Report2013) into our atmosphere.[5] These emissions outweigh what our global carbon net flux cycle can currently sequester into our forest and natural environments. Human consumption currently releases too much carbon dioxide into the atmosphere.

"The 17th Century was the age of stone. The 18th century was the peak of brick. The 19th century was the era of iron. The 20th century was the century of concrete. The 21st century will be the time for TIMBER."

ALEX DE RIJKE, DRMM

The built environment is moving toward a future of building with sequestered carbon timber. Forest respiration is responsible for the process by which a tree takes in carbon dioxide and releases oxygen. The amount of carbon dioxide a tree can hold is carbon sequestration. The forest sequesters this carbon dioxide by storing it in their trunks, branches, leaves and roots. This ecosystem is the largest terrestrial carbon sink on earth and this living factory powered by the sun has potential to take a leading role in solving both climate change and population growth. This material can not only be a structural system, but also a system to store embodied carbon. The construction of housing can thus become a carbon sink. Cutting back on emissions, storing carbon, and faster construction time all result in carbon savings. "The world is expected to use a million cubic meters of CLT this year, compared with 2,000 cubic meters in 2003."[6] (The Observer, Timber Architecture 01.29.18) CLT is currently getting a lot of attention, but it is just one type of engineered timber in a large umbrella of products. The use of new technology to turn wood and other natural materials into high performance structural products can help assist the evolution of building for a better future.

Can we maximize the use of wood products to sequester carbon without decimating our forests? The forest is our greatest asset of scrubbing our atmosphere and producing clean oxygen. Our forests have been steadily growing larger since 1990 and currently absorb 4.3 PgC/year from the atmosphere.[7] To balance this equation of population growth, growth of our built environment, and the use of harvested products to sequester carbon, we must make sure we have: Forest Growth (Silviculture) Active forest management to ensure a growing forest to bind carbon that will offset the country's carbon dioxide emissions; Carbon Storage in Products Carbon that remains in the products paired with low energy consumption in construction, reuse of material, and simple transportation; Substitution Effect Renewable resource such as forest industry products replace fossil fuel based products; and Regional Manufacturing and Materials Pallet. If these don't align, then the resulting changes will be insufficient to effectively resolve the current issues of climate change and population growth.



Basics – The Carbon Cycle

"Emissions of CO_2 from fossil fuel combustion, with contributions from cement manufacture, are responsible for more than 75% of the increase in atmospheric CO_2 concentration since pre-industrial times." (IPCC Fourth Assessment Report)

Source: IPCC Fifth Assessment Report (2013)
Line Widths proportional to inward of flow

Fig. 1 - Basic - The Carbon Cycle

2

UNDERSTANDING CONCEPTION

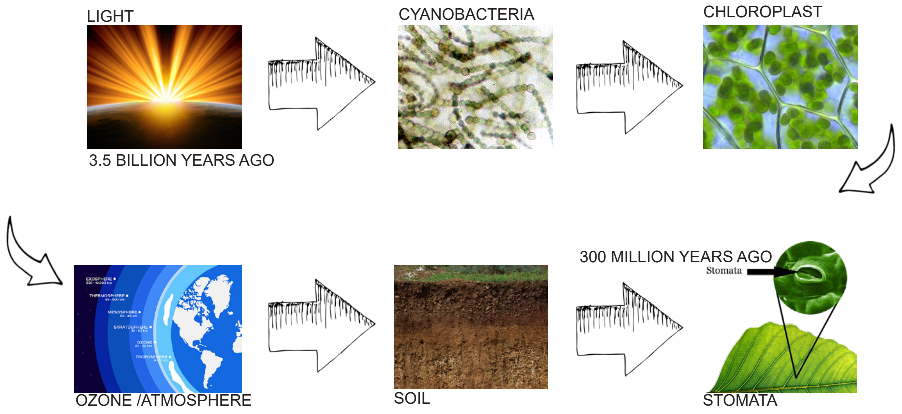


Fig. 2 - Conception of the Forest

LIFE FROM LIGHT: THE BEGINNING OF EVERYTHING.

Its all here because of one thing, "LIGHT" traveling 93 million miles from the sun. Harvesting energy from the sun and manufacturing life from light allowed plants to dominate our planet. PHOTOSYNTHESIS created a living world from a lifeless planet. Three billion years ago there was very little oxygen. The earth consisted of toxic gases like methane and sulfur dioxide. It was lifeless, with no ozone to edit out the suns purple ultraviolet rays. These rays were 100 times stronger than today. Nothing could survive on land, but this was about to change. Around 3.5 billion years ago plant life started, producing oxygen as a waste product. Oxygen pushed out gases, toxic to other forms of life, flooding the earth's atmosphere. Making the clear sky blue for the first time, the great oxidation event, the atmosphere filled with oxygen. Life began underwater with the waters surface acting as sun screen, protecting life below. The earliest organisms were tiny bacteria in the water. Purple bacteria were the first to mass produce and cover the worlds oceans. This purple earth was covered with millions of these microorganisms. These microorganisms only used part of the light and some rays reached deeper into the water. Green bacteria formed deeper in the ocean waters and had a colossal effect on the future. CYANOBACTERIA soon dominated the waters of the earth and this is why plants are green.[8] From the grasslands to the forest, breathing life into the lifeless land.

CYANOBACTERIA: THE ARCHITECTS OF EARTHS ATMOSPHERE.

The green microorganism became the ancestors of all plants on earth, and are why we live on a green planet. Green organisms did something their purple cousins couldn't do: they produced oxygen. Breathing life into our land, without this green bacteria earth might look like mars. Cyanobacteria are aquatic and photosynthetic, they live in the water, and can manufacture their own food. They are tiny, yet often grow in colonies large enough to see. They have the distinction of having become the oldest known fossils, more than 3.5 billion years old.[9] They are one of the largest and most important groups of bacteria on earth. The cyanobacteria have also been tremendously important in shaping the course of evolution and ecological change throughout earth's history. The oxygen atmosphere that we depend on was generated by cyanobacteria during the Archaean and Proterozoic eras. Before that time, the atmosphere had a very different chemistry, unsuitable for life as we know it today. Cyanobacteria are the origin of plants. The chloroplast with which plants make food for themselves is actually a cyanobacterium living within the plant's cells. Sometime in the late Proterozoic, or in the early Cambrian, cyanobacteria began to take up residence within certain eukaryote cells, making food for the eukaryote host in return for a home. This event is known as endosymbiosis, and is also the origin of the eukaryotic mitochondrion.

CHLOROPLASTS: WHERE PHOTOSYNTHESIS HAPPENS.

A microscopic world is packed into every cell acting like bacteria. Each chloroplast is 5000ths of a millimeter across and reacts to flashes of light. Every leaf on every planet is a close descendants of green bacteria "cyanobacteria". Light rays from the sun are known as photons (tiny fast moving particles) moving particles of electromagnetic energy. When they hit the surface the energy of the photons is captured. This is called the "Light harvesting complex". The energy of two photons can split a water molecule, forming its two elements Hydrogen and Oxygen. PLANTS use the HYDROGEN to live and grow, and pump out OXYGEN as a byproduct.

OZONE & SOIL: THE BASIS OF LIFE ON EARTH

As the planet started to get rich in oxygen from plants, high in the stratosphere the oxygen created ozone, blocking dangerous UV rays for the first time. During this Ordovician Period, 400 Million years ago, plants finally made the leap onto land. Roots evolved and allowed plants to move inland. These roots applied great pressure - up to 142 pounds per square inch breaking up small rocks as they took hold.[10] The crushed rock and dead plant materials created soil, essential in holding moisture for plant life, and supporting the cycle of life. Now the leaf-less boring plants could break free from the waters edge, colonize and invade dry land and influence all life on earth. Today soil covers 40% of the land on earth. This process requires 1000 years to make only two centimeters of soil. As plants spread inland, animals and insects could follow them in from the waters edge. Photosynthesis not only created a livable environment for animals, but also created (Glucose) sugars that provided a source of food for all other living creatures. Plants are the foundation of all living things and accounting for our being able to inhabit earth.

STOMATA: THE CREATION OF THE FOREST

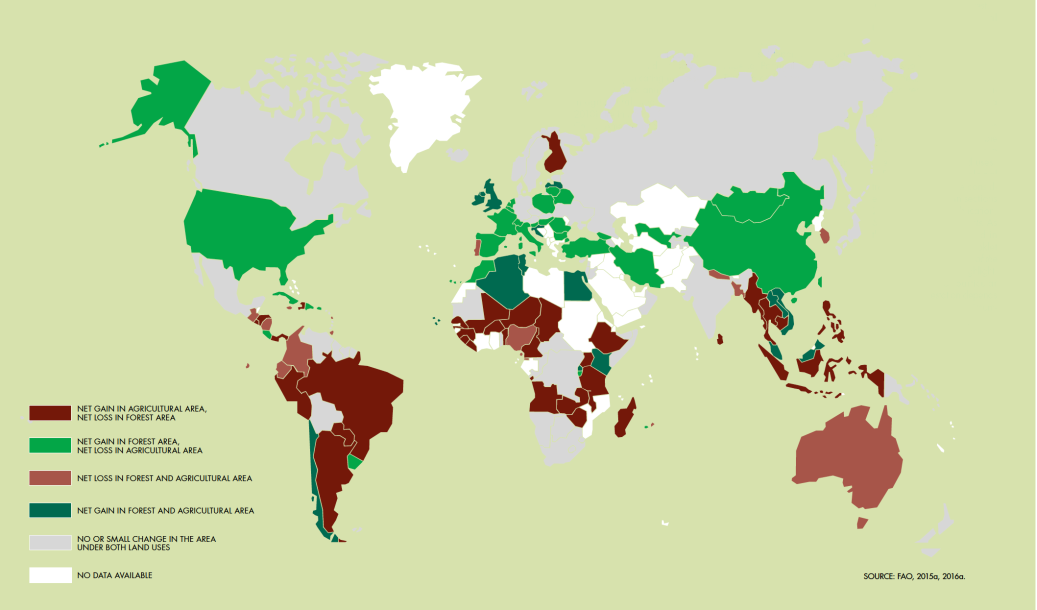
Three hundred and fifty six million years ago plants became victims of their own success. Plants were using up all the carbon dioxide causing C02 gases to plummet by 90%. They needed a more efficient way to procure CO2. Plants restructured themselves with new, complex breathing apparatuses: LEAVES. This maximized their surface. On the underside of leaves were the answer to problems of intake, stomata. There are 1000 stomata on every leaf, allowing each leaf to take in 5 liters of carbon dioxide. This new surface area captured more light and also blocked light to cause shade. This started a competition between plants desperate for the suns rays, forcing plants to reach and grow, higher and higher, creating the very first trees and the very first forest 300 million years ago.

3

SNAPSHOT: THE WORLDS FORESTS

The majority of the loss of forest area in the last 25 years has been in the tropical regions, where populations are growing, including in rural areas. In juxtaposition, there have been gains in net forest area in the temperate regions, where rural populations are decreasing and populations are migrating to cities. "There are clear associations between forest loss and national income: in 2000–2010, high-income countries registered an over all increase in forest area, while the upper-middle, lower-middle and low income country categories all showed over all decreases in forest area."[11] Studies have shown that the main reason for deforestation is the transformation of forest land to agricultural land use. In 2000–2010 the loss of forest in the world's tropical regions was (17 million acres per year) similar to the increase in agricultural area (14.8 million acres per year). Most of this forest loss, and increase in agricultural area, occurred in South America, Africa and South and Southeast Asia. It is estimated that, in the tropics and subtropics, large-scale commercial agriculture accounts for 40% of deforestation; local subsistence agriculture accounts for 33%; and urban expansion, infrastructure and mining account for 27%.

Global forest area declined by 318 million acres (3.1%) in the period from 1990 to 2015 and is now just under 9.8 billion acres, although the rate of global net forest loss slowed from an average of 18 million acres per year in the 1990s to 8.15 million acres per year in 2010–2015.[12] Halting the loss of forests will benefit hundreds of millions of people, including many of the world's poorest people, whose livelihoods depend on forest goods and environmental services. It will also help combat climate change, protect habitats for 75% of the world's terrestrial biodiversity, and maintain ecosystem resilience.



SOURCE: FAO, 2015a, 2016a.

THE WORLDS FORESTS: NET GAINS AND NET LOSS FOREST AREA & AGRICULTURAL AREA (2000 - 2016)

Fig. 3 - The World's Forests

4

FRAGMENTATION OF US FORESTS

England's hunger for trees jump-started the American economy long before tobacco and cotton. Early American wealth was built on timber starting in1600, peaking between 1850 and 1900. Wood also powered the nation's metal-making industries (CHARCOAL) and in the 1840's paper mills were built for the pulp industry. Wood has always been a root source for our economy. In the1900's forest acreage in the United States had dropped from one billion acres to an all-time low of 700,000,000 acres comprised of small second growth trees. Trees considered to be a hindrance, to be cut down and burned to clear land for agriculture.

<u>The deforestation of the United States fueled the Forest Preservation Movement:</u>

- 1875 American Forestry Association was organized
- 1881 the U.S. Department of agriculture created the devision of Forestry.
- 1891 sparked President Benjamin Harrison to set aside forest reserves on public lands.
- 1892- 1905 the U.S. Forest Service and Sierra Club were formed.
- 1900 Society of American Foresters was founded.

Starting in 1900 and for the next 90 years the common goal of government, industry, and concerned private citizens was to protect and preserve forests. The Sierra Club pushed for Wilderness Preservation. Logging on public lands was ruled on in court rooms, and delayed and halted on public lands by lawsuits from environmental groups. Government was concerned with the timber reserves supply of wood for national needs. While industry wanted to reduce forest losses from fire and natural disasters so there would be more timber to harvest. In addition to protecting forests from ourselves we pushed to protect them from natural disasters, making fire suppression a national policy.

Fig. 4 - Forest Preservation Time-line

Timber companies were vilified in national media. As the environmental movement gained traction through the 1970's and beyond, public campaigns urged people to save trees by using less paper and using materials other than lumber for building and furniture.

Good intentions and media campaigns have had little effect on the demand for wood products however, and demand has continued to climb. In 2001 an average American used 67 cubic feet of wood. In 2008 that figure climbed to 79 cubic feet. The country now uses more than 24 billion cubic feet of wood per year. As a country, we are very dependent on trees.

During the last several decades timber companies have broken up and sold off large parts of their holdings to private owners. In a natural response to rising land prices and lower timber values due to imports. 751 million acres: (38% public lands) 62% are owned privately (490,253,000 acres) by 10 million people, nonindustrial owners, individuals, families, and groups of friends. Few private owners can now afford to buy large wood lots, resulting is new owners holding smaller acreage.[13] With so many owners with different priories for their forests, poor forest management is common.

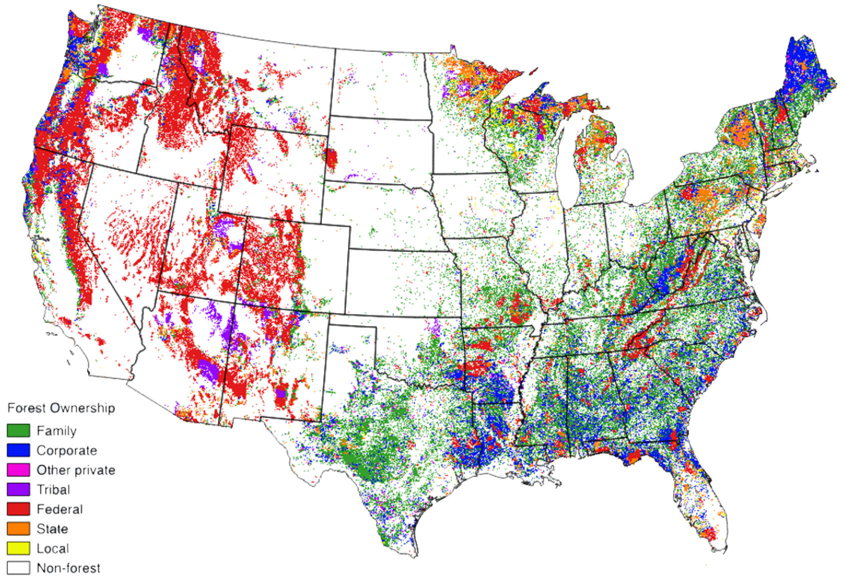
> "Nearly ¾ of private woodland owners have less than 100 acres of forest, a dramatic change from ownership patterns of the twentieth century. In previous generations, enormous tracts of woodlands were owned by timber companies, making integrated management possible over large areas." Forest Service, Who Owns America's Forests, 6

This has caused forest fragmentation which has caused negative impacts on local infrastructure, economy, and forest management. With 38% of our forest protected as public land and the remaining 62% in the hands of 10 million private owners, this creates a hurdle, slowing progress towards goals of national self sufficiency and long term forest sustainability.[14]

All U.S. forests are growing at a faster rate than wood is being harvested, and our forests are currently growing faster then they are being reduced to ash from natural disturbances and human harvest. These gains are offset by the lack of a cohesive management plan for harvesting our fragmented forest.

Our forests need human stewardship and a new understanding of forest management within the context of the large public owned forest stands, to the small plots of privately owned forest. Human presence long disturbed the natural processes of forests and then were left alone as we relied on unsustainable imported wood products. Numbers of, and tree size are up in the US and continue to increase, but overall condition of many stands has deteriorated from overcrowding, creating problems. Forests owners and management practices need to look towards harvesting timber to emulate natural process, using proper logging techniques to emulate natural disturbance while limiting risk of fire. National forests are dynamic, and so should be sustainable management

We need to elevate the forest heath and growth to provide a scrub for our atmosphere along with providing a renewable building material for our projected population growth that will sequester carbon in our built environments.



UNITED STATES FOREST OWNERSHIP

TOTAL ACRES OF FORESTED LAND:

- 751,000,000 (About one-third of the total land area)

FORESTED ACRES OWNED BY NONINDUSTRIAL PRIVATE OWNERS (NIPOs)

- 260,747,000 (490,253,000 62% of non-government-owned forested land)

NUMBER OF NONINDUSTRIAL PRIVATE FOREST OWNERS:

- 10 MILLION

SIZE OF LANDHOLDINGS:

- 61 % of NIPOs own between 1 and 9 acres, which equals just 7.6 % of privately owned forested land; 34% of NIPOs own between 10 to 100 acres, accounting for 40% of privately owned forested acreage; 5% own 100 to 199 acres, accounting for 39% of privately owned forested acreage.

SPECIES OF TREES IN UNITED STATES:

- 800+ (including 82 nonnatives)

TOTAL TIMBER VOLUME:

- About 1 trillion cubic feet; growth has exceeded harvest since the 1950's.

TIMBER MORALITY FROM INSECTS, DISEASE, AND OTHER NATURAL CAUSES IN 2006

- 7.8 billion cubic feet (highest level recorded to date)

NET TIMBER GROWTH IN 2006 (including harvests for lumber, pulp, biomass, firewood, and nonsalable thinning):

- 15.5 billion cubic feet

CHANGE IN TIMBER VOLUME IN 2006 (net growth minus timber removal):

- 11.2 billion cubic feet.

PROBABLE REASONS FOR INCREASED TREE MORTALITY:

- Nonnative insect and disease outbreaks, excessive drought in much of the United States, and overcrowding in forest stands, which leaves them vulnerable to further stress.

"Who owns America's Forests?" Forest Service publication Report WO-78 (2009)

5

US FOREST CARBON STOCK

WHERE CARBON STOCK IS STORED:

1) Live Biomass (live tree and under-story AG and BG), 2) Soil Organic Carbon (SOC), and 3) Dead Wood and Forest Floor.

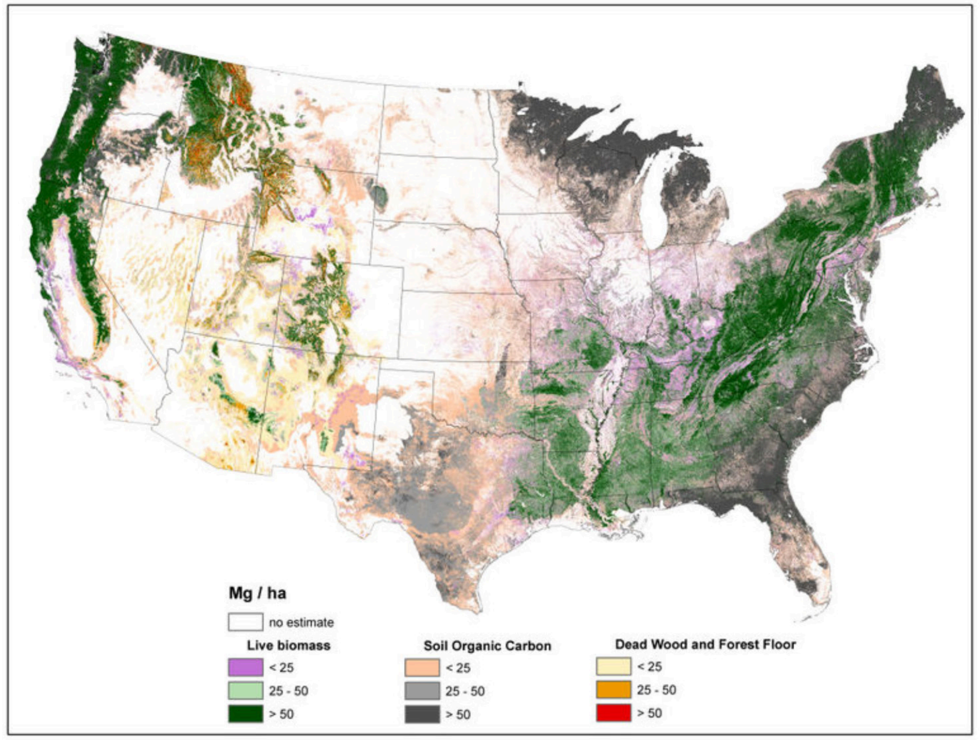
The forest ecosystems represent the largest terrestrial carbon sink on earth acting as our greatest asset for scrubbing our atmosphere, sequestrating carbon and producing clean oxygen.

While most forested areas of the U.S. have moderate C stock density (< 100 Mg/ha) (lower elevations of the Rocky Mountains, Central, and Plains states), there are other areas that have C densities in excess of 200 Mg/ha such as the Pacific Northwest and the upper Great Lakes. C stocks are comprised of diverse forest ecosystem components.[15]

Live tree carbon density is often highest on the best quality forest sites such as those found in the Pacific Northwest. Live Above Ground and Below Ground C stock density is highest in the Pacific Northwest, northwest California, northern Rockies, and Appalachian Mountains. The highest live AG C stock density often exceeds 80 Mg/ha.[16] As BG C stocks are modeled as a function of AG C stocks, their spatial distributions are closely aligned. Live under-story AG and BG C density follow spatial patterns in allocation similar to live tree distributions.

Standing dead tree C stock densities are highest (> 8 Mg/ha) in the Olympic Mountains, Cascade Range, and North and Central Rocky Mountains. In comparison to the western U.S., eastern standing dead tree C stock density is minimal with only the Adirondacks and isolated areas of the Appalachian Mountains having a stock density exceeding 2 Mg/ha. The highest downed dead C stock densities (> 12 Mg/ha) are almost exclusively found in the Pacific North-west and West Coast/Sierra Nevada.

TOTAL FOREST ECOSYSTEM CARBON DENSITY



The U.S. Forest Carbon Accounting Framework: Stocks and Stock Change, 1990-2016 United States Department of Agriculture

LIVE TREE (ABOVE GROUND) & LIVE TREE (BELOW GROUND)
DEAD TREES STANDING & DOWNED DEAD WOOD
FOREST FLOOR & SOIL ORGANIC CARBON

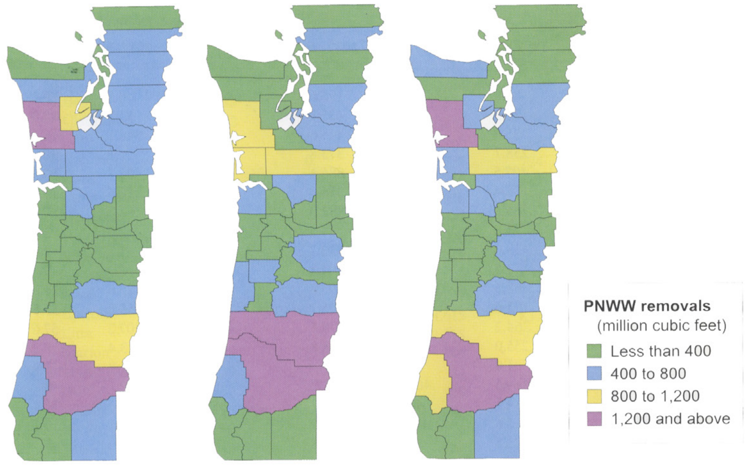
The detrital components of forest floor and SOC have spatial distributions fundamentally different from woody biomass C stock distributions. The highest C stock densities for forest floor (> 15 Mg/ha) are found in the Pacific Northwest, California, Rocky Mountains, upper peninsula of Michigan, and New England. The highest C stock densities for SOC (> 80 Mg/ha) are found in the upper Lake States, Pacific Northwest, northern New England, and coastal areas of the Southeast.[17]

The Pacific Northwests forests, mainly comprised of Douglas Fir and Western Hemlock provides one of the most diverse and healthy forests in the entire country. It has the highest carbon stock density in every major category. (Living biomass AG, Under-story, BG, Deadwood, Forest floor, & SOC.) The understanding of our forest carbon stock, siviculture and our harvest-ing techniques will allow the forest to continue to do what it does best sequester carbon.

Fig. 7 - U.S. Forest Carbon Stock Accounting

6

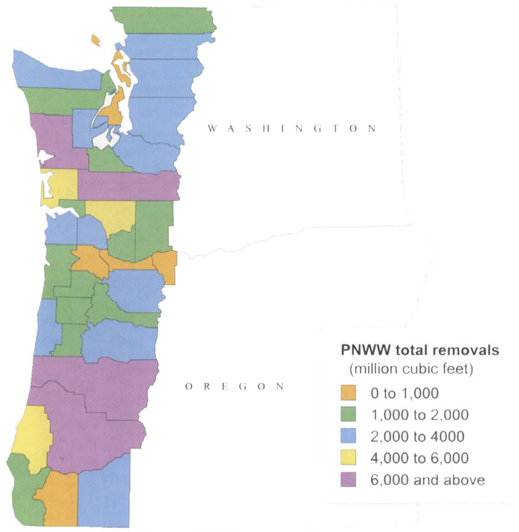
NORTHWEST TIMBER HARVEST



Period 0 (1997–2006) **Period 2** (2017–2026) **Period 4** (2037–2046)

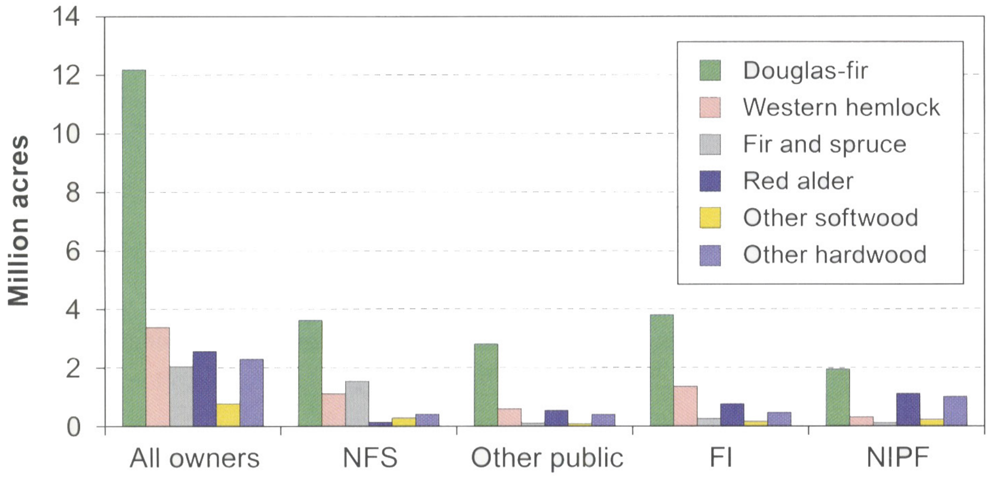
The northwest timber harvest (Washington and Oregon's west-side) is one of the largest timber production territory's in the United States. The total removals for this territory are projected to increase by 50% by 2050 from current stock, inventories will be sustained for the next 50 years.[18] Douglas-fir remains the major species accounting for 63 percent of total removals for 1997-2056. Soon all Douglas-fir removals from Forest Industry (FI) and Non-indusrial Private Forests (NIPF) will represent the 45 - 65 year age class. The National Forest System (NFS) will supply older Douglas-fir but in comparatively limited volumes. Nearly 50 percent of the total timber removals will come from the 10 west counties in Washington and Oregon, where much of the private land base is located. The sizes of future timber will be similar to log mixes today except for fewer logs in the 24 in plus category. If harvest age falls much below 40 years, substantial changes in mechanical properties of both species, and have a major influence on mechanical grade yields and the ability to use this material for engineered wood products. These projections provide a strong discussion of how forest resources might evolve in the northwest. As a region with a rich history of forest management these projections suggest a future in which landowners and managers improve forest stewardship by responding to the challenges imposed by changing markets and land use.

Fig. 8 - Northwest Timber Removals per Period



Accumulated removals during projection period by county for all ownerships.

Timberland West Side counties: 23.3 million Acres
Majority west-site forest types are Douglas Fir & Western Hemlock.



Timberland distribution among owners and forest types. NFS, FI,& NIPF

12 million acres Douglas Fir, **3.5 million acres** Western Hemlock, **2.5 million acres** Red Alder, **2.2 million acres** other hardwood, **2 million acres** Fir and Spruce, **.75 million acres** other softwoods.

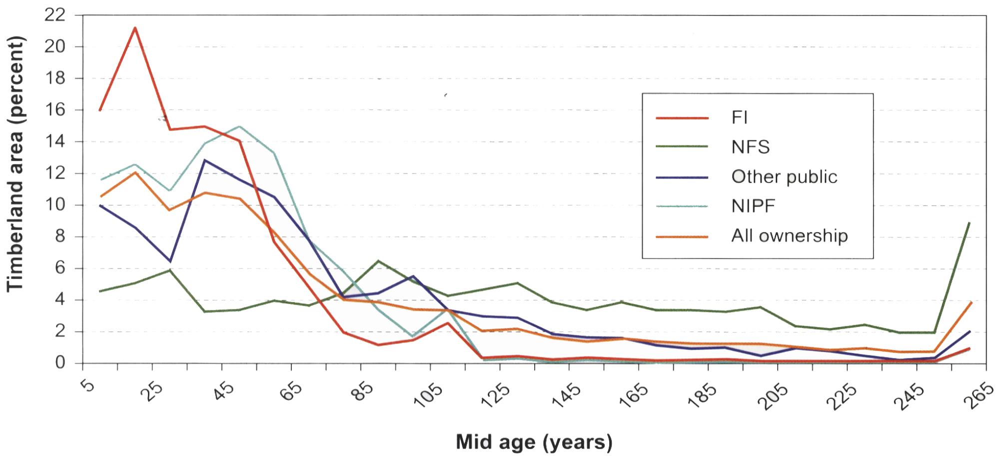
U.S. DEPARTMENT OF AGRICULTURE / FOREST SERVICE 2000

Fig. 9 - Northwest Timber Total Removals
Fig. 10 - Timberland Distribution Among Owners and Forest Types

The projections of future removals tends toward younger and smaller trees for all ownerships, especially for the private owners. An important questions for these owners is whether this will influence the wood characteristics and affect the log grades.

As far as visual grades are concerned, transition to a younger growth resource with fairly uniform characteristics has already occurred in coastal Washington and Oregon. This means that as the industry continues the shift to harvesting and processing smaller, younger trees little change in visual lumber grade yield should be expected.

As tree age for both Douglas Fir and Western Hemlock dips below age 40, the proportion of juvenile wood is expected to increase to the point where a substantial reduction in mechanical properties begins to occur.[19] This is particularly true for Western Hemlock and is somewhat less of an issue for Douglas Fir. This could have a major influence on the ability to use this material for engineered wood products. This could be alleviated through silvicultural practices adopted to each of the fragmented forest ownership groups.



Current age class distribution by ownership, NFS, FI, & NIPF

National Forest System (NFS) 31%, Public Ownership 20 %
Forest Industry (FI) 29%, Nonindustrial Private Forests (NIPF) 20%

Fig. 11 - NW Forest. Current Age Class Distribution

7

LIFE CYCLE ASSESSMENT (LCA)

How do we as architects build sustainable projects into the future? The use of LCA data (EN 15798) allows architects to understand environmental impacts associated with each stage of a buildings life cycle and its components. LCA standardizes a technique to track and report the environmental impacts of a product or process throughout its full life cycle. This tool breaks down the product showcasing the levels of pollutants in each stage of its life. These life stages are; material extraction, manufacturing, construction, use (operations, maintenance and refurbishment), demolition, and disposal.[20]

Fig. 12 - LCA Life Cycle Diagram

LCA: LIFE CYCLE ASSESSMENT (cradle to grave)

EN 15978. Assessment of environmental impacts associated with all the stages of a products life.

Product, Construction Process, Use, Total Operational Use, End of Life, & Beyond Building Life

Global Warming Potential: CO2

Fossil Fuel Consumption: MJ

Acidification Potential: SO2

Eutrophication Potential: N

HH Particulate: PM 2.5

Ozone Depletion Potential: CFC-11

Summary environmental impacts categories: Climate change, Acidification, Eutrophication, Ozone depletion, & Photochemical ozone creation/Smog. Inventory: Water Consumption, Energy Use and waste generation. This process can provide the analytical framework to identify environmental impacts, improve manufacturing processes and compare between alternatives. Breaking the building down to components of assembly to analyze and qualify the superior product and a new level in sustainability.

In this project LCA data was used as a tool to analyze building systems. An emerging system, cross laminated timber was compared with an established dimensional wood assembly, light frame wood construction, providing quantifiable metrics by which to asses the environmental impacts of these two products and processes. This environmental accounting looks at Energy, Raw Materials, Waste and Emissions.

Understanding how LCA data is measured:

Cradle to Gate: Manufacturing

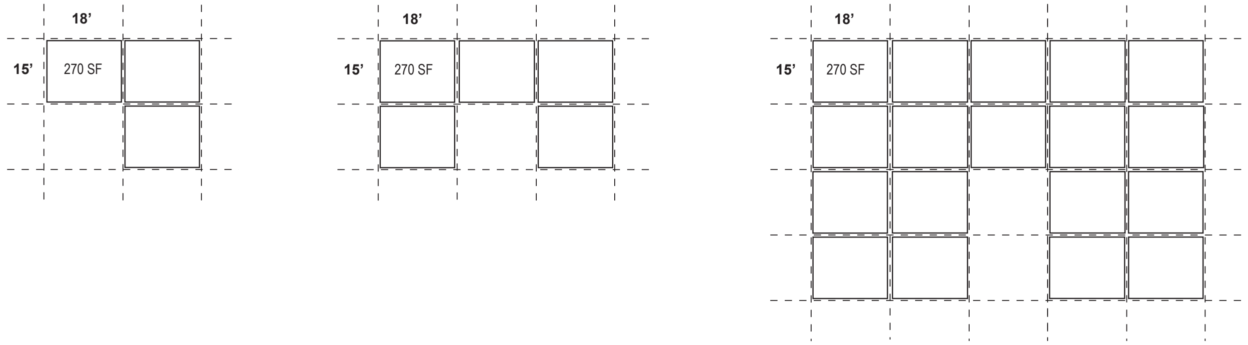
Cradle to Grave: Comprehensive life of a building

Cradle to Cradle: Products at End of Life become material resources

Fig. 13 - LCA Cradle to Grave, Environmental Impacts

8

DEFINING THE MODULAR GRID



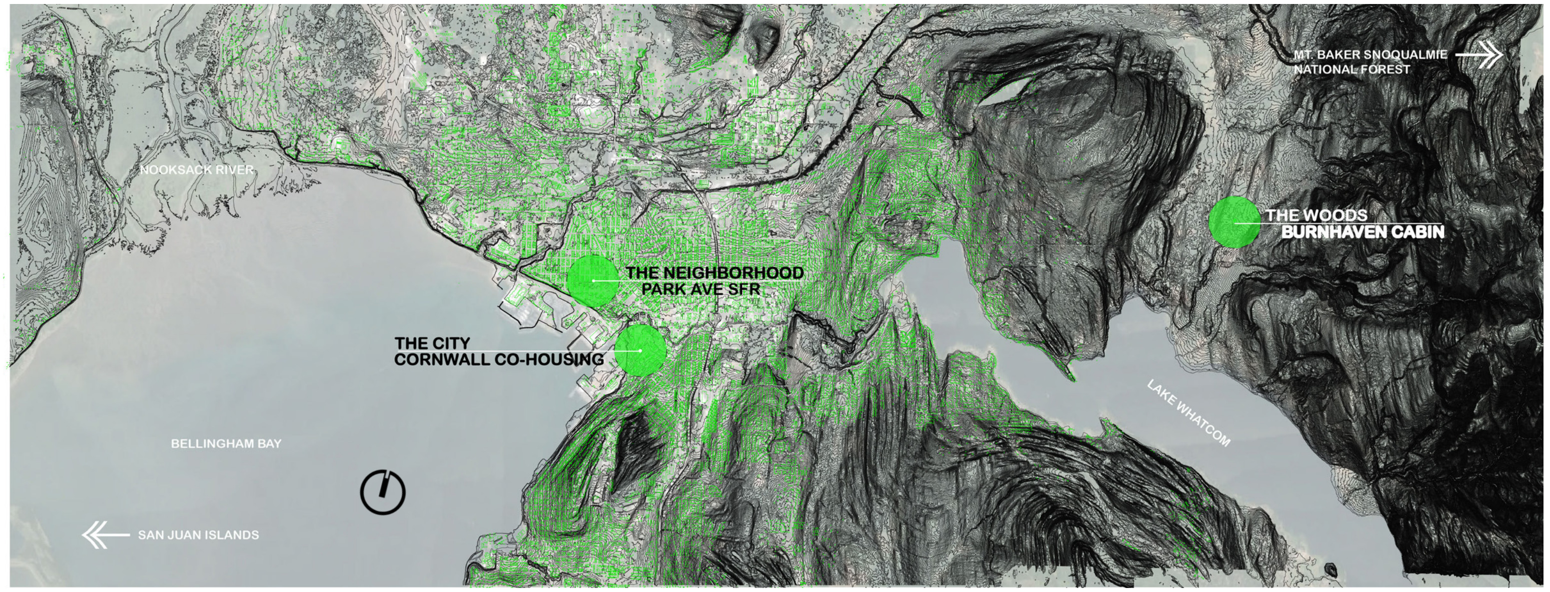
CABIN	SINGLE FAMILY RESIDENCE	CO-HOUSING
SF: 270 X 4 = 1080 SF	**SF: 270 X9 = 2430** SF	**SF: 270 X 18 X 8 = 38,880** SF
BASE: 3 (MODULAR GRID**)**	**BASE: 5 (**MODULAR GRID**)**	**BASE: 19 (**MODULAR GRID**)**
SPACE: 5 (VOLUME**)**	**SPACE: 10 (**VOLUME**)**	**SPACE: 152 (**VOLUME**)**
UNITS: 1	**UNITS: 1 - 4**	**UNITS: 62**
PEOPLE: 4	**PEOPLE: 4 - 8**	**PEOPLE: 62 - 124**

A modular grid was established to properly study these two assembly systems at multiple building scales. The modular grid was based on CLT dimensions, transportation or CLT via truck or train, appropriate square footage of each scale, and a scalable relationship. This project explores design and analysis of these three building scales: a cabin, a single-family residence, and an urban co-housing building. A modular grid creates a scalable relationship to each housing typology. Life Cycle Assessment tools were used to understand each building scale and the difference between two construction methods: Typical Light Frame Wood construction vs. Cross Laminated Timber. The objective of this research is to look towards analysis and new technologies to quantify how to design and build into the future. This modular grid gave a scalable relationship to properly asses at what point does it make sense to use these assembly systems.

Fig. 14 - Defining the Modular Grid Diagram

9

BELLINGHAM & THE THREE SITES

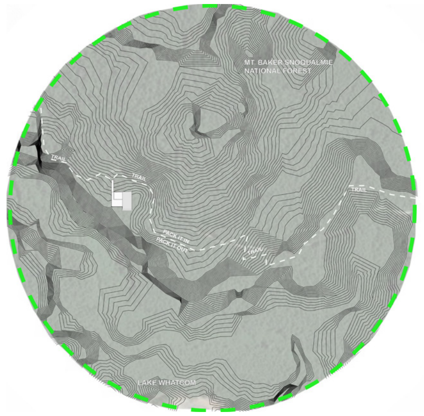


This research on our forests led the study to select the Pacific Northwest as the general area of focus and the site selection do to its above average healthy forests that sequesters more carbon in all six categories of carbon stock, along with its rich history in forest management.

The site was specifically selected for its proximity near two major metropolises, Vancouver BC 60 miles to the north and Seattle 90 miles to the south. These two populations are expanding and creating higher density in Bellingham, WA. Not only is Bellingham a site with projected growth but its proximity to the natural environment, with the Mt. Baker Snoqualmie National Forest to the East and the San Juan Islands to the West. Surrounded by timber as a local natural resource and four CLT factories located in near proximity makes this area a perfect test site for this analysis. This location allows for three sites that are in close adjacency to each other yet having uniquely diverse sites for each building typology: the Woods, the Neighborhood, and the City.

Fig. 15 - Bellingham, WA Vicinity Map

THE WOODS



BURNHAVEN CABIN

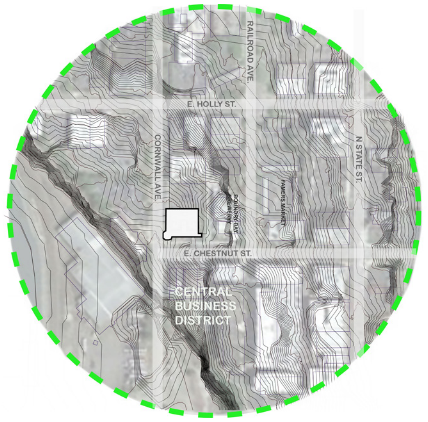
The Burnhaven Cabin is located fifteen minutes east of downtown Bellingham just outside of city limits in Whatcom County. It's placed at the foot hills of Mt. Baker Snoqualmie National Forest and inside the Lake Whatcom watershed.

THE NEIGHBORHOOD

PARK ST. SINGLE FAMILY RESIDENCE

The Park St. Single Family Residence is located in the Columbia district neighborhood across the street from Elizabeth Park. One of the oldest neighborhoods in the city that is currently the most desired area for young professional and families moving into the city.

THE CITY



CORNWALL CO-HOUSING

The Cornwall Co-housing building is located in the heart of downtown in the central business district. With the cities density growing, more business and population are relocating to downtown. This site has all necessities located in walking distance including farmers markets, breweries, restaurants, coffee shops, trail systems and parks.

Fig. 16 - The Woods, Burnhaven Cabin Vicinity Map
Fig. 17 - The Neighborhood, Park St.SFR Vicinity Map
Fig. 18 - The City, Cornwall Co-Housing Vicinity Map

10

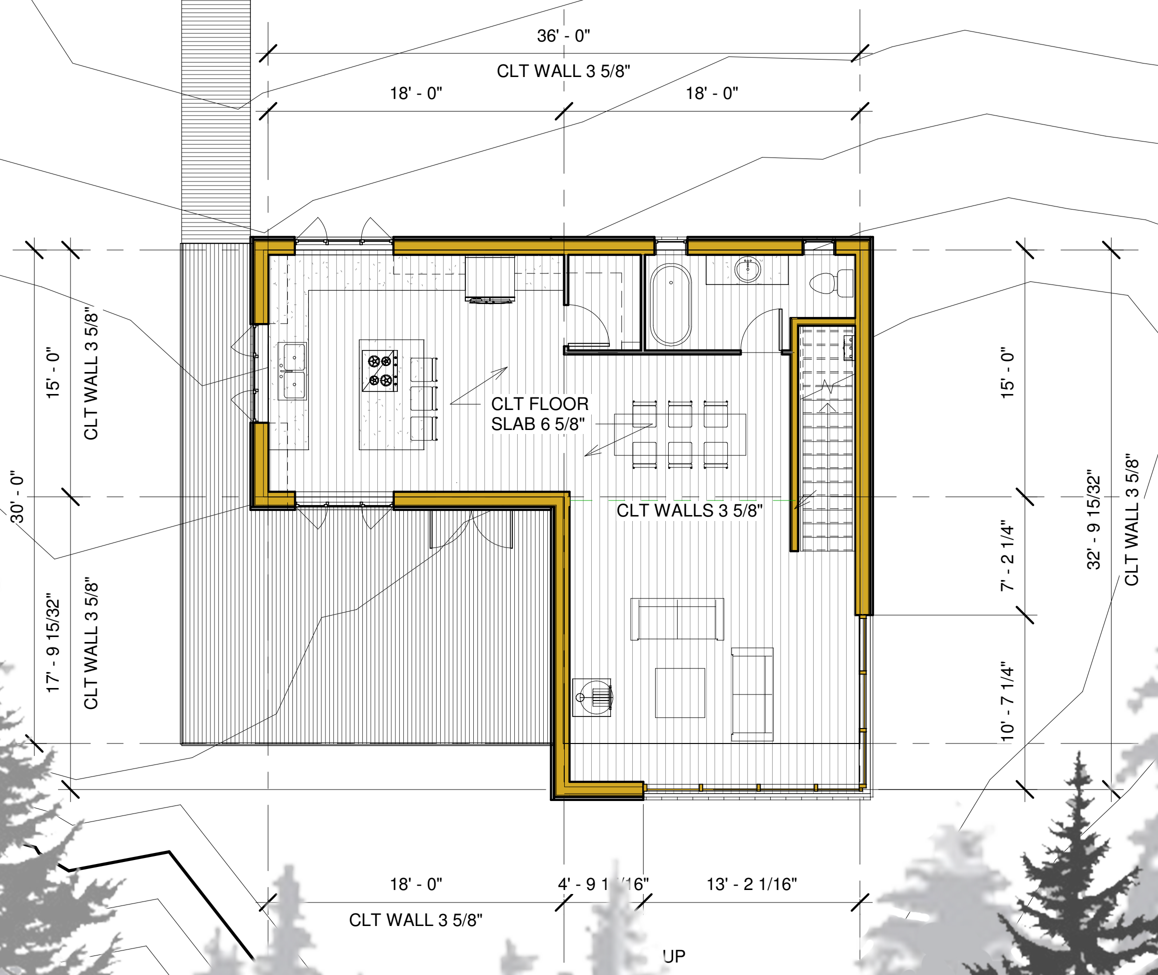
DESIGN & ANALYSIS: CABIN, SFR, CO-HOUSING

This project evaluates an emerging construction system using cross laminated timber, that is currently receiving a lot of attention and praise. This system will be evaluated with a modular gird that creates a scalable relationship to each housing typology. Along with LCA tools the focus is to understand each building scale and the difference between two construction methods, including tracking and reporting the environmental impacts of these system's full life cycle.

How does this new system of mass timber stand up in comparison to a standardized conventional construction system, dimensional light frame wood construction, seemingly efficient and sustainable use of material? Is mass timber a viable substitute for our future, or will this harvesting disrupt one of our greatest natural resource at carbon sequestration and scrubbing our atmosphere of toxic pollutants?

The first housing typology evaluated is the Burnhaven Cabin, this cabin could be used for a retreat to escape the city or a compact residence just outside of the city limits. It's 1,080 square feet, with a modular base of three, a modular volume of five, and it houses one to four people. This flat pack CLT system is designed for easy assembly, disassembly, and flexibility for expansion of future growth.

THE WOODS: BURNHAVEN CABIN



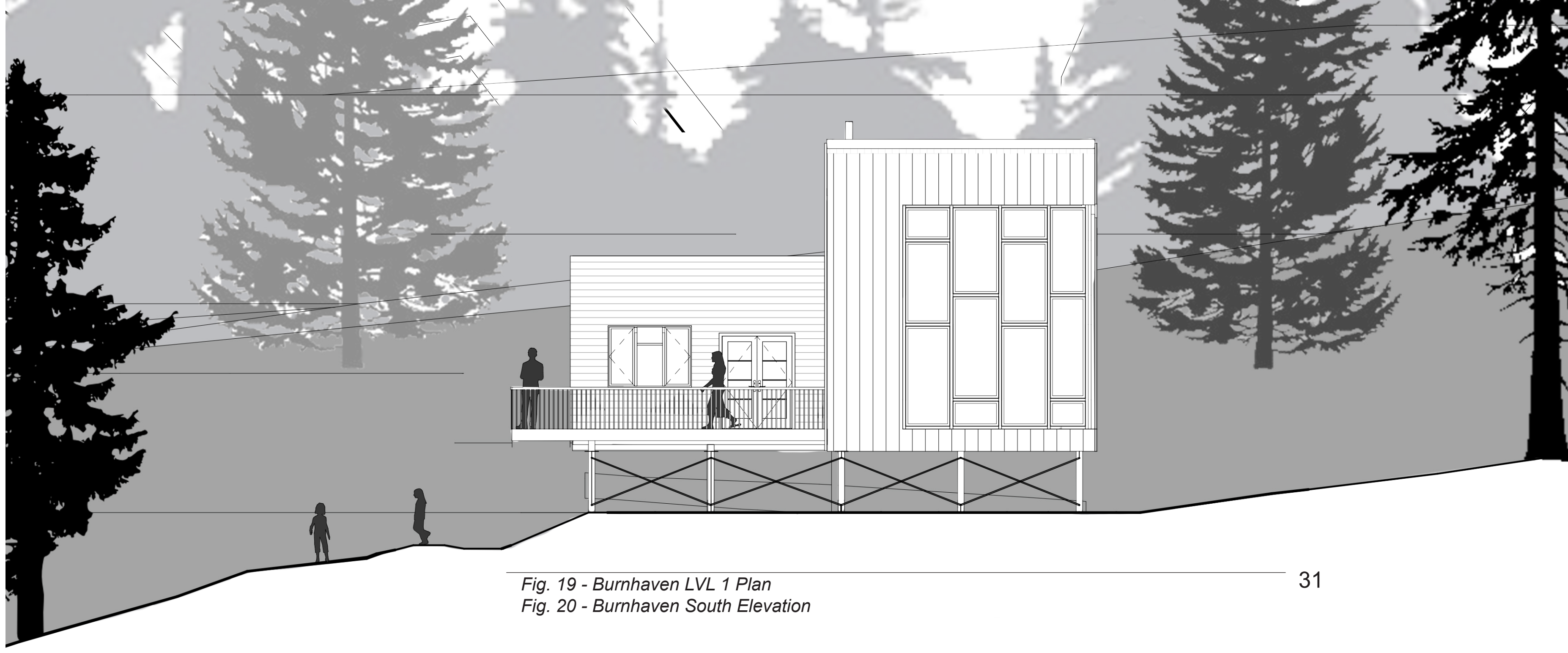
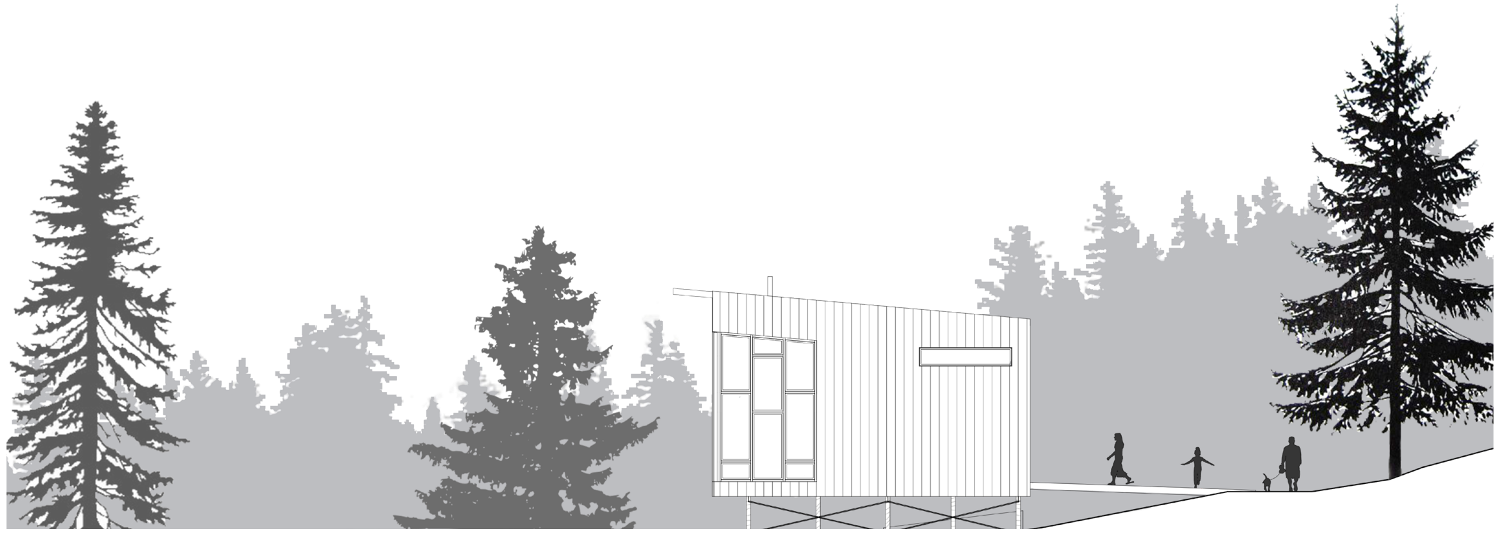


Fig. 19 - Burnhaven LVL 1 Plan
Fig. 20 - Burnhaven South Elevation

THE WOODS: BURNHAVEN CABIN / 1080 SF / MG BASE 3 / MG VOLUME 5 / UNITS 1/ PEOPLE 1-4



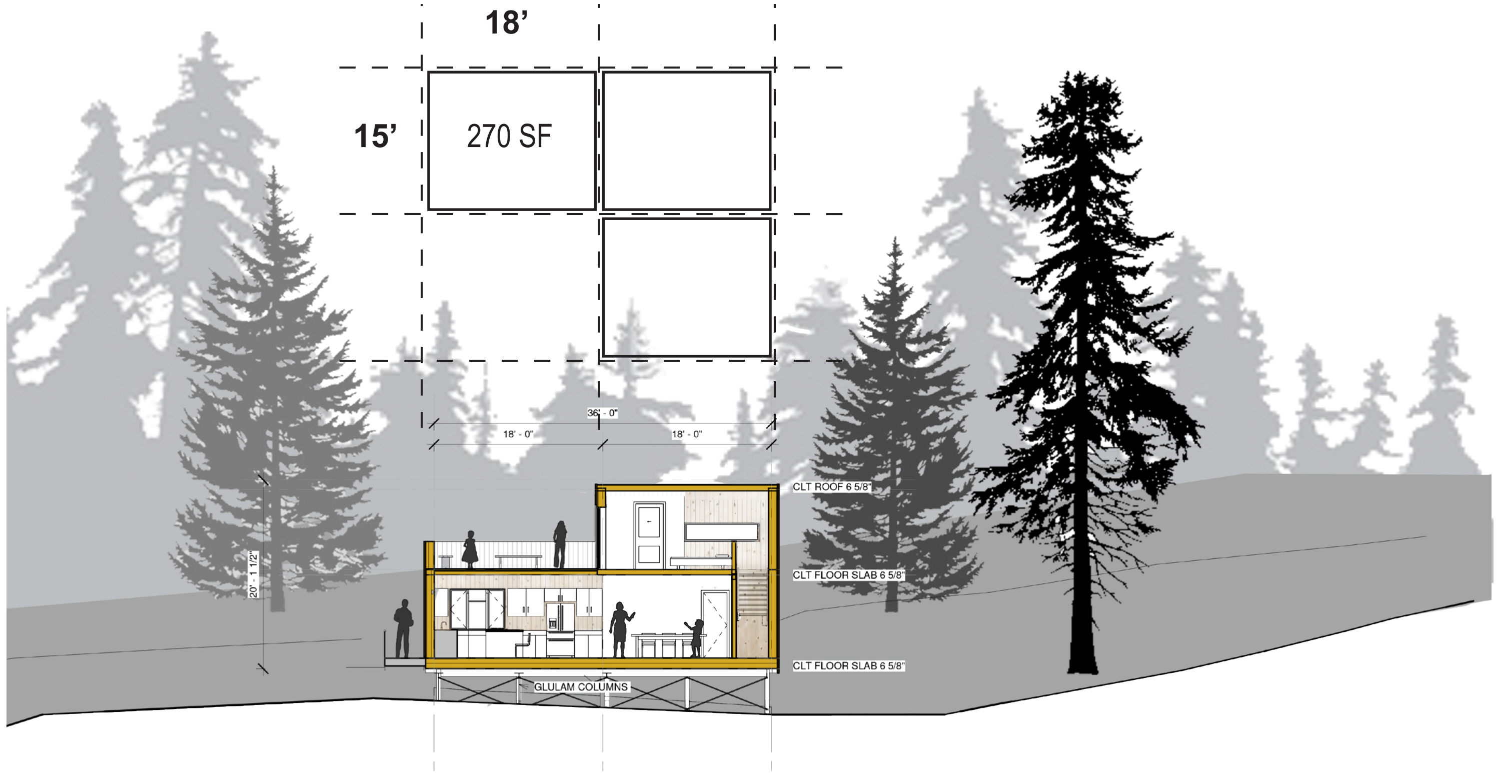
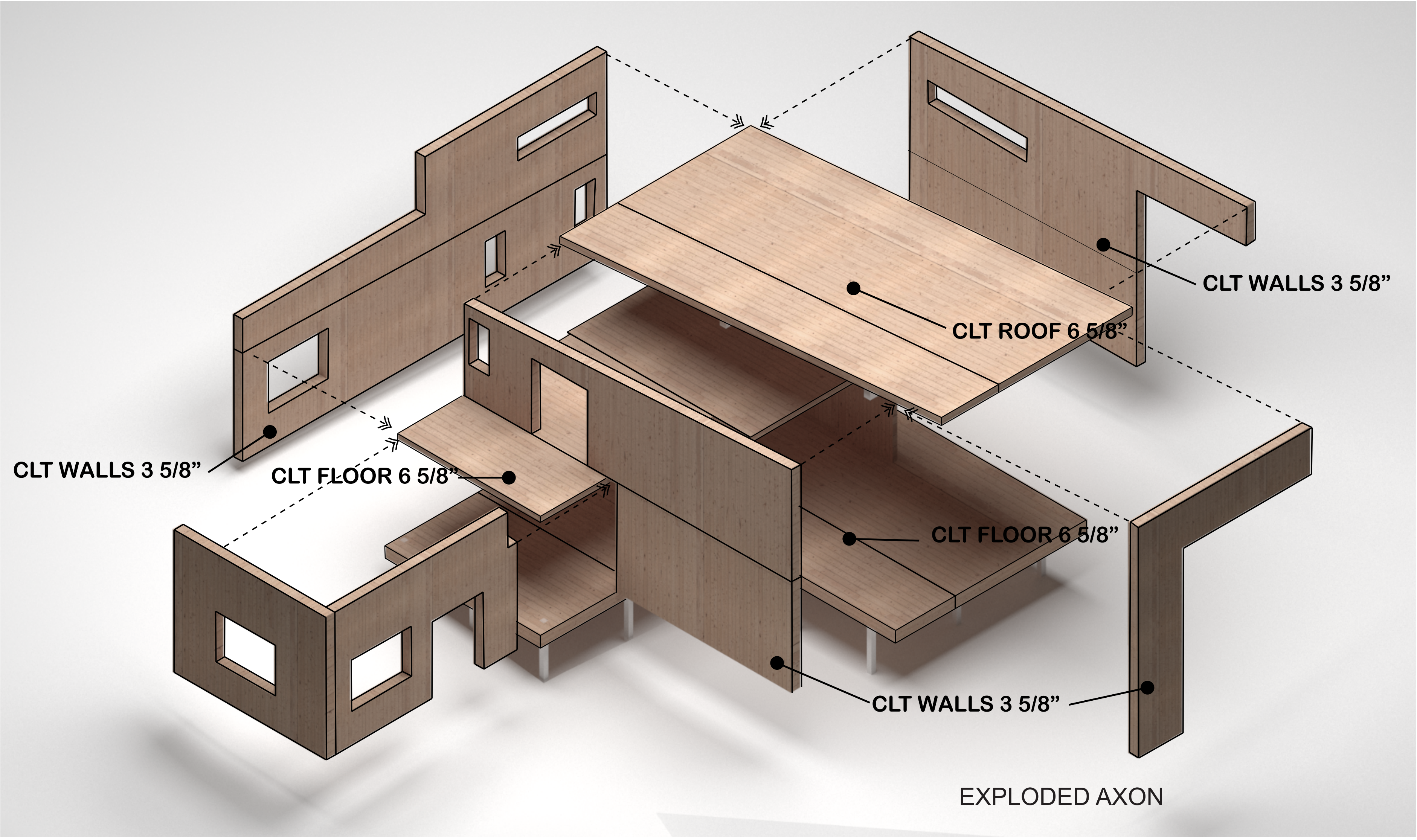


Fig. 21 - The Woods, Burnhaven Cabin Rendering 1
Fig. 22 - The Woods, Burnhaven Cabin South Section

Fig. 23 - The Woods, Burnhaven Cabin Rendering 2
Fig. 24 - The Woods, Burnhaven Cabin East Elevation



CLT WALL ASSEMBLY
TEN 3-ply 3 5/8” wall panels

CLT FLOOR & ROOF ASSEMBLY
EIGHT 5-ply 6 5/8” floor panels

CUBIC FEET: 2920 BOARD FEET: 35,040 TREES: 134

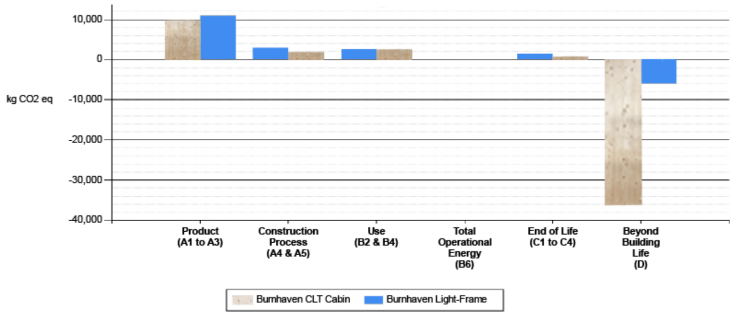
PEOPLE: 1 - 4 # OF TREES: 134 TREES PER PERSON: 33.5

This exploded axon diagram breaks down the structural building components of flat pack CLT floor, roof, and wall assemblies. Calculating the overall mass of material used to construct the Burnhaven Cabin. Systematically evaluating how much cubic feet of wood this project consists of, converting this mass to board feet, then equating how many average size Douglas-Fir trees (261 board feet per tree) it takes to construct this mass timber project. This analysis not only looks at environmental impacts but the max occupancy breaking it down to how many trees per person it houses. The Burnhaven Cabin has a residential capacity of 4 people equaling 134 trees to construct and 33.5 trees per person.

Fig. 25 - The Woods, Burnhaven Cabin Exploded Axonometric Diagram

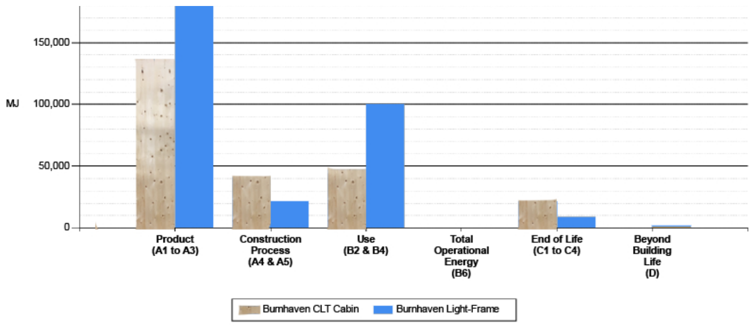
BURNHAVEN CABIN 1,080 SF: LIGHT FRAME WOOD CONSTRUCTION VS. CLT CONSTRUCTION

Comparison of Global Warming Potential CO2 (30/100)



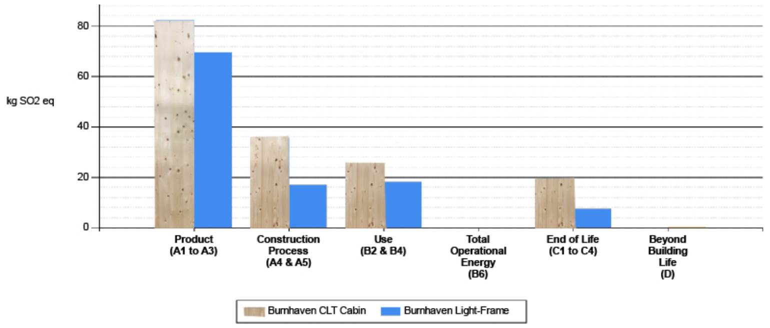
Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Burnhaven CLT Cabin	kg CO2 eq	9.65E+03	2.95E+03	2.57E+03	0.00E+00	1.44E+03	-3.61E+04	**-1.94E+04**
Burnhaven Light-Frame	kg CO2 eq	1.10E+04	1.71E+03	2.41E+03	0.00E+00	6.03E+02	-6.01E+03	**9.68E+03**
Total	**kg CO2 eq**	**2.06E+04**	**4.66E+03**	**4.98E+03**	**0.00E+00**	**2.05E+03**	**-4.21E+04**	**-9.77E+03**

Comparison of Fossil Fuel Consumption MJ (15/100)



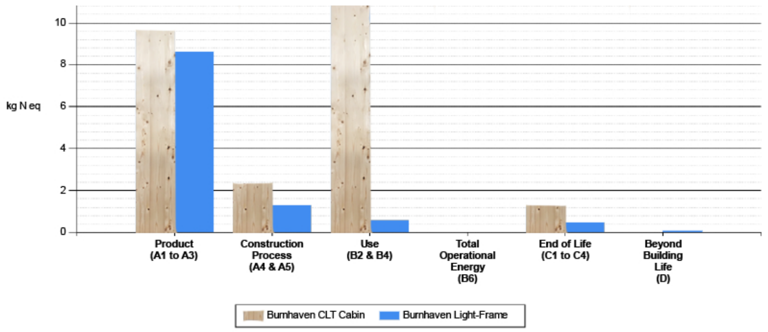
Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Burnhaven CLT Cabin	MJ	1.36E+05	4.13E+04	4.69E+04	0.00E+00	2.14E+04	0.00E+00	**2.45E+05**
Burnhaven Light-Frame	MJ	1.93E+05	2.15E+04	1.00E+05	0.00E+00	8.85E+03	1.22E+03	**3.25E+05**
Total	**MJ**	**3.29E+05**	**6.27E+04**	**1.47E+05**	**0.00E+00**	**3.02E+04**	**1.22E+03**	**5.70E+05**

Comparison of Acidification Potential SO2 (15/100)



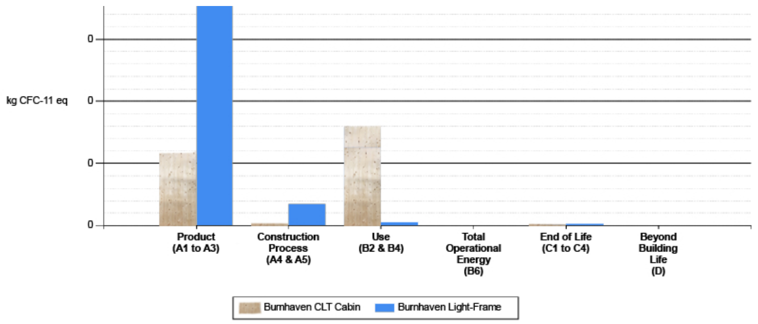
Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Burnhaven CLT Cabin	kg SO2 eq	8.24E+01	3.58E+01	2.57E+01	0.00E+00	1.94E+01	0.00E+00	**1.63E+02**
Burnhaven Light-Frame	kg SO2 eq	6.96E+01	1.71E+01	1.82E+01	0.00E+00	7.53E+00	3.03E-01	**1.13E+02**
Total	**kg SO2 eq**	**1.52E+02**	**5.29E+01**	**4.39E+01**	**0.00E+00**	**2.69E+01**	**3.03E-01**	**2.76E+02**

Comparison of Eutrophication Potential N (15/100)



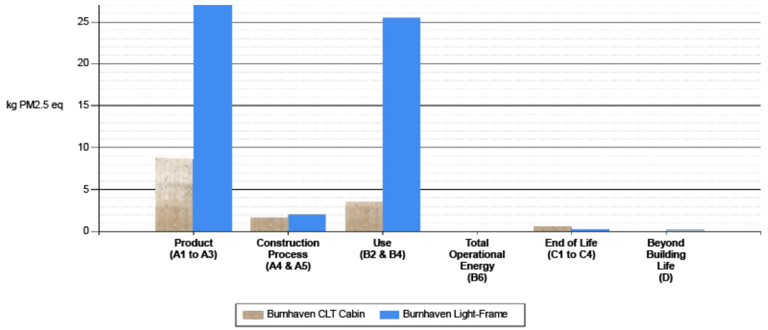
Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Burnhaven CLT Cabin	kg N eq	9.60E+00	2.24E+00	1.20E+01	0.00E+00	1.21E+00	0.00E+00	**2.50E+01**
Burnhaven Light-Frame	kg N eq	8.62E+00	1.31E+00	5.83E-01	0.00E+00	4.68E-01	1.56E-02	**1.10E+01**
Total	**kg N eq**	**1.82E+01**	**3.55E+00**	**1.25E+01**	**0.00E+00**	**1.68E+00**	**1.56E-02**	**3.60E+01**

Comparison of Ozone Depletion Potential CFC (12.5/100)



Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Burnhaven CLT Cabin	kg CFC-11 eq	1.14E-04	1.60E-06	1.58E-04	0.00E+00	6.07E-08	0.00E+00	**2.74E-04**
Burnhaven Light-Frame	kg CFC-11 eq	3.85E-04	3.43E-05	4.32E-06	0.00E+00	2.43E-08	0.00E+00	**4.24E-04**
Total	**kg CFC-11 eq**	**5.00E-04**	**3.59E-05**	**1.63E-04**	**0.00E+00**	**8.50E-08**	**0.00E+00**	**6.98E-04**

Comparison of HH Particulate PM 2.5 (12.5/100)



Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Burnhaven CLT Cabin	kg PM2.5 eq	8.57E+00	1.59E+00	3.44E+00	0.00E+00	5.54E-01	0.00E+00	**1.42E+01**
Burnhaven Light-Frame	kg PM2.5 eq	2.78E+01	2.08E+00	2.55E+01	0.00E+00	3.01E-01	1.33E-01	**5.58E+01**
Total	**kg PM2.5 eq**	**3.63E+01**	**3.68E+00**	**2.90E+01**	**0.00E+00**	**8.56E-01**	**1.33E-01**	**7.00E+01**

🟦 **LIGHT FRAME CONSTRUCTION**

🟫 **CLT CONSTRUCTION**

Fig. 26 - LCA Environmental Impacts of Light Frame Construction vs CLT Construction

To properly evaluate LCA (life cycle analysis) there is a scientific understanding of the environmental impacts the data is tracking and reporting on the life cycle of a building. This life cycle data is tracking five major points; product, construction, use, end of life, and beyond building life. All these environmental impacts are important to building a sustainable future, yet some bear more weight of importance with how our earth is being affected. We live in a society that is constantly polluting our natural environments, the effects are dynamic to geographic location and this weighs what categories are more significant than others. In our present time global warming is the most pressing environmental impact, how we acknowledge this affects how our Built Environments place strain on our planet.

These six environmental impacts are all relevant in evaluating a buildings life cycle but they are not all equally weighted in importance. Out of 100, Global Warming 30/100, Fossil Fuel Consumption 15/100, Acidification 15/100, Eutrophication 15/100, Ozone Depletion 12.5/100, and HH Particulate 12.5/100.

Assessing the data comparison of systems for the Burnhaven Cabin life cycle: There could be an argument for either system to work for a 1,080 SF residence, yet global warming potential, fossil fuel consumption, ozone depletion potential, and HH particulate that comprise for 70/100 all show staggering evidence that CLT construction systems have less impact on environmental pollution. With a notable conclusion for global warming potential with a focus on the Beyond Building Life. Showcasing the positive effect in sequestrating carbon and the potential for a system to have a longer life span than its competitor.

THE NEIGHBORHOOD: PARK ST SFR

The second housing typology evaluated is the Park Street single family residence. This house could be used for a SFR or as a fourplex as density from downtown Bellingham spreads out into its neighborhoods. With the move of rural populations moving into the U.S. cities, design needs to be more dynamic for future change instead of future demolition. The Park St. residence is 2,430 square feet, with a modular base of five, a modular volume of ten, potential for one to four units, and it houses four to eight people. This flat pack CLT system is designed for easy assembly, disassembly, and flexibility for expansion of future growth.

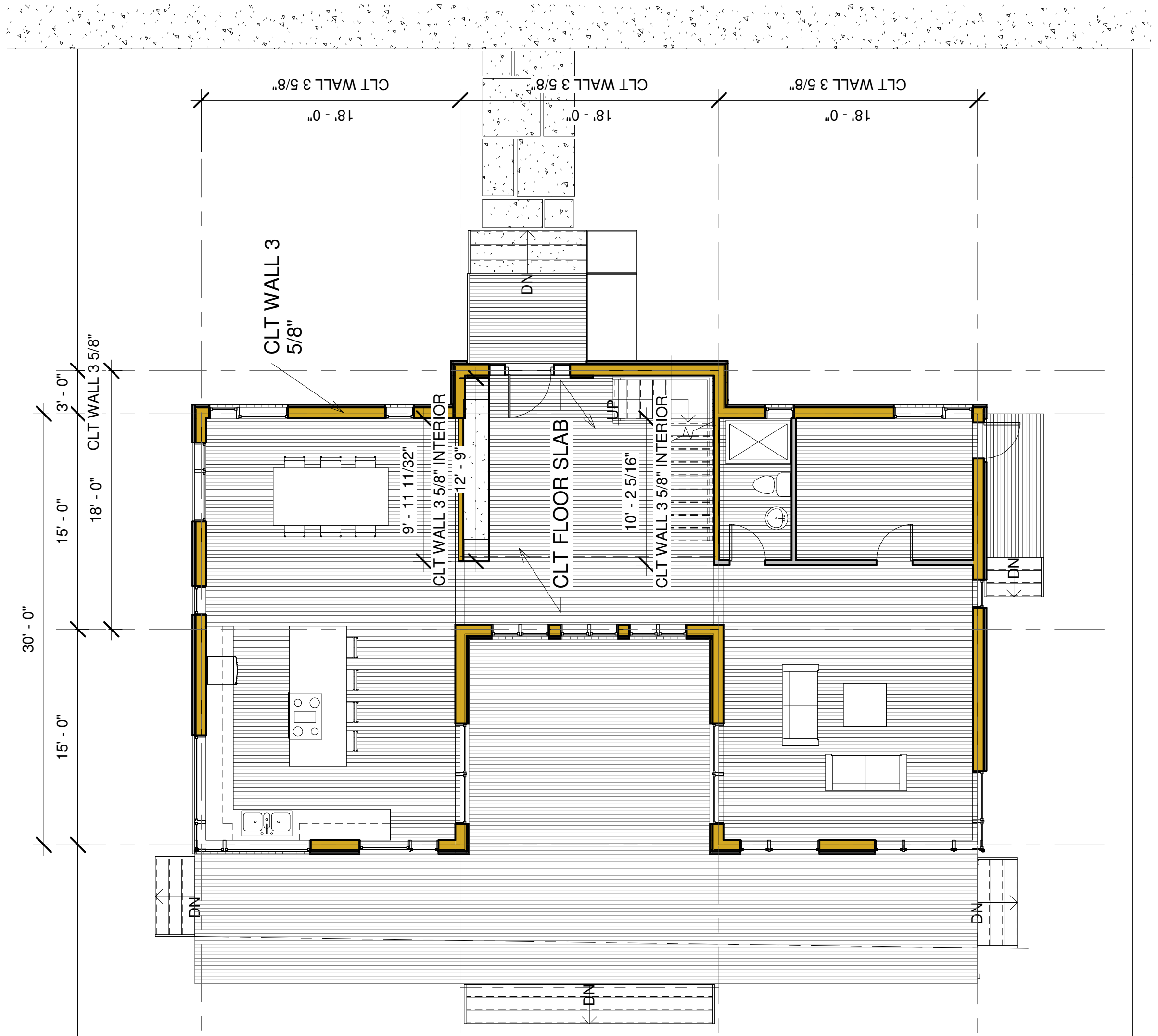


Fig. 27 - Park St. SFR, LVL 1 Plan
Fig. 28 - Park St. SFR, West Elevation

THE NEIGHBORHOOD: PARK ST. SFR / 2,430 SF / MG BASE 5 / MG VOLUME 10 / UNITS 1 - 4 / PEOPLE 4 - 8

Fig. 29 - Park St. SFR, Rendering 1
Fig. 30 - Park St. SFR, South Elevation

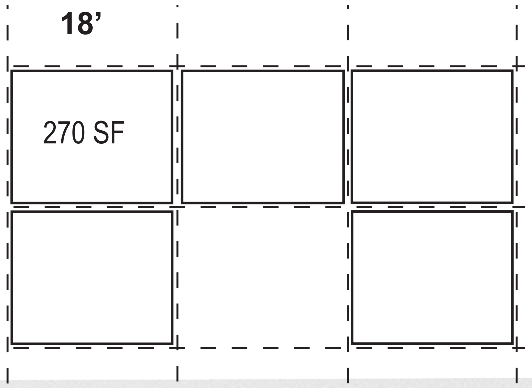
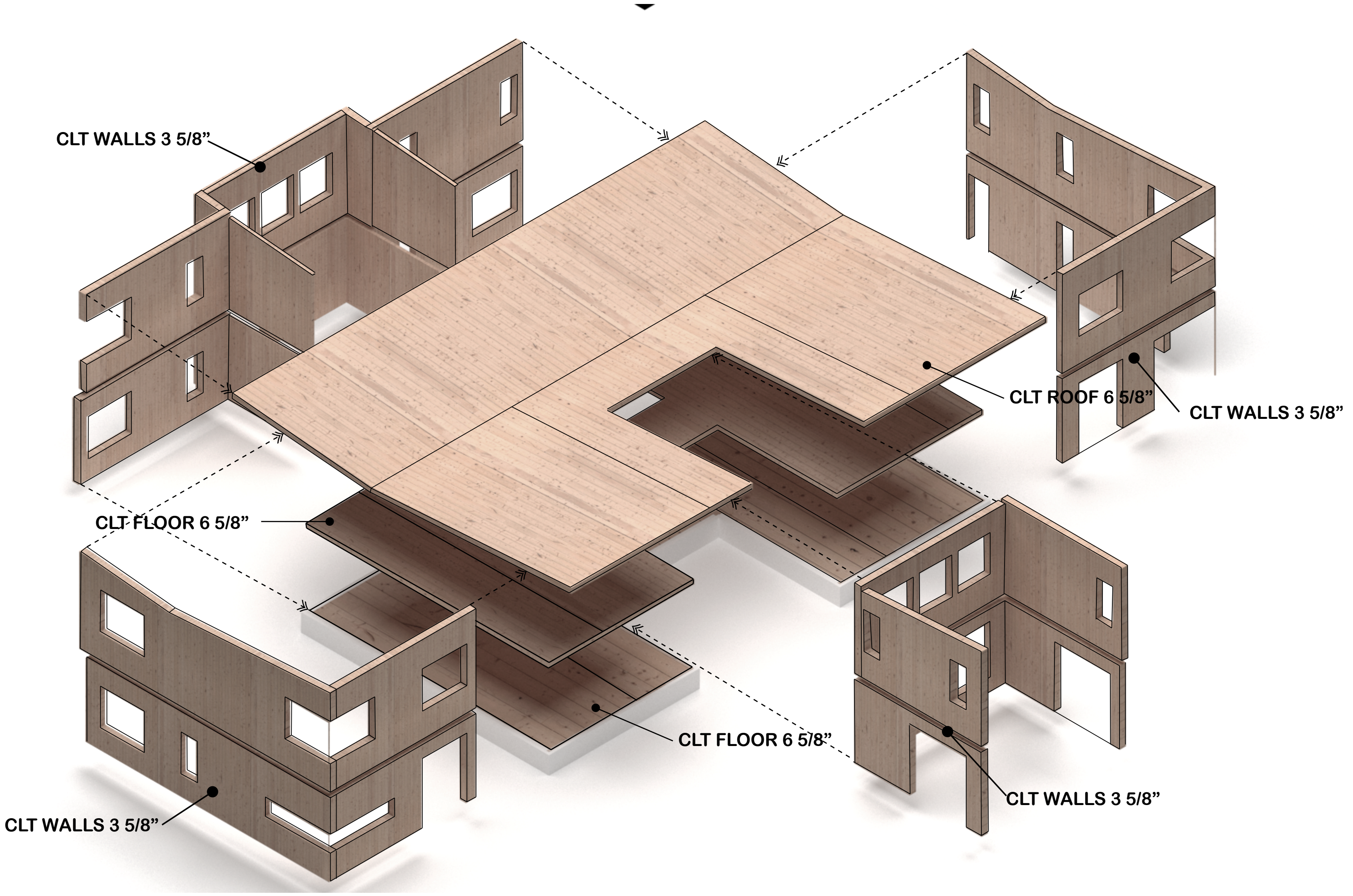


Fig. 31 - Park St. SFR, Rendering 2
Fig. 32 - Park St. SFR, Modular Grid Diagram
Fig. 33 - Park St. SFR, West Section



CLT WALL ASSEMBLY
TWENTY-FOUR 3-ply 3 5/8” wall panels

CLT FLOOR & ROOF ASSEMBLY
FIFTEEN 5-ply 6 5/8” floor panels

CUBIC FEET: 3373 BOARD FEET: 40,476 TREES: 155

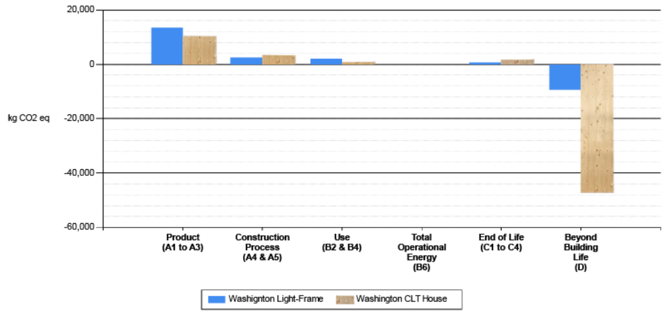
PEOPLE: 1 - 8 # OF TREES: 155 TREES PER PERSON: 19.375

This exploded axon diagram breaks down the structural building components of the flat pack CLT floor, roof, and wall assemblies. Calculating the overall mass in cubic feet of material used to construct the Park Street SFR. Systematically evaluating how much wood this project consist of, converting this cubic feet to board feet, then equating how many average size Douglas-Fir trees (261 board feet per tree) it takes to construct this mass timber project. This analysis not only looks at environmental impacts but the max occupancy gaging how many trees per person it houses. The Park Street SFR/Fourplex uses155 trees to construct and has a residential capacity of 8 people, equaling 19.375 trees per person.

Fig. 34 - Park St. SFR, Exploded Axonometric Diagram

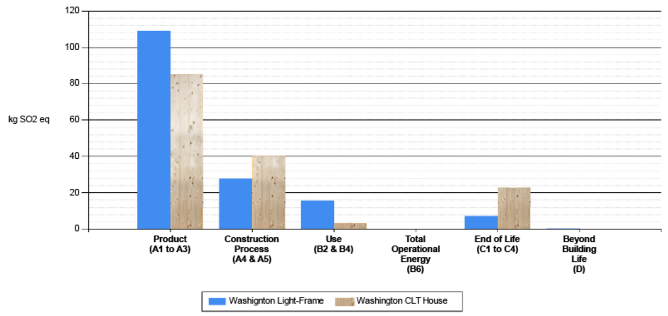
PARK ST. SFR 2,430 SF: LIGHT FRAME WOOD CONSTRUCTION VS. CLT CONSTRUCTION

Comparison of Global Warming Potential CO2 (30/100)



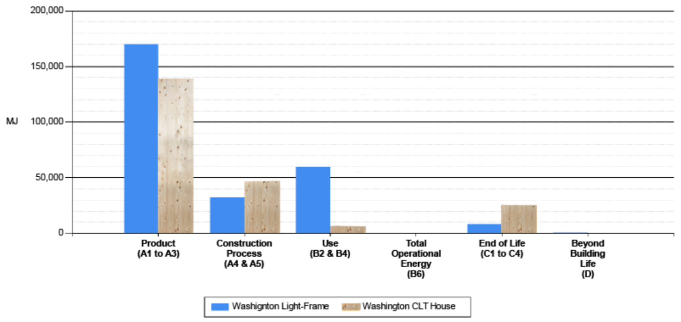
Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Washignton Light-Frame	kg CO2 eq	1.34E+04	2.52E+03	1.96E+03	0.00E+00	5.70E+02	-9.48E+03	**8.98E+03**
Washignton CLT House	kg CO2 eq	1.02E+04	3.30E+03	5.30E+02	0.00E+00	1.67E+03	-4.69E+04	**-3.12E+04**
Total	**kg CO2 eq**	**2.36E+04**	**5.82E+03**	**2.49E+03**	**0.00E+00**	**2.24E+03**	**-5.64E+04**	**-2.22E+04**

Comparison of Fossil Fuel Consumption MJ (15/30)



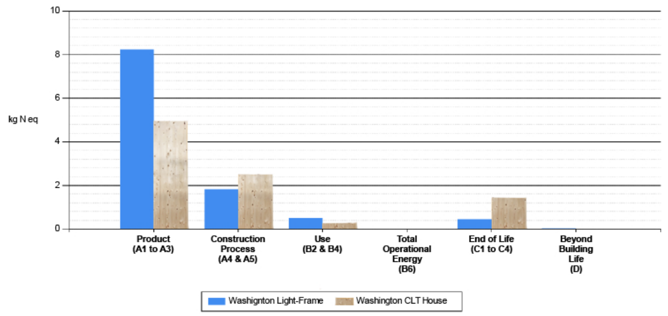
Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Washignton Light-Frame	kg SO2 eq	1.09E+02	2.78E+01	1.58E+01	0.00E+00	7.06E+00	2.29E-01	**1.60E+02**
Washignton CLT House	kg SO2 eq	8.52E+01	4.02E+01	3.34E+00	0.00E+00	2.24E+01	0.00E+00	**1.51E+02**
Total	**kg SO2 eq**	**1.94E+02**	**6.81E+01**	**1.92E+01**	**0.00E+00**	**2.95E+01**	**2.29E-01**	**3.11E+02**

Comparison of Acidification Potential SO2 (15/100)



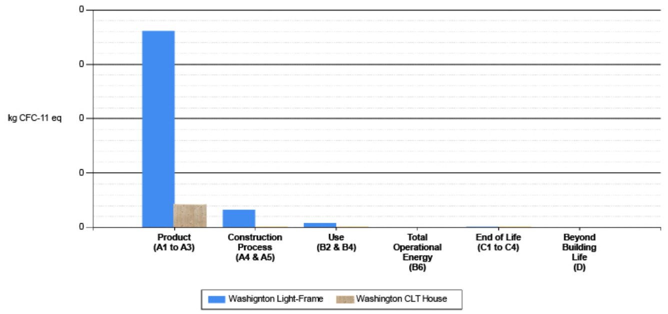
Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Washignton Light-Frame	MJ	1.70E+05	3.24E+04	5.94E+04	0.00E+00	8.38E+03	9.21E+02	**2.71E+05**
Washignton CLT House	MJ	1.39E+05	4.65E+04	5.90E+03	0.00E+00	2.47E+04	0.00E+00	**2.16E+05**
Total	**MJ**	**3.09E+05**	**7.88E+04**	**6.53E+04**	**0.00E+00**	**3.31E+04**	**9.21E+02**	**4.87E+05**

Comparison of Eutrophication Potential N (15/100)



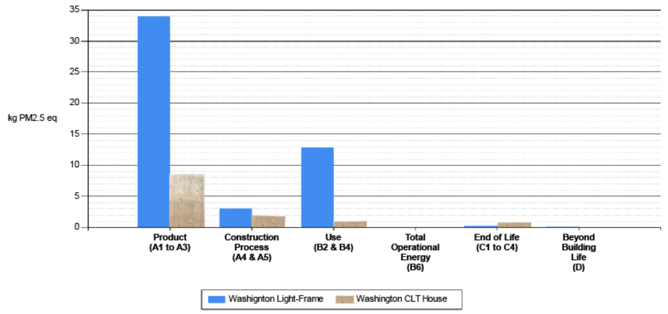
Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Washignton Light-Frame	kg N eq	8.23E+00	1.82E+00	5.14E-01	0.00E+00	4.40E-01	1.18E-02	**1.10E+01**
Washignton CLT House	kg N eq	4.92E+00	2.48E+00	2.37E-01	0.00E+00	1.40E+00	0.00E+00	**9.04E+00**
Total	**kg N eq**	**1.32E+01**	**4.30E+00**	**7.51E-01**	**0.00E+00**	**1.84E+00**	**1.18E-02**	**2.01E+01**

Comparison of Ozone Depletion Potential CFC (12.5/100)



Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Washignton Light-Frame	kg CFC-11 eq	3.61E-04	3.27E-05	8.39E-06	0.00E+00	2.29E-08	0.00E+00	**4.02E-04**
Washignton CLT House	kg CFC-11 eq	4.17E-05	1.05E-06	8.76E-09	0.00E+00	7.00E-08	0.00E+00	**4.29E-05**
Total	**kg CFC-11 eq**	**4.03E-04**	**3.38E-05**	**8.40E-06**	**0.00E+00**	**9.29E-08**	**0.00E+00**	**4.45E-04**

Comparison of HH Particulate PM 2.5 (12.5/100)



Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Washignton Light-Frame	kg PM2.5 eq	3.39E+01	3.01E+00	1.29E+01	0.00E+00	2.72E-01	1.01E-01	**5.02E+01**
Washignton CLT House	kg PM2.5 eq	8.36E+00	1.80E+00	8.86E-01	0.00E+00	6.41E-01	0.00E+00	**1.17E+01**
Total	**kg PM2.5 eq**	**4.23E+01**	**4.81E+00**	**1.38E+01**	**0.00E+00**	**9.13E-01**	**1.01E-01**	**6.18E+01**

🟦 **LIGHT FRAME CONSTRUCTION**

▨ **CLT CONSTRUCTION**

To properly evaluate LCA (life cycle analysis) there is a scientific understanding of the environmental impacts the data is tracking and reporting on the life cycle of a building. This life cycle data is tracking five major points; product, construction, use, end of life, and beyond building life. All these environmental impacts are important to building a sustainable future, yet some bear more weight of importance with how our earth is being affected. We live in a society that is constantly polluting our natural environments, the effects are dynamic to geographic location and this weighs what categories are more significant than others. In our present time global warming is the most pressing environmental impact, how we acknowledge this affects how our Built Environments place strain on our planet.

These six environmental impacts are all relevant in evaluating a buildings life cycle but they are not all equally weighted in importance. Out of 100, Global Warming 30/100, Fossil Fuel Consumption 15/100, Acidification 15/100, Eutrophication 15/100, Ozone Depletion 12.5/100, and HH Particulate 12.5/100.

Assessing the data comparison of systems for the Park Street SFR life cycle: There is a strong argument for the CLT system to work for a 2,430 SF residence. Looking at all categories global warming potential, fossil fuel consumption, Acidification Potential, eutrophication potential, ozone depletion potential, and HH particulate that comprise for 100/100 all show staggering evidence that CLT construction systems have less impact on environmental pollution. With a notable conclusion for global warming potential with a focus on the Beyond Building Life. Showcasing the positive effect in sequestrating carbon and the potential for a system to have a longer life span than its competitor.

Fig. 35 - LCA Environmental Impacts of Light Frame Construction vs CLT Construction

THE CITY: CORNWALL CO-HOUSING

The third housing typology evaluated is the Cornwall Co-Housing residence, this residence has 10 private SEDU per six residential levels with shared co-housing space, living/social space, kitchens, and shared work space. The ground level features commercial space to engage the street and the lively downtown. Level two is designed for open collaborative office space to create a hub to serve the downtown population. This building is designed to be easily adaptable for future uses by implementing light frame wood walls separating interior spaces allowing versatility. With the migration of rural populations moving into the U.S. cities, design needs to be more dynamic for future change instead of future demolition. The Cornwall Co-Housing residence is 38,880 square feet, with a modular grid base of nineteen, a modular grid volume of152, sixty-two units, and it houses sixty-two to one-hundred-twenty-four people. This flat pack CLT system is designed for easy assembly, disassembly, and flexibility for expansion of future adaptaion.

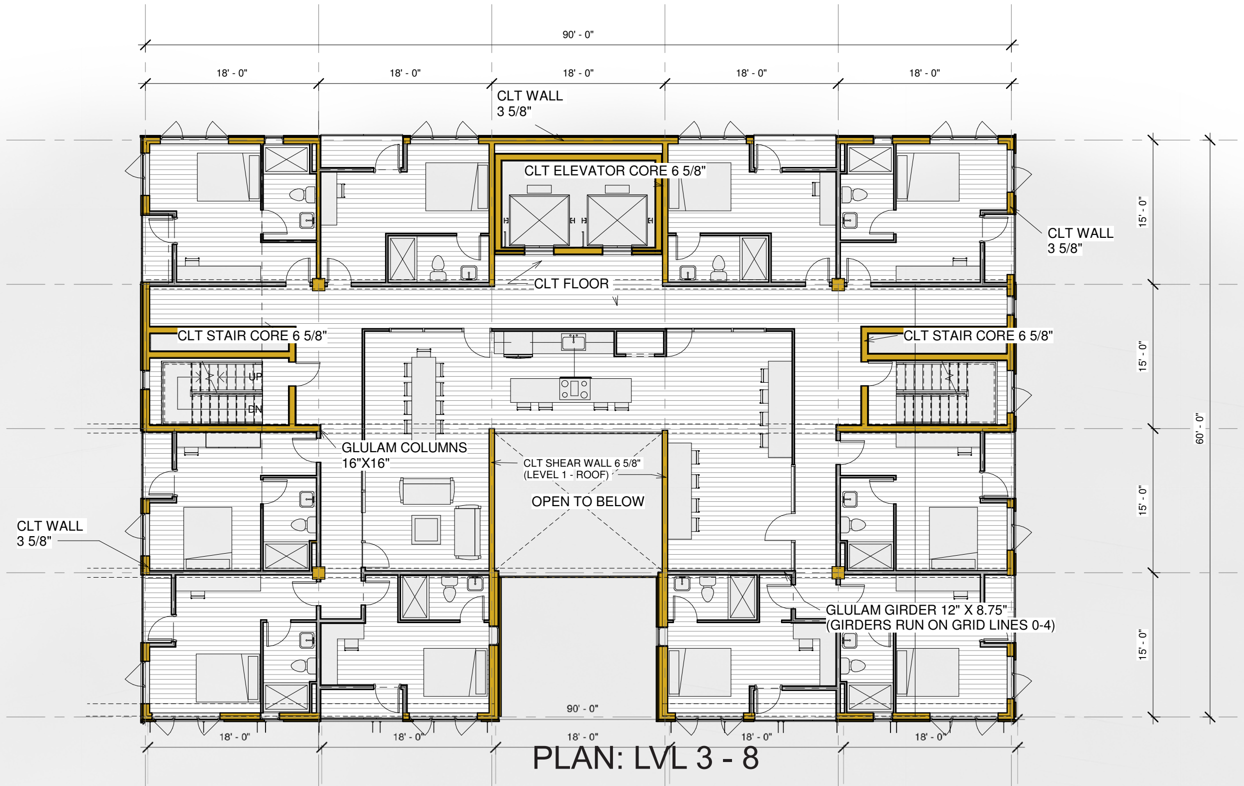


Fig. 36 - Cornwall Co-Housing, LVL 3 - 8 Plan
Fig. 37 - Cornwall Co-Housing, South Elevation

THE CITY: CORNWALL CO-HOUSING / 38,880 SF / MG BASE 19 / MG VOLUME 152 / UNITS 62 / PEOPLE 62 - 124

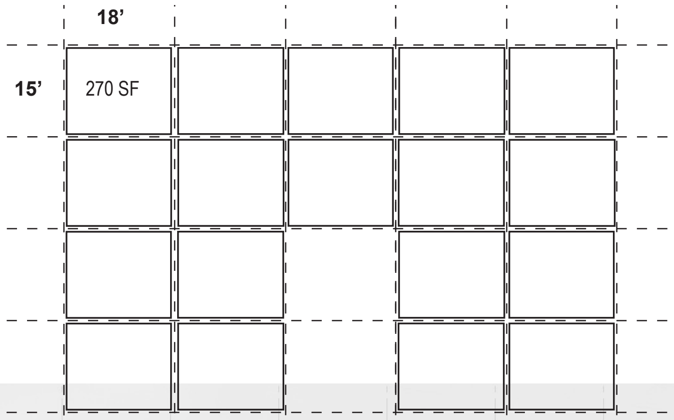
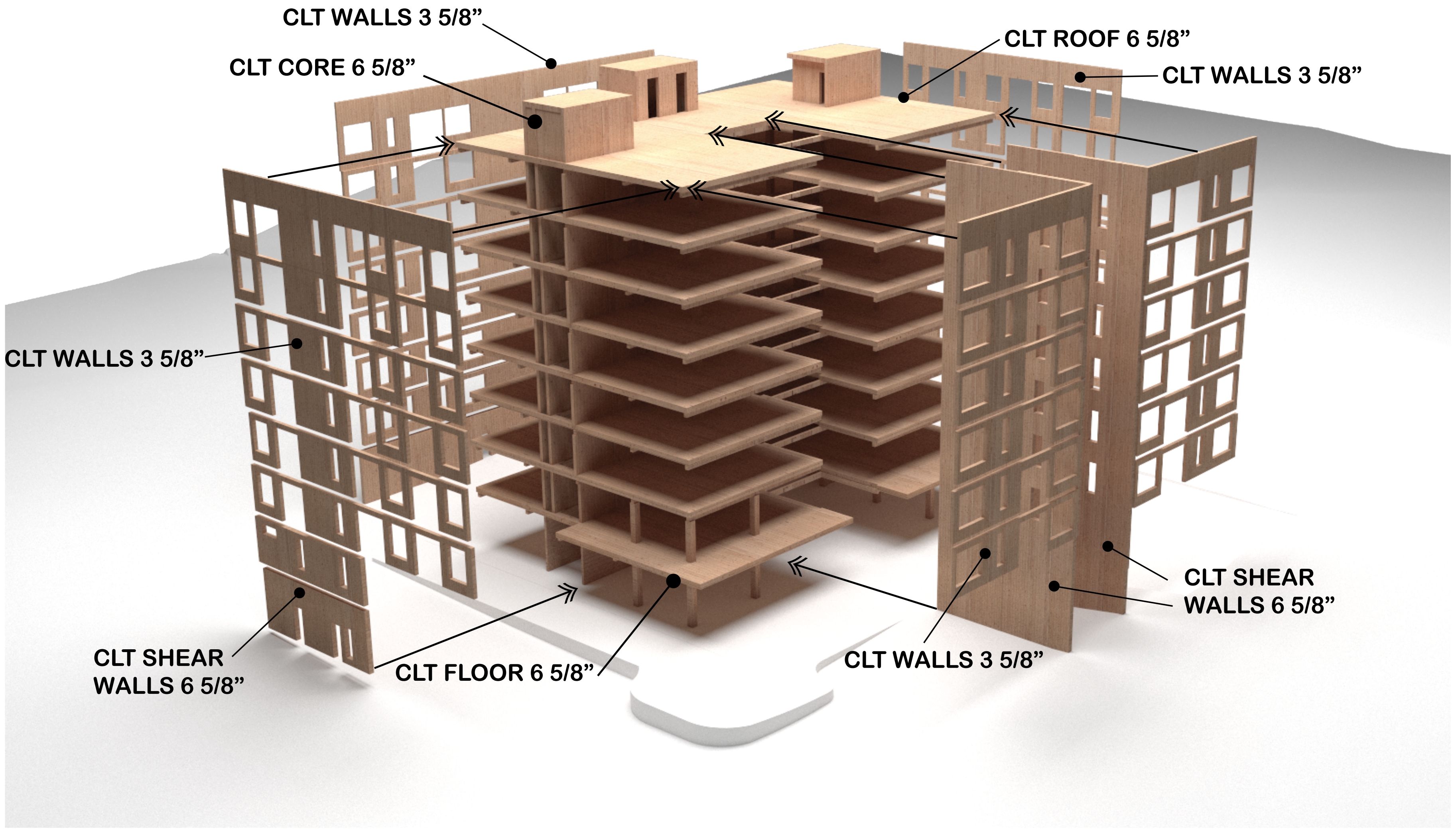


Fig. 38 - Cornwall Co-Housing, Rendering 1
Fig. 39 - Cornwall Co-Housing, West Elevation
Fig. 40 - Cornwall Co-Housing, West Section

Fig. 41 - Cornwall Co-Housing, Rendering 2
Fig. 42 - Cornwall Co-Housing, Modular Grid Diagram
Fig. 43 - Cornwall Co-Housing, South Section



CLT FLOOR & ROOF ASSEMBLY
SIXTY-FOUR 5-ply 6 5/8” floor panels

CLT WALL ASSEMBLY
THIRTY 3-ply 3 5/8” wall panels
EIGHTEEN 5-ply 6 5/8” wall panels

GLULAM GIRDERS & COLUMNS
FORTY 16”X 16” COLUMNS
FORTY-SIX 12”X 8.75” GIRDERS

CUBIC FEET: 35,629 BOARD FEET: 427,548 TREES: 1,644

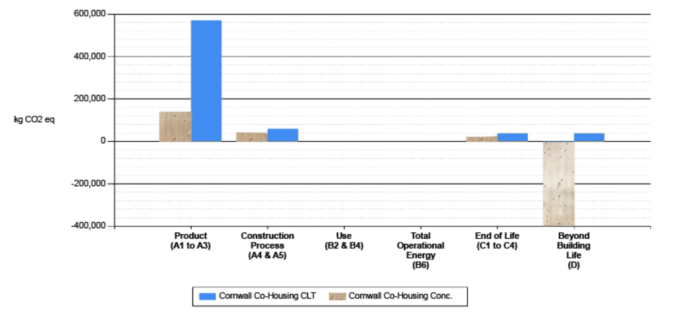
PEOPLE: 62 - 124 # OF TREES: 1,644 TREES PER PERSON: 13.25

This exploded axon diagram breaks down the structural building components of the flat pack CLT floor, roof, and wall assemblies. Calculating the overall mass in cubic feet of material used to construct the Cornwall Co-Housing building. Systematically evaluating how much wood this project consist of, converting this cubic feet to board feet, then equating how many average size Douglas-Fir trees (261 board feet per tree) it takes to construct this mass timber project. This analysis not only looks at environmental impacts but the max occupancy gaging how many trees per person it houses. Cornwall Co-Housing uses1,644 trees to construct and has a residential capacity of 124 people, equaling 13.25 trees per occupant.

Fig. 44 - Cornwall Co-Housing, Exploded Axonometric Diagram

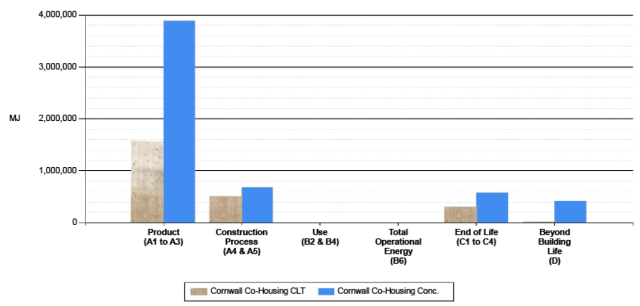
CORNWALL CO-HOUSING 38,880 SF: CONCRETE & STEEL CONSTRUCTION VS. CLT CONSTRUCTION

Comparison of Global Warming Potential CO2 (30/100)



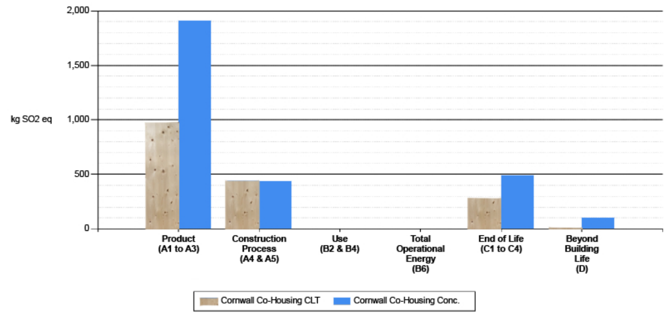
Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Cornwall Co-Housing CLT	kg CO2 eq	1.36E+05	3.80E+04	0.00E+00	0.00E+00	2.05E+04	-3.95E+05	**-2.00E+05**
Cornwall Co-Housing Conc.	kg CO2 eq	5.68E+05	6.08E+04	0.00E+00	0.00E+00	3.92E+04	3.73E+04	**7.05E+05**
Total	**kg CO2 eq**	**7.04E+05**	**9.87E+04**	**0.00E+00**	**0.00E+00**	**5.98E+04**	**-3.57E+05**	**5.05E+05**

Comparison of Fossil Fuel Consumption MJ (15/100)



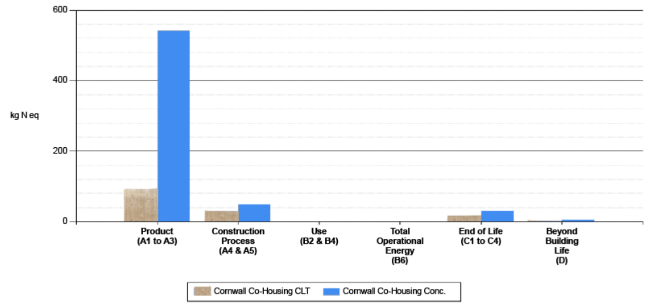
Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Cornwall Co-Housing CLT	MJ	1.56E+06	5.02E+05	0.00E+00	0.00E+00	3.04E+05	2.27E+03	**2.37E+06**
Cornwall Co-Housing Conc.	MJ	3.89E+06	6.85E+05	0.00E+00	0.00E+00	5.71E+05	4.16E+05	**5.57E+06**
Total	**MJ**	**5.46E+06**	**1.19E+06**	**0.00E+00**	**0.00E+00**	**8.75E+05**	**4.19E+05**	**7.94E+06**

Comparison of Acidification Potential SO2 (15/100)



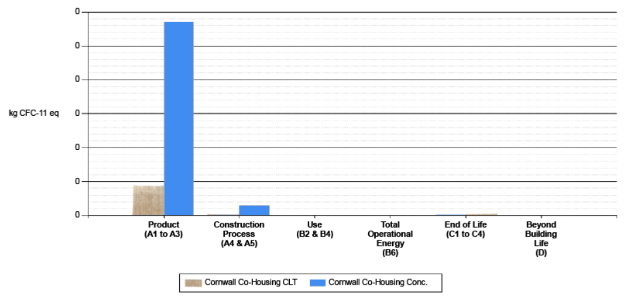
Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Cornwall Co-Housing CLT	kg SO2 eq	9.59E+02	4.39E+02	0.00E+00	0.00E+00	2.75E+02	5.66E-01	**1.67E+03**
Cornwall Co-Housing Conc.	kg SO2 eq	1.91E+03	4.37E+02	0.00E+00	0.00E+00	4.87E+02	1.04E+02	**2.94E+03**
Total	**kg SO2 eq**	**2.87E+03**	**8.76E+02**	**0.00E+00**	**0.00E+00**	**7.62E+02**	**1.04E+02**	**4.61E+03**

Comparison of Eutrophication Potential N (15/100)



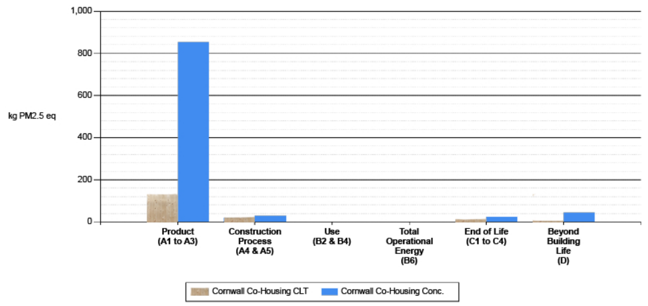
Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Cornwall Co-Housing CLT	kg N eq	9.17E+01	2.82E+01	0.00E+00	0.00E+00	1.72E+01	2.91E-02	**1.37E+02**
Cornwall Co-Housing Conc.	kg N eq	5.42E+02	4.78E+01	0.00E+00	0.00E+00	3.02E+01	5.33E+00	**6.26E+02**
Total	**kg N eq**	**6.34E+02**	**7.60E+01**	**0.00E+00**	**0.00E+00**	**4.74E+01**	**5.36E+00**	**7.63E+02**

Comparison of Ozone Depletion Potential CFC (12.5/100)



Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Cornwall Co-Housing CLT	kg CFC-11 eq	1.68E-03	5.30E-05	0.00E+00	0.00E+00	8.62E-07	0.00E+00	**1.74E-03**
Cornwall Co-Housing Conc.	kg CFC-11 eq	1.14E-02	5.72E-04	0.00E+00	0.00E+00	1.58E-06	0.00E+00	**1.20E-02**
Total	**kg CFC-11 eq**	**1.31E-02**	**6.25E-04**	**0.00E+00**	**0.00E+00**	**2.45E-06**	**0.00E+00**	**1.37E-02**

Comparison of HH Particulate PM 2.5 (12.5/100)



Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Cornwall Co-Housing CLT	kg PM2.5 eq	1.24E+02	2.01E+01	0.00E+00	0.00E+00	7.96E+00	2.48E-01	**1.52E+02**
Cornwall Co-Housing Conc.	kg PM2.5 eq	8.52E+02	3.09E+01	0.00E+00	0.00E+00	2.48E+01	4.55E+01	**9.53E+02**
Total	**kg PM2.5 eq**	**9.76E+02**	**5.10E+01**	**0.00E+00**	**0.00E+00**	**3.27E+01**	**4.57E+01**	**1.11E+03**

🟦 **CONCRETE & STEEL CONSTRUCTION**

🟫 **CLT CONSTRUCTION**

Fig. 45 - LCA Environmental Impacts of Concrete & Steel Construction vs CLT Construction

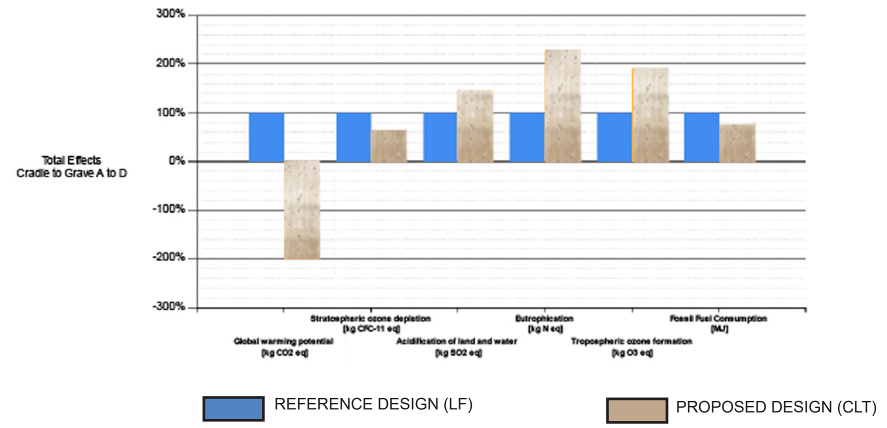
To properly evaluate LCA (life cycle analysis) there is a scientific understanding of the environmental impacts the data is tracking and reporting on the life cycle of a building. This life cycle data is tracking five major points; product, construction, use, end of life, and beyond building life. All these environmental impacts are important to building a sustainable future, yet some bear more weight of importance with how our earth is being affected. We live in a society that is constantly polluting our natural environments, the effects are dynamic to geographic location and this weighs what categories are more significant than others. In our present time global warming is the most pressing environmental impact, how we acknowledge this affects how our Built Environments place strain on our planet.

These six environmental impacts are all relevant in evaluating a buildings life cycle but they are not all equal weighted in importance. Out of 100, Global Warming 30/100, Fossil Fuel Consumption 15/100, Acidification 15/100, Eutrophication 15/100, Ozone Depletion 12.5/100, and HH Particulate 12.5/100.

Assessing the data comparison of systems for the Cornwall Co-Housing life cycle: There is a very strong argument for the CLT system to work for a 38,880 SF residence. Looking at all categories global warming potential, fossil fuel consumption, Acidification Potential, eutrophication potential, ozone depletion potential, and HH particulate that comprise for 100/100 all show staggering evidence that CLT construction systems have less impact on environmental pollution. With a notable conclusion for global warming potential with a focus on the Beyond Building Life. Showcasing the positive effect in sequestrating carbon and the potential for a system to have a longer life span than its competitor.

BURNHAVEN CABIN 1080 SF: LIGHT FRAME WOOD CONSTRUCTION VS. CLT CONSTRUCTION

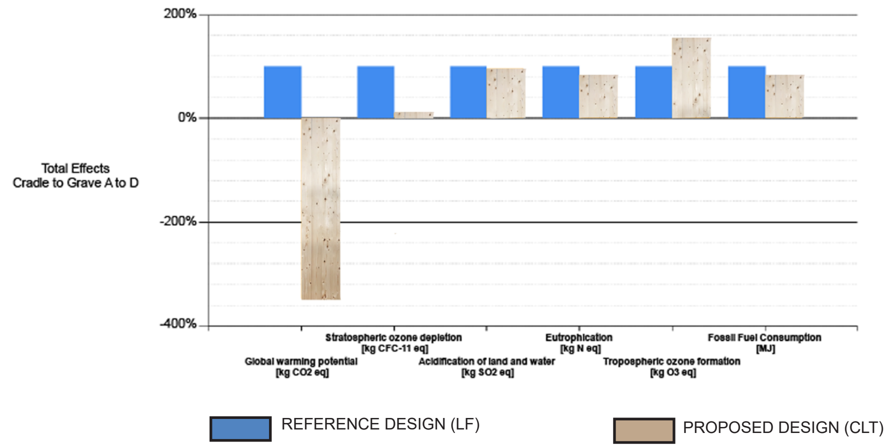
LCA Measure Comparison Report Cradle to Grave (60 year cycle)



Summary Measure	Unit	Reference Design Total Effects Cradle to Grave A to D	Proposed Design Total Effects Cradle to Grave A to D	% Difference
Global warming potential	kg CO2 eq	9.68E+03	-1.94E+04	-300.88%
Stratospheric ozone depletion	kg CFC-11 eq	4.24E-04	2.74E-04	-35.26%
Acidification of land and water	kg SO2 eq	1.13E+02	1.63E+02	44.80%
Eutrophication	kg N eq	1.10E+01	2.50E+01	127.71%
Tropospheric ozone formation	kg O3 eq	1.85E+03	3.56E+03	91.99%
Fossil Fuel Consumption	MJ	3.25E+05	2.45E+05	-24.58%

PARK STREET SFR 2430 SF: LIGHT FRAME WOOD CONSTRUCTION VS. CLT CONSTRUCTION

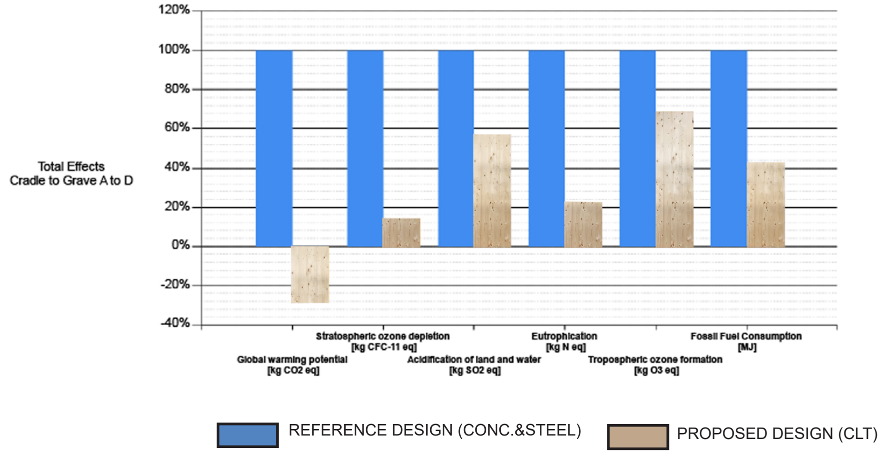
LCA Measure Comparison Report Cradle to Grave (60 year cycle)



Summary Measure	Unit	Reference Design Total Effects Cradle to Grave A to D	Proposed Design Total Effects Cradle to Grave A to D	% Difference
Global warming potential	kg CO2 eq	8.98E+03	-3.12E+04	-447.38%
Stratospheric ozone depletion	kg CFC-11 eq	4.02E-04	4.29E-05	-89.34%
Acidification of land and water	kg SO2 eq	1.60E+02	1.51E+02	-5.55%
Eutrophication	kg N eq	1.10E+01	9.04E+00	-18.02%
Tropospheric ozone formation	kg O3 eq	2.45E+03	3.80E+03	54.86%
Fossil Fuel Consumption	MJ	2.71E+05	2.16E+05	-20.36%

CORNWALL CO-HOUSING 38,880 SF: CONCRETE & STEEL CONSTRUCTION VS. CLT CONSTRUCTION

LCA Measure Comparison Report Cradle to Grave (60 year cycle)



Summary Measure	Unit	Reference Design Total Effects Cradle to Grave A to D	Proposed Design Total Effects Cradle to Grave A to D	% Difference
Global warming potential	kg CO2 eq	7.05E+05	-2.00E+05	-128.42%
Stratospheric ozone depletion	kg CFC-11 eq	1.20E-02	1.74E-03	-85.54%
Acidification of land and water	kg SO2 eq	2.94E+03	1.67E+03	-43.01%
Eutrophication	kg N eq	6.26E+02	1.37E+02	-78.08%
Tropospheric ozone formation	kg O3 eq	6.20E+04	4.26E+04	-31.36%
Fossil Fuel Consumption	MJ	5.57E+06	2.37E+06	-57.38%

Reference Design - Proposed Design

LCA Measure Comparison Report Cradle to Grave (60 year cycle)

The LCA comparison report compiles all six environmental impacts into one graph while comparing the reference design (LFT) to the proposed design (CLT). These graphs and the percent difference summary shows a clear representation of the data to understand if the proposed design is a feasible alternative.

BURNHAVEN CABIN: The proposed design compared to the reference design has a clear sine curve, expressing the positive environmental impact of sequestration of carbon dioxide represented in the global warming (% difference -300) column, while the sine curve peaks from negative environmental impacts illustrated in the euthrophication (% difference 127) column. Evaluating this data could establish an argument for either construction system for a project at this scale. By weighing your losses global warming carries more weight for the current state of our planets environment, it could be established that the proposed design (CLT) would have a stronger positive long term effect on our environment.

PARK ST. SFR: The proposed design compared to the reference design has a clear advantage in environmental impacts of the two construction systems. This graph and percent difference data express a strong case that any residential structure at or over 2,430 square feet supports the proposed design (CLT) as a great alternative. A notable mention for the proposed design is the global warming column with a -447 percent difference to the reference design.

CORNWALL CO-HOUSING: The proposed design compared to the reference design conveys a superior system in environmental impacts. In every environmental category the proposed design has a negative percent difference to its competitor. If we are looking to minimize our future environmental impacts the proposed design (CLT) should be our focal point in this building typology.

Fig. 46 - Burnhaven - LCA Comparison Report Cradle to Grave
Fig. 47 - Park St. - LCA Comparison Report Cradle to Grave
Fig. 48 - Cornwall Co-Housing - LCA Comparison Report Cradle to Grave

11

SYSTEMS: ASSEMBLY & DISASSEMBLY

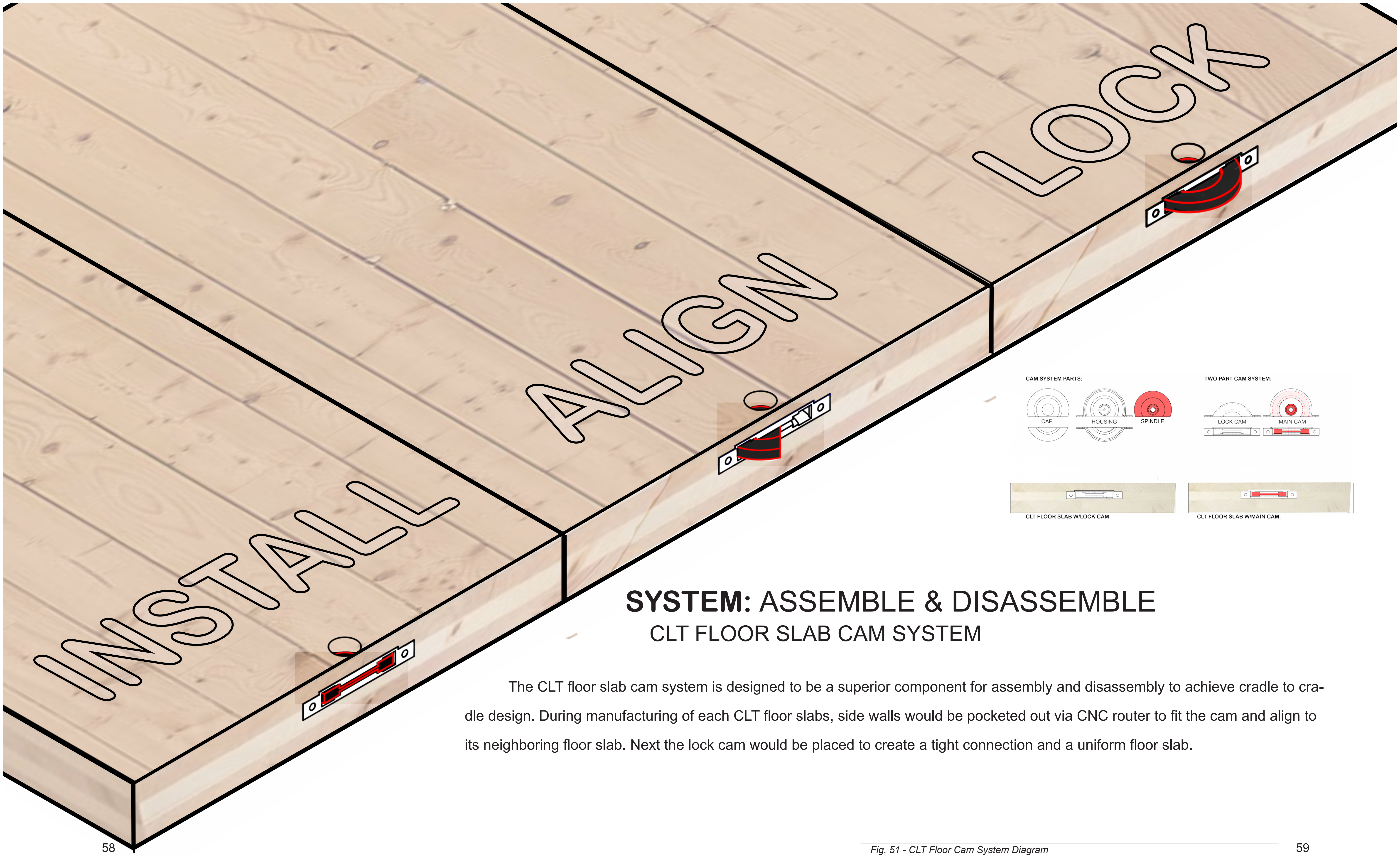
HOW SHOULD WE DESIGN FOR THE FUTURE?

WE NEED TO APPROACH DESIGN AS CRADLE TO CRADLE.

In this study of cross laminated timber (CLT) as a structural construction system has been proven to have a significant positive effects on environmental impacts compared to its competitor. Looking into this research and study of data it has revealed that design doesn't stop with good data results. As architects we can do more to make an even stronger impact on this versatile structural product. CLT as a flat pack structural construction system has strengths in durability, overall weight (compared to concrete mass system), and as a easily workable material. Additionally the already successful manufacturing process of CLT can be expanded. The manufacturing process uses a CNC router and G-code to cut the CLT slabs into specific walls, floors, roofs, and rough openings for doors/ windows. How can we double up on this CNC router process to get more out of this material and set up a sophisticated system for assembly and disassembly with the goal of creating an overall construction system that steps out of the Cradle to Grave and into Cradle to Cradle product?

> "The US currently demolishes about 1 billion square feet of buildings a year."
>
> Larry Strain - Carbon Leadership Forum

Fig. 49 - Demolition 1
Fig. 50 - Demolition 2



SYSTEM: ASSEMBLE & DISASSEMBLE

CLT FLOOR SLAB CAM SYSTEM

The CLT floor slab cam system is designed to be a superior component for assembly and disassembly to achieve cradle to cradle design. During manufacturing of each CLT floor slabs, side walls would be pocketed out via CNC router to fit the cam and align to its neighboring floor slab. Next the lock cam would be placed to create a tight connection and a uniform floor slab.

Fig. 51 - CLT Floor Cam System Diagram
Fig. 52 - CLT Floor Cam System Parts & Section

SYSTEM: ASSEMBLE & DISASSEMBLE

CLT FLOOR SLAB CAM SYSTEM

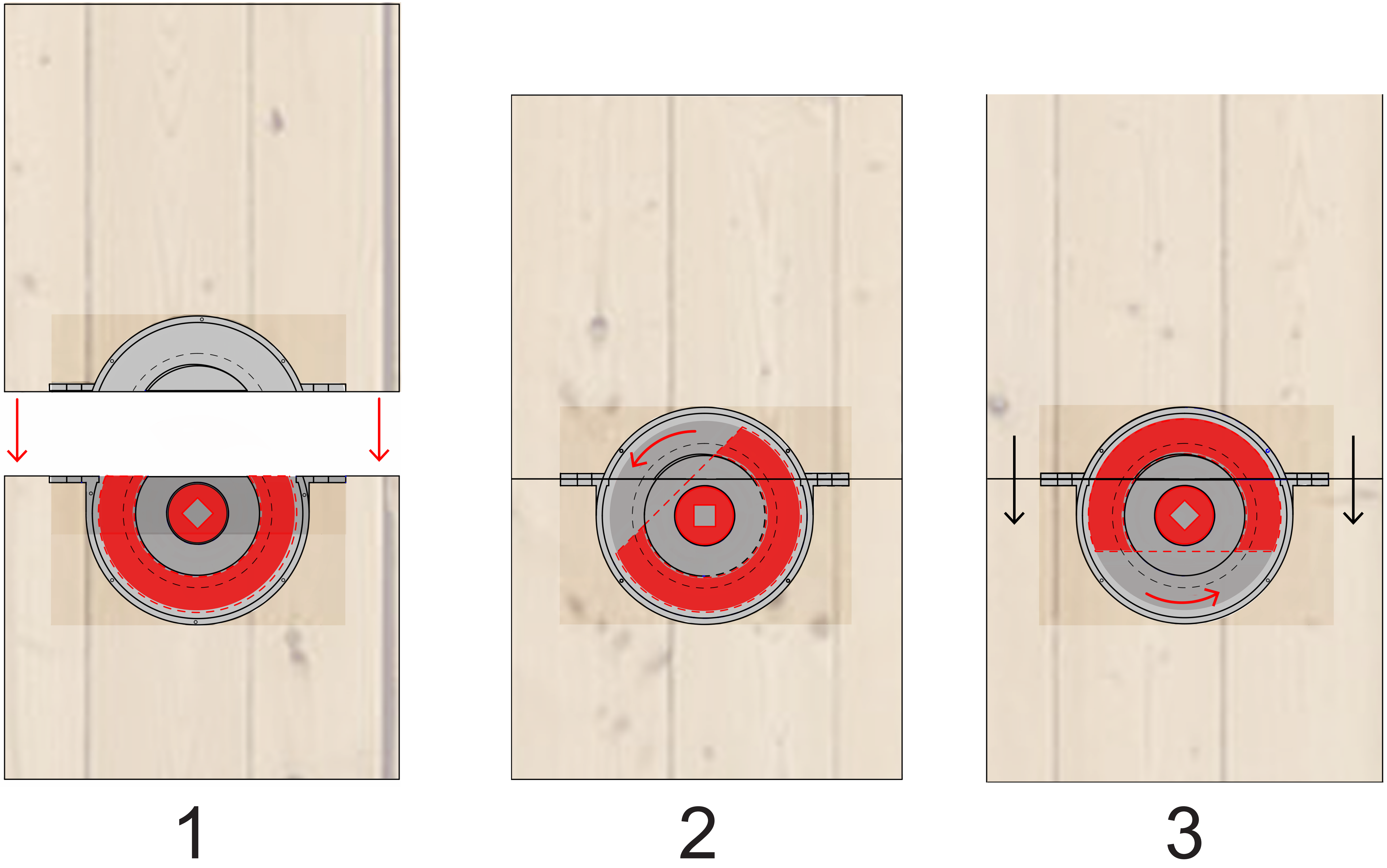
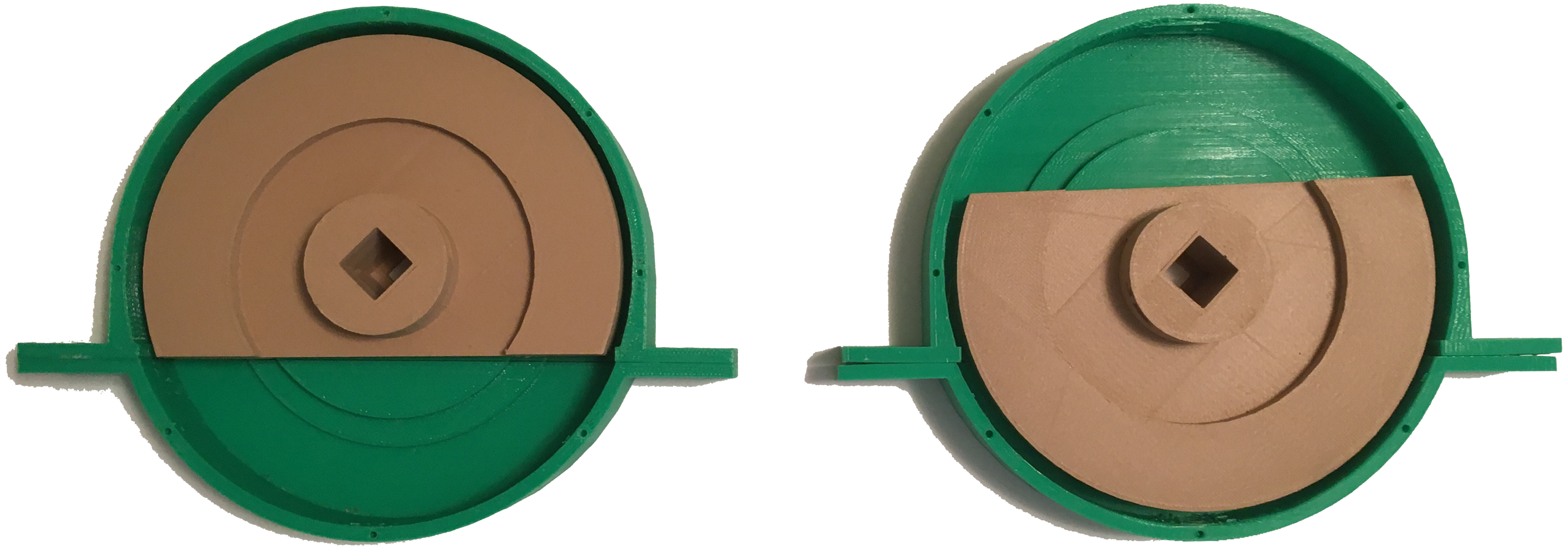


Fig. 53 - CLT Floor Cam System Diagram 2

SYSTEM: ASSEMBLE & DISASSEMBLE

CLT FLOOR SLAB CAM SYSTEM, 3D PRINTED FLOOR CAM



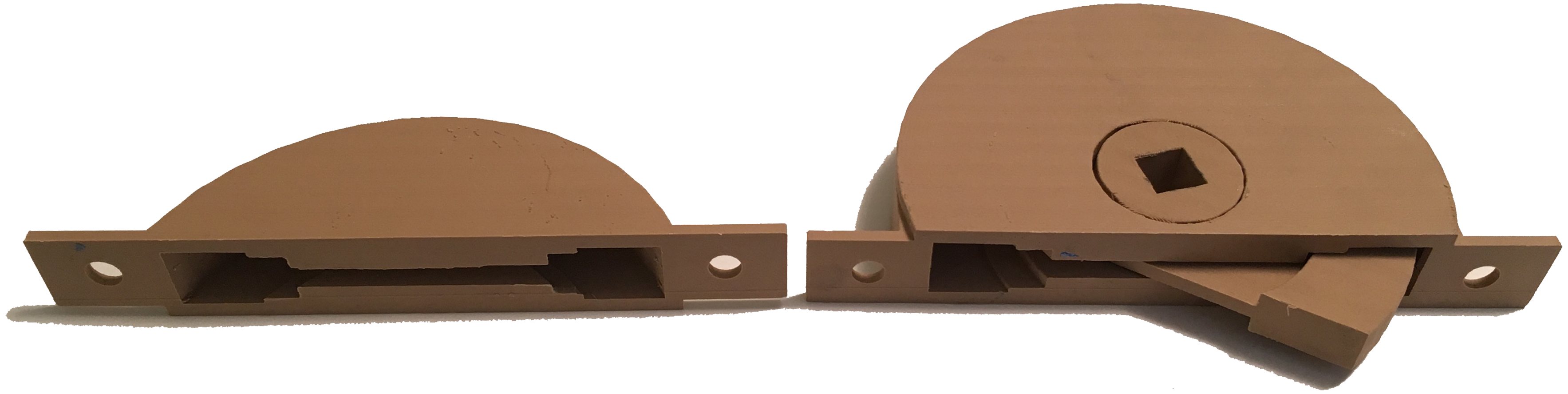


Fig. 54 - CLT Floor Cam System - 3D Printed Cam - Section
Fig. 55 - CLT Floor Cam System - 3D Printed Cam - Prototype

SYSTEM: ASSEMBLE & DISASSEMBLE

CLT WALL SYSTEM

The CLT wall system is designed for plug and play components for a superior assembly and disassembly to achieve cradle to cradle design. During manufacturing of each CLT wall the router would engrave a track system for specific component elements. This clean datum would eliminate the crux of the solid CLT walls. CLT has always had a particular point of difficulty; how to run electrical, placing lighting systems, and attaching building elements like cabinetry without drilling right into the solid walls and altering them for reuse. These track systems would allow for easy accessibility to electrical, power/lighting systems and installation and removal of residential accessories like cabinetry. False panels in the CLT would allow for additional support for pluming and electrical. At last resort, the components could be removed and the structural system could be easily dissembled and flat packed with no extrusions in the way.

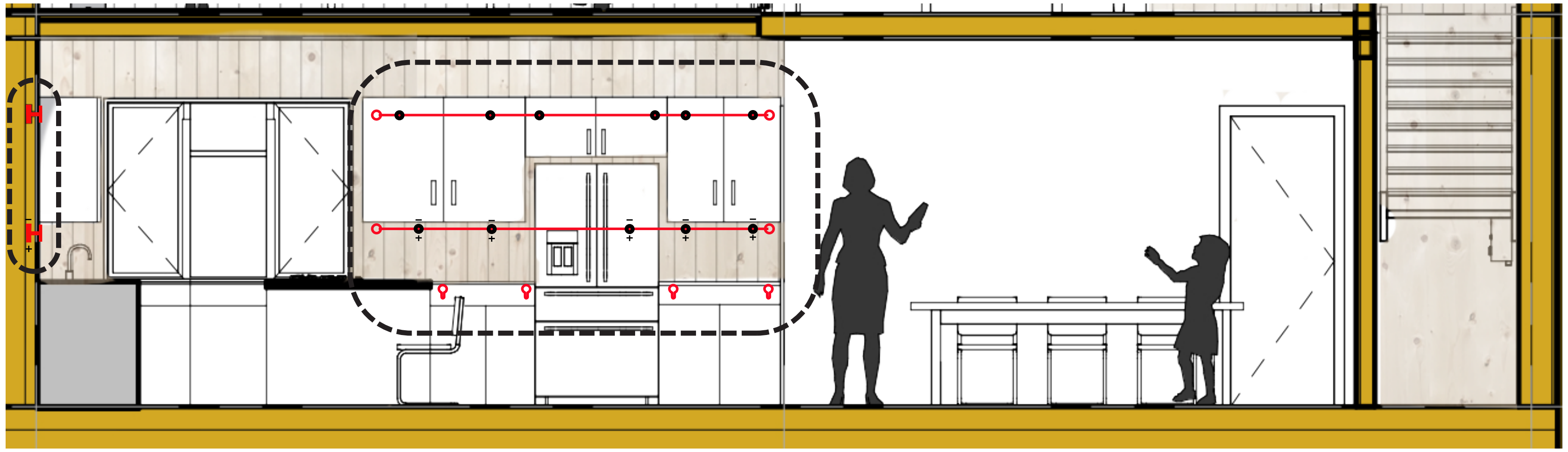
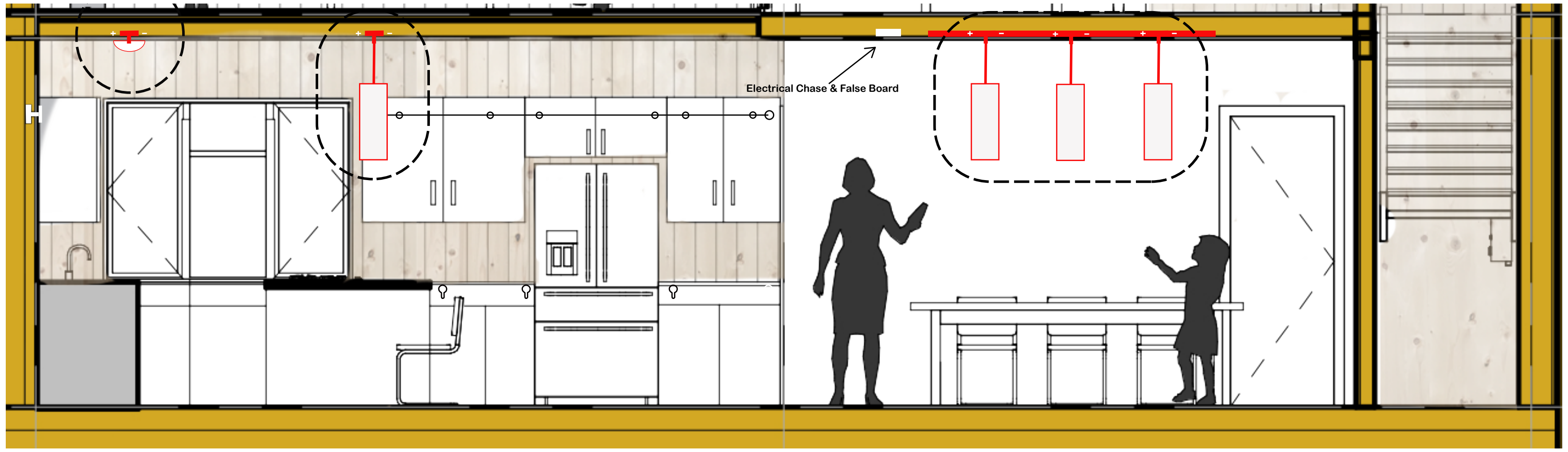


Fig. 56 - CLT Wall System - CNC CLT Test Wall/3D Printed Wall Hooks & Cabinet mount
Fig. 57 - CLT Wall System - South Section (Burnhaven Cabin)

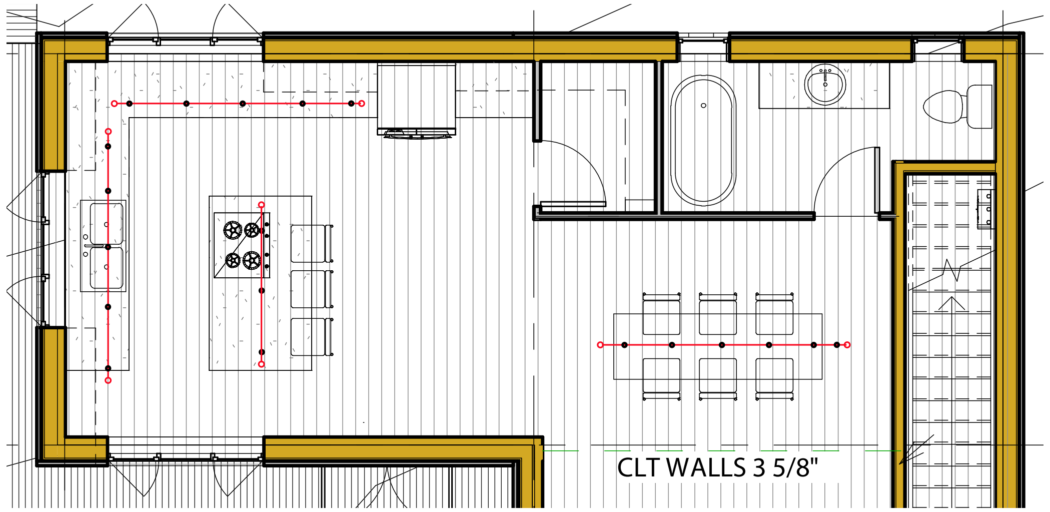
SYSTEM: ASSEMBLE & DISASSEMBLE

CLT CEILING SYSTEM

The CLT ceiling system is designed for plug and play components for a superior assembly and disassembly to achieve cradle to cradle design. During manufacturing of each CLT ceiling the router would engrave a track system for specific component elements. This clean datum would eliminate the crux of the solid CLT walls. CLT has always had a particular point of difficulty: how to run electrical, placing lighting systems, and alleviate altering them for reuse. These track systems would allow for easy accessibility to electrical, power/lighting systems and installation and removal of residential accessories. False panels in the CLT would allow for additional support for pluming and electrical. At last resort, the components could be removed and the structural system could be easily dissembled and flat packed with no extrusions in the way.



South Section (Burnhaven Cabin)

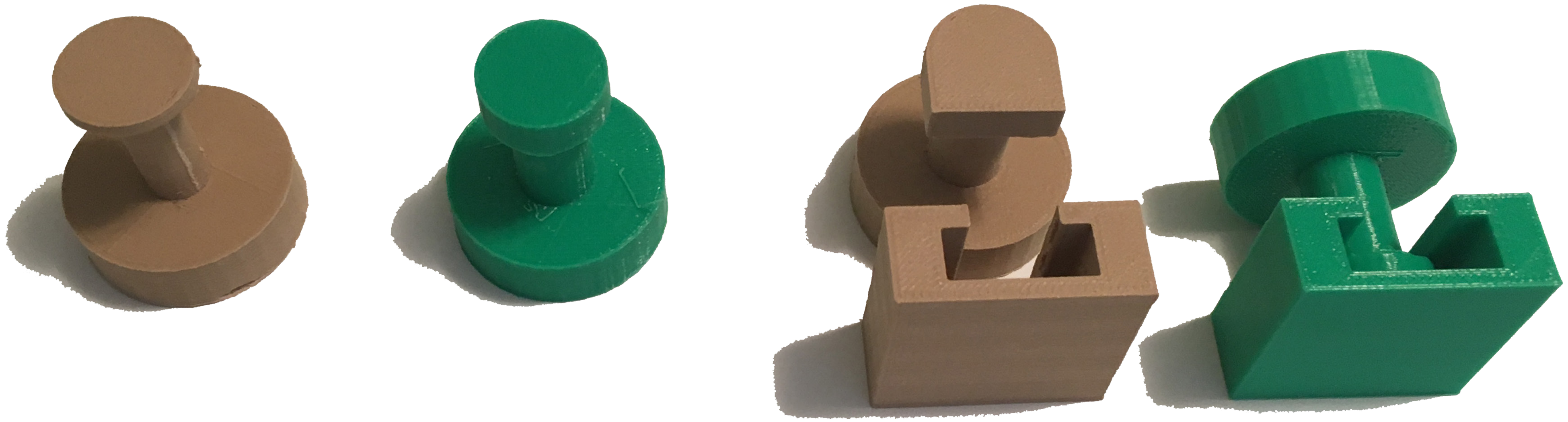


RCP (Burnhaven Cabin)

Fig. 58 - CLT Ceiling System - CNC CLT Test Ceiling/3D Printed Wall Hooks & Cabinet mount
Fig. 59 - CLT Ceiling System - South Section (Burnhaven Cabin)
Fig. 60 - CLT Ceiling System - RCP (Burnhaven Cabin)

SYSTEM: ASSEMBLE & DISASSEMBLE

CLT CEILING SYSTEM



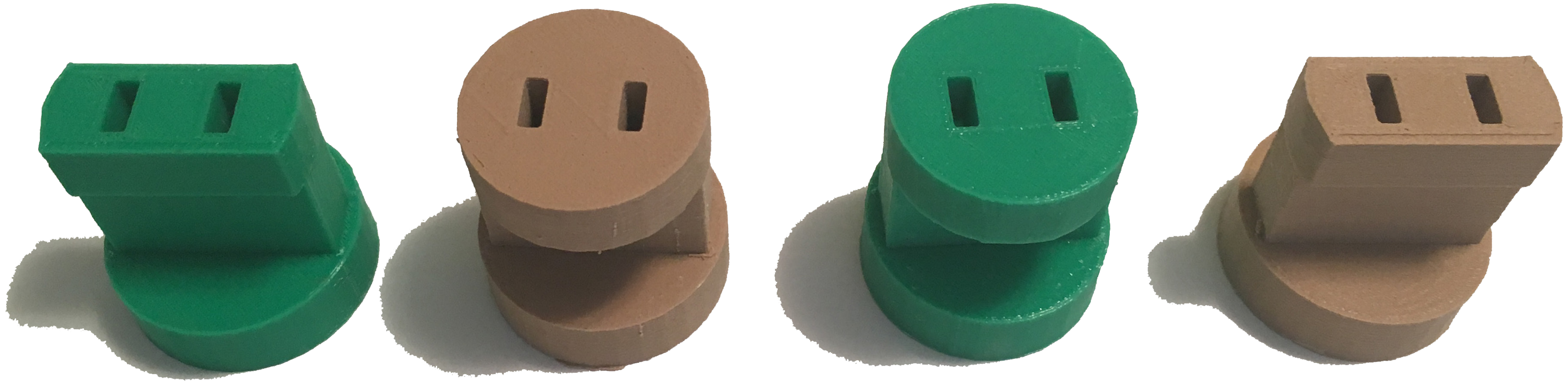
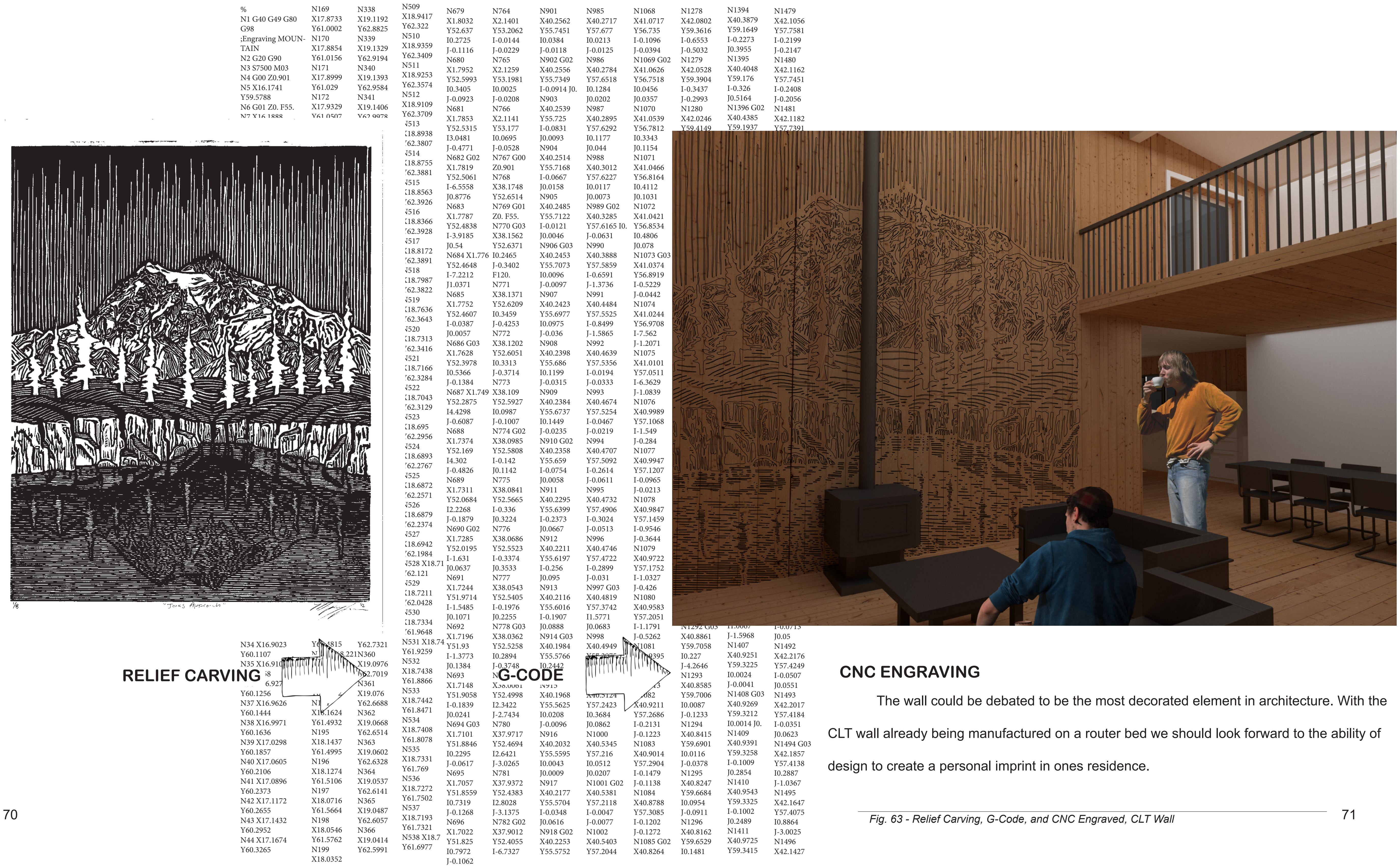


Fig. 61 - CLT Wall & Ceiling System - 3D Printed Wall Hooks & Cabinet mount
Fig. 62 - CLT Wall & Ceiling System - 3D Printed Electrical Plugs

12

ART & ARCHITECTURE



CNC ENGRAVING

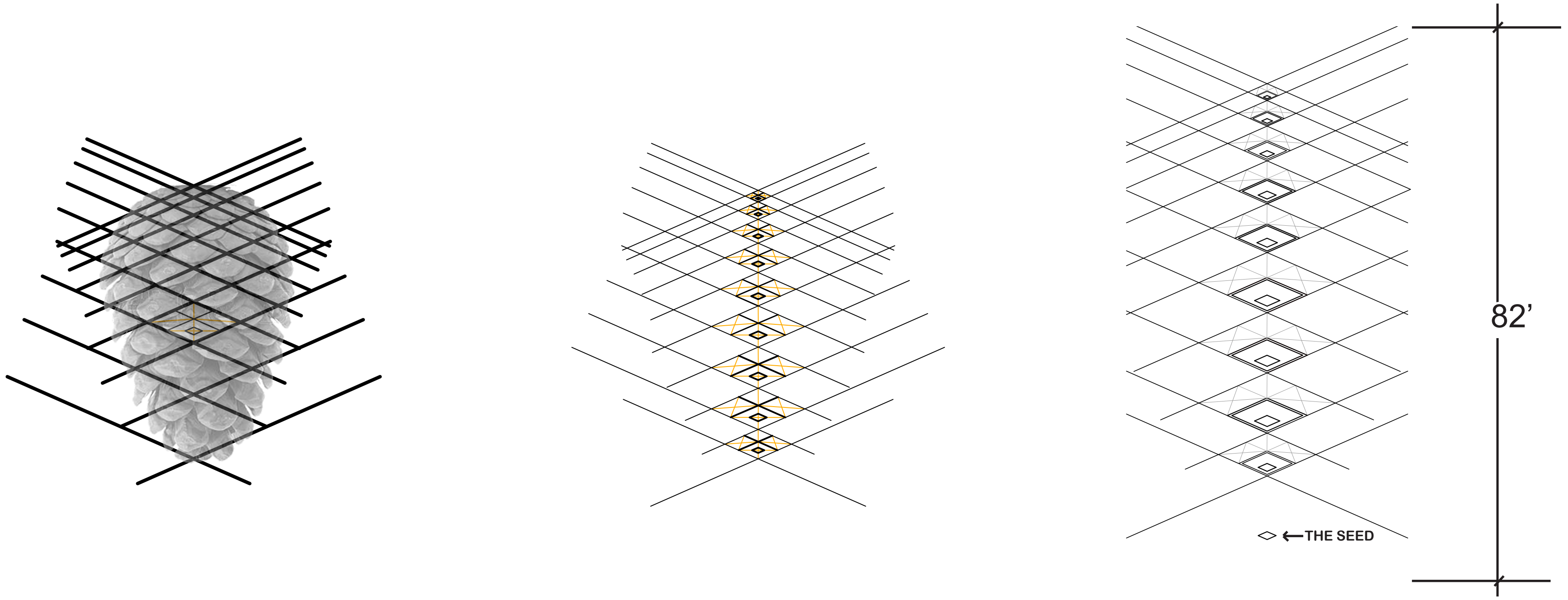
The wall could be debated to be the most decorated element in architecture. With the CLT wall already being manufactured on a router bed we should look forward to the ability of design to create a personal imprint in ones residence.

Fig. 63 - Relief Carving, G-Code, and CNC Engraved, CLT Wall

13

DESIGN TO ENGAGE

PINE CONE SHEAR WALL: CLT WALL THREE AXIS MILLING



Design to engage the residence of the Cornwall Co-Housing building, this eighty-two foot tall CLT shear wall was inspired by afforestation. The pine cone is the fertile sower of seeds and the king of afforestation. This three axis CNC design was inspired by the geometry of a pine cone and the act of dropping a seed to plant another tree. As the residence and the commercial customers enter the main entrance of the Cornwall Co-Housing building they are engaged with the act of planting a seed, to educate them that this building structure started as a tiny seed. The volume of this seed suggest how many trees "THE SEED" could re-plant and how many buildings it could grow.

Fig. 64 - Pine Cone Design
Fig. 65 - Pine Cone Design - CNC Three Axis Milling, CLT Wall

DOUGLAS FIR SEED: 1/4 X 1/4 X 1/8 **1 CUBIC INCH =** 128 DOUG FIR SEEDS **THE SEED:** 108.42 cubic inches **13,878.4 DOUGLAS FIR SEEDS** **13,878.4 SEEDS / 1,644 TREES =** 8.4 CO-HOUSING BUILDINGS

Fig. 66 - Three Axis Milled - Pine Cone Design Shear Wall - Rendering - Cornwall Co-Housing

14

CONCLUSION

We live in a disposable society that takes our natural resources and our natural environment for granted. As architects we need to understand where our products come from and what kind of environmental impacts are associated with material use and manufacturing processes. We have the technology and tools to make educated assessments to change the way we impact our world, with this we can design a future that limits these impacts. In this study of the Pacific Northwest's timber resources we compared two structural systems to understand how to move forward. The projections show a 50% increase of harvesting by 2050 from current stock, this will be sustained for the next 32 years.[21] Yet we should be designing a cradle to cradle 120 year CLT product that surpass the harvesting time-line of healthy timber. If harvesting of Douglas Fir and Western Hemlock dips below age 40 we will be left with juvenile wood that won't have mechanical properties to build our future built environments. This will lead us to dip deeper into our natural resources causing deforestation of unsustainable harvesting practice. The sequestration of carbon into our buildings will only be successful if we design for product longevity and a cohesive silviculture.

CONE

SEED

FIR TREE

SHELTER

Fig. 67 - How to Grow a Building

END NOTES

Endnotes

1 US Census bureau statista 2017

2 Bowyer, J. Carbon Implications of Building Materials Selection. [PDF Document]. Retrieved from Lecture Notes Online Website: http://www.woodworks.org/wp-content/uploads/15NC01-BOWYER-Carbon-implications-of-Material-Selection-WSF-160323.pdf

3 Bowyer, J. Carbon Implications of Building Materials Selection. [PDF Document]. Retrieved from Lecture Notes Online Website: http://www.woodworks.org/wp-content/uploads/15NC01-BOWYER-Carbon-implications-of-Material-Selection-WSF-160323.pdf

4 Bowyer, J. Carbon Implications of Building Materials Selection. [PDF Document]. Retrieved from Lecture Notes Online Website: http://www.woodworks.org/wp-content/uploads/15NC01-BOWYER-Carbon-implications-of-Material-Selection-WSF-160323.pdf

5 Bowyer, J. Carbon Implications of Building Materials Selection. [PDF Document]. Retrieved from Lecture Notes Online Website: http://www.woodworks.org/wp-content/uploads/15NC01-BOWYER-Carbon-implications-of-Material-Selection-WSF-160323.pdf

6 Moore, R. (2018, January 28). Why wood is back at the top of the tree for architects. The Guardian. Retrieved from https://www.theguardian.com/artanddesign/2018/jan/28/wood-engineered-timber-housing-needs

7 Bowyer, J. Carbon Implications of Building Materials Selection. [PDF Document]. Retrieved from Lecture Notes Online Website: http://www.woodworks.org/wp-content/uploads/15NC01-BOWYER-Carbon-implications-of-Material-Selection-WSF-160323.pdf

8 Healy, D. (Producer), & Walk, N. (Director). (2012), *How To Grow A Planet* [Motion Picture]. United Kingdom: BBC.

9 Healy, D. (Producer), & Walk, N. (Director). (2012), *How To Grow A Planet* [Motion Picture]. United Kingdom: BBC.

10 Healy, D. (Producer), & Walk, N. (Director). (2012), *How To Grow A Planet* [Motion Picture]. United Kingdom: BBC.

11 Food and Agriculture Organization of the United Nations. (2016). State of the Worlds Forests. Retrieved from http://www.fao.org/3/a-i5588e.pdf

12 Food and Agriculture Organization of the United Nations. (2016). State of the Worlds Forests. Retrieved from http://www.fao.org/3/a-i5588e.pdf

13 United States Department of Agriculture. (2015). Who Owns Americas Trees, Woods, and Forests? Retrieve from https://www.fs.fed.us/nrs/pubs/inf/nrs_inf_31_15-NWOS-whoowns.pdf

14 United States Department of Agriculture. (2015). Who Owns Americas Trees, Woods, and Forests? Retrieve from https://www.fs.fed.us/nrs/pubs/inf/nrs_inf_31_15-NWOS-whoowns.pdf

15 Woodall, C. W., Coulston, J. W., Domke, G. M., Walters, B. F., Wear, D. N., …, Wilson, B. T. (2015). The U.S. Forest Carbon Accounting Framework: Stocks and Stock Change, 1990-2016. Newton Square, PA: U.S. Department of Agriculture, Forest Service.

16 Woodall, C. W., Coulston, J. W., Domke, G. M., Walters, B. F., Wear, D. N., …, Wilson, B. T. (2015). The U.S. Forest Carbon Accounting Framework: Stocks and Stock Change, 1990-2016. Newton Square, PA: U.S. Department of Agriculture, Forest Service.

17 Woodall, C. W., Coulston, J. W., Domke, G. M., Walters, B. F., Wear, D. N., …, Wilson, B. T. (2015). The U.S. Forest Carbon Accounting Framework: Stocks and Stock Change, 1990-2016. Newton Square, PA: U.S. Department of Agriculture, Forest Service.

18 Zhou, X., Haynes, R. W., & Barbour, J. (2005). Projections of Timber Harvest in Western Oregon and Washington by County, Owner, Forest Type, and Age Class. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

19Zhou, X., Haynes, R. W., & Barbour, J. (2005). Projections of Timber Harvest in Western Oregon and Washington by County, Owner, Forest Type, and Age Class. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

20 Simonen, K. (2014). Life Cycle Assessment. London, UK: Routledge.

21 Zhou, X., Haynes, R. W., & Barbour, J. (2005). Projections of Timber Harvest in Western Oregon and Washington by County, Owner, Forest Type, and Age Class. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

LITERARY REFERENCES

Bowyer, J. Carbon Implications of Building Materials Selection. [PDF Document]. Retrieved from Lecture Notes Online Website: http://www.woodworks.org/wp-content/uploads/15NC01-BOWYER-Carbon-implications-of-Material-Selection-WSF-160323.pdf

Caspersen, J. P., Vanderwel, M. C., Cole, W. G., & Purves, D. W. (2011, December 13). How Stand Productivity Results from Size and Competition Dependent Growth and Mortality. PLOS ONE, 6. Retrieved from http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0028660

Craggs, G. (2016, July 26). The Role of Old-Growth Forests in Carbon Sequestration. Future Directions International. Retrieved from http://www.futuredirections.org.au/publication/role-old-growth-forests-carbon-sequestration/

Food and Agriculture Organization of the United Nations. (2016). State of the Worlds Forests. Retrieved from http://www.fao.org/3/a-i5588e.pdf

Hasen, A. L., Severson, M., & Waterman, D. L. (2011). A Landowners Guide to Managing your Woods. North Adams, MA: Storey Publishing.

Healy, D. (Producer), & Walk, N. (Director). (2012), *How To Grow A Planet* [Motion Picture]. United Kingdom: BBC.

Larsson, M. (2016, October 10). Active forestry is the best for the climate. Think Green. Retrieved from http://www.forestindustries.se/news/news/2016/10/active-forestry-is-the-best-for-the-climate/

Luyssaert, S., Schulze, E. D., Borner, A., Knohl, A., Hessenmoller, D., Law, B. E., … Grace, J. (2008, September 11). Old-growth forests as global carbon sinks. Nature. Retrieved from https://www.nature.com/articles/nature07276

Moore, R. (2018, January 28). Why wood is back at the top of the tree for architects. The Guardian. Retrieved from https://www.theguardian.com/artanddesign/2018/jan/28/wood-engineered-timber-housing-needs

Norris, L. (2011, June 17). What Trees Absorb the Most Carbon Dioxide? Hunker. Retrieved from https://www.hunker.com/12557632/what-trees-absorb-the-most-carbon-dioxide

Poage, N., & Tappeiner II, J. C. (2002). Long-term patterns of diameter and basal area growth of old-growth Douglas-fir trees in western Oregon. Canadian Journal of Forest Research, 32. Retrived from http://www.nrcresearchpress.com/doi/pdf/10.1139/x02-045

Simonen, K. (2014). Life Cycle Assessment. London, UK: Routledge.

Spengler, Teo. (2011, March 28). How Fast Does a Douglas Fir Tree Grow? Hunker. Retrieved from https://www.hunker.com/13428635/how-fast-does-a-douglas-fir-tree-grow

Stephenson, N. L., Das, A. J., & Zavala, M. A. (2014, January 15). Rate of tree carbon accumulation increases continuously with tree size. Nature. Retrieved from http://www.nature.com/articles/nature12914

Talk, Earth. (2018, February 17). Which Trees Offset Global Warming Best? Retrieved from https://www.thoughtco.com/which-trees-offset-global-warming-1204209

Van Engelen, A. (2008, June 12). Clearing Forests of Dead Wood Prevents Massive C02 emissions. Triple Pundit. Retrieved from https://www.triplepundit.com/2008/06/clearing-forests-of-dead-wood-prevents-massive-co2-emissions/

Walsh, B. (2014, January 15). When It Comes to the Climate, Older Trees Do It Better. Time. Retrieved from http://science.time.com/2014/01/15/study-shows-older-trees-absorb-more-carbon/

Weiskittel, A. R., Garber, S. M., Johnson, G. P., Maguire, D. A., & Monserud, R. A. (2007). Annualized diameter and height growth equations for Pacific Northwest plantation-grown Douglas-fir, western hemlock and red alder. Forest Ecology and Management, 250. Retrieved from https://pdfs.semanticscholar.org/9851/65230a85c893299f12c7572b06d2c6133fa7.pdf?_ga=2.165823737.656727532.1528483611-1848184377.1528483611

Wenzl, H. F. J. (1970). The Chemical Technology of Wood. Cambridge, MA: Academic Press.

Wikipedia contributors. (2018, May 18). Silviculture. In Wikipedia, The Free Encyclopedia. Retrieved June 8, 2018 https://en.wikipedia.org/w/index.php?title=Special:CiteThisPage&page=Silviculture&id=841837686

Wilson, B. T., Woodall, C. W., & Griffith, D. M. (2013, January 11). Imputing forest carbon stock estimates from inventory plots to a nationally continuous coverage. Carbon Balance and Management, 8. Retrieved from https://cbmjournal.springeropen.com/articles/10.1186/1750-0680-8-1

Woodall, C. W., Coulston, J. W., Domke, G. M., Walters, B. F., Wear, D. N., …, Wilson, B. T. (2015). The U.S. Forest Carbon Accounting Framework: Stocks and Stock Change, 1990-2016. Newton Square, PA: U.S. Department of Agriculture, Forest Service.

Zhou, X., Haynes, R. W., & Barbour, J. (2005). Projections of Timber Harvest in Western Oregon and Washington by County, Owner, Forest Type, and Age Class. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

VISUAL REFERENCES

All images created by author unless otherwise noted.

Title Page
The woods of Burnhaven & Photo of three axis milled CLT Wall.

Chapter 1 - Introduction
*Fig. 1 - Basic - The Carbon Cycle, (*IPPC Fifth Assessment Report2013)

Chapter 2 - Understanding Conception
Fig. 2 - Conception of the Forest

Chapter 3 - Snapshot: The World's Forests
Fig. 3 - The World's Forests, (Food and Agriculture Organization of the United Nations, 2016)

Chapter 4 - Fragmentation of US Forests
*Fig. 4 - Forest Preservation Time-line, (*Forest Service, "Who Owns America's Forests".)
*Fig. 5 - United States Forest Ownership, (*Forest Service, "Who Owns America's Forests".)
*Fig. 6 - U.S. Forests by the Numbers, (*Forest Service, "Who Owns America's Forests".)

Chapter 5 - US Forest Carbon Stock
Fig. 7 - *U.S. Forest Carbon Stock Accounting, (United States Department of Agriculture, The U.S. Forest Carbon Accounting Framework: Stocks and Stock Change, 1990-2016)*

Chapter 6 - Northwest Timber Harvest
Fig. 8 - Northwest Timber Removals per Period, 2000 USDA Forest Service, Zhou, Hayes, & Barbour Projections of Timber Harvest in Western Oregon and Washington by County, Owner, Forest Type, and Age Class.
Fig. 9 - Northwest Timber Total Removals, 2000 USDA Forest Service, Zhou, Hayes, & Barbour
Fig. 10 - Timberland Distribution Among Owners and Forest Types, 2000 USDA Forest Service, Zhou, Hayes, & Barbour
Fig. 11 - NW Forest. Current Age Class Distribution, 2000 USDA Forest Service, Zhou, Hayes, & Barbour

Chapter 7 - Life Cycle Assessment (LCA)
Fig. 12 - LCA Life Cycle Diagram, Kathrina Simonen, Life Cycle Assesment (Pocket Architecture)
Fig. 13 - LCA Cradle to Grave, Environmental Impacts

Chapter 8 - Defining the Grid
Fig. 14 - Defining the Modular Grid Diagram

Chapter 9 - Bellingham & The Three Sites
Fig. 15 - Bellingham, WA Vicinity Map
Fig. 16 - The Woods, Burnhaven Cabin Vicinity Map
Fig. 17 - The Neighborhood, Park St.SFR Vicinity Map
Fig. 18 - The City, Cornwall Co-Housing Vicinity Map

Chapter 10 - Design & Analysis: Cabin, SFR, Co-Housing
Fig. 19 - Burnhaven LVL 1 Plan
Fig. 20 - Burnhaven South Elevation
Fig. 21 - The Woods, Burnhaven Cabin Rendering 1
Fig. 22 - The Woods, Burnhaven Cabin South Section
Fig. 23 - The Woods, Burnhaven Cabin Rendering 2
Fig. 24 - The Woods, Burnhaven Cabin East Elevation
Fig. 25 - The Woods, Burnhaven Cabin Exploded Axonimetric Diagram
Fig. 26 - LCA Environmental Impacts of Light Frame Construction vs CLT Construction
Fig. 27 - Park St. SFR, LVL 1 Plan
Fig. 28 - Park St. SFR, West Elevation
Fig. 29 - Park St. SFR, Rendering 1
Fig. 30 - Park St. SFR, South Elevation
Fig. 31 - Park St. SFR, Rendering 2
Fig. 32 - Park St. SFR, Modular Grid Diagram
Fig. 33 - Park St. SFR, West Section
Fig. 34 - Park St. SFR, Exploded Axonimetric Diagram
Fig. 35 - LCA Environmental Impacts of Light Frame Construction vs CLT Construction
Fig. 36 - Cornwall Co-Housing, LVL 3 - 8 Plan
Fig. 37 - Cornwall Co-Housing, South Elevation
Fig. 38 - Cornwall Co-Housing, Rendering 1
Fig. 39 - Cornwall Co-Housing, West Elevation
Fig. 40 - Cornwall Co-Housing, West Section
Fig. 41 - Cornwall Co-Housing, Rendering 2
Fig. 42 - Cornwall Co-Housing, Modular Grid Diagram
Fig. 43 - Cornwall Co-Housing, South Section
Fig. 44 - Cornwall Co-Housing, Exploded Axonimetric Diagram
Fig. 45 - LCA Environmental Impacts of Concrete & Steel Construction vs CLT Construction
Fig. 46 - Burnhaven - LCA Comparison Report Cradle to Grave
Fig. 47 - Park St. - LCA Comparison Report Cradle to Grave
Fig. 48 - Cornwall Co-Housing - LCA Comparison Report Cradle to Grave

Chapter 11 - Systems: Assembly & Disassembly

Chapter 12 - Art & Architecture

Chapter 13 -Design to Engage

Chapter 14 - Conclusion