Prototype Mass Timber Office Building Models: Material Quantities and Preliminary Life Cycle Assessment

Market and Environmental Assessment of CLT Production in the Olympic Peninsula: Mid-Rise Non-Residential Construction Application

This work is supported by the United States Department of Agriculture (USDA) via the 2015 McIntire-Stennis Research Grant: "Assessing the Impact of Trade Policies on the Competitiveness of Wood Exports from Washington State."

Objective: To develop a viable architectural model of mid-rise non-residential building with different levels of CLT use.

Internal Report

February 2018
Version 2

PIs and Co-PIs
Indroneil Ganguly, PI
Ivan Eastin, Co-PI
Kathrina Simonen, Co-PI

Architectural Team
Ezekiel T. Jones, BA Arch/CM
Mariam Hovhannisyan, MArch
Monica Huang, MSCE
Weston Norwood, MArch
Barbara X. Rodriguez, PhD Student
Kathrina Simonen, Associate Professor (Architectural Team Lead)
Kristen Strobel, MArch/MSCE

Forestry Team
Indroneil Ganguly, Assistant Professor (Forestry Team Lead)
Francesca Pierobon, Research Associate

Table of Contents

Appendix A: Analysis of Whole Building LCA Results by Arch 425/525

Appendix B: Assessment of Exemplary Buildings, Wall Sections, and Window Layouts

Appendix C: Overview of Structural Optimization Results

Appendix D: Foundation Study

EXECUTIVE SUMMARY

The goal of this work was to develop material quantity estimates of a typical mid-rise office building in the Pacific Northwest and to deliver the results to the Forestry Research Team in the University of Washington (UW) College of the Environment School of Environmental and Forest Sciences. The Forestry Research Team will then use these results to develop regionally specific life cycle inventory data to support the greater study funded by the 2015 McIntire-Stennis Research Grant, which is "to assist small and medium-sized wood products companies and Native American tribal enterprises to understand and adapt to changing market conditions" (http://depts.washington.edu/sefsifr/2015-mcintire-stennis-grant-winners/).

The work done by the UW Department of Architecture team was executed under the umbrella of three activities: 1) Literature review, 2) preliminary studies, and 3) the creation of a prototype wood building.

In Activity 1, the literature review found that use of CLT in buildings has been advancing around the world, and guidelines for CLT design have been developed in recent years, namely the CLT Handbook, sections of the National Design Standards (NDS), and a chapter in the International Building Code (IBC). Current Seattle building code restricts buildings made of wood products to no more than 85 feet in height and no more than 6 stories depending on the use of the building, but this limitation is currently under review by the City of Seattle, coinciding with the timeliness of this study.

Activity 2 evaluated screening level studies performed by students of an architectural life cycle assessment class at the University of Washington (Arch 425/525), and surveyed a number of buildings that were either in design or under construction in the Pacific Northwest to evaluate typical structural systems and cladding types. This research helped identify a reference building that was representative of typical office building construction that could be used as the reference building for this study.

In Activity 3, a set of wood prototype buildings were developed based on the reference building. First, the wood structural design was developed using a parametric model that sized gravity framing members for various geometries and configurations using current code design standards. Then, the building model was subjected to a brute-force parametric algorithm to design thousands of buildings by varying geometric properties. From the resulting dataset of wood buildings, four prototypical configurations were selected, each with a charring design and a non-charring design, resulting in eight buildings total. For the non-structural quantities (exterior wall, roof, and subgrade waterproofing options), estimates were developed using professional judgement and unit quantity estimates. See Table 13 for the total mass quantities for the wood prototype buildings, and Table 14 for the per unit area mass quantities. It should be noted that the per unit area mass quantities also averaged the non-structural quantities (foundations, subgrade, shear wall, exterior wall, roof) in order to convey the coarseness of these component estimates. The footprint of the buildings were approximately 160' x 90', with grid spacing variations determining the overall footprint of the buildings. All of the wood buildings were 8 stories tall and had 3 subgrade levels.

The evaluation of 1600 structural design iterations highlighted the following observations within the mass timber system that could result in lower volumes of wood (glulam and CLT):

- Excluding charring design (meaning that it is preferable to use gypsum wallboard for fireproofing)
- Including slab composite action between the CLT slab and the concrete topping slab, though composite action was not included for the wood prototype buildings because it is not typical in design practice
- Having at least one intermediate beam subdividing a bay (resulting in shorter CLT spans). Ideal CLT spans are likely between 10 – 17 feet.

The preliminary environmental impacts for the wood prototype buildings and concrete baseline building were explored using data from the Athena Impact Estimator version 5.1. The life cycle scope of the impacts were limited to Stage A. Global warming potential was explored in more detail. The key findings are summarized as follows:

- The global warming potential of the wood prototype buildings ranged from 3,750,000 – 4,328,000 kg CO_2e total, and per unit area values ranged from 394 – 405 kg CO_2e/m^2. The global warming potential of the concrete baseline building was estimated at 5,672,000 kg CO_2e total, or 530 kg CO_2e/m^2.
- The total global warming potential of the wood building was approximately comprised by the building components as follows: structure ≈ 20%, subgrade ≈ 20%, foundation ≈ 15%, lateral system ≈ 12%, and envelope (exterior wall and roof) ≈ 33%.
- The slab (CLT and concrete) constituted approximately 70% of the environmental impact of the building structure.
- The concrete materials in wood prototype buildings comprised the majority of the environmental impact.

There are a number of limitations to the results of this work, described in Section 7. Key limitations include:

- The prototype/baseline building represents engineering judgement of the research team and is not a result of a statistical sampling of building stock or actual design practice. In particular, the estimates for the non-structural components of the building (foundations, subgrade, shear wall) are very coarse, and are included only to provide order-of-magnitude estimates to put the wood structure into the context of the whole building.
- Non-structural features such as mechanical, electrical, and HVAC systems were not included.
- Given that the LCA in this report is preliminary, it has not undergone a critical review, and comparative assertions should not be made from this data.

At the conclusion of this report, the following future research needs were identified:

1. Develop regionally specific LCI data for materials
2. Refine structural design of gravity system with professional input
3. Develop prototype CLT lateral system
4. Develop competitive (thinner and more materially efficient) floor system
5. Explore the effects of reduced building weight on foundation and lateral system requirements
6. Develop simplified parametric model for office building LCA studies
7. Develop a statistically representative model for office building construction
8. Develop a more comprehensive model of office building LCA (MEP, finishes etc.)
9. Develop design tools to explore optimization alternatives for mass timber buildings

1 INTRODUCTION

Recently, a large number of new laws, regulations, policies and programs have been adopted around the Pacific Rim that could significantly affect the specification, use, and trade of wood products from Washington State. At the University of Washington's School of Environmental and Forest Sciences (SEFS) in the College of the Environment (CoE), Professors Ivan Eastin and Indroneil Ganguly have initiated a study titled "Assessing the Impact of Trade Policies on the Competitiveness of Wood Exports from Washington State," which implements "a program of research and extension activities designed to assist small and medium-sized wood products companies and Native American tribal enterprises to understand and adapt to these changing market conditions" (https://depts.washington.edu/sefsblog/tag/mcintire-stennis/). This work is funded by the United States Department of Agriculture (USDA) via the 2015 McIntire-Stennis Research Grant.

As part of this study, the viability of wood buildings in the Pacific Northwest is being assessed by Professor Kathrina Simonen and her team in the Department of Architecture (referred to as 'the research team' in this report). To do so, the research team was tasked to develop a prototypical mid-rise (typically defined as 4 – 10 stories) commercial office building made primarily of wood structural components. These material quantities will allow the SEFS/CoE research team to assess the impacts of commercial wood buildings in the Pacific Northwest using regionally specific LCA data models.

This report documents the research methodology of developing the wood prototype building and presents resulting material quantity take-offs.

2 PROJECT OBJECTIVE

The primary objective of this project is to provide estimates of architectural and structural material quantities of a prototypical mid-rise commercial office building constructed of mass timber in the Pacific Northwest. This material consumption data will be used by SEFS/CoE team to evaluate the building using regionally specific Life Cycle Assessment (LCA) data of cross-laminated timber (CLT). The final results consist of low, medium, and high estimates of material quantities for the following components of the prototype building:

- Structure
  - Gravity system
    - Building structure: Beams, columns, slabs, and fireproofing if needed
    - Subgrade: Basement walls, columns, and suspended slabs
    - Foundation: Slab-on-grade, continuous footings, and column footings
  - Lateral system
    - Building structure: Shear walls
    - Foundation: Mat foundation
- Enclosure
  - Exterior walls
  - Roof
  - Subgrade waterproofing

3 RESEARCH METHODOLOGY

This report has defined three building terms as follows:

- Reference building: An existing building that was selected to be representative of the building stock of interest: mid-rise office buildings in the Seattle area. The reference building is used to inform the design of the baseline and prototype building.
- Baseline building: The simplified version of the reference building; details are changed to facilitate quantity take-off calculations and to protect the identity of the reference building.
- Prototype building: The wood version of the baseline building.

Three major activities were undertaken before developing the prototype building.

The first activity involved a literature review of mass timber applications in mid-rise commercial office buildings. The literature review also explored optimization studies that aimed to reduce material quantities in mid-rise building structures. Additionally, given that a major objective of this research work was to define the prototype building, the literature review identified different methodologies to define such a building in accordance with accepted standards.

A reference building, also known as a 'baseline building,' can be described as "a building characterized by and representative of their functionality and geographic condition, including indoor and outdoor climate conditions" (Corgnati, Fabrizio, Filippi, & Monetti, 2013). The reference building for this project was defined using the Example Reference Building Methodology (ERB). In this report, the reference building is the unnamed, existing building that was recently built in Seattle, and the prototype is the simplified wood version of the reference building. The final prototype building includes the description of the structural core (load bearing floors, columns, walls and foundation) and exterior enclosure ('core and shell'), as this is the most common scope for initial construction of commercial office buildings (USGBC, 2014) (DGNB, 2014) (Initiative, G. B. , 2013).

Activity 2 involved preliminary studies of wood buildings and exemplary buildings in the Seattle area. The findings are contained in Appendices A and B.

Activity 3 developed the prototype building. First, the research team selected a concrete framed commercial office building recently built in Seattle upon which the prototype building would ultimately be based to serve as the reference building. To develop the wood structure, the research team analyzed the results of a parametric algorithm developed by Kristen Strobel, a recent UW graduate, for her thesis project titled "(Mass) Timber: Structurally Optimized Timber Buildings" (Strobel, 2016). This structural optimization study provided the material quantity estimates for the gravity system of the prototype building. For the other parts of the prototype building, the reference building was simplified into a baseline building from which material quantities could be estimated without disclosing identifying features of the reference building. Individual components of the baseline building, such as the cladding, roof assemblies, and subgrade components, were developed somewhat independently of the reference building. All of the different components were pulled together to describe the final prototype building, and the environmental impacts were also calculated for both the wood prototype building and the baseline concrete building.

4 ACTIVITY 1: LITERATURE REVIEW

A literature review was undertaken to explore existing work that could support the development of the prototype building. First, to obtain the context for the viability of a commercially attractive wood building in the Pacific Northwest, the research team explored the topic of mass timber in mid-rise commercial buildings. Second, since a materially efficient wood building would be more economically attractive, the literature review looked for possible guidance on designing an optimized wood building.

Finally, the literature review gathered information on the methodology of establishing a reference building in order to develop the prototypical reference building to current standards.

This work was conducted by: Ezekiel Jones, Mariam Hovhannisyan, and Barbara Rodriguez.

4.1 Mass Timber in Mid Rise Commercial Buildings

Over the last ten years, cross laminated timber (CLT) has increased its share in market popularity, particularly in use for residential buildings, office buildings, schools, as well as other fields of construction (Brandner, Flatscher, Ringhofer, Schickhofer, & Thiel, 2016). According to Brandner et al, production capacities have grown rapidly at 15-20% per year with a worldwide production volume of roughly 500,000 m3 per year (2012) and 625,000 m3 per year (2014).

CLT continues to push the limits for tall timber buildings (Brandner, Flatscher, Ringhofer, Schickhofer, & Thiel, 2016). Europe has continued to lead CLT construction, with the recent construction of the 14-story combined CLT and glulam building -- 'The Treet' in Bergen, Norway (Timber Design and Technology, 2015). Other salient developments include the first 10-story commercial-residential Forte Building in Melbourne, Australia (2012), the 8-story Life Cycle Tower One in Dornbirn, Austria, and two institutional buildings at the University of British Columbia in Vancouver, Canada: the 5-story Earth Sciences building (2012) and the 4-story Bioenergy Research & Demonstration Facility (2014) (BSLC, 2014). In the United States, the 7-story T3 wood office building in Minneapolis was scheduled for completion in Fall 2016 (BizJournals, 2016).

Whether CLT has the capability to break into the commercial building market as an alternative building material in Seattle depends on the ability of mass timber to compete with standard construction materials for mid-to-high rise building typologies, such as residential towers and commercial office buildings (Hovhannisyan, 2015). According to the Energy Information Administration (EIA), 18% of all buildings constructed in 2012 in the U.S. were office buildings, which is greater than any other building typology (EIA, 2012). In Seattle, of the 93 projects active in 2014, 58 were residential buildings and 13 (the next highest category) were office buildings.

The current Seattle building code restricts buildings made of wood products to no more than 85 feet in height and no more than 6 stories, depending on the use of the building. The City of Seattle, with the aid of the Construction Codes Advisory Board (CCAB) Innovation Advisory Committee, are deciding whether to allow mass timber construction for larger and/or taller buildings (Seattle Gov, 2012). Other advancements in the use of CLT include the publication the CLT Handbook in 2011 (Canadian) and the publication of the U.S. version in 2013. In 2015, a chapter on CLT was added to the National Design Standards (NDS) for wood and is referenced by the International Building Code (IBC) with its own product chapter (ICC, 2015)

4.2 Optimization of Mass Timber Buildings

The few studies that have explored the optimization of material quantities in mass timber buildings have been done within a European context, using simulated annealing, genetic algorithms, and particle swarm optimization to explore structural design and life cycle impacts of wood buildings. According to Eurocode 5, Kaziolas et al are one of the few to have developed a methodology to optimize timber structural components, in addition to performing life cycle analysis calculations (Eurocode, 2004) (Kaziolas, Bekas, Zygomalas, & Stavroulakis, 2015). Other studies have optimized the thermal, structural and environmental aspects of a building, taking into account the industrial feasibility, design methods, and regulatory constraints (Armand Decker, et al., 2014).

Other studies have explored the competitiveness of optimized timber buildings versus other construction systems using a comparative approach. Such is the case of Winter et al, who carried out a case study to find out why and how the estimated costs for a timber variant differs so much from a reinforced concrete structure. They found that design choices were critical for the optimization of timber buildings. For example, floor elements had to consider the span width in order to be materially efficient. It was also determined that CLT ceiling panels were economic up to a span of 4-5 m, which consequently determined the positions of load bearing walls (Winter, Weber, Hernandez, & Brigola, 2012).

4.3 Defining Reference Buildings

Recent studies have established diverse methodologies in the development of reference buildings, but there is no standard methodology to date. It is difficult to represent most of the commercial building stock with a small set of building models due to the diversity of buildings and the limited data on their characteristics (Torcellini, Deru, Griffith, & Benne, 2008).

Corgnati et al classified the methodologies for defining reference buildings in three categories. The first is the 'Example Reference Building' (ERB), which can be used when there is no data about the building stock. The description of the reference building is then the most reasonable approximation using expert opinion to define a probable building. The second methodology, 'Real Reference Building' (RRB) takes an existing building, selected with characteristics to match those that are typical of construction, ideally through a statistical analysis. Finally, the 'Theoretical Reference Building' (TRB) relies on statistical data to define a reference building as a statistical composite of the features found within a category of buildings in the stock (Corgnati, Fabrizio, Filippi, & Monetti, 2013).

For this study, the research team used a modification of the 'Example Reference Building' (ERB) methodology to define the reference building as having the most probable characteristics within the category of commercial office buildings as determined by experts. Additionally, the results will be put in context of other LCA studies compiled by the Embodied Carbon Benchmark Project (Simonen, et al., 2017). The ERB is a building for which construction documentation is known and provides a good example of typical construction practices. The building was modified slightly to provide a more generic reference case and maintain the anonymity of the actual building used.

5 ACTIVITY 2: PRELIMINARY STUDIES

In the process of defining the prototype building, a number of subactivities were carried out to explore exemplary and desired characteristics. As a part of the exploratory phase, the following two subactivities were performed:

1. Subactivity 2a: Analysis of Whole Building Life Cycle Assessment (WBLCA) Results
2. Subactivity 2b: Assessment of Exemplary Buildings

5.1 Subactivity 2a: Analysis of Whole Building LCA Results by Arch 425/525

This work was conducted by: Weston Norwood.

The students of ARCH 425/525 performed screening level studies on a set of baseline buildings and also on proposed buildings that were created by modifying a single feature of the baseline buildings (such as changing the material type of a particular building component). The Athena Impact Estimator for Buildings was used to calculate the life cycle impacts. Operational energy was excluded. Although the studies were performed by students with a nascent understanding of LCA, there were trends from that point to some valuable lessons. For example, substituting timber for concrete or steel in a building structure resulted in reduced life cycle environmental impacts. The results of these studies were compiled in a report developed by Weston Norwood, shown in Appendix A. The goal of the report was to highlight some of the difficulties of screening level studies, and to investigate the limitations of the requirements for LEED Whole Building Life Cycle Assessment credits.

With regards to the development of the prototypical reference building, these studies offer the following preliminary insights:

- Substituting timber for concrete or steel structural members usually results in significant reductions in environmental impact. Thus, a wood structure appears to be a favorable option if the owner is interested in reducing the overall environmental impact of a building.
- Favorable cladding materials include vinyl siding, cedar siding, and fiberboard. High-impact cladding materials include: stucco and split-faced brick (highest).

Of note, these studies were performed by students and did not undergo a significant quality control review.

5.2 Subactivity 2b: Assessment of Exemplary Buildings

This work was conducted by: Ezekiel Jones and Barbara Rodriguez

This subactivity aimed to define the typical Seattle office building in terms of the structural system and exterior cladding system. The study surveyed a wide range of buildings that were either in design or under construction in the Pacific Northwest, evaluating the structural systems and typical cladding types. Surveys were conducted by students, assembled into 8 reports, and assessed by Ezekiel Jones with input from Barbara Rodriguez.

For typical office buildings, it was found that:

- The average parcel size was 170’ x 250’.
- The average building height was 6.66 stories. The recommended building height for the reference building is 7 stories.
- The typical floor-to-ceiling height is 10 ft (based on big tech companies).
- The typical column spacing is 30’ on center (based on big tech companies to account for 10’ desk modules).
- Below-grade parking is generally 1 parking spot per 800-1000 gross square feet.
- Column dimensions are typically 18”x24” on typical floors, and 24”x24” on floors where the vertical span is greater than 10’.
- Shear cores are largely dependent on architectural layout considerations

- The foundations are primarily concrete. Below-grade retaining walls extend 2-3 stories (depending on the number of parking stalls in the building), with floor-to-floor heights of 9 feet and widths of 10-12" depending on soil type. Continuous footings are typically 2-4 ft wide and 1.5-2 ft deep, and are located around the perimeter of a building under the retaining walls. Below each column are spot footings that are typically 10' x 10' x 3'. Below the shear cores are typically 3' deep mat footings. Mat foundations are based on the shear core dimensions.
- The office building envelope is usually either 1) a curtain wall system with spandrel glass, or 2) a punched window and solid wall system. Both systems typically result in 40% glazing, which is consistent with IBC requirements. The first option is most popular in the Seattle and Portland areas.

See Appendix B for a full report of this work, which includes diagrams of typical buildings layouts and cross-sections of the wall and cladding systems. The cladding systems were explored in more detail and the results are presented in Section 6.3, which focuses on exterior walls.

6 ACTIVITY 3: DEFINING THE PROTOTYPE BUILDING

In defining the prototype building, the following subactivities were performed:

1. Subactivity 3a: Description of the Reference Building, Baseline Building
2. Subactivity 3b: Wood Gravity System
3. Subactivity 3c: Exterior Wall
4. Subactivity 3d: Roof
5. Subactivity 3e: Foundation and Subgrade
6. Subactivity 3f: Lateral System
7. Subactivity 3g: Wood Prototype Buildings
8. Subactivity 3h: Concrete Baseline Building
9. Subactivity 3i: Preliminary Environmental Impacts and Comparisons

6.1 Subactivity 3a: Description of the Reference Building, Baseline Building, and Prototype Building

This work was conducted by: Ezekiel Jones and supplemented by Monica Huang.

A reference building was selected to provide the basis for a commercially viable mid-rise office building in the Seattle area. This particular reference building was selected because its geometry and construction were assessed by professional judgement to be representative of the region, and because the research team had access to the original construction documents to estimate material quantities. The identity of this building is not disclosed for confidentiality reasons. It is a concrete-framed building located in the South Lake Union neighborhood of Seattle, and was built within the past five years. It includes 3 levels of subgrade parking supporting 8 stories above. The lateral system is a concrete shear wall, and the exterior walls are comprised of curtain wall. Columns are spaced approximately 30 ft by 20 ft on center with thickened slabs spanning 30 ft as beams.

The reference building was simplified into a baseline building in order to facilitate quantity take-offs and to conceal identifying characteristics of the reference building. Quantity take-offs were performed on the baseline building and the results were used to define parts of the prototype building that would not be substituted by mass timber, such as the lateral system and foundation.

The wood prototype evolved to consist of eight buildings based on four configurations and two fire design options. These multiple options were developed because 1) a 30'x20' grid spacing is unusual for office buildings, so basing the prototype building solely on that grid spacing is not necessarily reflective of typical practice, and 2) the optimal design for a wood building could have occurred at a different layout than a concrete building, due to differing material properties and efficiencies. The four building configurations are described as follows:

1. Wood optimum. This configuration is intended to be the most materially efficient option per unit area (total area above grade), with all grid layouts considered.
2. Typical office building. This configuration reflects a typical office space with 30'x30' column spacing.
3. Reference building. This configuration reflects the 30'x20' grid spacing of the reference building.
4. Floor clearance optimum. This configuration reflects the market preference for high ceiling heights, with all grid layouts considered.

Each configuration was given two fire design options: one was with charring design (thickening the beams and slabs to withstand fire), and the other was with fireproofing protection in lieu of charring design. Thus, eight wood prototype buildings were developed for this study.

6.2 Subactivity 3b: Wood Gravity System

This work was conducted by: Kristen Strobel and supplemented by Monica Huang.

6.2.1 Parametric algorithm

To explore the structural optimization of a wood building, Kristen Strobel, a graduate student in architecture and structural engineering, created a parametric algorithm to design wood buildings for her Masters of Architecture thesis project. The algorithm employed the brute force method to iterate over all possible combinations of parameters within the solution space (as long as the iteration didn't exceed a certain calculation time) to provide a full set of possible solutions (Strobel, 2016). The algorithm was developed using Grasshopper, a graphical algorithm editor for Rhinoceros 5 (Rhino), which is a 3D geometric modeling CAD environment. See Figure 1 for a screenshot of the working environments of Rhino and Grasshopper. Thousands of buildings were designed using this method, producing results related to material quantities, environmental impact, cost, and more. All members (beams and columns), slabs, and shear walls were structurally optimized, meaning that the algorithm searched for the smallest members that could carry the structural loads, satisfy deflection limits, and meet other design criteria.

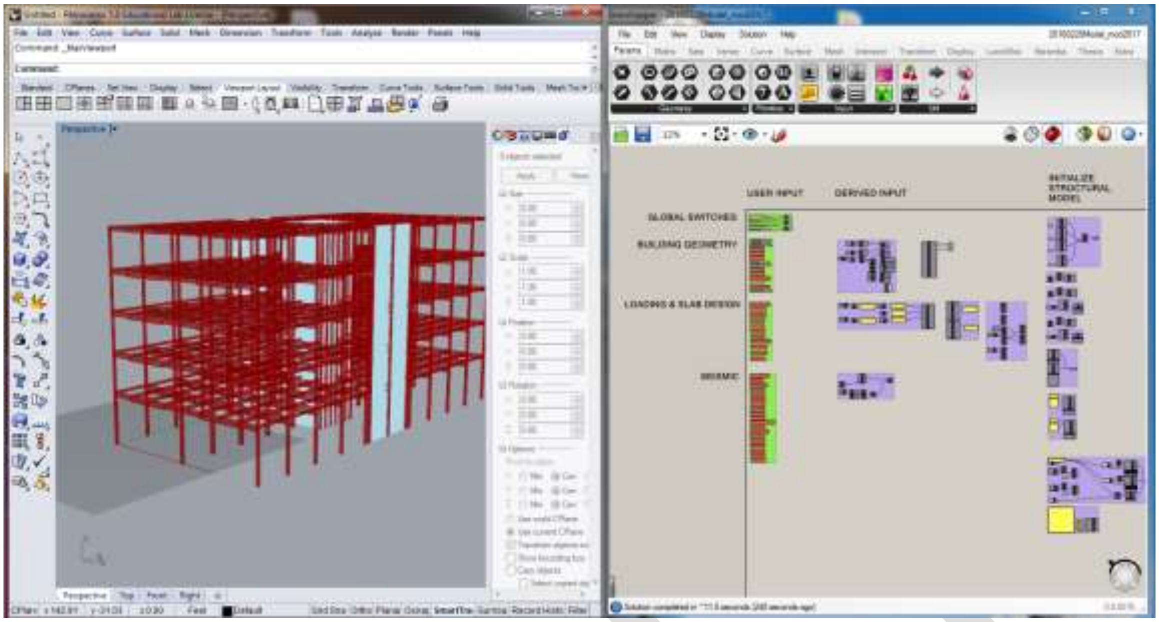


Figure 1. Screenshot of Rhino (left) and Grasshopper (right) environments from structural optimization study.

For the purposes of developing the wood prototype building for this project, the building was limited to a 90'x160' footprint and a 114' building height to match the reference building. Grid spacing (distance between columns) varied from 20' – 40' at increments of 5'. The core dimensions were 20'x20'. In preliminary studies, it was observed that variations in floor-to-floor heights at increments of 1 ft and slab thicknesses at increments of 0.5" between 2 – 3" did not significantly impact overall structural quantities. Thus, the floor-to-floor heights were constrained at 16' on the first floor and 14' on typical floors to match the reference building dimensions. The topping slab thickness was held constant at 2.5" and was assumed to have reinforcement of #4 @ 18" spacing on center each way.

See Figure 2 for a diagram of a generic building in plan and profile. The actual wood buildings vary in grid dimensions, but story heights are the same.

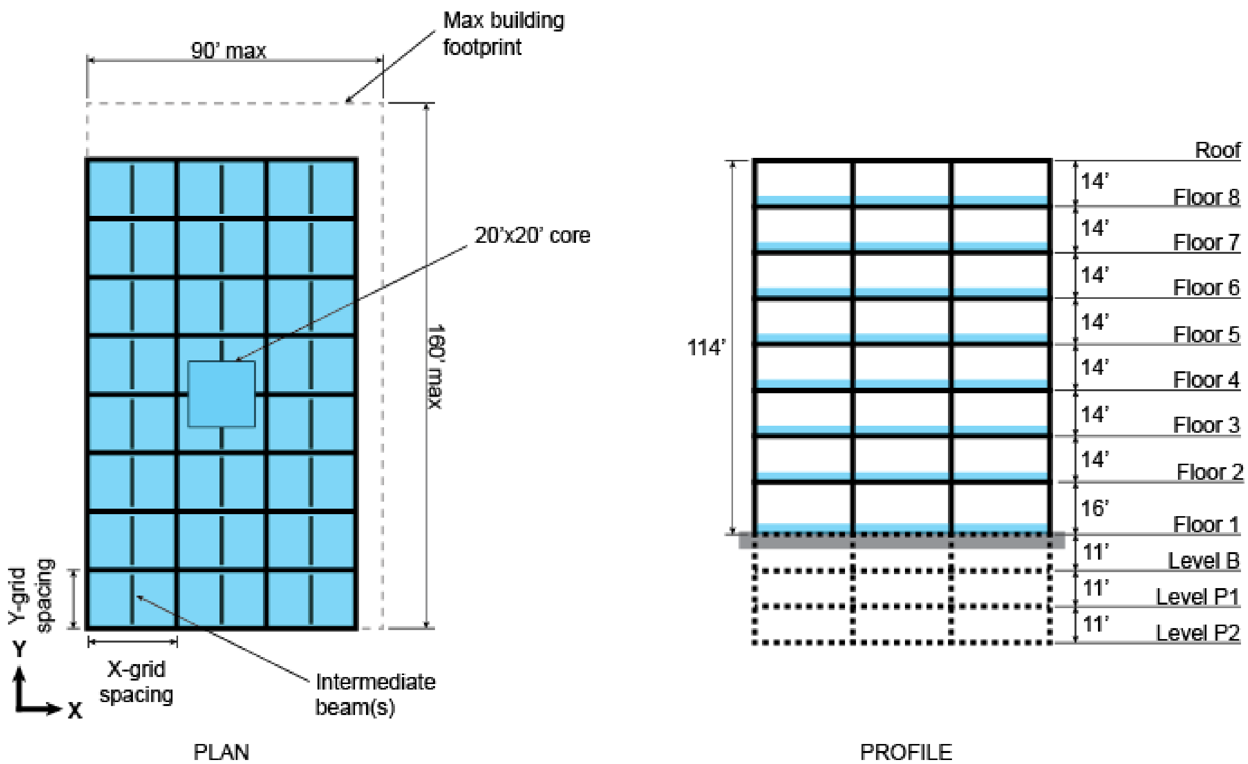


Figure 2. Prototype building plan (left) and profile (right). Blue area shading indicates total area of floor used to calculate per unit area quantities. Dotted lines in the Profile indicate subgrade levels.

Table 1 presents a list of the input parameters that were varied in the structural optimization study.

Table 1. Variable input parameters in structural optimization algorithm.

Parameter name	Description	Options
IncludeCharring(T/F)	True if floors, beams, and columns were designed for charring; false if not.	True (T) or false (F)
TimberConcreteCompositeSlab(T/F)	True if slabs were designed for composite action between CLT and concrete slabs; false if not.	T or F
CompositeBeamSlab(T/F)	True if beams were designed for composite action with CLT slabs; false if not.	T or F
X-GridSpace(ft)	Column spacing in the X direction.	20, 25, 30, 35, 40
Y-GridSpace(ft)	Column spacing in the Y direction.	20, 25, 30, 35, 40
SortByDepth(T/F)	True if glulam members were selected based on ascending member depth; false if members were selected based on ascending cross-sectional area.	T (sort by depth) or F (sort by area)
NumberIntermediateBeams	The number of intermediate beams dividing a bay in the X direction.	0, 1, 2, 3

Table 2 presents the full list static design parameters for the structural design that were not varied in the parametric algorithm.

Table 2. Static design parameters in structural optimization algorithm.

Field Name	Value
X Dimension Max (ft)	90
Y Dimension Max (ft)	160
Maximum Building Height (ft)	114
Core Dim X (ft)	20
Core Dim Y (ft)	20
Number of Interior Core Walls X-Dir	5
Length of Façade Wall Segments (ft)	25
Floor Topping Slab Thickness (in)	2.5
Floor Finishes (psf)	5
Floor MEP (psf)	5
Floor Occupancy LL (psf)	50
Floor Partition LL (psf)	30
Earthquake Partition (psf)	10
Earthquake Beams (psf)	7
Roof Topping Slab Thickness (in)	2.5
Roof Insulation (psf)	5
Roof MEP (psf)	5
Roof LL (psf)	20
Risk Category [ASCE 7-10 T1.5-1]	2
Ie [ASCE 7-10 T1.5-1]	1
Site Class [ASCE 7-10 11.4.2]	C
Ss (g)	1.368
S1 (g)	0.53
Sds (g)	0.912
Sd1 (g)	0.459
Tl (s)	6
Fa [ASCE 7-10 T11.4-2]	1
Fv [ASCE 7-10 T11.6-1]	1.3
Seismic Design Category [ASCE 7-10 11.6-1]	D

Fpga	1
System Type [ASCE 7-10 11.4.2]	CLT Shear Walls (ignore)
R	3.2
Cd	3.2
Omega 0	1.4
x	0.75
Ct	0.02
K	1.12

The model was run for all possible scenarios, resulting in 1600 buildings.

6.2.2 Summary of results

The resulting data was filtered to exclude iterations that had undesirable or unfeasible characteristics, which are as follows:

- Slabs failing to pass deflection and vibration checks
- Runs for which no viable design was possible, which meant that one or more members could not be sized to meet demand loads (for fire or non-fire conditions), meet deflection criteria, etc.
- Floor clearance greater than 8 feet

After these constraints were applied, 1384 buildings remained.

The results of the analysis found that the following strategies contributed to more optimal wood volumes in the floor structural systems:

- Excluding charring design (which would require a different fireproofing system)
- Including slab composite action (beam-to-slab composite action resulted in negligible improvements)
- Having at least one intermediate beam subdividing a bay (shorter spans of CLT)
- Slab spans between 10 – 18 feet.

For a detailed summary of the results, please see Appendix C.

From Strobel's thesis, a key observation was that façades and floor systems contributed roughly 75% of the overall environmental impacts of the building structure (excluding subgrade and foundations). Façades could be optimized by reducing the amount of glazing, which could be done by placing shear walls along the perimeter of the building, although this is unlikely to meet developer standards for Class A office space. It was also observed that floor systems in the wood buildings tend to be rather deep (2 – 4 ft), which makes them unattractive in comparison with steel or concrete alternatives. To overcome this, an innovative composite floor system could to be developed, or zoning height allowances could be increased for wood buildings to offset the increased floor-to-floor heights (Strobel, 2016).

6.2.3 Building selection

For the purposes of this study, an additional constraint was applied: no composite action would be used in the slabs or beams. This reduced the number of available buildings to 332. Even though composite action typically results in greater structural efficiency, it is rarely used for wood buildings because it is costly to install.

The optimization analysis focused on the combined volume of the beams, columns, and slabs as the quantity to be optimized, normalized per unit area (square foot, or sf) of total floor area over 8 stories. This quantity was defined as *TotalWoodVol(ft3/sf)*. Although this parametric model included the design of CLT shear walls and bearing walls, the results from the model were not yet aligned with emerging experimental data and thus not appropriate to use in this study.

As described in Section 6.1, four building configurations were selected, each with a charring option and a no-charring option. The buildings were selected after applying the constraints to the building dataset and using the optimization parameter to select a single building from the resulting selection.

The building selection process and criteria are summarized in Table 3. Figure 3 presents a visual representation of the building selection process for Configurations #1 – 3, which were optimized on wood volume. Figure 4 does the same for Configuration # 4, which was optimized on floor clearance.

Table 3. Building selection criteria.

Configuration	Fire option	Constraints applied	Optimization parameter
1. Wood optimum (min. of beam + column + slab)	Charring design	• IncludeCharring(T/F) = TRUE	Minimum of TotalWoodVol(ft3/sf)
	No charring	• IncludeCharring(T/F) = FALSE	Minimum of TotalWoodVol(ft3/sf)
2. Typical office building (30x30 grid)	Charring design	• IncludeCharring(T/F) = TRUE • X-GridSpace(ft) = 30 • Y-GridSpace(ft) = 30 • SortbyDepth(T/F) = FALSE	Minimum of TotalWoodVol(ft3/sf)
	No charring	• IncludeCharring(T/F) = FALSE • X-GridSpace(ft) = 30 • Y-GridSpace(ft) = 30 • SortbyDepth(T/F) = FALSE	Minimum of TotalWoodVol(ft3/sf)
3. Reference building (30x20)	Charring design	• IncludeCharring(T/F) = TRUE • X-GridSpace(ft) = 30 • Y-GridSpace(ft) = 20 • SortbyDepth(T/F) = FALSE	Minimum of TotalWoodVol(ft3/sf)
	No charring	• IncludeCharring(T/F) = FALSE • X-GridSpace(ft) = 30 • Y-GridSpace(ft) = 20 • SortbyDepth(T/F) = FALSE	Minimum of TotalWoodVol(ft3/sf)

4. Floor clearance optimum	Charring design	• IncludeCharring(T/F) = TRUE • SortbyDepth(T/F) = TRUE	Maximum of FloorClear(ft)
	No charring	• IncludeCharring(T/F) = FALSE • SortbyDepth(T/F) = TRUE	Maximum of FloorClear(ft)

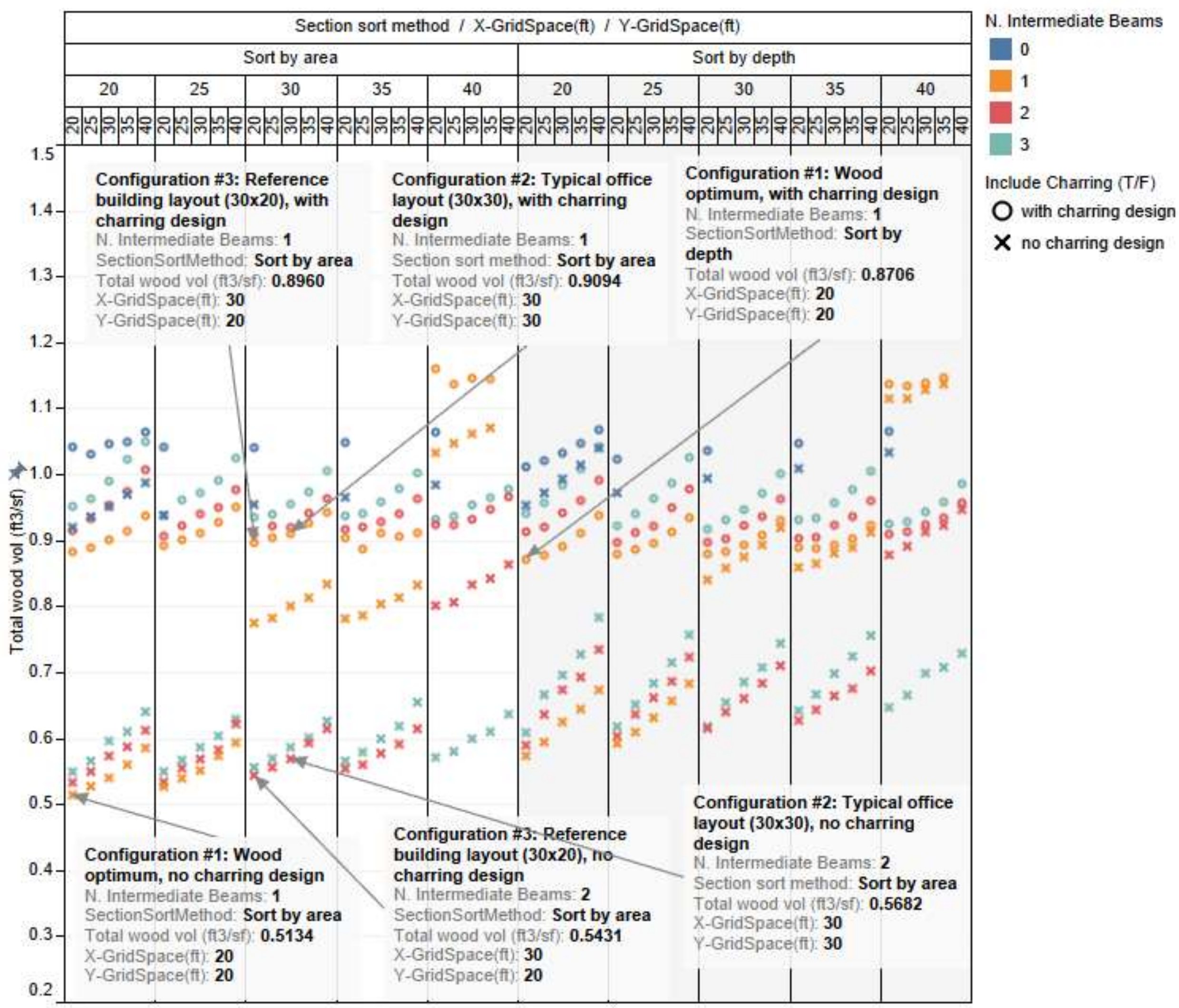


Figure 3. Selection of wood prototype buildings for Configurations #1 – 3.

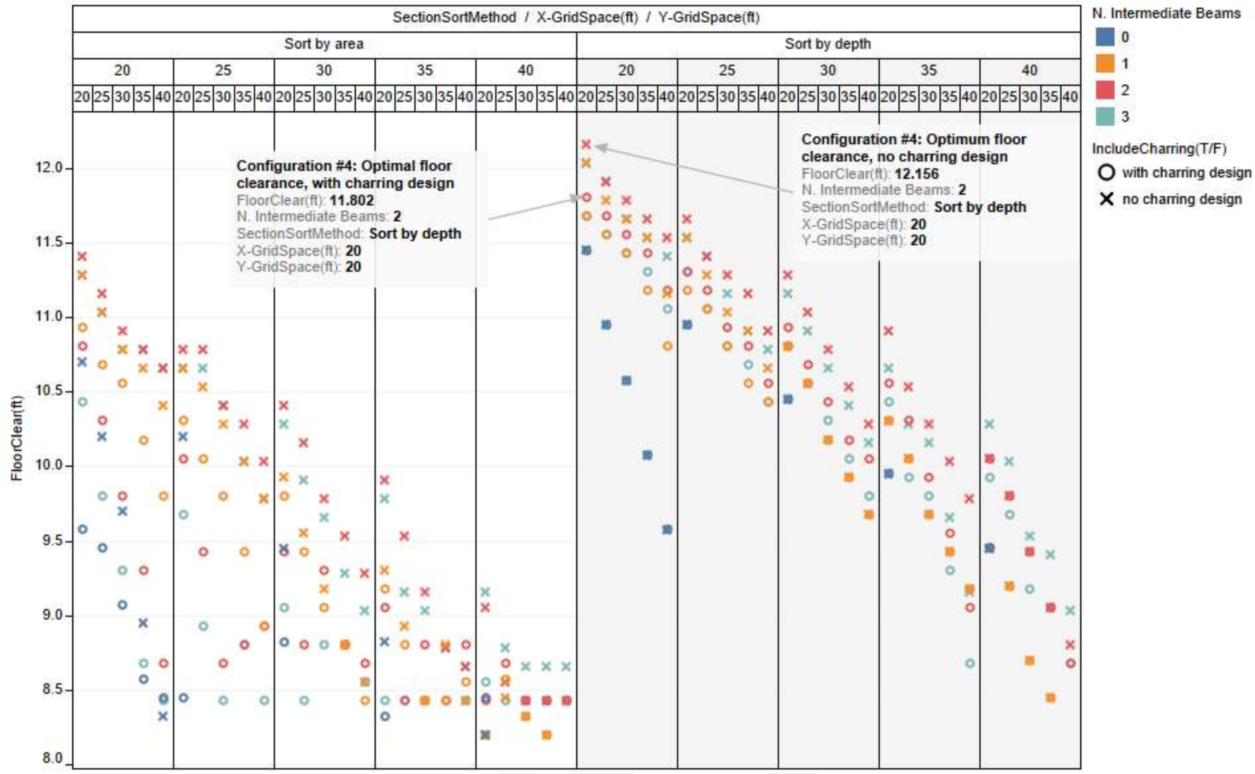


Figure 4. Selection of wood prototype buildings for Configuration #4.

6.2.4 Fireproofing

Fireproofing had to be applied to the buildings that did not have charring design. Fireproofing in the form of sheetrock or gypsum wall board was estimated per square foot of floor area. This was done by estimating the fireproofing needed for 1) the underside of the slabs, 2) the exposed area of a typical beam, and 3) the surface area of a typical column. These estimated quantities were bundled into factors to be applied to the total floor area of the building. A summary of the contributing and final factors is shown in Table 4.

Table 4. Factors used to estimate fireproofing as a function of floor area.

Estimate level	Description	Estimated factor per floor unit area
Components	Slabs	1
	Beams	0.75
	Columns	0.26
	Combined	2.01
Final	1 layer fireproofing	2
	2 layers fireproofing	4

For a 2-hour fire rating, fireproofing in the form of two layers of 5/8" gypsum wall board would be needed per the Gypsum Association Fire Resistance Design Manual. Thus, per Table 4, the total area of fireproofing for the underside of the CLT slabs, beams, and columns is approximately four times the unit area of floor.

6.3 Subactivity 3c: Exterior Wall

This work was conducted by: Ezekiel Jones.

For the exterior wall, a cladding study was conducted to evaluate 12 types of cladding systems for their material quantities and environmental impacts. The cladding types were based on a combination of 3 siding types with 3 wall structure types, and the curtain wall group was further broken down into 40%, 60%, and 90% glazing, representing the percentage area that is covered by glass, with the remaining area covered by metal panels. The cladding types are summarized in Table 5. Diagrams of the cladding cross-sections and window layouts for the curtain walls are contained in Appendix B.

Table 5. Description of cladding types evaluated.

Cladding type abbreviation	Siding type	Wall structure type
BM	Brick	Metal Stud
MM	Metal Panel	Metal Stud
WM	Wood Siding	Metal Stud
BW	Brick	CLT
MW	Metal Panel	CLT
WW	Wood Siding	CLT
CW40	N/A	Curtain Wall (40%)
CW60	N/A	Curtain Wall (60%)
CW90	N/A	Curtain Wall (90%)
BC	Brick	Concrete Wall
MC	Metal Panel	Concrete Wall
WC	Wood Siding	Concrete Wall

The cladding quantities were originally calculated for 640 SF of wall using the Athena Impact Estimator for Buildings Version 5.1, then the results were normalized to 1 SF. Table 6 contains a sample of the information provided per cladding type. The quantities are also provided in their equivalent mass values in pounds.

Table 6. Sample cladding material quantity information per SF, for Brick – Metal Stud (BM).

Material	Quantity	Unit	Mass Value	Mass Unit
3 mil Polyethylene	8.35E-01	sf	1.28E-02	lbs
5/8” Regular Gypsum Board	1.73E+00	sf	3.65E+00	lbs
Air Barrier	8.35E-01	sf	1.03E-02	lbs
Aluminum Window Frame	5.81E-01	lbs	5.81E-01	lbs
Cold Rolled Sheet	1.63E-05	Tons (short)	3.25E-02	lbs
Double Glazed Soft Coated Air	1.98E+00	sf	6.58E+00	lbs
Extruded Polystyrene	8.20E-01	sf (1")	2.07E-01	lbs
FG Batt R11-15	3.25E+00	sf (1")	2.08E-01	lbs
Galvanized Studs	3.08E-04	Tons (short)	6.15E-01	lbs

Joint Compound	1.77E-04	Tons (short)	3.54E-01	lbs
Metric Modular (Modular) Brick	8.27E-01	sf	1.78E+01	lbs
Mortar	2.64E-03	yd3	5.69E+00	lbs
Nails	1.16E-05	Tons (short)	2.31E-02	lbs
Paper Tape	2.03E-06	Tons (short)	4.06E-03	lbs
Screws Nuts & Bolts	1.08E-05	Tons (short)	2.16E-02	lbs

The global warming potential (a.k.a. embodied carbon) was evaluated. Figure 5 presents the global warming potential per square foot of cladding type in life cycle stage A only (A1 – A5). From this figure, it can be observed that curtain walls have the highest environmental impacts of the wall structure types, followed by concrete walls, metal stud walls, then CLT walls.

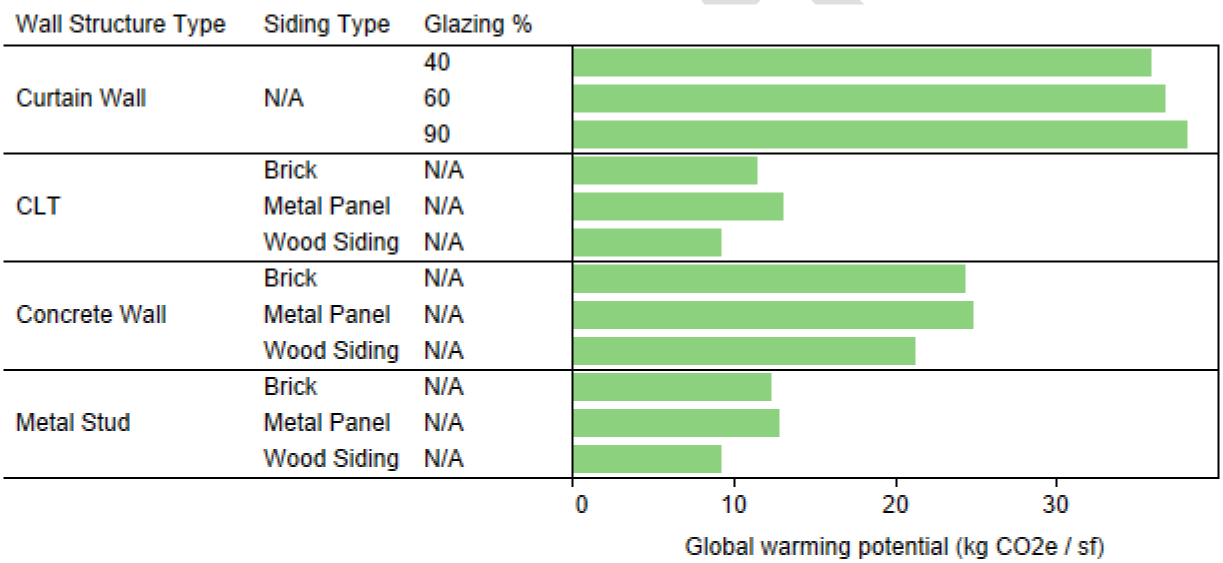


Figure 5. Global warming potential of cladding types by wall structure type and siding type (where applicable), and glazing percentage for curtain walls.

The results were sorted by magnitude and are presented in Figure 6.

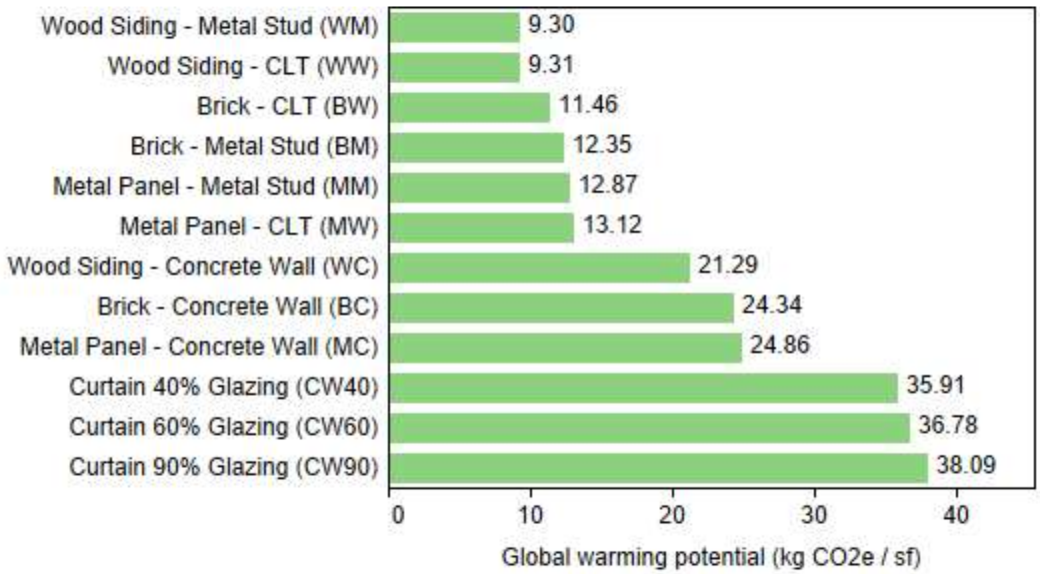


Figure 6. Global warming potential of cladding types, sorted from smallest to largest values.

In the end, the curtain wall 40% glazing option was selected for both the wood prototype building and baseline concrete building to reflect typical design practice in the region.

6.4 Subactivity 3d: Roof

The typical roof assembly was obtained from the reference building plans as having the following components:

- Elastomeric membrane roofing
- 1/2" Cement board
- 8" Rigid insulation
- Vapor retarder

The final roofing materials selected from the Athena database is shown Table 7. These were selected to be the highest global warming potential of the possible options.

Table 7. Roof assembly material selection.

Item	Selected material
Membrane	EPDM membrane (black, 60 mil)
Rigid board	1/2" Moisture Resistant Gypsum Board
Insulation	Extruded Polystyrene
Vapor retarder	6 mil Polyethylene

6.5 Subactivity 3e: Foundation and Subgrade

This work was performed by: Ezekiel Jones and Monica Huang.

Four sources of data were used to estimate the material quantities for the foundation and subgrade of the prototype building.

First, a general foundation study was performed to estimate average concrete and rebar quantities in the foundation of a typical Seattle office building. This was done by conducting phone interviews with local structural engineers and architects and examining the construction drawings of two recently built commercial buildings in Seattle. The goal of the study was to produce a spreadsheet that would estimate concrete and rebar quantities given certain parameters. Although the student responsible was not able to finalize the work before graduating, the work was used to help estimate the material quantities for the prototype building. The generalized findings from this foundation study are summarized in Table 8, and the full foundation study can be found in Appendix D.

Table 8. Observations from surveying structural engineers in foundation study.

Topic	**Observations**
General	a. Sub-grade parking: 1 parking spot/1000 gsf
	b. Types of footings: Generally, spot footings are used below columns, continuous footings around perimeter, mat footings below shear cores and major vertical elements
Columns	c. Typical dimensions: 18”x24”, according to Structural Engineers; 24”x24” according to construction drawings.
	d. Rebar quantities: Average # rebar/ floor can be calculated by summing the total amount of rebar in a full line of columns down the building and dividing by number of floors.
Shear Walls	e. Shear wall design is unpredictable and is largely based on architectural drawings.
	f. For the general spreadsheet, 16” shear walls are used. Based on architectural and structural engineer consultations, 12-14” thick shear walls are typical, with the possibility of 20” shear walls below grade.
Below Grade	g. Foundation walls are typically 10-12” thick, with at least 9’ of clearance for cars and mechanical systems
	h. Foundation wall quantities: #5 @ 12” O.C. Vertical, Each Face, #6 24” O.C. Each Face.
	i. Spot footings below columns: Assume 10’x10’x3’. Mat Footings below shear cores: Assume 12-15 ft square by 3’ deep. Continuous footings 2-4 feet wide, 1.2-2 feet deep around the entire perimeter of the building.
	j. Piles are used on buildings that have floors near or below the water table, especially in the South Lake Union Area.

Second, the reference building plans were used to estimate material quantities for the subgrade components and foundations. Typical details were used to calculate per-unit values (e.g. cubic yards of concrete per foot of subgrade wall, pounds of rebar per square foot of slab-on-grade). Due to time constraints, the rebar quantities of the suspended slabs were not calculated from the reference building plans.

Third, data from a local structural engineering firm (SE), including data from a general contractor (GC), were applied to the reference building. These two sources were particularly valuable for components where rebar quantity take-offs of the original reference building were not performed (e.g. suspended slabs).

From these four sources, the average values were calculated to form the estimates for the prototype building. The total estimates of rebar and foundation for the prototype building using these four sources of data are shown in Figure 7 and Figure 8.

Some exceptions to this calculation process should be noted:

- Slab-on-grade: Since the professional unit estimates did not distinguish between suspended slabs and slab-on-grade (suspended slabs should have more reinforcement), the final value was based on the slab-on-grade design in the reference building and had a relatively high degree of confidence because the calculation was very straightforward and taken directly from the plans.
- Mat foundation: Student 1's value appeared to be an outlier (see Figure 8). It is approximately 15% of that of the other estimates, so that value was excluded from the final assessment.

Note that data was not available for all building components, particularly for rebar data. The rebar estimates had a greater variation in values, while the concrete estimates were fairly well clustered together, largely because the many of the values were used repeatedly (for example, the SE and GC concrete values were taken as an average of the other two values).

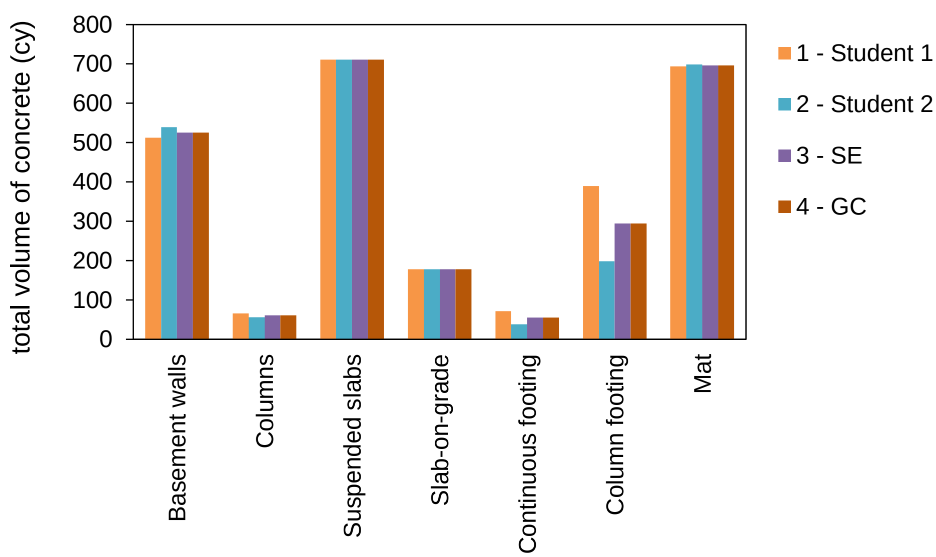


Figure 7. Comparison of estimated quantities of concrete in subgrade and foundation for prototype building. SE = structural engineering firm, GC = general contractor.

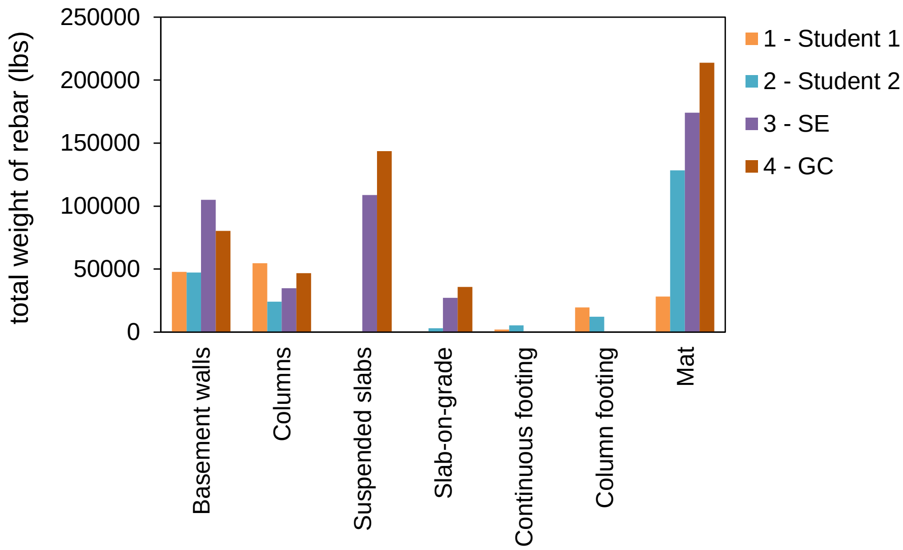


Figure 8. Comparison of estimated quantities of rebar in subgrade and foundation for prototype building.

The foundation and subgrade quantities were categorized in a way that allowed for the separation of the lateral system (mat foundation) from the subgrade gravity system (basement walls, columns, suspended slabs, and footings), which could be excluded without removing the foundation components (footings, slab-on-grade) if one wanted to assume that the building had no basement. The waterproofing for subgrade and foundation was separated similarly, and is discussed in the following subsection.

6.5.1 Waterproofing

Waterproofing and drainage for the basement walls and foundation slab were estimated based on the following material selections:

- For the basement walls, the waterproofing material could be TPO, modified bitumen, or PVC. The drainage would be 1" mat. These materials were applied to the outer surface of the basement walls.
- For the slab-on-grade, the waterproofing materials were the same as for the basement walls (TPO, modified bitumen, or PVC). Three aggregate options were selected from the Athena material database: coarse aggregate natural, coarse aggregate crushed stone, and crushed recycled concrete. The aggregate was assumed to be 4" thick and applied to an area equal to that of the building footprint.

The final selection of waterproofing and drainage materials for the subgrade and foundation were selected to be the most conservative in terms of highest global warming potential, and are shown in Table 9.

Table 9. Subgrade and foundation waterproofing and drainage material selections and environmental impacts for prototype building.

Component	Item	Selected Material
Subgrade	Waterproofing	PVC Membrane 48 mil
	Drainage	VR 1" Drainage Mat

Foundation	Waterproofing	PVC Membrane 48 mil
	Drainage	Coarse Aggregate Crushed Stone

6.6 Subactivity 3f: Lateral System

This work was performed by Ezekiel Jones and Monica Huang.

The material quantity estimates for the shear walls were based on the reference building drawings. There were 9 shear walls throughout the reference building. Quantity take-offs of rebar and concrete for shear walls 2 – 5 were performed earlier by Student 1, and the remaining shear wall quantities were calculated by estimating the volume of concrete from the reference building plans, and applying a unit value for rebar (pounds of rebar per cubic yard of concrete) to estimate the amount of rebar. The unit quantities of rebar from these three sources are compared in Table 10.

Table 10. Comparison of rebar per volume of concrete from Student 1, the structural engineer (SE), and the general contractor (GC).

Source	**Rebar per volume of concrete (lbs/cy)**
Student 1 average of SW-2 through SW-5	174.67
Structural Engineer	200
General Contractor	342

The final volume of concrete was taken directly from the quantity take-off estimates, and the rebar was estimated as the average of the three estimates in Table 10 and applied to the concrete volume to obtain total weight of rebar.

6.7 Subactivity 3g: Wood Prototype Buildings

This work was performed by: Monica Huang.

The results of the previous subactivities were pulled together to assemble the prototype building. A summary of how prototype building properties were determined by the subactivities is summarized in Table 11.

Table 11. Contributing subactivities to components of the prototype building, and how subactivity data was used for the prototype building.

Category	**Component**	**Subactivity**	**Measurement used for prototype buildings**
Structure	Gravity system	Subactivity 3b: Wood Gravity System	Unit quantities (per square foot of above grade floor area) of glulam beam, glulam column, CLT slab, and concrete slab were taken from the optimization study for the proposed prototype buildings (selected per the criteria in Table 3).
		3e: Foundation and Subgrade	Unit quantities for concrete volumes were taken as an average of survey data and reference

			building typical details, and rebar weights were based on the average of estimates from these sources. Unit quantities were applied to the geometries of each building to obtain overall quantities.
	Lateral system	3f: Lateral System	Concrete volume was estimated directly from the reference building drawings. Rebar quantities were based on quantity take-offs from the reference building plans combined with rebar per volume estimates from a local structural engineer and general contractor; the final value was taken as the average of these estimates. (For the mat foundation, see 3e: Foundation and Subgrade). These estimates were not varied by building geometry.
Enclosure	Areas of roof and exterior wall	Subactivity 3a: Description of the Reference Building, Baseline Building, and Prototype Building	Based on building geometry from Subactivity 3b: Wood Gravity System.
	Exterior wall type	3c: Exterior Wall	Curtain wall with 40% glazing was selected to match the original building and typical Seattle glazing ratios.
	Roof	3d: Roof	Appropriate materials were selected from the Athena database to match the roofing detail requirements. Where multiple materials were available, the material with the highest GWP was selected to be a conservative option. Unit quantities were then applied to the geometry of each building.
	Waterproofing	3e: Foundation and Subgrade	Similar to Roof (above) but for waterproofing and drainage requirements.

6.7.1 Properties

Table 12 presents the key dimensions of the 4 prototype buildings, with slight differences in the designed dimensions (intermediate beams, CLT thickness, floor clearance) depending on the fire design option.

Table 12. Dimensions of prototype buildings.

	Configuration			
Property	**1. Wood optimum**	**2. Typical office building (30x30 grid)**	**3. Reference building (30x20 grid)**	**4. Floor clearance optimum**

		Fire-proofing	Charring design	Fire-proofing	Charring design	Fire-proofing	Charring design	Fire-proofing	Charring design
Input	**X-grid spacing (ft)**	20	20	30	30	30	30	20	20
	Y-grid spacing (ft)	20	20	30	30	20	20	20	20
Derived	**Building length X (ft)**	80	80	90	90	90	90	80	80
	Building length Y (ft)	160	160	150	150	160	160	160	160
	N. bays X	4	4	3	3	3	3	4	4
	N. bays Y	8	8	5	5	8	8	8	8
	N. of columns per floor	45	45	24	24	36	36	45	45
	Perimeter (ft)	480	480	480	480	500	500	480	480
	Area[1] per floor (footprint area) (ft2)	12800	12800	13500	13500	14400	14400	12800	12800
	Total area[1] of all floors (above grade) (ft2)	102400	102400	108000	108000	115200	115200	102400	102400
	Total area[2] of exterior wall (ft2)	54720	54720	54720	54720	57000	57000	54720	54720
	Total area[2] of basement walls (ft2)	15840	15840	15840	15840	16500	16500	15840	15840
Designed	**N. intermediate beams**	1	1	2	1	2	1	2	2
	Thickness of CLT slab (in)	4.125	6.875	4.125	6.875	4.125	6.875	4.125	6.875
	Floor clearance (ft)	11.3	11.7	9.8	9.1	10.4	9.8	12.2	11.8

[1]Floor areas do not account for floor openings for elevators and stairs.
[2]Wall areas do not account for exterior doors. Uniform wall assembly is assumed across all exterior surfaces.

6.7.2 Material Quantities

The total material quantities of the prototype buildings are presented in Table 13. The quantities were converted to mass (kg) to facilitate calculations for the Forestry Team.

Since the sizes of the buildings varied by area due to differing grid spacings, the total quantities were divided by the total area of above-grade floors for each building (shown in Figure 2) to normalize the quantities by area. Furthermore, in order to obscure the suggested precision of the non-structural quantity estimates, the non-structural quantities of the building (which is everything except for the building structure) were averaged across the eight prototype buildings. These per unit area results are shown in Table 14. It is recommended that the final environmental impact evaluations be based on these material quantities per unit area.

Table 13. Total material quantities (in kilograms) for prototype buildings. The cells highlighted in gray indicate values that differ from the counterpart concrete baseline building.

System	Sub-system	Component	Item	Material	Material quantities (kg) by configuration and fireproofing option: 1. Wood optimum (min. of beam + column + slab)		2. Typical office building (30x30 grid)		3. Reference building (30x20 grid)		4. Floor clearance optimum	
					Fire-proofing	Charring design	Fire-proofing	Charring design	Fire-proofing	Charring design	Fire-proofing	Charring design
Structure	Gravity system	Building structure	Beams	Glulam	145,957	244,318	227,237	340,384	205,494	328,321	230,759	291,222
			Columns	Glulam	49,936	99,351	46,070	69,326	53,363	91,308	52,149	100,853
			CLT slabs	CLT	474,899	791,498	500,870	834,783	534,261	890,436	474,899	791,498
			Concrete slabs	Concrete	1,390,619	1,390,619	1,466,668	1,466,668	1,564,446	1,564,446	1,390,619	1,390,619
				Rebar	41,581	41,581	43,855	43,855	46,778	46,778	41,581	41,581
			Steel connections	Steel	12,943	12,943	11,755	11,755	13,348	13,348	12,943	12,943
			Floor underlayment	Fiberglass reinforced backer board 7/16"	106,801	106,801	112,641	112,641	120,151	120,151	106,801	106,801
			Fireproofing	Gypsum wall board	155,885	-	164,410	-	175,371	-	155,885	-
		Subgrade	Walls	Rebar	39,608	39,608	39,608	39,608	41,258	41,258	39,608	39,608
				Concrete	1,081,987	1,081,987	1,081,987	1,081,987	1,127,070	1,127,070	1,081,987	1,081,987
			Columns	Rebar	61,422	61,422	32,759	32,759	49,138	49,138	61,422	61,422
				Concrete	378,928	378,928	202,095	202,095	303,143	303,143	378,928	378,928
			Concrete slabs	Rebar	50,999	50,999	53,788	53,788	57,374	57,374	50,999	50,999
				Concrete	1,112,495	1,112,495	1,173,334	1,173,334	1,251,557	1,251,557	1,112,495	1,112,495
		Foundation	Continuous footing	Rebar	1,616	1,616	1,616	1,616	1,683	1,683	1,616	1,616
				Concrete	90,003	90,003	90,003	90,003	93,753	93,753	90,003	90,003
			Column footing	Rebar	11,317	11,317	6,036	6,036	9,054	9,054	11,317	11,317
				Concrete	803,255	803,255	428,402	428,402	642,604	642,604	803,255	803,255
			Slabs-on-grade	Rebar	1,222	1,222	1,289	1,289	1,375	1,375	1,222	1,222
				Concrete	278,124	278,124	293,334	293,334	312,889	312,889	278,124	278,124
	Lateral system	Foundation	Mat	Rebar	77,748	77,748	77,748	77,748	77,748	77,748	77,748	77,748
				Concrete	1,225,251	1,225,251	1,225,251	1,225,251	1,225,251	1,225,251	1,225,251	1,225,251
		Shear wall	Shear wall	Rebar	112,453	112,453	112,453	112,453	112,453	112,453	112,453	112,453
				Concrete	1,802,330	1,802,330	1,802,330	1,802,330	1,802,330	1,802,330	1,802,330	1,802,330

Enclosure	Exterior wall	Curtain wall	Wall	5/8" Regular Gypsum Board	45,403	45,403	45,403	45,403	47,295	47,295	45,403	45,403
			Wall	Air Barrier	244	244	244	244	255	255	244	244
			Window	Aluminum Extrusion	82,391	82,391	82,391	82,391	85,824	85,824	82,391	82,391
			Wall	EPDM membrane (black, 60 mil)	3,479	3,479	3,479	3,479	3,624	3,624	3,479	3,479
			Wall	FG Batt R11-15	13,220	13,220	13,220	13,220	13,771	13,771	13,220	13,220
			Wall	Galvanized Studs	9,887	9,887	9,887	9,887	10,299	10,299	9,887	9,887
			Wall	Glazing Panel	291,765	291,765	291,765	291,765	303,922	303,922	291,765	291,765
			Wall	Joint Compound	4,407	4,407	4,407	4,407	4,591	4,591	4,407	4,407
			Wall	Nails	288	288	288	288	300	300	288	288
			Wall	Paper Tape	54	54	54	54	57	57	54	54
			Wall	Screws Nuts & Bolts	3,428	3,428	3,428	3,428	3,571	3,571	3,428	3,428
			Spandrel	Spandrel Panel	32,272	32,272	32,272	32,272	33,617	33,617	32,272	32,272
	Roof	Roof assembly	Membrane	EPDM membrane (black, 60 mil)	2,909	2,909	3,068	3,068	3,272	3,272	2,909	2,909
			Rigid board	1/2" Moisture Resistant Gypsum Board	10,737	10,737	11,324	11,324	12,079	12,079	10,737	10,737
			Insulation (8")	Polyiso Foam Board (unfaced)	7,181	7,181	7,574	7,574	8,079	8,079	7,181	7,181
			Vapor retarder	3 mil Poly-ethylene	91	91	96	96	103	103	91	91

	Waterproofing	Subgrade	Water-proofing	PVC Membrane 48 mil	2,376	2,376	2,376	2,376	2,475	2,475	2,376	2,376
			Drainage	VR 1" Drainage Mat	1,429	1,429	1,429	1,429	1,488	1,488	1,429	1,429
		Foundation	Water-proofing	PVC Membrane 48 mil	1,920	1,920	2,025	2,025	2,160	2,160	1,920	1,920
			Drainage	Coarse Aggregate Natural	290,797	290,797	306,700	306,700	327,147	327,147	290,797	290,797

Table 14. Per unit area material quantities (in kilograms per square meter) for wood prototype buildings. The cells highlighted in gray indicate values that differ from the counterpart concrete baseline building. Quantities that were not part of the building structure were averaged across the eight prototype buildings, indicated by gray text.

System	Sub-system	Component	Item	Material	Material quantities (kg/m^2) by configuration and fireproofing option: 1. Wood optimum (min. of beam + column + slab) – Fire-proofing	1. Wood optimum – Charring design	2. Typical office building (30x30 grid) – Fire-proofing	2. Typical office building (30x30 grid) – Charring design	3. Reference building (30x20 grid) – Fire-proofing	3. Reference building (30x20 grid) – Charring design	4. Floor clearance optimum – Fire-proofing	4. Floor clearance optimum – Charring design
Structure	Gravity system	Building structure	Beams	Glulam	15.33	25.67	22.64	33.91	19.19	30.66	24.24	30.60
			Columns	Glulam	5.25	10.44	4.59	6.91	4.98	8.53	5.48	10.60
			CLT slabs	CLT	49.89	83.16	49.89	83.16	49.89	83.16	49.89	83.16
			Concrete slabs	Concrete	146.10	146.10	146.10	146.10	146.10	146.10	146.10	146.10
				Rebar	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37
			Steel connections	Steel	1.36	1.36	1.17	1.17	1.25	1.25	1.36	1.36
			Floor underlayment	Fiberglass reinforced backer board 7/16"	11.22	11.22	11.22	11.22	11.22	11.22	11.22	11.22
			Fireproofing	Gypsum wall board	16.38	0.00	16.38	0.00	16.38	0.00	16.38	0.00
		Subgrade	Walls	Rebar	4.03	4.03	4.03	4.03	4.03	4.03	4.03	4.03
				Concrete	110.10	110.10	110.10	110.10	110.10	110.10	110.10	110.10
			Columns	Rebar	5.19	5.19	5.19	5.19	5.19	5.19	5.19	5.19

				Concrete	32.02	32.02	32.02	32.02	32.02	32.02	32.02	32.02
			Concrete slabs	Rebar	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36
				Concrete	116.88	116.88	116.88	116.88	116.88	116.88	116.88	116.88
		Foundation	Continuous footing	Rebar	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
				Concrete	9.16	9.16	9.16	9.16	9.16	9.16	9.16	9.16
			Column footing	Rebar	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
				Concrete	67.87	67.87	67.87	67.87	67.87	67.87	67.87	67.87
			Slabs-on-grade	Rebar	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
				Concrete	29.22	29.22	29.22	29.22	29.22	29.22	29.22	29.22
	Lateral system	Foundation	Mat	Rebar	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84
				Concrete	123.48	123.48	123.48	123.48	123.48	123.48	123.48	123.48
		Shear wall	Shear wall	Rebar	11.33	11.33	11.33	11.33	11.33	11.33	11.33	11.33
				Concrete	181.64	181.64	181.64	181.64	181.64	181.64	181.64	181.64
Enclosure	Exterior wall	Curtain wall	Wall	5/8" Regular Gypsum Board	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62
			Wall	Air Barrier	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
			Window	Aluminum Extrusion	8.38	8.38	8.38	8.38	8.38	8.38	8.38	8.38
			Wall	EPDM membrane (black, 60 mil)	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
			Wall	FG Batt R11-15	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35
			Wall	Galvanized Studs	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
			Wall	Glazing Panel	29.69	29.69	29.69	29.69	29.69	29.69	29.69	29.69
			Wall	Joint Compound	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
			Wall	Nails	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
			Wall	Paper Tape	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
			Wall	Screws Nuts & Bolts	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
			Spandrel	Spandrel Panel	3.28	3.28	3.28	3.28	3.28	3.28	3.28	3.28

	Roof	Roof assembly	Membrane	EPDM membrane (black, 60 mil)	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
			Rigid board	1/2" Moisture Resistant Gypsum Board	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13
			Insulation (8")	Polyiso Foam Board (unfaced)	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
			Vapor retarder	3 mil Poly-ethylene	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Waterproofing	Subgrade	Water-proofing	PVC Membrane 48 mil	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
			Drainage	VR 1" Drainage Mat	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
		Foundation	Water-proofing	PVC Membrane 48 mil	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
			Drainage	Coarse Aggregate Natural	30.55	30.55	30.55	30.55	30.55	30.55	30.55	30.55

6.8 Subactivity 3h: Concrete Baseline Building

6.8.1 Properties

Table 15 presents the key dimensions of the baseline concrete building. Most dimensions match Configuration #3 of the wood prototype buildings (which represents the Reference Building), except for the beams, columns, and slabs.

Table 15. Dimensions of the baseline building.

Property		Dimension
X-grid spacing (ft)		30
Y-grid spacing (ft)		20
Building length X (ft)		90
Building length Y (ft)		160
N. of columns per floor		45
Perimeter (ft)		480
Area[1] per floor (footprint area) (ft2)		12800
Total area[1] of all floors (above grade) (ft2)		102400
Total area[2] of exterior wall (ft2)		54720
Total area[2] of basement walls (ft2)		15840
Thickened beams	Width (in)	48
	Depth (in)	14
Columns	Width (in)	24
	Depth (in)	24
Slab thickness (in)		8

[1]Floor areas do not account for floor openings for elevators and stairs.
[2]Wall areas do not account for exterior doors. Uniform wall assembly is assumed across all exterior surfaces.

6.8.2 Material Quantities

The material quantities of the concrete baseline building is presented in Table 16. As with the wood prototype buildings, the non-structural quantities lack precision, and so the per unit area quantities were taken to match those from the wood building so that comparisons between the concrete and wood buildings would not be focused on the non-structural quantities. This means that the material quantities for the non-structural components of the concrete building are not internally consistent with the building dimensions, but are consistent with the wood building values.

Rebar quantities were estimated by averaging rebar unit weight estimates from Student 2, the SE, and the GC. For beams + slabs, this number was 37.6 tons / cubic yard of concrete. For columns, it was 25.7 tons / cubic yard of concrete.

Table 16. Material quantities for baseline concrete building (based on the Configuration #3 Reference Building). The cells highlighted in gray indicate values that differ from the counterpart wood prototype building. The non-structural per unit area quantities were taken from the average of the wood prototype buildings (Table 14), indicated by gray text.

System	Sub-system	Component	Item	Material	Material quantities (total kg)	Material quantities (kg/m2)
Structure	Gravity system	Building structure	Slabs + thickened beams	Rebar	273,768	25.57
				Concrete	6,911,722	645.48
			Columns	Rebar	186,595	17.43
				Concrete	1,314,135	122.73
		Subgrade	Walls	Rebar	41,258	4.03
				Concrete	1,127,070	110.10
			Columns	Rebar	49,138	5.19
				Concrete	303,143	32.02
			Concrete slabs	Rebar	57,374	5.36
				Concrete	1,251,557	116.88
		Foundation	Continuous footing	Rebar	1,683	0.16
				Concrete	93,753	9.16
			Column footing	Rebar	9,054	0.96
				Concrete	642,604	67.87
			Slabs-on-grade	Rebar	1,375	0.13
				Concrete	312,889	29.22
	Lateral system	Foundation	Mat	Rebar	77,748	7.84
				Concrete	1,225,251	123.48
		Shear wall	Shear wall	Rebar	112,453	11.33
				Concrete	1,802,330	181.64
Enclosure	Exterior wall	Curtain wall	Wall	5/8" Regular Gypsum Board	47,295	4.62
			Wall	Air Barrier	255	0.02
			Window	Aluminum Extrusion	85,824	8.38
			Wall	EPDM membrane (black, 60 mil)	3,624	0.35
			Wall	FG Batt R11-15	13,771	1.35
			Wall	Galvanized Studs	10,299	1.01
			Wall	Glazing Panel	303,922	29.69
			Wall	Joint Compound	4,591	0.45
			Wall	Nails	300	0.03
			Wall	Paper Tape	57	0.01
			Wall	Screws Nuts & Bolts	3,571	0.35
			Spandrel	Spandrel Panel	33,617	3.28
	Roof	Roof assembly	Membrane	EPDM membrane (black, 60 mil)	3,272	0.31
			Rigid board	1/2" Moisture Resistant Gypsum Board	12,079	1.13
			Insulation (8")	Polyiso Foam Board (unfaced)	8,079	0.75
			Vapor retarder	3 mil Polyethylene	103	0.01
	Water-proofing	Subgrade	Waterproofing	PVC Membrane 48 mil	2,475	0.24
			Drainage	VR 1" Drainage Mat	1,488	0.15
		Foundation	Waterproofing	PVC Membrane 48 mil	2,160	0.20
			Drainage	Coarse Aggregate Natural	327,147	30.55

6.9 Subactivity 3i: Preliminary Environmental Impacts and Comparisons

This section presents a preliminary assessment of the global warming potential (GWP) for the wood prototype buildings and the concrete baseline building. The material quantities identified in the previous sections were multiplied by the GWP coefficients, life cycle stage A1 – A5, for the relevant materials from the Athena Impact Estimator (Version 5.1.01). This study excludes the effects of biogenic carbon sequestered during growth of timber, operational energy consumption, maintenance and repair of the structure, and end of life treatments and/or credits outside the system boundary. This building models structure and enclosure only, and excludes the impacts of interior partitions, finishes, mechanical and electrical systems, furniture, and site work.

Figure 9 presents the overall environmental impacts per square meter for the five of the most common environmental impact categories for the buildings. From this figure, it can be seen that the environmental impact of the concrete building exceeds that of the wood buildings in all impact categories except for ozone depletion potential. Fireproofed versions of the wood buildings tended to have lower impacts than the corresponding buildings designed for charring.

Figure 10 presents a comparison of the global warming potential in life cycle stage A of the concrete and wood versions of the reference building configuration (#3). Concrete is a major contributor in both the concrete and wood buildings, but most significantly in the slabs + thickened beams of the concrete building, which exceed the impacts of the glulam beams and CLT slabs in the counterpart wood building.

Figure 11 compares the proportion contribution to overall global warming potential (life cycle stage A) by the major components in the wood prototype buildings (averaged across the eight buildings), and the concrete baseline building. The wood building structure comprises a lower percentage of the overall impact than the concrete building structure in the concrete building.

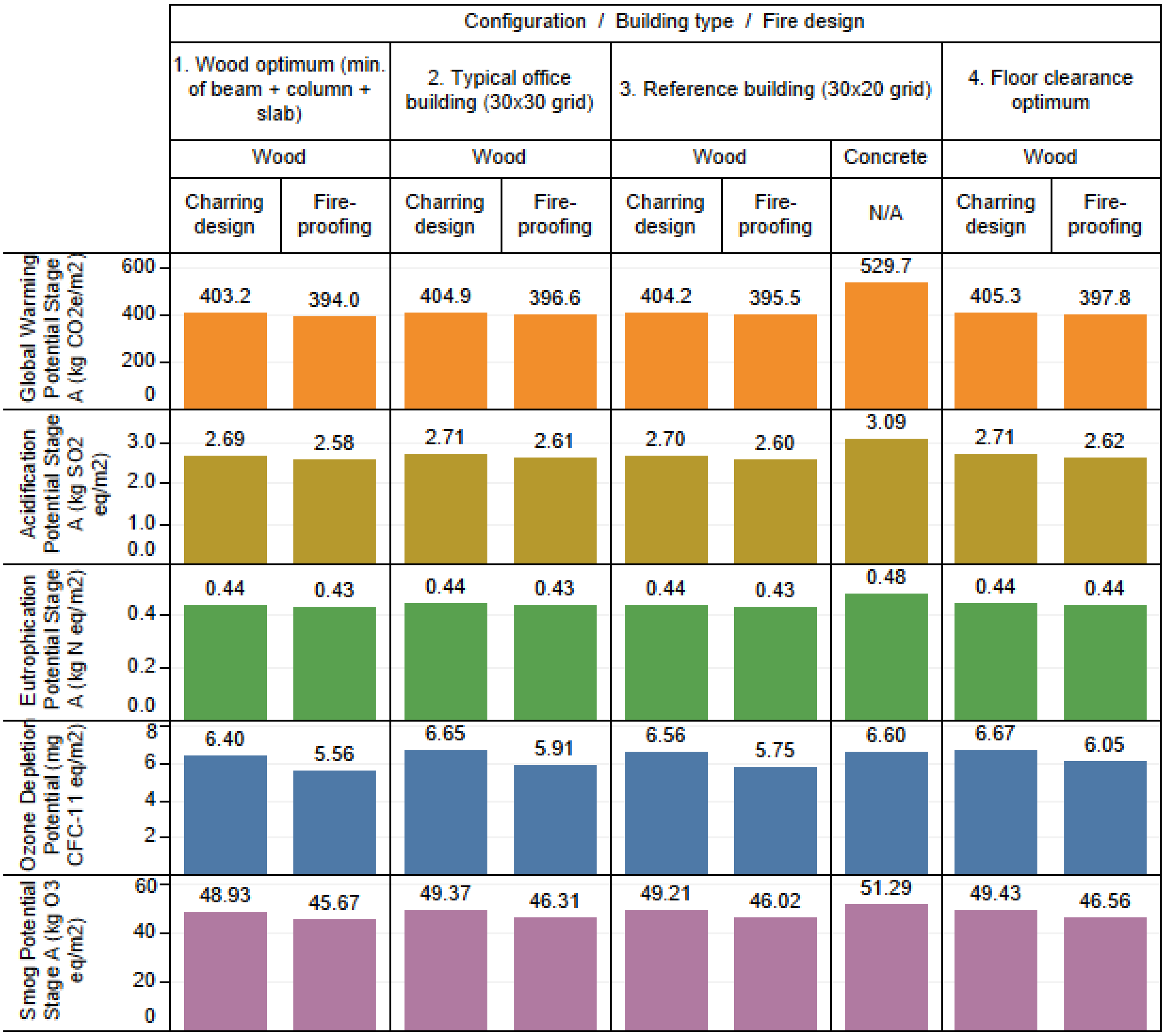


Figure 9. Overall environmental impacts for the eight prototype wood buildings and the concrete baseline building, life cycle stage A (A1 – A5).

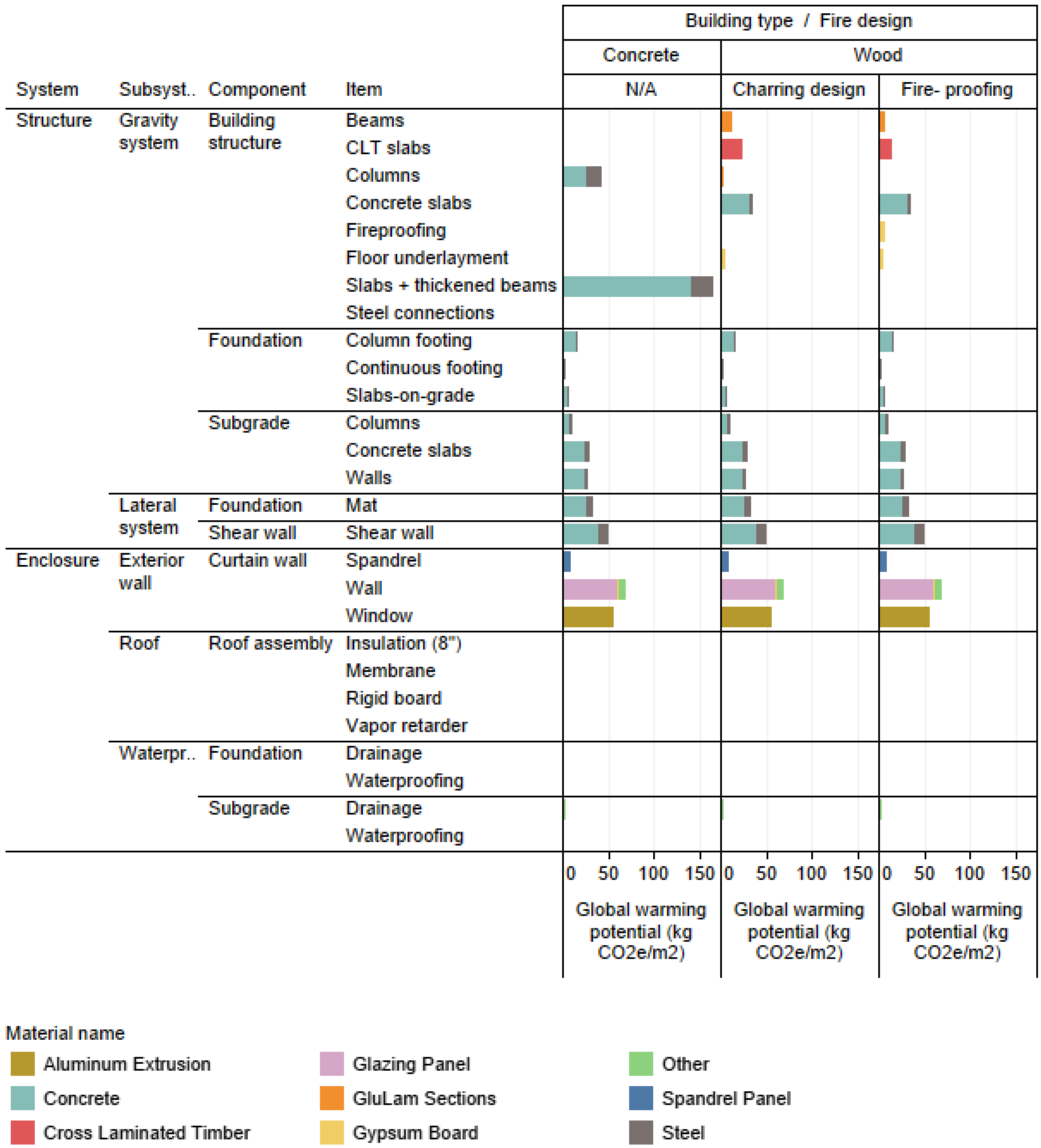


Figure 10. Global warming potential, life cycle stage A (A1 – A5) only, for the baseline concrete building ("Concrete") and the prototype wood building ("Wood") and its two fire protection options, by building system, subsystem, component, and item. Color-coding indicates material contribution to overall global warming potential by the top ten contributing materials, and an "Other" category (comprising the remaining materials).

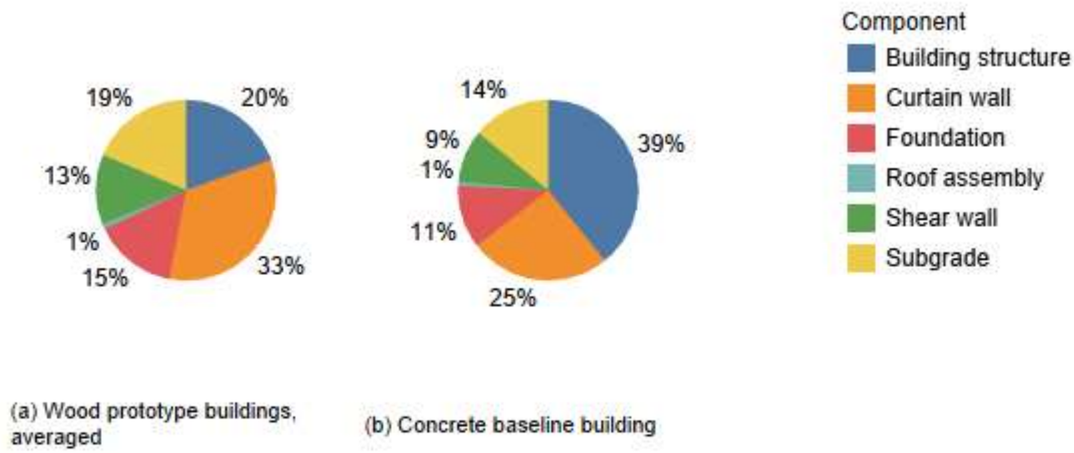


Figure 11. Comparison of the proportion contribution to overall global warming potential, life cycle stage A only, by the major components in (a) the average of the 8 wood prototype buildings, and (b) the concrete baseline building.

7 LIMITATIONS

Listed below are limitations to the results of the study.

Regarding material quantities:

- The prototype/baseline building was not designed to be statistically representative of the typical mid-rise commercial building in the Seattle area, so the material quantities per unit area are not asserted to be statistically representative.
- The wood structural quantities were derived solely from an optimization algorithm, and do not necessarily reflect actual design practice. This level of alignment/exactness was not deemed necessary for the purposes of this study, which was focused more on representing big picture quantities and possible ranges in values.
- The materials used in the prototype/baseline building were limited to the list of available materials from the Athena Impact Estimator Database version 5.1.
- Systems such as mechanical, electrical, and HVAC were not included. Most architectural finishes were also not included.
- The level of detail in the building is very broad, i.e. the building was not modeled in Revit so the material quantity estimates are similarly coarse. Presumably, not all possible materials in the building are listed – just the major items in each component. For example, epoxy was not included as part of the reinforced concrete quantities.
- The prototype building was ‘assembled’, not ‘designed’, so the various components of the prototype building are not integrated by design, i.e. the foundation and shear walls were not designed for the wood building, which is likely to weigh significantly less than the concrete building.

Regarding environmental impacts:

- Environmental impact data was based on the Athena Impact Estimator version 5.1, so the results are not comparable with results based on other databases or life cycle inventories.

- Environmental impact data was limited to life cycle stage A1 – A5. The results do not account for use/operations (stage B), end-of-life (stage C), or beyond building life (stage D), meaning that re-use, recycling, carbon sequestration, or possible incineration were not accounted for
- Results are not regionally specific, therefore the impacts of transportation, on-site construction impacts, or material procurement, etc. are not representative of the Pacific Northwest.
- These results are not meant to make definitive comparative assertions between structural material types, even though Section 6.8 shows that the impacts of the concrete baseline building are greater than that of the wood prototype building, because the full building life cycle was not considered in this assessment. Even if it were included, the end-of-life impacts have significant LCA methodology issues (recycling steel, decomposition of wood) that would need careful resolution. LCA standards require a third party critical review in order for making a comparative assertion that one product or system is preferable to another.

8 DIRECTIONS FOR FUTURE RESEARCH

The research team has identified the following projects to be of significant value for future research.

1. Develop regionally specific LCI data for materials

   The UW School of Environmental and Forest Sciences team is working to develop regionally specific Life Cycle Inventory data for the wood products in order to develop a more refined environmental Life Cycle Assessment of these prototype buildings. Comparing the difference between bottom up LCI data and the data currently available in publically accessible LCA tools will be interesting. Additionally, other LCA impacts and life cycle stages should be evaluated.

2. Develop structural design with professional input

   The structural optimization was developed based upon a parametric model created by a Masters student. The design could also be developed by, or in tandem with, a professional structural engineering firm with greater experience designing and building mass timber buildings. This could result in a single design for the prototype building or a range of potential designs. This would enable more precise checks of member size calculations and would address uncertainty in modeling of elements such as columns and permit the development of prototypical CLT lateral resisting elements (see Section 3).

3. Develop a CLT lateral system

   The designs in this project do not evaluate the potential of CLT shear walls. Preliminary estimates of CLT shear wall design were not developed with sufficient confidence as the technology and methodology were still in development. Current research and practice to implement tall CLT shear walls will soon enable credible preliminary design of CLT walls to be integrated into a similar research project. Of note, the concrete shear walls contribute significantly to the overall building carbon footprint and this is an area for potential additional environmental improvement of tall timber buildings over conventional construction.

4. Develop a competitive floor system

Results from the structural optimization indicate that wood floor systems are very deep (2 – 6 ft, including beam depths), making them uncompetitive to concrete or steel systems. Reducing the overall thickness of the slabs + beams would make a wood-based floor system competitive in the building market, allowing developers to maximize the number of floors and thus the amount of leasable floor space in the building. Floor systems, along with façades, “contribute roughly 75% of the impacts of the building” (Strobel, 2016), if one disregards the concrete components of the building (foundations, subgrade, and concrete shear wall), making floor optimization a point of environmental sustainability as well. Otherwise, zoning height allowances would have to be increased to offset floor-to-floor height increases (Strobel, 2016).

5. <u>Explore the effects of reduced building weight on foundation and lateral system requirements</u>

Wood buildings may be assumed to weigh less than their concrete or steel concrete counterparts, but is this true? If so, the reduced weight of the building may reduce the foundation requirements, and possibly lateral system requirements as well.

6. <u>Develop simplified parametric model for office building LCA studies</u>

The estimates of material quantity data in this report have been normalized per unit of area. This base data could be developed to predict whole building LCA results given a range of building parameters such as building area, stories, ratio of exterior skin to floor area, numbers of underground levels and building energy efficiency as well as LCA parameters such as material impacts, grid emissions and assumptions regarding carbon sequestration of bio based products.

7. <u>Develop statistically representative model for office building construction</u>

A statistical analysis of the existing building stock could be performed to establish the characteristics of a statistically representative reference building could be completed. This would provide additional information needed to define appropriate ‘benchmarks’ by which to compare novel mass timber construction against. A statistical sample of the existing building stock could be defined to establish the characteristics of a statistically representative reference building. This would provide accurate information needed to define appropriate ‘benchmarks’ by which to compare novel mass timber construction against. A statistically representative sample within a broader region or national range would also help our understanding in defining typical building characteristics according to climate, hazard zones and different soil types.

8. <u>Develop a more comprehensive model of office building LCA</u>

Significant components of the buildings environmental impacts are not included in this study, perhaps most critically: the interior finishes and fit outs that occur at relatively frequent cycles; the impacts of the mechanical, electrical and plumbing systems of the building; and the operating energy impacts. The research team suggests expanding the study to include these components to better understand the relative impact the structural system has on the overall building environmental impact.

9. <u>Develop design tools to explore optimization alternatives for mass timber buildings</u>

The emergent literature on mass timber structure optimization in buildings show the implementation of different techniques to explore alternatives for reducing overall wood quantities. Some of these techniques include multicriteria decision making, optimization matrix, simulated annealing, scenario planning, and genetic algorithms. With increasing empirical data related to building structures and environmental impacts in the future, new tools will be needed to assist designers in sorting the different variables that may reduce mass timber sections.

9 ACKNOWLEDGMENTS

We would like to thank the United States Department of Agriculture for supporting this work through the McIntire-Stennis Research Grant. We would also like to thank members of the Carbon Leadership Forum for their input and assistance with our material quantity estimates.

10 REFERENCES

(2004). *EN 1995-1-1:2004, Eurocode 5, Design of timber structures. Part 1-1: General -Common rules and rules for buildings.* Standard.

Armand Decker, S., Ndiaye, A., Brangeon, B., Sempey, A., Galimard, P., Pauly, M., . . . Bos, F. (2014). Design of Multi Story Timber Building Using Multi-Objective Particle Swarm Optimization. *World Conference on Timber Engineering 2014.* Quebec.

BizJournals. (2016, January 19). Retrieved March 21, 2016, from http://www.bizjournals.com/twincities/blog/real_estate/2016/01/hines-woodent3-office-building-starts-seeing.html

Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., & Thiel, A. (2016). Cross laminated timber (CLT): overview and development. *Eur. J. Wood Prod.*, 331–351.

BSLC. (2014). *Summary Report: Survey of International Tall Wood Buildings.* Surrey: Binational Softwood Lumber Council.

Corgnati, S., Fabrizio, E., Filippi, M., & Monetti, V. (2013). Reference buildings for cost optimal analysis: Method of definition and application. *Applied Energy*, 983-993.

DGNB. (2014). *DGNB System Reference Book.* DGNB.

EeB Guide. (2012, October 23). *EeB Guide Project*. Retrieved November 21, 2015, from http://www.eebguide.eu/?p=1739

EIA. (2012). *Commercial Buildings Energy Consumption Survey*. Retrieved from U.S. Energy Information Administration, Independent Statistics and Analysis: http://www.eia.gov/consumption/commercial/

Eurocode. (2004). *EN 1995-1-1:2004, Eurocode 5, Design of timber structures. Part 1-1: General -Common rules and rules for buildings.* Standard.

Grann, B. (2014). *Wood Innovation and Design Centre Building Life Cycle Assessment.* Vancouver: FP Innovations.

Hovhannisyan, M. (2015). *Wood Cityscapes: Mass Timber Office Building.* Seattle: University of Washington.

ILFI. (2014). *International Living Future Institute.* Retrieved October 15, 2015, from Documentation Requiremens: https://living-future.org/sites/default/files/reports/14-0828%20v3.0%20Doc%20Reqs%20-FINAL%2Bcover.pdf

Initiative, G. B. . (2013). *Green Globes for New Construction Technical Manual.* Portland: Green Building Initiative, Inc.

ISO. (2006). *14044 (2006) Environmental management—life cycle assessment.* Geneva, Switzerland: ISO.

ISO. (2006). *ISO 14040:2006 Environmental Management – Life Cycle Assessment – Principles and framework," vol. 2006. .* Geneva, Switzerland: International Organization for Standarization .

ISO. (2007). *Sustainability in building construction -- Environmental declaration of building products.* Geneva: International Standard Organization.

Kaziolas, D., Bekas, G., Zygomalas, I., & Stavroulakis, G. (2015). Life Cycle Analysis and Optimization of a Timber Building. *Energy Procedia*, 41-49.

Lucuik, M. (2014, March 28). *LEED V4 LCA Credit and Case Study.* Retrieved November 15, 2015, from Canadian Wood Council: http://cwc.ca/wp-content/uploads/2013/11/LEED-Case-Study.pdf

Seattle Gov. (2012, October 21). Retrieved November 2, 2015, from http://www.seattle.gov/DPD/codesrules/changestocode/crosslaminatedtimber/whatwhy/

Simonen, K., Rodriguez, B., Barrera, S., Huang, M., McDade, E., & Strain, L. (2017). *Embodied Benchmark Project: LCA for Low Carbon Construction.* Retrieved from http://hdl.handle.net/1773/38017

Strobel, K., & Simonen, K. (2016). *(Mass) timber : Structurally optimized timber buildings.* Seattle: University of Washington.

Timber Design and Technology. (2015). Retrieved November 23, 2015, from http://www.timberdesignandtechnology.com/treet-the-tallest-timber-framed-building-in-the-world/

Torcellini, P., Deru, M., Griffith, B., & Benne, K. (2008). DOE Commercial Building. *ACEEE Summer Study on Energy Efficiency in Buildings* (pp. NREL/CP-550-43291). Pacific Grove: NREL.

USGBC. (2014). *LEED V4 for building design and construction.* Washington, DC: US Green Building Council.

Winter, W., Weber, G., Hernandez, S., & Brigola, B. (2012). Strategies to increase the use of timber in multey story buildings-Case studies. *World Conference on Timber Engineering.* Auckland.

Comparing Student LCA Reports

This report compares a number of case studies prepared by students for the final project in a Life Cycle Assessment course at the University of Washington. Though these are screening level studies created by individuals with a nascent understanding of building construction and the science behind LCA, there are trends among them that point to some valuable lessons. With these patterns in mind, the goal of this report is to highlight some of the difficulties of screening level studies, and to investigate the limitations of the requirements for LEED Whole Building Life-Cycle Assessment credits.

The course, taught by professor Kathrina Simonen in the College of Built Environments at the University of Washington, focuses on the life cycle of buildings. The final project of the course gives students an opportunity to conduct a screening level LCA in order to reinforce knowledge of the LCA process. Specifically, the assignment challenges students to model a reference building and a proposed building with a single, significant modification of the baseline. Models for this assignment were created using Athena Impact Estimator for Buildings, and students were asked to include the results and interpretations of those results in their reports. Engineered timber products were a central theme of the course, so while students choose a variety of modifications, many of the case studies revolve around the substitution of timber for steel or concrete.

One of the goals of this report is to identify some common pitfalls of modeling a building for an LCA, and to explore possible solutions. It should be noted that students enrolled in the course had no previous knowledge of the LCA process, and the depth and accuracy of their studies is bounded by the complexity of modeling in Athena paired with the students' limited knowledge of building systems.

The other goal of this paper is to highlight the somewhat arbitrary and exclusionary nature of requirements for the Whole Building Life-Cycle Assessment credits as outlined in the LEED version 4 guidelines. LEED version 4 states that in order to receive three points for conducting an LCA on a new building, the proposed building must demonstrate a "minimum of 10% reduction, compared with a reference building, in at least three of the six impact measures listed below, one of which must be global warming potential. No impact category assessed as part of the life-cycle assessment may increase by more than 5% compared with the reference building."[1]

The impact measures that fall into the scope of LEED's LCA credit are global warming potential, depletion of the stratospheric ozone layer, acidification of land and water sources, eutrophication, formation of tropospheric ozone (or smog), and depletion of nonrenewable energy resources. Under the current LEED guidelines each of the impact measures are treated with equal importance despite the fact that certain measures are of greater urgency than others. For example, though stratospheric ozone depletion once posed an imminent threat, global efforts, formalized in the 1987 Montreal Protocol banned the production of halons and CFCs. Due to these efforts, natural ozone production is projected to heal the ozone layer in the next 50 years.[2] (http://www.epa.gov/ozone/science/sc_fact.html) Meanwhile, the production and release of CO_2 continues to warm the globe and pose a threat to life on earth. To address the relative importance of these factors, efforts have been made to normalize the impact measures. Figure xx shows normalization factors that have been assigned to each impact measure.

The table further illustrates that all measures should not be judged equally. A number of the included case studies show substantial reductions in a number of impact measures, but fail to qualify for the lead credits, because of an increase in a single measure. For this reason, LEED should reevaluate the requirements for the whole building LCA credit.

Goal

The following baseline buildings were developed through a student survey of commercial buildings currently under construction in Portland, Seattle, Tacoma, and Bellevue:

Baseline A1_5/9

5/9 Story Shell & Core Office Building

Overall Dimensions: 100’ x 200’

Structural Grid: 28 Columns on a 33’ x 33’ grid

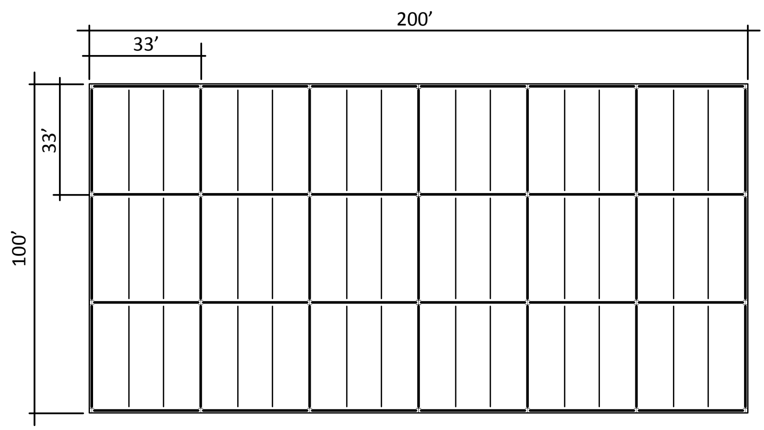
Concrete Option: Post Tension 12” flat slab, concrete columns, and concrete shear walls.

Steel Option: Composite concrete deck, steel wide flange beams, steel wide flange girders, steel wide flange columns, and steel braced frames.

Cladding: Metal stud and brick wall assembly, with R-18 insulation.

Glazing: 40% glazing to wall ration, with aluminium frames.

Roof: EPDM with R-39 insulation.



Baseline A2_5

5 Story Shell & Core Office Building

Overall Dimensions: 100’ x 200’

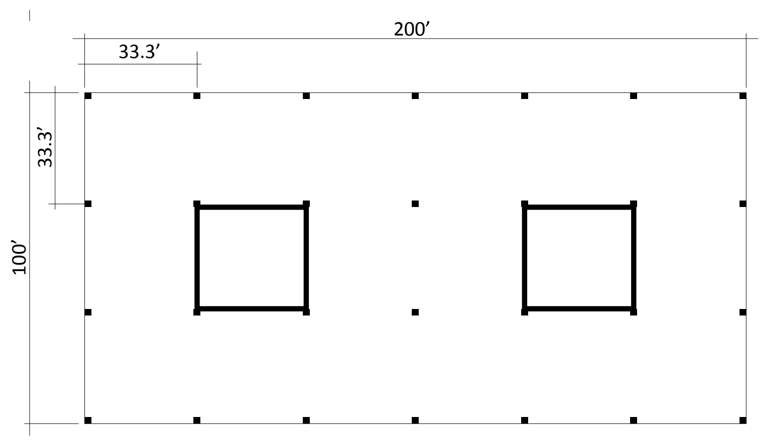
Structural Grid: 36 Columns on a 26’ x 33’ grid

Steel Structure: Composite concrete deck, steel wide flange beams, steel wide flange girders, steel wide flange columns, and steel braced frames.

Cladding: Metal stud and brick wall assembly, with R-18 insulation.

Glazing: 40% glazing to wall ration, with aluminium frames.

Roof: EPDM with R-39 insulation.



Baseline B_5

5 Story Shell & Core Office Building

Overall Dimensions: 150’ x 300’

Structural Grid: 25’ x 45’ & 25’ x 30’

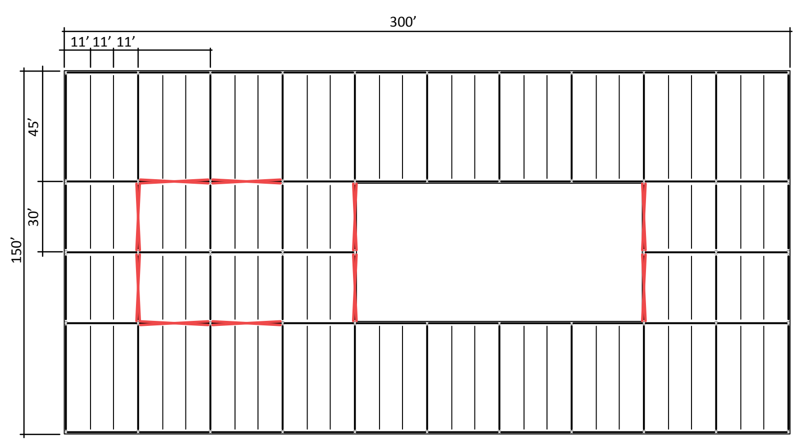
Concrete Option: Post Tension 12” flat slab, concrete columns, and concrete shear walls.

Steel Option: Composite concrete deck, steel wide flange beams, steel wide flange girders, steel wide flange columns, and steel braced frames.

Cladding: Metal stud and brick wall assembly, with R-18 insulation.

Glazing: 40% glazing to wall ration, with aluminium frames.

Roof: EPDM with R-39 insulation.



Reference Buildings

Students selected a reference building and developed a model in Athena Impact Estimator for Buildings. To produce a working model, students included the lifespan of the building, the project's location, and the type of building. These parameters along with the building's constituent assemblies give Athena the inputs necessary to generate materials and impacts reports. Table xx shows what is included in the scope of Athena's analysis. Nearly all students elected to study in life cycle stages A-D.

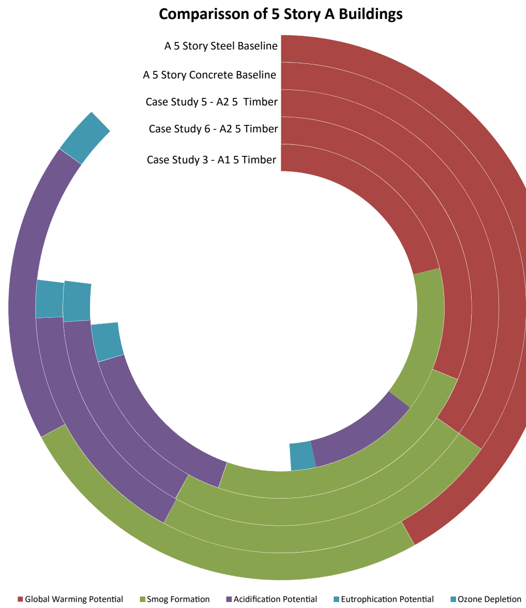
Stage	Included (green)			Omitted (red)			
PRODUCT (A1 to A3)	Raw Material Supply	Transportation	Manufacturing `	Forest Ecology	Resource Managment	Human Health	Employee Transit
CONSTRUCTION PROCESS (A4 & A5)	Construction & Installation	Transportation		Site Work	Human Health	Employee Transit	
USE (B2, B4 & B6)	Use	Maintenance & Repair	Replacement & Refurbishment	Operational Energy use	Operational Water Use	Employee Transit	
END OF LIFE (C1 to C4)	Deconstruction & Demo	Transport	Disposal	Waste Processing?			
BEYOND BUILDING LIFE (D)	Reuse(ability) of product?			Leaching & Off-gassing?			

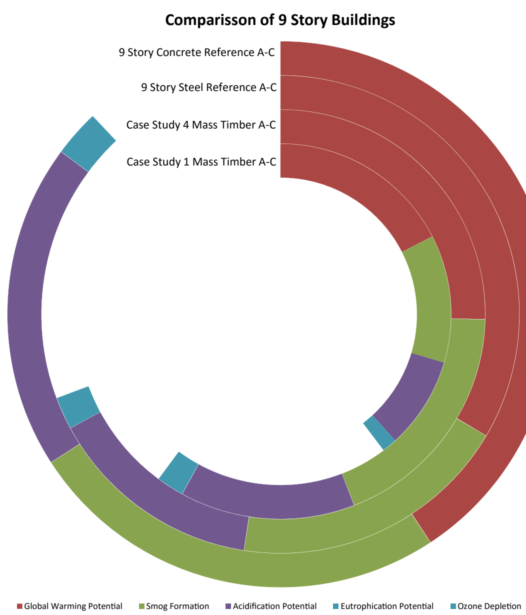
Table 0.3 - The above table outlines the scope of what Athena covers. Items in green are included in each analysis and item in red are omitted.

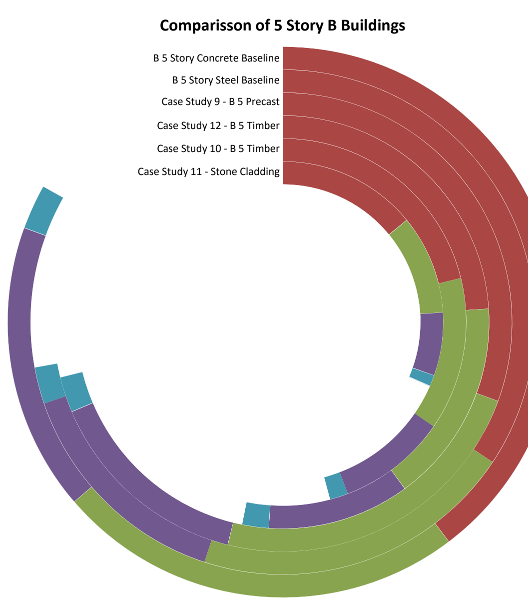
The studies are alike in their basic methodology as well as their limitations. None of the studies included a comparison of operational energy. This could be a significant factor in a number of studies. For example , in study x the student studied the impact of an increase in building density. One potential benefit of increased density is the ability to centralize building systems for a greater number of tenants or units. Knowledge or inclusion of operational energy in the report could have strengthened the argument. Athena does not account for changes in dead load when it calculates the bill of materials. This would be a limiting factor in many of the studies that involved the transformation of structural systems. For example, changing from a steel and concrete decking system to a mass timber system would likely decrease the live load, which would result in smaller supporting members. Since Athena does not account for this change, it is possible that an automatically generated bill of materials would be inaccurate. Similarly, the foundation needed to support each building would differ depending on the structural system, however, a the same reference foundation is used in each of the case studies.

Another category of limitations stems from the location of the studies. While Athena uses location information to calculate the fuel used to transport raw materials and products, it does not account for the relative importance of impact measures based on region. For example eutrophication may not be an existing problem in a particular region, so higher eutrophication levels may be a reasonable trade off for lower carbon emissions. Similarly, Athena does not account for secondary impacts of material harvesting such as deforestation or denuded landscapes. Many of these studies look at substituting timber for concrete or steel, but none of them include forestry, mining practices, or resource management in their scope.

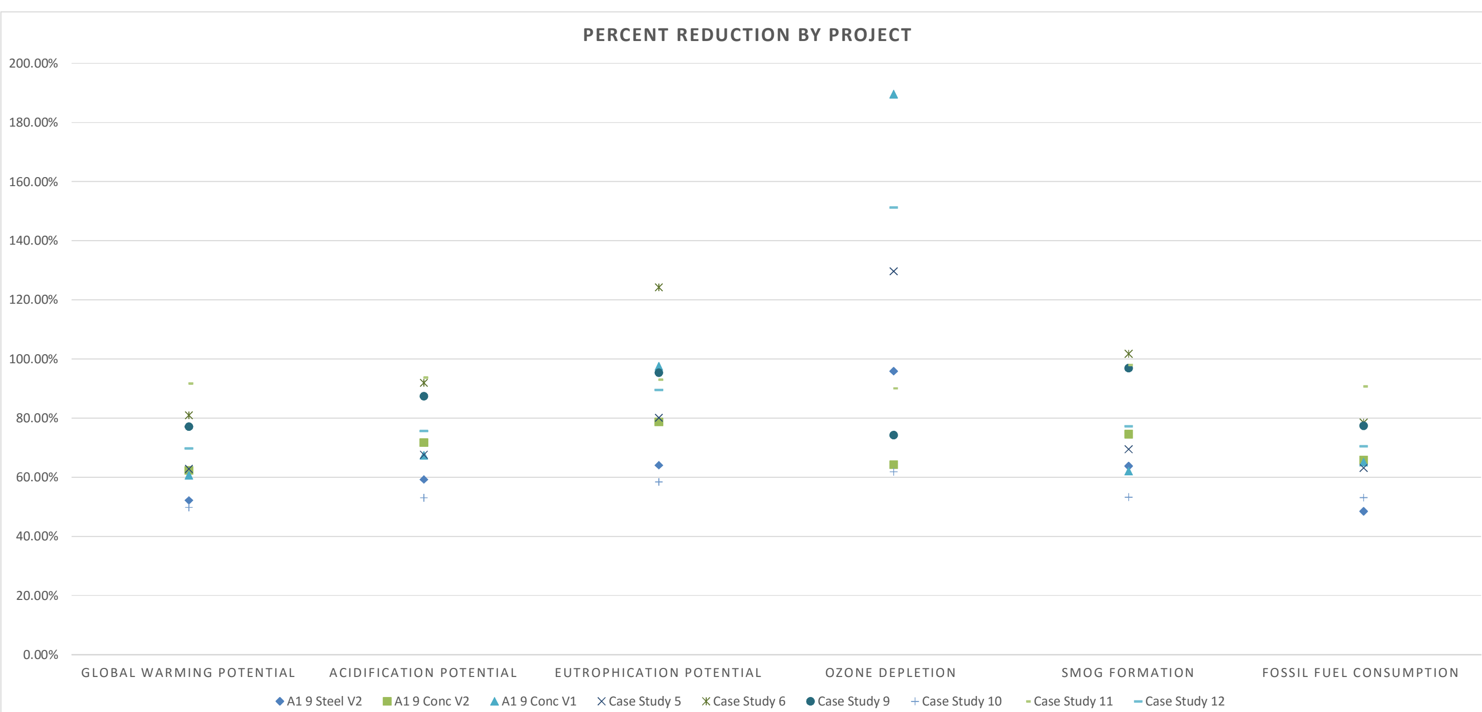
Methodology and Limitations







Methodology and Limitations



Methodology and Limitations

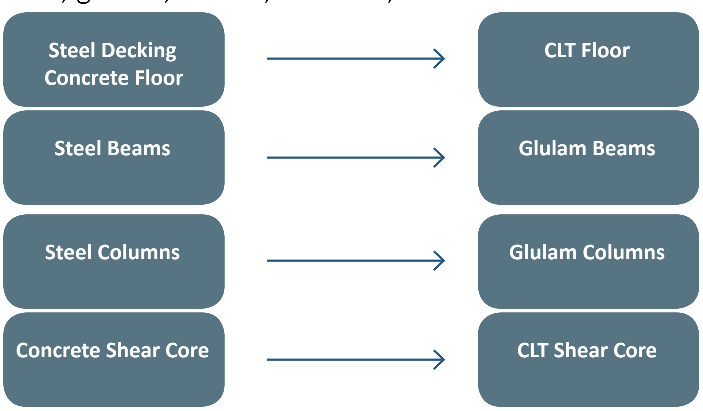
Case Study 1: Substitution of Mass Timber for Steel and Concrete in the Structural System of a 9-Story, Steel, Commercial Building.

Goal

The intended use of this LCA study is to compare the structural materials of a 9 story steel frame structure with concrete post tension slab floors (Baseline Building) with a mass timber structural alternative. The proposed mass timber model is adapted from a design developed by SOM architects, and uses a concrete link beam around the perimeter, with CLT shear walls surrounding the central core for lateral support. The results of this study are intended to be shared with colleagues and to understand the impact of using alternative methods of construction such as CLT and glulam.

Scope

The functional unit for this study is the structural system for a mid rise commercial building with a lifespan of 60 years. The structural system includes the floor, girders, beams, columns, and a shear core.



This study involves the modification of the Reference Building's structural system. The composite floor system, comprised of metal decking and a 3" topping slab, is replaced by CLT panels; the wide-flange beams and columns are replaced by glulam; and the concrete shear core is replaced by a CLT alternative. Additionally, the reference building's metal curtain wall and brick cladding are replaced by light wood framing and 2" insulated metal paneling.

Several limitations to this study were identified. Athena does not have a preset CLT assembly, and because many materials were added manually as extra materials, a project comparison by assembly group is not possible. Additionally, the software does not adjust the size of structural members when there is a change in dead load. In this case, changing from a steel system to a CLT system would decrease the dead load from the slab, which would lead to a reduction of column size and ultimately the size of the foundation.

Inventory

Table 1.1 shows the material inventory for the steel reference building and the proposed mass timber alternative, and highlights the key material differences between the two buildings. While many of the material quantities remain constant between the two models, the mass timber proposal shows a 56% decrease, or about 10,351 short tons, in the total amount of concrete. Additionally, the proposed building model shows a 58% decrease, or about 1,683 short tons, in the total amount of steel. Conversely, the proposed building, with it's mass timber structure, requires 277 short tons of engineered timber products that are not present in the steel structure.

To put that in perspective, the steel reference building would require the equivalent mass of 739,385 cinder blocks of concrete, and 1,403 cars worth of steel, more than the proposed building, while the proposed building would require the equivalent timber mass of 2,806 utility poles.

Material	Reference	Proposed	Difference	Units
1/2" Gypsum Fibre Gypsum Board	57.8399	42.2438	15.5961	Tons
2" Insulated Metal Panel	92.3097	92.3097	0	Tons
5/8" Gypsum Fibre Gypsum Board	31.4786	0	31.4786	Tons
6 mil Polyethylene	1.0723	1.0604	0.0119	Tons
8" Concrete Block	789.9759	0	789.9759	Tons
Air Barrier	0.3039	0.3039	0	Tons
Aluminum	0.17	0	0.17	Tons
Aluminum Window Frame	13.1166	13.1166	0	Tons
Ballast (aggregate stone)	406.6617	0	406.6617	Tons
Cross Laminated Timber	0	178.7461	-178.7461	Tons
Concrete 20 MPa (flyash av)	6966.0684	3358.95	3607.1184	Tons
Concrete 30 MPa (flyash 25%)	9258.4319	4725	4533.4319	Tons
Double Glazed No Coating Air	183.572	183.572	0	Tons
EPDM membrane (black, 60 mil)	12.6323	12.6323	0	Tons
FG Batt R11-15	7.3965	7.3965	0	Tons
FG Batt R20	7.8329	7.8329	0	Tons
Galvanized Decking	263.083	0	263.083	Tons
Galvanized Sheet	0.0887	0	0.0887	Tons
Galvanized Studs	25.0467	0	25.0467	Tons
Glulam Sections	0	13.0206	-13.0206	Tons
Glazing Panel	0.3353	0.3353	0	Tons
Hollow Structural Steel	52.487	0	52.487	Tons
Joint Compound	7.3981	0	7.3981	Tons
Laminated Veneer Lumber	0	0.0801	-0.0801	Tons
Mortar	1014.2102	0	1014.2102	Tons
Nails	0.3793	0.8388	-0.4595	Tons
Oriented Strand Board	0	39.5895	-39.5895	Tons
Paper Tape	0.0849	0.0849	0	Tons
Polyester felt	1.9489	0	1.9489	Tons
Polyethylene Filter Fabric	0.4162	0	0.4162	Tons
Rebar, Rod, Light Sections	1595.4196	252.5	1342.9196	Tons
Screws Nuts & Bolts	10.4676	6.695	3.7726	Tons
Small Dimension Softwood Lumber	0	45.5	-45.5	Tons
Water Based Latex Paint	4.9994	0	4.9994	Tons
Wide Flange Sections	966.1077	0	966.1077	Tons

Table 1.1 - Bill of materials comparison for two buildings.

Impact Assessment

Charts 1.1 and 1.2 show the relative impacts of each building model. Both charts show a decrease in each of the impact categories, and a decrease of greater than 35% in five of six measured impacts, more than meeting the requirements for the LEED Whole Building Life Cycle Assessment credits. Charts 1.3 and 1.4 illustrate that when the different impact measures are normalized, the most significant of the impacts, Global Warming Potential, Fossil Fuel Consumption , and Smog Formation Potential, are ozone depletion are among the most significant reductions. Meanwhile, Ozone Depletion, the impact measure with the lowest normalization and weighting factor, is the one category with modest reductions.

Interpretation and Conclusion

It seems clear that using mass timber in the place of steel and concrete in the structural system of a medium-rise commercial building, can considerably reduce the impacts of the building's construction, life, and afterlife. The results of this study could be more encouraging yet, if the study itself were more rigorous. Because the design of the proposed building is adapted from a unique building solution, it would be helpful to have a digital model explaining exactly what was modeled in Athena. Additionally, this study took on a several parts of a building and in doing so created more room for error and less clarity in which system is responsible for the greatest changes in impact. It would be good to see the study broken down into smaller pieces.

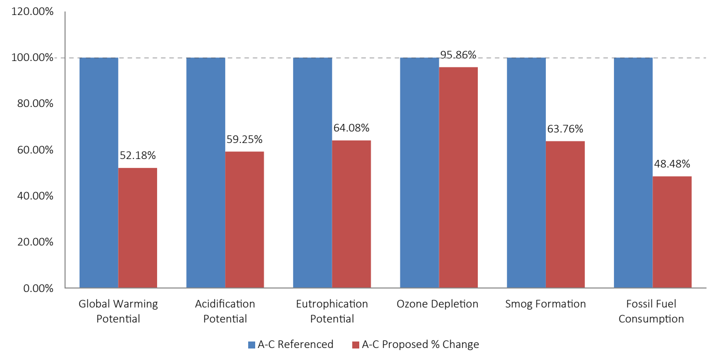


Chart 5.1 - Life cycle stages A-C impact measure comparisson for referenced and proposed buildings.

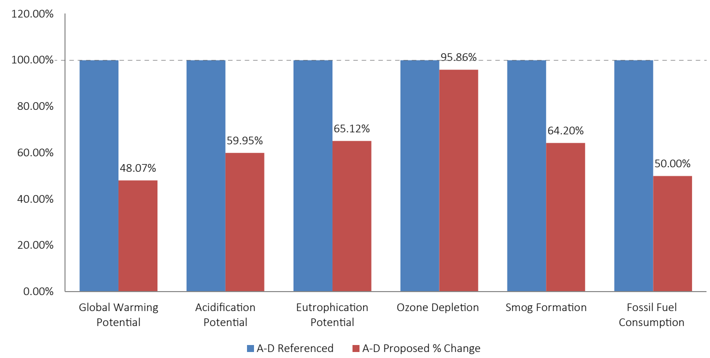


Chart 5.2 - Life cycle stages A-D impact measure comparisson for referenced and proposed buildings.

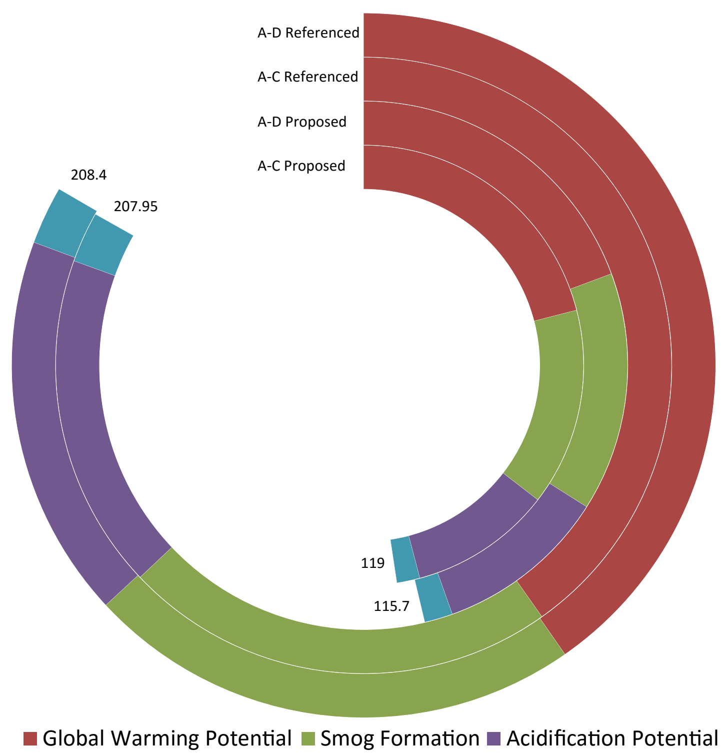


Chart 12.3 - Impact measures are normalized to reflect the number of units per person, per year in the United States, and weighted to reflect the importance of each measure. The chart shows the significance of the reduction of GWP, Smog, and Acidification, the relatively minor contribution of Eutrophition and Ozone Depletion.

Case Study 2: Exploring the Effects of Increased Density: LCA comparison of a 5-Story and 7-Story, Commercial Building.

Goal

The goal of this study is to compare the impact of a 5 story office building to that of a 7 story building, in order to determine if increasing density decreases environmental impact per square foot of leasable space. A further goal of this study is to develop an understanding of how to add density to urban areas with minimal environmental impacts, and looking for an optimal building type.

Scope

The Functional unit is defined as 1 square foot of leasable space in a mid rise office building is Seattle, WA, with sufficient structure to carry a 150 lb. live load and a life span of 60 years.

This study involves the addition of two floors to the Reference Building. The additional floors are identical to those included in the baseline model, and the remainder of the model, including the foundation, remains constant.

There are several factors which limit the scope and accuracy of this study. This study does not include the operational energy of the baseline or Proposed Buildings. This is problematic, because much of the efficiency of adding two stories to a building rather than making a separate structure can be found in having centralized building systems. Similarly, Athena does not account for the energy used by or the impacts of excavation or site work. The weight of the extra floors has not been accounted for in the structural system or in the foundation of the proposed building model.

Inventory

Table 2.1 shows the material inventory for the 5 story reference building and the proposed 7 story alternative, and highlights the key material differences between the two buildings. While many of the material quantities remain constant between the two models, the 7 story building shows a 693 ton or 4 % increase in the amount of concrete, and a 150 ton or 12% increase in rebar used in the two story addition. To put that in perspective, the 7 story building would require the equivalent mass of 25,264 cinder blocks of extra concrete, and 125 cars worth of additional steel.

Material	Unit	5 Story	7 Story	Increase
Aluminum Clad Wood Window Frame	lbs	100.0	100.0	0 lbs
Concrete 20 MPa (flyash av)	yd3	7022.1	7022.1	0 yd3
Concrete 30 MPa (flyash av)	yd3	1414.9	1768.6	353.7134 yd3
EPDM membrane (black, 60 mil)	lbs	1626.3	1626.3	0 lbs
FG LF Open Blow R31-40	sf (1")	21000.0	21000.0	0 sf (1")
Galvanized Studs	Tons (short)	15.2	15.2	0 Tons (short)
Glazing Panel	Tons (short)	356.4	356.4	0 Tons (short)
Ontario (Standard) Brick	sf	31710.0	31710.0	0 sf
Precast Concrete	yd3	2836.9	2836.9	0 yd3
Rebar, Rod, Light Sections	Tons (short)	1065.7	1216.0	150.377 Tons (short)
Welded Wire Mesh / Ladder Wire	Tons (short)	31.3	31.3	0 Tons (short)

Table 2.1 - The material inventory for the two projects.

Impact Assessment

Chart 2.1 shows the increase in each of the impact measures for the proposed 7-story building. The additional two floors of the building add a total of xxxx ft^2 or a 40% of leasable floor space, while all of the impact measures stay below a 20 % increase. Additionally the two most significant factors, Global Warming Potential and Fossil Fuel Consumption, see a modest 11% and 10% increase respectively.

Interpretation and Conclusion

The results of the study point towards greater density leading to greater efficiency. There are a couple of initial clues that point to these results. The reference building is only 5 stories, and it has a three story foundation. So, when 2 stories are added and the foundation remains a constant, the 2 additional stories account for a relatively small portion of the building. Additionally, the roof also remains unchanged. Though there would be differences in the foundations of the Reference and Proposed buildings, there would likely be energy saved by only performing excavation at one site and building a single foundation.

These findings may be obvious, and to really understand the impact of adding density, it would be helpful to conduct further studies. Is there a point where additional structure and services for a tall building, and its construction and material impacts more than account for the benefit of the added floor space? It would be good to see multiple studies comparing proposed buildings at various heights with properly modified foundations. To study this issue further, it would be interesting to conduct a "density LCA" and chart the possible impacts of building up a small district. An area of a few blocks could be modeled as 1 story houses, 2 story apartments, and 5 and 7 story apartments. This study could look at differences in impacts per square foot for urban housing. It could also include considerations about lifestyle, by modeling Residents transit habits as well as building energy uses.

Additionally, in order to build confidence in this study, it would be useful to create a more rigorous models that accounts for additional structure and foundation work. Specifically, it would be helpful to see the reference building modeled as two separate buildings, one at 5 stories and the other at 2 stories, to greater understand the savings of building a single foundation and roof.

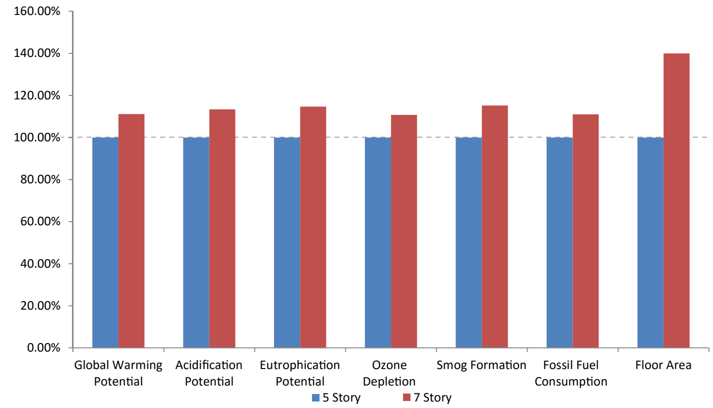


Chart 2.1 - Life cycle stages A-C impact measure comparisson for referenced and proposed buildings.

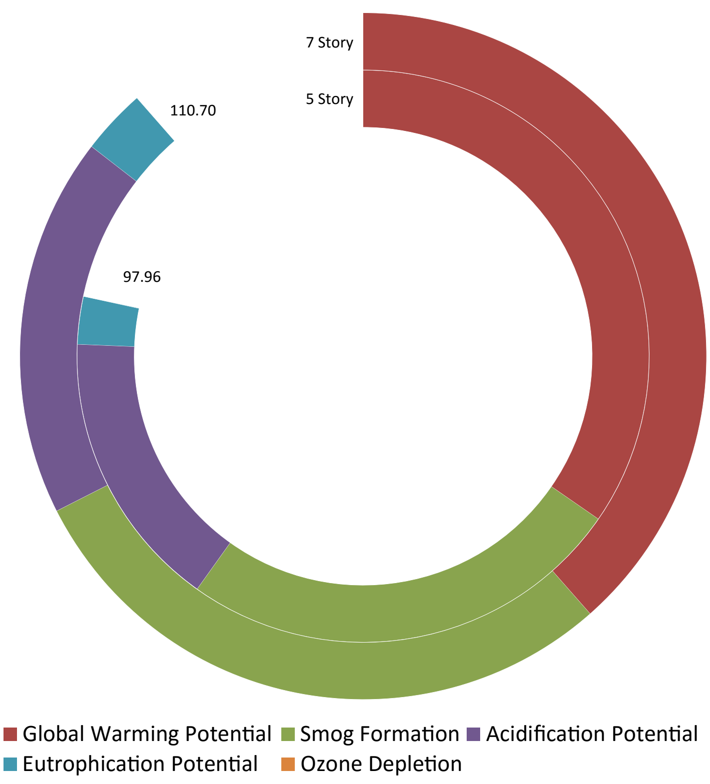


Chart 12.3 - Impact measures are normalized to reflect the number of units per person, per year in the United States, and weighted to reflect the importance of each measure. The chart shows the significance of the reduction of GWP, Smog, and Acidification, the relatively minor contribution of Eutrophition and Ozone Depletion.

Case Study 3: Substitution of a Glulam Floor System for Post Tension Concrete Slab in a 5-Story, Commercial Building.

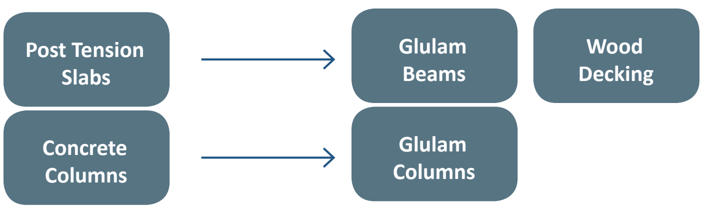
Goal

The goal of this project is to understand the environmental impact of changing a building's structural system to heavy timber, and to identify whic life cycle stages they have the greatest impact.

Scope

The functional unit for this study is a five-story office building, with a 70% glazed curtain wall, a column grid of 33' x 33', structure sufficient to carry a 150 lb. live load, and a life span of 60 years.

This study involves the modification of the Reference Building's structural system. The post tension slab is replaced by wood decking which is supported by glulam beams and girders, and the concrete columns are replaced by glulam columns. This modification is consistent throughout all five floors of the office building, while the foundation and the three levels below ground remain unchanged.



Several limitations of this study's scope were identified. Because the proposed building does not have a topping slab on the wood decking, the flooring systems are not actually functionally equivilant. Athena does not account for the energy required to excavate for a building foundation. Additionally, the software does not adjust the size of structural members when there is a change in dead load. In this case, changing from a concrete slab to a mass timber alternative would decrease the dead load from the floor system, which would lead to a reduction of column size, and ultimately the size of the foundation. Another important consideration is the exclusion of operational energy. Again, because the purpose of the study is to compare concrete and mass timber, this will be disregarded.

Inventory

Table 3.1 shows the material inventory for the concrete reference building and the proposed mass timber alternative, and highlights the key material differences between the two buildings. While many of the material quantities remain constant between the two models, the mass timber proposal shows a 72% decrease, or about 10,154 short tons, in the total amount of concrete, and a 32 %, or 208 ton decrease in steel used in construction. Conversely, the proposed building, with it's glulam structure and wood decking, requires 573 tons of timber products that are not present in the concrete structure.

Material	Reference	Proposed	Difference	Units
8" Concrete Block	245.76	222.9	22.86	Tons
Aluminum	0.2266	0.2266	0	Tons
Concrete 20 MPa (flyash av)	12224.7	2007.6	10217.1	Tons
Concrete 30 MPa (flyash av)	1711.8	1774	-62.2	Tons
Fiberglass Window Frame	5.5	4.98	0.52	Tons
Glazing Panel	0.44	0.4	0.04	Tons
GluLam Sections	0	245.5	-245.5	Tons
Mortar	52.9	48	4.9	Tons
Nails	0.0173	2.8	-2.7827	Tons
Precast Panels	386.6	350	36.6	Tons
Rebar, Rod, Light Sections	634.6	426	208.6	Tons
Small Dimension Softwood Lumber, kiln-dried	0	327.5	-327.5	Tons
Triple Glazed Hard Coated Air	38.5	34.96	3.54	Tons
Welded Wire Mesh / Ladder Wire	1.85	1.67	0.18	Tons

Table 3.1 - Bill of materials generated by Athena.

To put that in perspective, the concrete reference building would require the equivalent mass of 725,285 extra cinder blocks of extra concrete, and 173 cars of additional steel. Conversely, the proposed building would require the equivalent timber mass of 955 utility poles.

Impact Assessment

Charts 3.1 and 3.2 show the relative impacts of each building model. Both charts show a greater than 30% reduction in four of the impact categories, more than meeting the first requirement for the LEED Whole Building Life Cycle Assessment credits. The second requirement however, states that no single impact category can have a greater than 5% increase. With stratospheric ozone depletion increasing so dramatically, this study would not qualify for the lead credit. Chart 3.3 shows the impact measures after they have each been normalized and weighte. LEED's LCA criteria treate each impact category equally, however, chart 3.3 illustrates that each impact measure has a different signicance. Though ozone depleteion increased significantly from the reference building to the proposed building, It is clear that compared with the other impact measures, ozone depletion is of

Reference Building
A1 5 Story Concrete

Proposed Building
5 Story Glulam

minor significance. This is important, because design decisions could potentially hindge on the fulfillment of a LEED requirement, and in this case significant benefits could be disregaurded for the sake of ozone depletion, an issue of relatively minor concern.

Interpretation and Conclusion

The data produced during this study indicates that using mass timber in the place of concrete in the structural system of a medium-rise commercial building, can considerably reduce the impacts of the building's construction, life, and afterlife. The results of this study would be more conclusive with further investigation. Of all the case studies, this particular model produced one of the largest increases in Stratospheric Ozone Depletion, and there is no clear cause of that increase. Further modeling, or the substitution of other building assemblies could reveal the culprit of this uncharacteristic increase.

Additonally, this studies bill of materials reveals that the building modeled in Athena is likely inaccurate and missing components. A digital model of the building as a visual aid, could provide more confidence in the the models assembled in Athena.

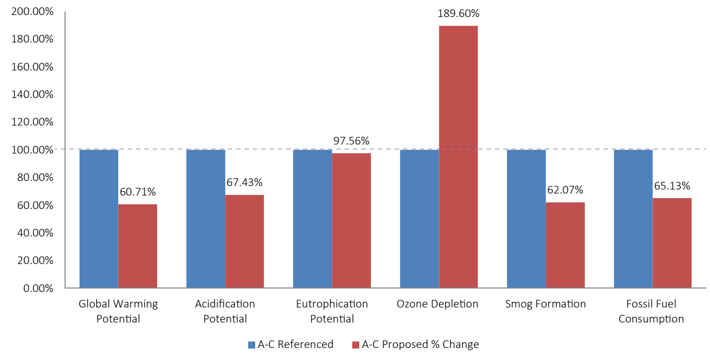


Chart 3.1 - Life cycle stages A-C impact measure comparisson for referenced and proposed buildings.

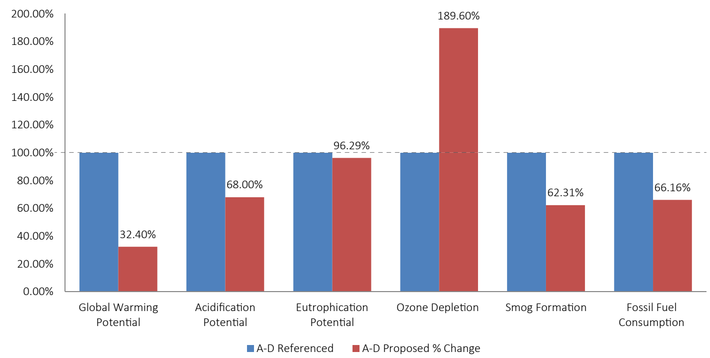


Chart 3.2 - Life cycle stages A-D impact measure comparisson for referenced and proposed buildings.

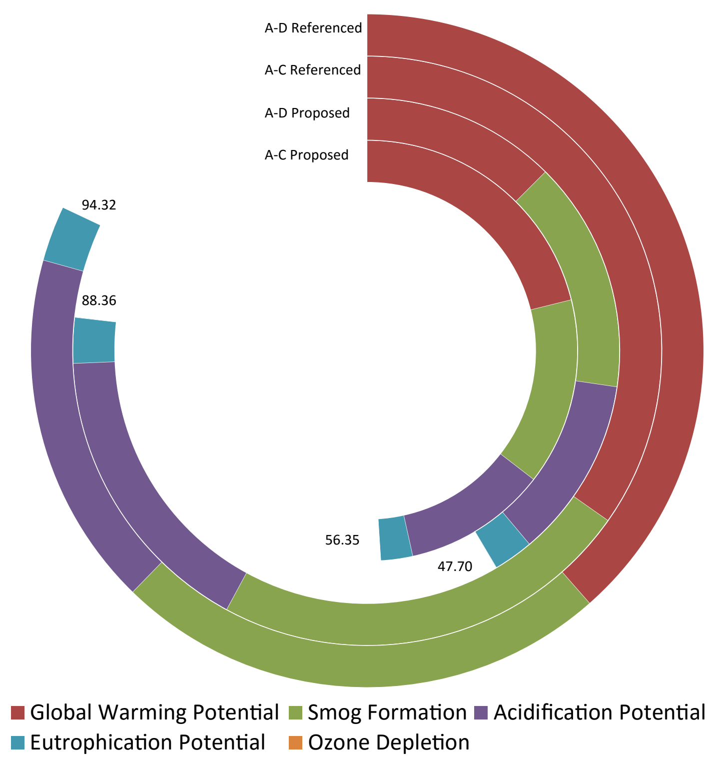
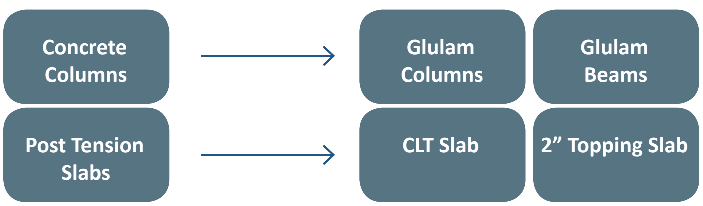


Chart 3.3 - Impact measures are normalized to reflect the number of units per person, per year in the United States, and weighted to reflect the importance of each measure. The chart shows the significance of the reduction of GWP, Smog, and Acidification, the relatively minor contribution of Eutrophition and Ozone Depletion.

Case Study 4: (Weston) Substitution of Mass Timber for Concrete in the Gravity System of a 9-Story, Commercial Building.

Goal
The goal of this study is to guage the relative environmental impacts of substituting mass timber for concrete in the gravity system of a typical 9-story office building. Wood is a renewable source of building material in the Pacific Northwest, and has been shown to have a lower embodied energy than equivalent structural members made of steel or concrete. With so many variables in play, it is difficult to use this information to inform design. So, in addition to learning how to make an LCA, the purpose of this exercise will be to try to develop an intuition of the benefits and costs of using mass timber. This study will be shared with members of my cohort who are interested in discussing what I've learned this quarter.

Scope
The functional unit for this study is a nine-story office building, with a 70% glazed curtain wall, a column grid of 33' x 33', structure sufficient to carry a 150 lb. live load, and a life span of 60 years.



This study involves the modification of the Reference Building's structural system. The post tension slab is replaced by a CLT panel with a 2" topping slab. CLT slabs cannot span 33' in both directions, so glulam beams are added to decrease one direction of the span to 16.5'.

Several limitations to this study were identified. Athena does not account for the energy required to excavate for a building foundation. Additionally, the software does not adjust the size of structural members when there is a change in dead load. In this case, changing from a concrete slab to a CLT slab would decrease the dead load from the slab, which would lead to a reduction of column size. Another important consideration is the exclusion of operational energy. Again, because the purpose of the study is to compare concrete and mass timber, this will be disregarded. Finally, and perhaps most importantly, this study does not account for harvesting techniques, degradation of the forest, or resource management.

Inventory
Table 4.1 shows the material inventory for the concrete reference building (Baseline) and the proposed mass timber alternative, and highlights the key material differences between the two buildings. While many of the material quantities remain constant between the two models, the mass timber proposal shows a 47% decrease, or about 13,480 short tons, in the total amount of concrete. Conversely, the proposed building, with it's mass timber structure, requires 1,410.5 short tons of engineered timber products that are not present in the concrete structure.

Material	Baseline	Mas Timber	Quantity	Units
5/8" Fire-Rated Type X Gypsum Board	89.5058	89.5058	0	Tons
6 mil Polyethylene	0.3133	0.3133	0	Tons
Aluminum	104.9048	104.9048	0	Tons
Ballast (aggregate stone)	407.3743	407.3743	0	Tons
Concrete 20 MPa (flyash av)	0	2031.9871	-2031.9871	Tons
Concrete 30 MPa (flyash av)	28727.3014	13215.4653	15511.8361	Tons
Cross Laminated Timber	0	1329.712	-1329.712	Tons
EPDM membrane (black, 60 mil)	16.6836	16.6836	0	Tons
FG Batt R11-15	19.8946	19.8946	0	Tons
Galvanized Sheet	7.44	7.44	0	Tons
Glass Facer	1.1028	1.1028	0	Tons
Glazing Panel	360.6387	360.6387	0	Tons
GluLam Sections	0	80.8042	-80.8042	Tons
Joint Compound	8.4994	8.4994	0	Tons
Nails	1.2201	1.2201	0	Tons
Paper Tape	0.0975	0.0975	0	Tons
Polyiso Foam Board (unfaced)	23.517	23.517	0	Tons
Rebar, Rod, Light Sections	1108.3669	262.6775	845.6894	Tons
Screws Nuts & Bolts	3.3492	3.3492	0	Tons
Small Dimension Softwood Lumber, kiln-drie	1.9857	1.9857	0	Tons
Softwood Plywood	0.1968	0.1968	0	Tons
Solvent Based Alkyd Paint	0.0234	0.0234	0	Tons
Spandrel Panel	28.7429	28.7429	0	Tons
Welded Wire Mesh / Ladder Wire	1.851	1.851	0	Tons

Table 4.1 - Bill of materials generated by Athena.

To put that in perspective, the concrete reference building would require the equivalent mass of 962,857 more cinder blocks than the proposed building, while the proposed building would require the equivalent timber mass of 2,350 standard, utility poles.

Impact Assessment
Charts 4.1 and 4.2 show the relative impacts of each building model. Both charts show a greater than 20% reduction in each of the impact categories, more than meeting the requirements for the LEED Whole Building Life Cycle Assessment credits. Chart 4.3 shows the impact measrues after they have been normalized to the annual impact of an average US citizen, and weighted according to the EPA's attributed signicance. This chart illustrates that while there may be similar reductions across the different impact measures, global warming potential, smog formation, and acidification are the more significant impact reductions, and

Reference Building
A1 9 Story Concrete

Proposed Building
9 Story Mass Timber

eutrophication and ozone depletion are minor issues in comparrison.

Interpretation and Conclusion

It seems clear that using mass timber in the place of concrete in the structural system of a medium-rise commercial building, can considerably reduce the impacts of the building's construction, life, and afterlife. Though the results of this study are encouraging, there are a number of things that would make the study more rigorous and conclusive. Further investigation of the foundation and sizing of structural members would produce more accurate results, and could lower the impact of the proposed building even more. A better set of drawings, including sections and perspectives, would provide a more complete picture of what is included in the model. Additionally, better regional data could add to the the already compelling argument.

This is a screening level LCA study, and a more comprehensive study would need to addressa broder scope of issues. For example, what are the costs or benefits to the occupants of these buildings? What are the impacts of the adhesives used in the engineered timber products? Where exactly is the timber coming from and what are the forestry practices and impacts on the ecostystem?

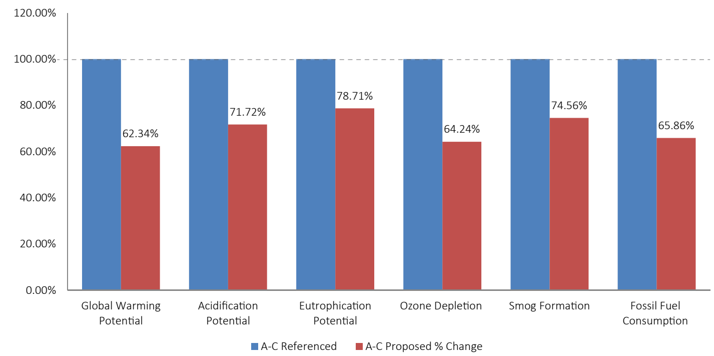


Chart 4.1 - Life cycle stages A-C impact measure comparisson for referenced and proposed buildings.

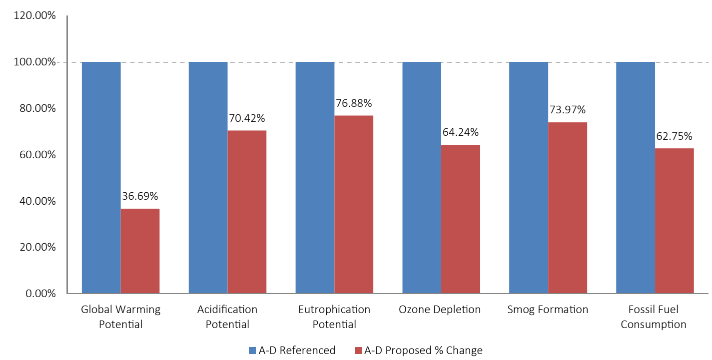


Chart 4.2 - Life cycle stages A-D impact measure comparisson for referenced and proposed buildings.

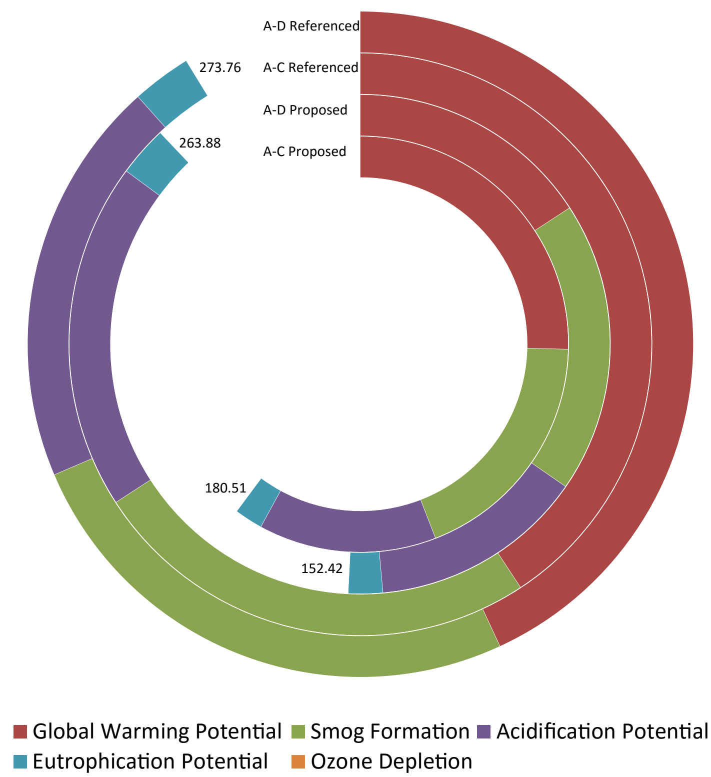


Chart 4.3 - Impact measures are normalized to reflect the number of units per person, per year in the United States, and weighted to reflect the importance of each measure. The chart shows the significance of the reduction of GWP, Smog, and Acidification, the relatively minor contribution of Eutrophition and Ozone Depletion.

Case Study 5 (Janee): Substitution of Mass Timber for Steel in the Gravity System of a 5-Story, Commercial Building.

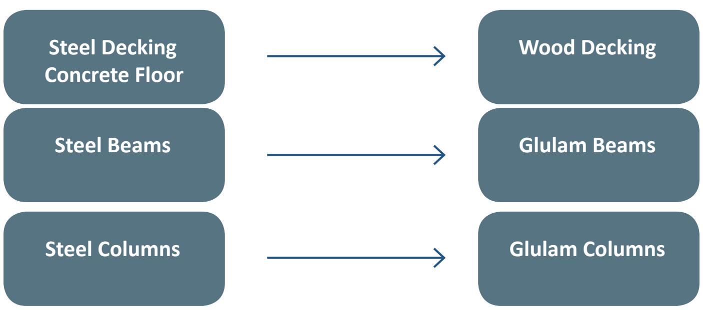
Goal

The goal of this LCA is to study the environmental impacts of substituting mass timber for steel in the gravity system of a typical 5-story office building.

Scope

The functional unit for this study is a five-story office building, with a 70% glazed curtain wall, a column grid of 33' x 25', structure sufficient to carry a 150 lb. live load, and a life span of 60 years.

This study involves the modification of the Reference Building's structural system. The steel and concrete composite floor system, steel beams, and steel columns of the reference building are replaced with wood decking, glulam beams, and glulam columns, respectively.



During the course of this study, several limitations were identified. Athena does not account for the energy required to excavate for a building foundation. Additionally, the foundations are modeled as extra materials rather than in a foundation assembly, so changes in the foundation are not cosidered with the new, lighter structure. Similarly, the software does not adjust the size of structural members when there is a change in dead load. In this case, changing from a steel and concrete deck to wood decking would decrease the dead load from the floor system, which would lead to a reduction of beam and column size. Another important consideration is the exclusion of operational energy. Again, because the purpose of the study is to compare concrete and mass timber, this will be disregarded.

Inventory

Table 5.1 shows the material inventory for the steel reference building and the proposed mass timber alternative, and highlights the key material differences between the two buildings. While many of the material quantities remain constant between the two models, the mass timber proposal shows a 33% decrease, or about 4,184 short tons, in the total amount of concrete, and a 76% reduction, or 801 tons in the total amount of steel. Conversely, the proposed building, with it's mass timber structure, requires 594 short tons of engineered timber products that are not present in the steel structure.

Material	Reference	Proposed	Difference	Units
5/8" Gypsum Fibre Gypsum Board	34.7	34.7	0	Tons
6 mil Polyethylene	0.75	0.75	0	Tons
Aluminum Window Frame	7.3	7.3	0	Tons
Ballast (aggregate stone)	407	407	0	Tons
Cold Rolled Sheet	0.555	0.555	0	Tons
Concrete 30 MPa (flyash 25%)	12413	8229	4184	Tons
Double Glazed No Coating Air	58.2	58.2	0	Tons
EPDM membrane (black, 60 mil)	12.6	12.6	0	Tons
Extruded Polystyrene	21.56	21.56	0	Tons
Galvanized Decking	158	0	158	Tons
Galvanized Sheet	8.66	8.66	0	Tons
Galvanized Studs	12.75	12.75	0	Tons
Glulam Sections	0	331.5	-331.5	Tons
Joint Compound	3	3	0	Tons
Modified Bitumen Membrane	15.6	15.6	0	Tons
Mortar	300.4	300.4	0	Tons
Nails	0.3669	2.6	-2.2331	Tons
Paper Tape	0.0346		0.0346	Tons
Rebar, Rod, Light Sections	334.9	252.5	82.4	Tons
Screws Nuts & Bolts	5.2	0.51	4.69	Tons
Small Dimension Softwood Lumbe	1.98	264.54	-262.56	Tons
Softwood Plywood	18.33	18.33	0	Tons
Split-faced Concrete Block	1270.37	1270.37	0	Tons
Water Based Latex Paint	2.928	2.928	0	Tons
Wide Flange Sections	561	0	561	Tons

Table 5.1 - Bill of materials generated by Athena.

To put that in perspective, the Steel reference building would require the equivalent mass of 298,857 cinder blocks of concrete, and 667 cars worth of steel, more than the proposed building, while the proposed building would require the equivalent timber mass of 823 utility poles.

Impact Assessment

Charts 5.1 and 5.2 show the relative impacts of each building model. Both charts show greater than 30% reduction in four of the six impact categories, more than fulfilling the first part of the LEED V4 LCA requirements. The LEED requirments also stipulate that no single impact measure can show an increase of great than 5%, which would disqualify this proposal. As with a couple of the other case studies, the impact that shows an increase is stratospheric ozone depletion. Though this used to be a serious global issue, ozone depletion is now a minor issue compared with the other impact measures. Chart 5.3 illustrates this by showing the different impact measures after they have been normalized and weighted. After this process, ozone depletion is nearly negligible.

Interpretation and Conclusion

It seems clear that using mass timber in the place of concrete in the structural system of a medium-rise commercial building, can considerably reduce the impacts of the building's construction, life, and afterlife. Though the results of this study are encouraging, there are a number of things that would make the study more rigorous and conclusive. Further investigation of the foundation and sizing of structural members would produce more accurate results, and could lower the impact of the proposed building even more. A better set of drawings, including sections and perspectives, would provide a more complete picture of what is included in the model. Additionally, better regional data could add to the the already compelling argument.

This is a screening level LCA study, and a more comprehensive study would need to addressa broder scope of issues. For example, what are the costs or benefits to the occupants of these buildings? What are the impacts of the adhesives used in the engineered timber products? Where exactly is the timber coming from and what are the forestry practices and impacts on the ecostystem?

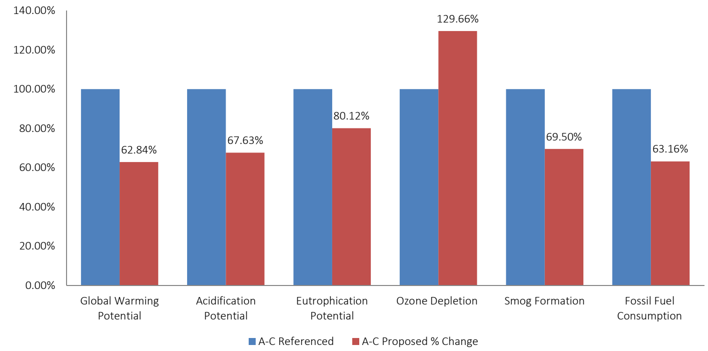


Chart 5.1 - Life cycle stages A-C impact measure comparisson for referenced and proposed buildings.

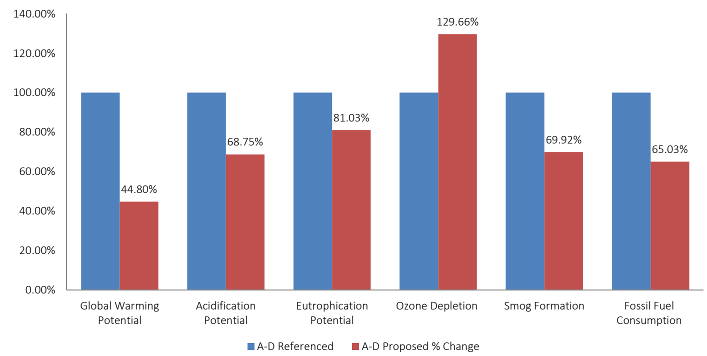


Chart 5.2 - Life cycle stages A-D impact measure comparisson for referenced and proposed buildings.

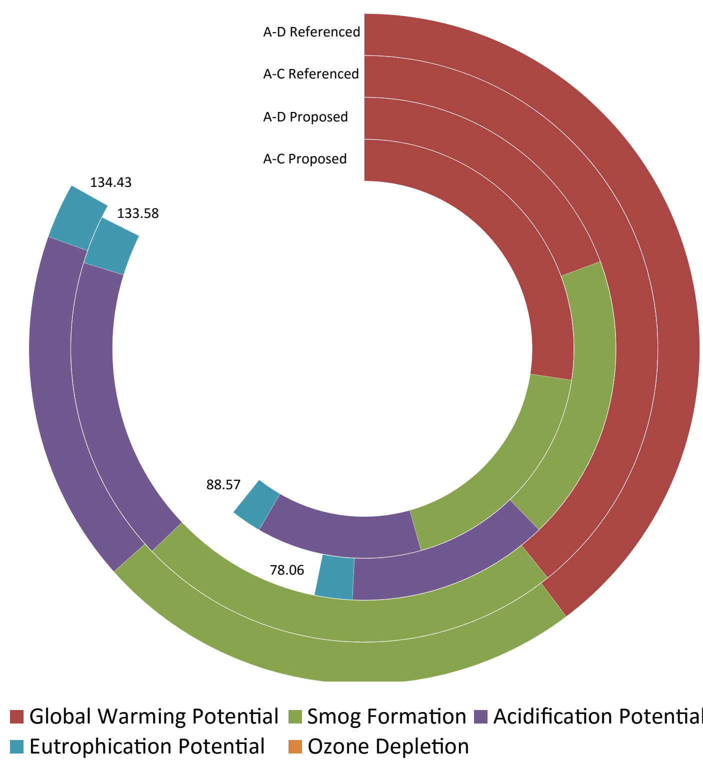


Chart 5.3 - Impact measures are normalized to reflect the number of units per person, per year in the United States, and weighted to reflect the importance of each measure. The chart shows the significance of the reduction of GWP, Smog, and Acidification, the relatively minor contribution of Eutrophition and Ozone Depletion.

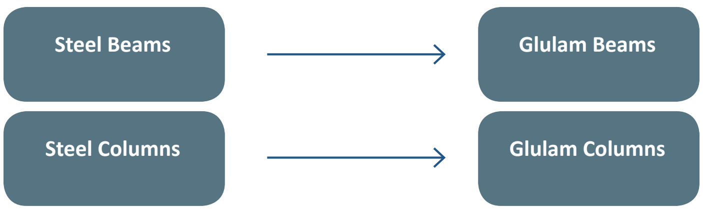
Case Study 6(ali): Substitution of Mass Timber for Steel in the Columns and Beams of a 5-Story, Commercial Building.

Goal

The goal of this assessment is to evaluate the environmental impacts of a steel office building and estimate the reduction of those impacts in the case of a proposed glulam timber design. The audience of the LCA is the class instructor and classmates.

Scope

The functional unit for this study is a five-story office building, with a 70% glazed curtain wall, a column grid of 33’ x 25’, structure sufficient to carry a 150 lb. live load, and a life span of 60 years.



This study involves the modification of the Reference Building’s structural system, specifically targeting the steel columns and beams. The steel beams and girders are replaced by structurely equivilant glulam members, and the steel columns are replaced by glulam columns. The other assemblies in the building, including the foundation, floors, walls, shear core, and roof, are each modeled as part of the reference building, and remain constatnt in the proposed design.

During the course of this study, several limitations were identified. Athena does not account for the energy required to excavate for a building foundation. Additionally, the foundations are modeled as extra materials rather than in a foundation assembly, so changes in the foundation are not cosidered with the new, lighter structure. Similarly, the software does not adjust the size of structural members when there is a change in dead load. In this case, changing from a steel and concrete deck to wood decking would decrease the dead load from the floor system, which would lead to a reduction of beam and column size.

Inventory

Table 6.1 shows the material inventory for the steel reference building and the proposed mass timber alternative, and highlights the key material differences between the two buildings. While many of the material quantities remain constant between the two models, the mass timber proposal shows a 14% decrease, or about 496.5 short tons, in the total amount of concrete, and a 72% reduction, or 843 tons in the total amount of steel. Conversely, the proposed building, with it’s mass timber structure, requires 811 short tons of engineered timber products that are not present in the steel structure.

Material	Reference	Proposed	Difference	Units
Concrete 20 MPa (flyash av)	3476.1936	2979.5945	496.5991	Tons
Concrete 30 MPa (flyash 25%)	8229.7173	8229.7173	0	Tons
Galvanized Sheet	0.1909	0.1909	0	Tons
GluLam Sections	0	811.8126	-811.8126	Tons
Large Dimension Softwood Lumber, kiln-dried	7.07	7.0744	-0.0044	Tons
Nails	0.1476	0.1476	0	Tons
Rebar, Rod, Light Sections	330.8331	319.6426	11.1905	Tons
Screws Nuts & Bolts	40.5697	0	36.2938	Tons
Softwood Plywood	4.2759	4.2759	0	Tons
Wide Flange Sections	795.6395	0	795.6395	Tons

Table 6.1 - Bill of materials generated by Athena.

To put that in perspective, the Steel reference building would require the equivalent mass of 35,471 cinder blocks of concrete, and 702 cars worth of steel, more than the proposed building, while the proposed building would require the equivalent timber mass of 1,353 utility poles.

Impact Assessment

Charts 6.1 and 6.2 show the relative impacts of each building model. Both charts show a greater than 10% decrease in both global warming potential and fossil fuel consumption as well as a 8% decrease in acidificaiton. While there are some impact measures that show a decrease, eutrophication, smog formation, and ozone depletion, show an increase of 24%, 1.75%, and 250%, respectivley. Interestingly, even with unexpededly high increases in some areas, chart 6.3 shows that once the values for each building are normalized and weighted, the proposed building still has a lower environmental score. When accounting for lifecycle stages A-D, the chart shows that the proposed building has a 28% lower enviornmental impact score of the reference building.

Reference Building

A2 5 Story Steel

Proposed Building

5 Story Mass Timber

Interpretation and Conclusion

The data from this study suggests that substituting mass timber for steel in a the structure of a commerical office building could lead to reductions in the overall environmental impact of the building. Other case studies which attempted similar modifications exhibited similar reductions, but did not have some of the same increases. The large increase in a few of the impact measures could stem from the a single component of an assembly that is unique to this project, or there could be an error in the modeling of the proposed building. The bill of materials for this case study does not include window assemblies or a roof assembly. The presence of a clear set of drawings or a digital model would help to clarify the methodology of this study. Additionally, further iterations might help to identify any problems and lead to more consistent results.

This is a screening level LCA study, and a more comprehensive study would need to address a broder scope of issues. For example, what are the costs or benefits to the occupants of these buildings? What are the impact s of the adhesives used in the engineered timber products? Where exactly is the timber coming from and what are the forestry practices and impacts on the ecostystem?

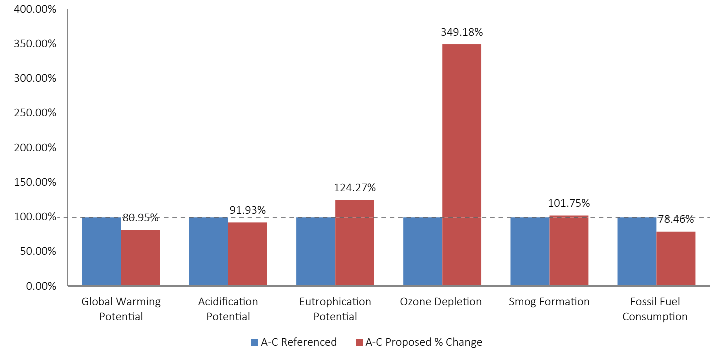


Chart 6.1 - Life cycle stages A-C impact measure comparisson for referenced and proposed buildings.

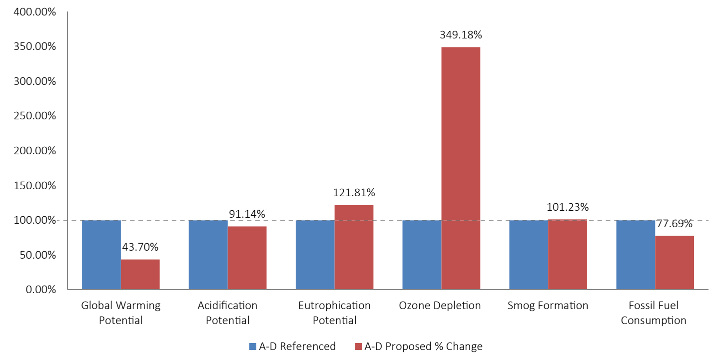


Chart 6.2 - Life cycle stages A-D impact measure comparisson for referenced and proposed buildings.

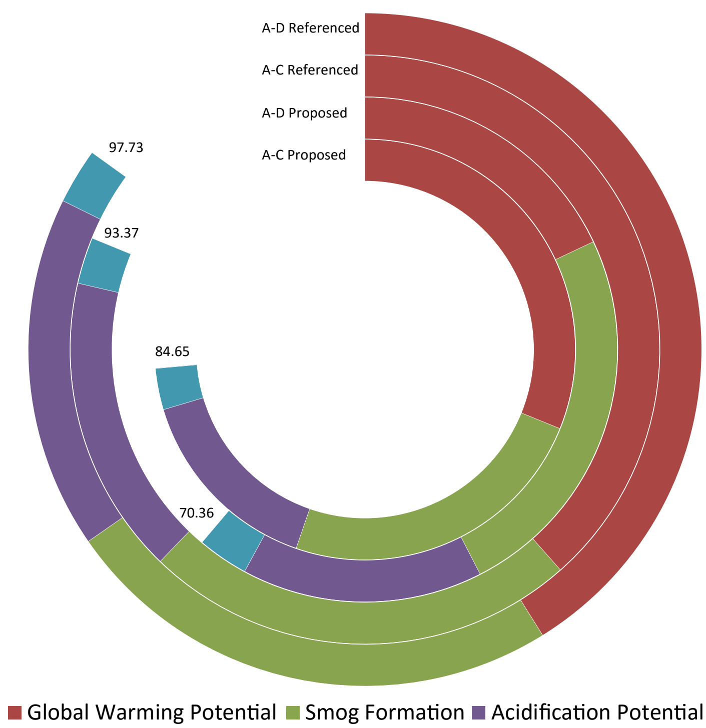


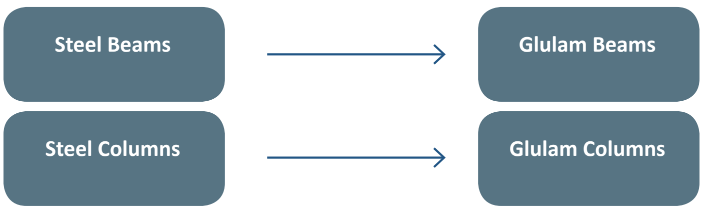
Chart 12.3 - Impact measures are normalized to reflect the number of units per person, per year in the United States, and weighted to reflect the importance of each measure. The chart shows the significance of the reduction of GWP, Smog, and Acidification, the relatively minor contribution of Eutrophition and Ozone Depletion.

Case Study 7(Sue): Substitution of Mass Timber for Steel in the Columns and Beams of a 5-Story, Commercial Building.

Goal

Scope

Inventory



Material	Reference	Proposed	Difference	Units
Concrete 20 MPa (flyash av)	3476.1936	2979.5945	496.5991	Tons
Concrete 30 MPa (flyash 25%)	8229.7173	8229.7173	0	Tons
Galvanized Sheet	0.1909	0.1909	0	Tons
GluLam Sections	0	811.8126	-811.8126	Tons
Large Dimension Softwood Lumber, kiln-dried	7.07	7.0744	-0.0044	Tons
Nails	0.1476	0.1476	0	Tons
Rebar, Rod, Light Sections	330.8331	319.6426	11.1905	Tons
Screws Nuts & Bolts	40.5697	0	36.2938	Tons
Softwood Plywood	4.2759	4.2759	0	Tons
Wide Flange Sections	795.6395	0	795.6395	Tons

Table 6.1 - Bill of materials generated by Athena.

Impact Assessment

Interpretation and Conclusion

Reference Building

A2 5 Story Steel

Proposed Building

5 Story Mass Timber

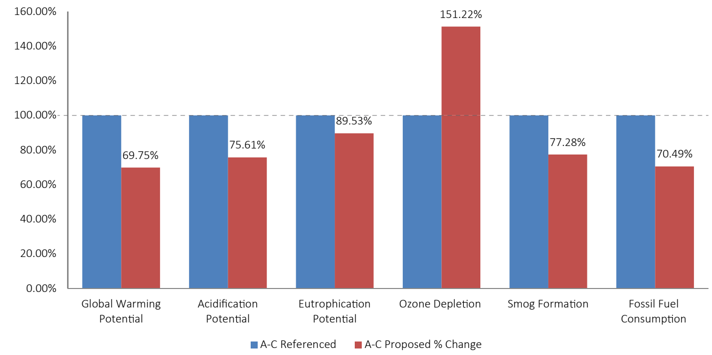


Chart 12.1 - Life cycle stages A-C impact measure comparisson for referenced and proposed buildings.

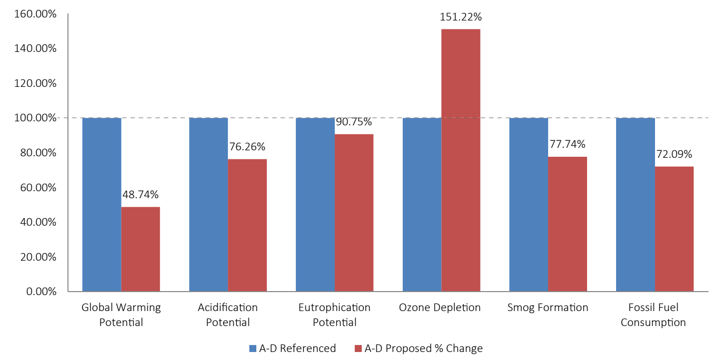


Chart 12.2 - Life cycle stages A-D impact measure comparisson for referenced and proposed buildings.

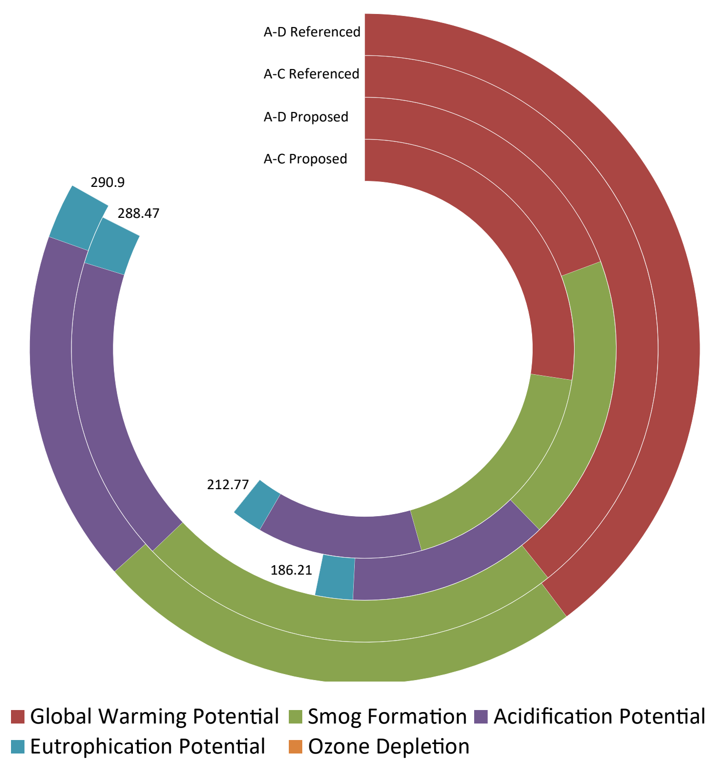


Chart 12.3 - Impact measures are normalized to reflect the number of units per person, per year in the United States, and weighted to reflect the importance of each measure. The chart shows the significance of the reduction of GWP, Smog, and Acidification, the relatively minor contribution of Eutrophition and Ozone Depletion.

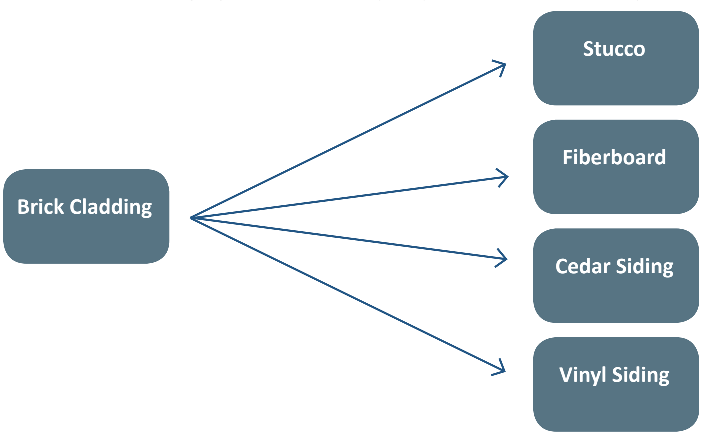
Case Study 8 B1(Tyler): Substitution of Various Cladding Systems in a 5-Story, Concrete, Commercial Building.

Goal

The Goal of this study is to provide quantitative information on the environmental impacts of different cladding systems in a typical office building. A secondary goal is to develop an intuitive understanding of how changing something as seemingly trivial as a cladding system can have a profound effect on the overall environmental impact of a building. The intended audience for this study is professor Kate Simonen and the students in the class.

Scope

The scope of this study is focused on the exterior layer of the cladding surface. The structure and insulation of the wall systems are assumed to be constants in order to focus on the impact of the cladding material. While there is a slight difference in the R-Value of this outermost layer, this difference is considered negligible for the purpose of this study.



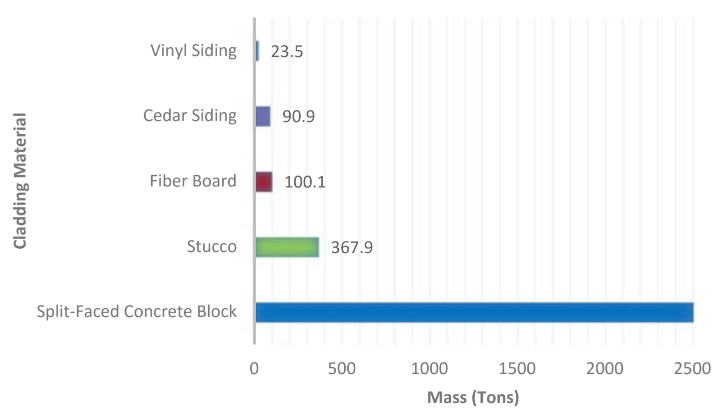
The baseline building for this LCA study is the 5 story concrete structure located in Seattle Washington that is buildt to current building code. With a footprint that measures 300' x 150' and a floor to ceiling height of 14 ft, the building's skin covers <u>88,200 square feet</u>. 40% of the skin's surface area is glazed, leaving 60% or 52,920 square feet of cladding. In this report only the wall assemblies will be analysed because the structure accounts for more impact and the results are not dramatic enough to analyse. The functional unit for this study will be one square foot of external cladding material that projects the wall assembly from the elements and has a lifespan of 60 years. The insulation will stay the same, however, the cladding and hardware needed to install the cladding will change per different assembly. The insulation will remain fibreglass Batt R11-15 and Polystyrene Extruded throughout the all of the different cladding options. The cladding options will have slight differences in their R-values but this should not be enough to skew the results.

Inventory

Table 8.1 shows the material inventory for the brick-clad, reference building, and shows that the buildings primary structure is not included in the bill of materials or impact reports. While most of the material quantities remain constant between the two models, each cladding system introduces a diffrent mass of new materials to the building. Chart 8.1 shows the relative mass of each cladding system.

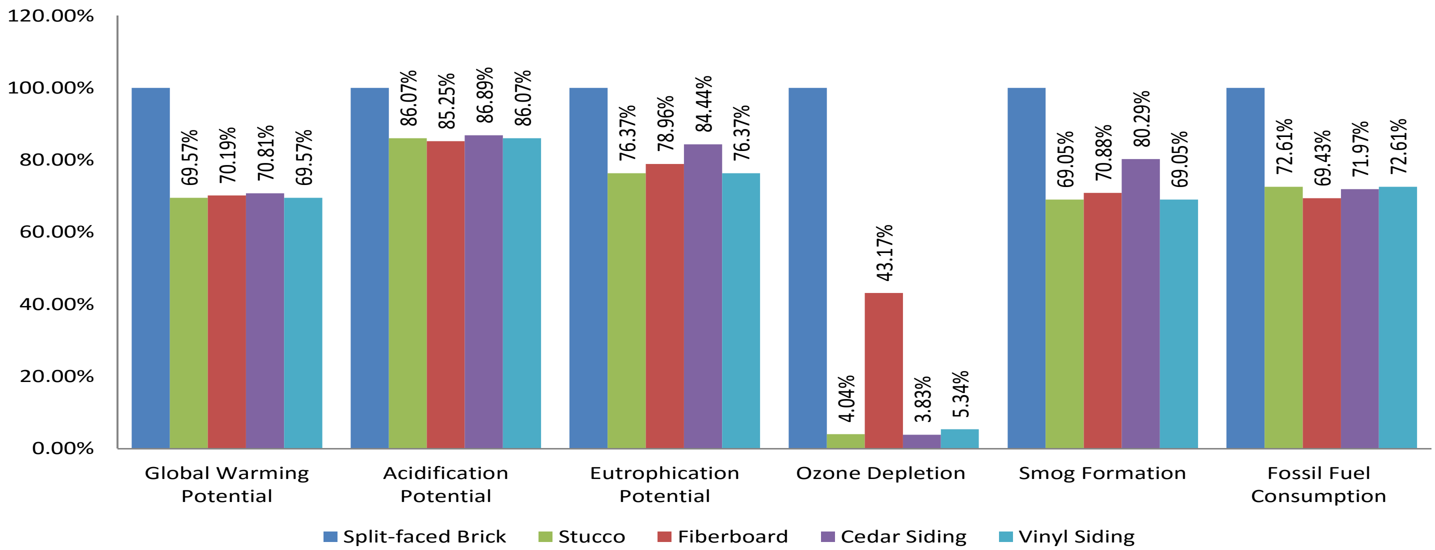
Material	Mass Value	Ma
3 mil Polyethylene	0.4312	Tons
5/8" Moisture Resistant Gypsum Board	68.4366	Tons
5/8" Regular Gypsum Board	61.3426	Tons
Aluminum	80.7496	Tons
Aluminum Window Frame	13.4782	Tons
Cold Rolled Sheet	1.0947	Tons
EPDM membrane (black, 60 mil)	2.8204	Tons
Extruded Polystyrene	10.3988	Tons
FG Batt R11-15	7.0008	Tons
Glazing Panel	144.2555	Tons
Joint Compound	11.8991	Tons
Modified Bitumen membrane	27.9101	Tons
Mortar	592.0731	Tons
Nails	0.7815	Tons
Paper Tape	0.1366	Tons
Screws Nuts & Bolts	2.3444	Tons
Spandrel Panel	40.2401	Tons
Split-faced Concrete Block	2503.7783	Tons

Table 8.1 - Bill of materials generated by Athena.



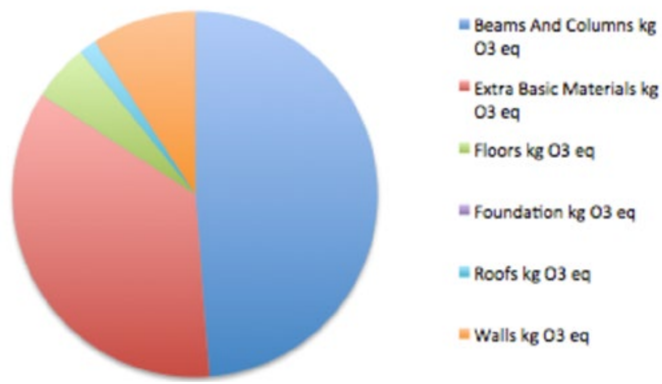
Reference Building
5 Story Brick Clad

Proposed Building
5 Story With Various Cladding Systems



Impact Assessment

Chart 8.2 shows how each cladding system compard to the baseline brick-clad building. The chart indicates that, when compard with these alternatives, the baseline has the worst environmental performance. While the chart shows each of the alternative schemes with a greater than 10% reduction in all of the impact measrues, the proposals would not qualify the design for the LEED V4 LCA credit, because the rest of the building is not included. If the rest of the building were to be included, the decrease in impacts would be much less significant. Chart 8.3 shows the impact of each constituent assembly, and illustrates why the cladding system is isolated for the purposes of this study. Chart 8.4 shows the impact measures weighted an normalized and emphasizes the relative impact of global warming potential, smog formation, and acidification.



Interpretation and Conclusion

The data of the impacts does not very greatly, but it is clear, vinyl siding is the least impactful cladding option. There is a strong correlation between weight and reduction of impacts, but this in not necessarily causal. The heavier brick has more mass, and more material is needed, but it is not clear what makes that material more impactful. While fiberboard, cedar siding, stucco, and vinyl siding has some variance in their impacts the results are not so far apart to say one is exceptionally better than the other. The choice in cladding options may end up not changing and the decision will be based on cost and visual aesthetics.

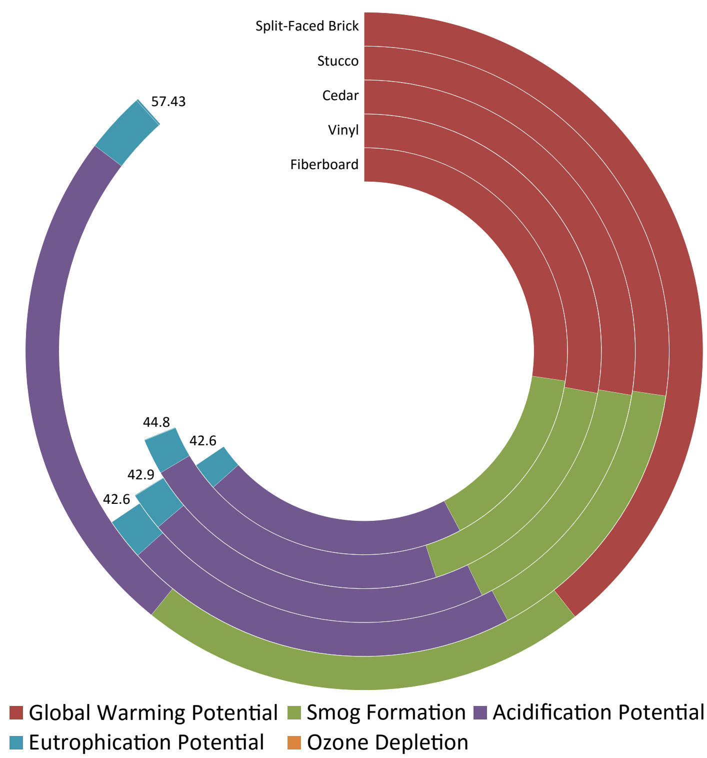


Chart 8.4 - Impact measures are normalized to reflect the number of units per person, per year in the United States, and weighted to reflect the importance of each measure. The chart shows the significance of the reduction of GWP, Smog, and Acidification, the relatively minor contribution of Eutrophition and Ozone Depletion.

Case Study 9(Steven): Modifcation Of The Concrete Strucure In A 5-Story, Commercial Building.

Goal

This LCA is a study of a typical office building in Seattle. The study is an informal assessment at the screening level, as part of the M.Arch coursework at the University of Washington. The study has been initiated in order to determine the crade-to-grave environmental profile of a 5-story concrete office building and identify key environmental inputs and outputs of new construction in the Seattle area. The study will analyze a baseline building that will act as a reference to a whole building LCA for a speculative design proposal. The new design proposes an alternative structural scheme, opting for a pre-cast concrete system with longer spans and fewer columns. The study is intended to determine if the material loss from column removal is outweighed by material gained from the thicker slab. The study will also look at the different manufacturing and construction processes of site-cast concrete systems and precast concrete systems.

Scope

The functional equivalency for this LCA will be based on the two buildings having the same use, gross floor area, and location to make them comparable. In addition, the two will have the same object of assessment (concrete structure), system boundary, study period, scope, and LCA tool. Both buildings are 189,000 ft^2 commercial office buildings in Seattle being assessed for a 60 year lifespan. They are the same in every aspect except the primary structure which includes column and beam construction, floor construction and roof construction. Changing the column grid inherently changes the layout of the building and possibly alters the use. In a more comprehensive LCA, this would effect the functional equivalecy. For the purposes of this study it is assumed that the use remains the same for both buildings regardless of column grid and floorplan layout.

Inventory

For the purposes of the study, the foundation was modeled as an extra basic material accounting for 9000 yd^3 of 30 MPa (flyash avg.) concrete. This was modeled with low confidence in accuracy and will effect the impact assessment, but was the same for both buildings and therefore will have little significance in comparative analysis between the two. The walls were modeled as light gauge steel framing supporting a brick veneer rainscreen. Windows were estimated at 80 per floor and 40% of the total envelope. The lateral system for both buildings are concrete shear walls and were modeled the same.

Material	Sitecast Concrete	Precast Concrete	Difference	Units
3 Mil Polyethylene	0.457	0.457	0	Tons
5/8" Moisture Resistant	72.5404	72.5404	0	Tons
5/8" Regular Gypsum	65.021	65.021	0	Tons
6 Mil Polyethylene	2.1223	2.1223	0	Tons
Air Barrier	0.3719	0.3719	0	Tons
Aluminum Window Frame	8.34	8.34	0	Tons
Ballast (Aggregate stone)	696.7843	696.7843	0	Tons
Cold Rolled Sheet	1.1604	1.1604	0	Tons
Concrete 20 MPA (flyash av)	0	2824.208	-2824.21	Tons
Concrete 30 MPa (flyashav)	40814.2025	20086.5631	20727.64	Tons
Double Glazed Soft CoatedArgon	143.8472	143.8472	0	Tons
EPDM Membrane (black, 60mil)	23.9229	23.9229	0	Tons
Expanded Polystyrene	0.0317	0.0317	0	Tons
Extruded Polystyrene	39.9959	39.9943	0.0016	Tons
FG Batt R20	8.7789	8.7789	0	Tons
Galvanized Sheet	2.7146	2.7146	0	Tons
Galvanized Stud	21.0971	21.0971	0	Tons
Glazing Panel	0.5291	0.5291	0	Tons
Hot Rolled Sheet	0	13.1558	-13.1558	Tons
Joint Compound	12.6127	12.6127	0	Tons
Modified Bitumen Membrane	29.5837	29.5837	0	Tons
Mortar	627.5766	627.5766	0	Tons
Nails	0.8355	0.8355	0	Tons
Paper Tape	0.1448	0.1448	0	Tons
Precast Concrete	0	10379.7655	-10379.8	Tons
Rebar, Rod, Light Sections	1599.8281	849.46	750.3681	Tons
Screw Nuts & Bolts	0.1546	0.1546	0	Tons
Small Dimension softwood lumber	3.7539	3.7539	0	Tons
Softwood Plywood	0.372	0.372	0	Tons
Solvent Gbased Alkyd Paint	0.003	0.003	0	Tons
Split-faced Concrete Block	2653.9167	2653.9167	0	Tons
Water Based Latex Paint	6.1171	6.1171	0	Tons
Welded Wire Mesh / Ladder Wire	0	35.536	-35.536	Tons

Table 9.1 - Bill of materials generated by Athena.

Table 9.1 shows the material inventory for the sitecast reference building and the precast altervative, and highlights the key material differences between the two buildings. While many of the material quantities remain constant between the two models, the precast concrete proposal shows an 18% decrease, or 7523.6 short tons, in the total amount of concrete, and a 43% reduction, or 701.6 tons in the total amount of steel. To put that in perspective, the sitecast reference building would require the equivalent mass of 537,404 cinder blocks of concrete, and 584 cars worth of steel, more than the proposed building.

Reference Building

B 5 Story Sitecast Concrete

Proposed Building

B 5 Story Precast Concrete

Impact Assessment

Charts 9.1 and 9.2 show the relative impacts of each building model. The proposed building has reduced impacts in all of the envrionmental factors studied. Most notable are the significant reduction in global warming potential and fossil fuel consumption, each by nearly 25%. Although there is a large proportional reduction for ozone depletion, the quantities are still small and ozone depletion is not an impact of primary concern. Acidification also has a noteworthy reduction of 12.6%. This is an important factor to consider for coastal such as Seattle, because acidification has a large impact on the health of freshwater and saltwater ecosystems. Chart 10.3 shows that while there are reductions in euthrophication and ozone depletion, these factors are relatively insignificant compard to the other factors.

Interpretation and Conclusion

As previously stated, the proposed building outperforms the baseline building in all impact categories. Yet when the results are broken down into a more detailed view, the prosed building does show some greater effects when considering life cycle stage individuallyu. The proposed building has significatn increase in acidification, euthrophication, and smog for the life cycle stage of concstruciton and use. For construction, the increases are most likely related to differences in the transportation and scarcity of suppliers in the case of a precast system.

The incresases in use are surprising and ultimately inconclusive in terms of why this is. The use stage includes maintenance, repair and replacement, and when considering two concrete buildings for a 60 year study period it would be asumed that the impacts would be identical. The fact that the proposed building has increases would allude to a precast system having a smaller longevity and requiring a greater amount of repair.

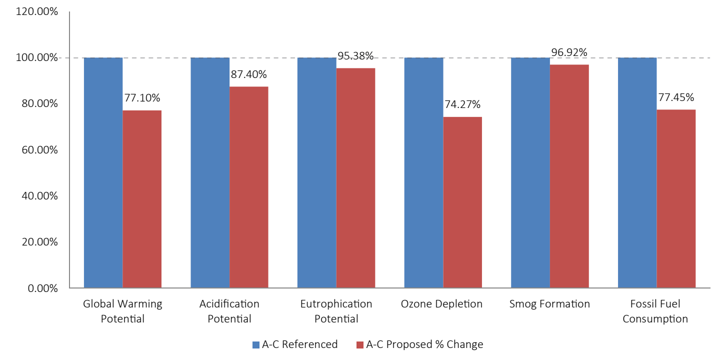


Chart 9.1 - Life cycle stages A-C impact measure comparisson for referenced and proposed buildings.

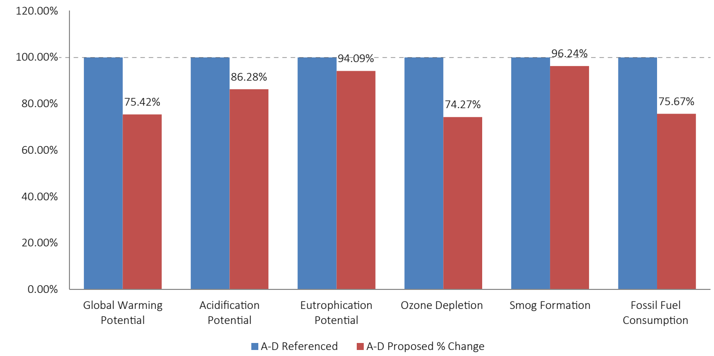


Chart 9.2 - Life cycle stages A-D impact measure comparisson for referenced and proposed buildings.

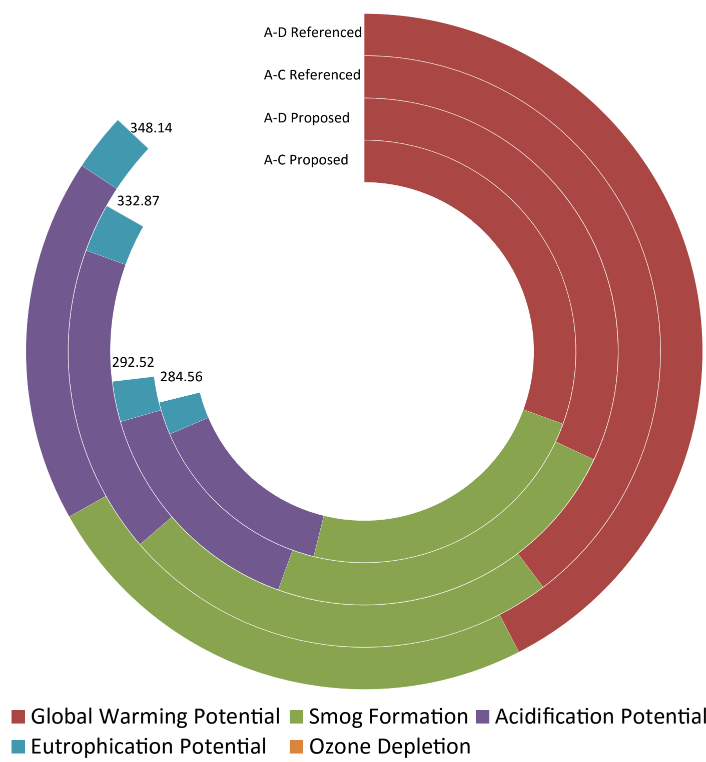


Chart 10.3 - Impact measures are normalized to reflect the number of units per person, per year in the United States, and weighted to reflect the importance of each measure. The chart shows the significance of the reduction of GWP, Smog, and Acidification, the relatively minor contribution of Eutrophition and Ozone Depletion.

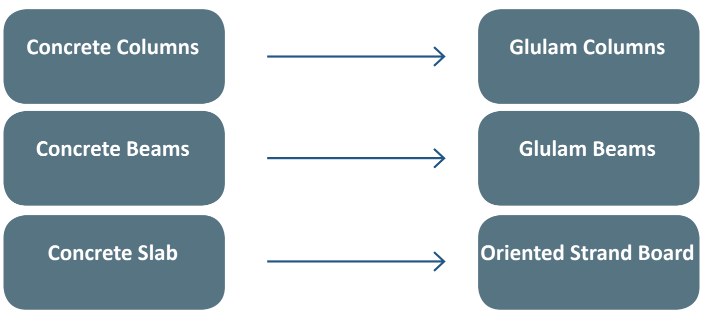
Case Study 10(Mingjun): Modifcation Of The Concrete Strucure In A 5-Story, Commercial Building.

Goal

The purpose of this project is to determine whether a heavy timber structure office building has an overall environmental advantage over an office building constructed with concrete structure. To achieve this goal, life cycle inventory data of the office building with the two different structures will be used to conduct a life cycle assessment.

Scope

This study proposes a heavy timber structure in the place of a concrete structure. The functional unit for the study is the total leasable space in both buildings. The study is broken in to the following lifecycle stages: product(A1-A3); construction progress(A4,A5); use(B2,B4 and B6); end of life(C1-C4); and Beyond building life(D). Operational energy is excluded.



This study focuses on modifying gravity system of the building by changing the concrete columns and beams to equivilant glulam members and replacing a concrete slab with oriented strand board.

Throughout the study several limitations were identified. Athena can only model concrete columns and beams with the same span and the same by size at one time, so the building has to be seperated into parts to model an irregualar space. This led to some overlapping columns and beams and may have led to inaccurate results. Additionally, Athena does not account for the change of a structure's weight. When the concrete members in the reference building are replaced with the lighter wood, Athena does not reduce the size of the supporting members.

Inventory

For the purposes of the study, the foundation was modeled as an extra basic material and consists of 9000 yd^3 of 30 MPa (flyash avg.) concrete. This was modeled with low confidence in accuracy and will effect the impact assessment, but is the same for both buildings and therefore will have little significance in the comparisson. The walls were modeled as light gauge steel framing supporting a brick veneer rainscreen. Windows were estimated at 80 per floor and 40% of the total envelope. The lateral system for both buildings are concrete shear walls and were modeled the same.

Materials	Concrete	Mass Timber	Difference	Units
1/2" Gypsum Fibre Gypsum Board	133.2	133.2	0.0	Tons
3 mil Polyethylene	0.4	0.4	0.0	Tons
6 mil Polyethylene	2.1	2.1	0.0	Tons
Air Barrier	0.3	0.3	0.0	Tons
Aluminum	0.5	0.5	0.0	Tons
Aluminum Window Frame	5.7	5.7	0.0	Tons
Ballast (aggregate stone)	696.8	696.8	0.0	Tons
Cold Rolled Sheet	1.1	1.1	0.0	Tons
Concrete 30 MPa (flyash av)	46404.1	20086.6	26317.6	Tons
Double Glazed Hard Coated Argon	136.7	136.7	0.0	Tons
EPDM membrane (black, 60 mil)	23.9	23.9	0.0	Tons
Extruded Polystyrene	64.2	64.2	0.0	Tons
Galvanized Sheet	1.7	9.3	-7.7	Tons
Galvanized Studs	19.8	19.8	0.0	Tons
Glazing Panel	0.9	0.9	0.0	Tons
Glulam Sections	0.0	127.3	-127.3	Tons
Joint Compound	11.9	11.9	0.0	Tons
Large Dimension Softwood Lumber		344.7	-344.7	Tons
Metric Modular (Modular) Brick	595.8	595.8	0.0	Tons
Mortar	190.8	190.8	0.0	Tons
Nails	0.8	5.8	-5.0	Tons
Oriented Strand Board	45.6	231.6	-186.0	Tons
Paper Tape	0.1	0.1	0.0	Tons
Rebar, Rod, Light Sections	2233.3	588.9	1644.4	Tons
Screws Nuts & Bolts	0.1	0.1	0.0	Tons
Small Dimension Softwood Lumber	3.8	3.8	0.0	Tons
Softwood Plywood	0.4	0.4	0.0	Tons
Water Based Latex Paint	5.8	5.8	0.0	Tons

Table 10.1 - Bill of materials generated by Athena.

Table 10.1 shows the material inventory for the concrete reference building and the timber altervative, and highlights the key material differences between the two buildings. While many of the material quantities remain constant between the two models, the timber proposal shows an 56% decrease, or 26,317 short tons, in the total amount of concrete, and a 73% reduction, or 1636.6 tons in the total amount of steel. To put that in perspective, the concrete reference building would require the equivalent mass of 1,879,825 cinder blocks of concrete, and 1363 cars worth of steel, more than the proposed building. Conversely, the proposed building, with it's mass timber structure, requires

1,410.5 short tons of engineered timber products, or the equivilant of 1,096 utility poles, that are not present in the concrete structure.

Impact Assessment

Charts 10.1 and 10.2 show the relative impacts of each building model. The proposed building has dramaticly reduced impacts in all of the envrionmental factors studied. Nearly all of the impact categories show a reduction of over 40%. Stratopheric Ozone Depletion has a slightly smaller reduction of 38.2%. According to LEED V4, these results would qualify the proposed design for the LCA credits. While there are large reductions in each of the impact categories, chart 10.3 illustrates that some of those reductions are more significatn than others. While ozone depletion decreases nearly 30% and eutrophication nearly 35%, when weighted and normalized, it becomes apparent that they have a relatively small impact.

Interpretation and Conclusion

By replacing the concrete structure with heavy timber structure, there is a 56% and 73% reduction in the quantify of concrete and steel used, repsectively, and with that reduction in materials comes significant reductions in the environmental impacts of the building. The extent of the impacts is encouraging, however, there is evidence of inaccuracies in the building models that prevent the two buildings from being functionally equivilant. The column grids appear to be modeled accurately, however, the floor system in the proposed building does not appear to be sufficient. Additional beams are necessary to carry the specified loads, and the floor surface is not currently equivialant to a concrete slab. An accurate set of drawings and a complete digital model, would help to visualize the modifications and build confidence in the study.

This is a screening level LCA study, and a more comprehensive study would need to address a broder scope of issues. For example, what are the costs or benefits to the occupants of these buildings? What are the impacts of the adhesives used in the engineered timber products? Where exactly is the timber coming from and what are the forestry practices and impacts on the ecostystem?

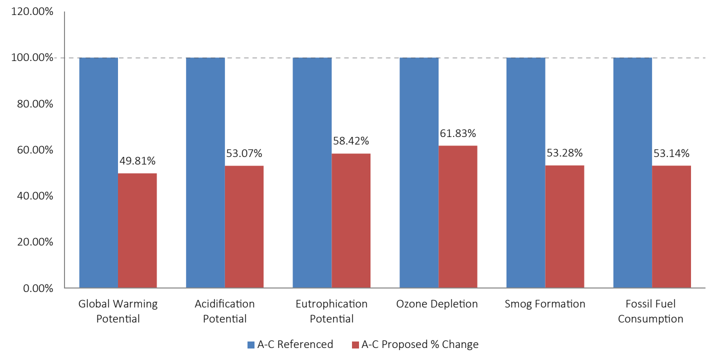


Chart 10.1 - Life cycle stages A-C impact measure comparisson for referenced and proposed buildings.

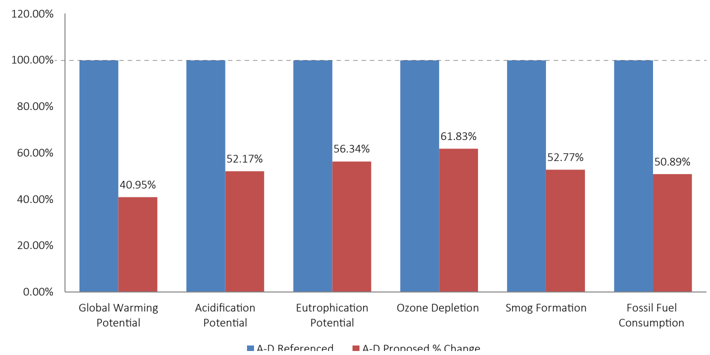


Chart 10.2 - Life cycle stages A-D impact measure comparisson for referenced and proposed buildings.

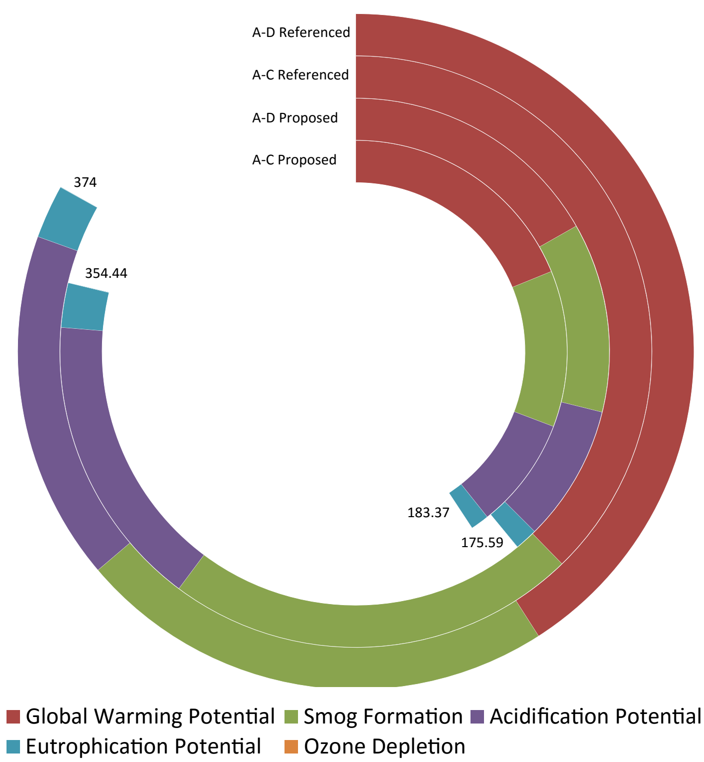


Chart 10.3 - Impact measures are normalized to reflect the number of units per person, per year in the United States, and weighted to reflect the importance of each measure. The chart shows the significance of the reduction of GWP, Smog, and Acidification, the relatively minor contribution of Eutrophition and Ozone Depletion.

Case Study 11 (Jacob): Comparrison of Two Cladding Systems in a 5 Story Commercial Office Building.

Goal

The goal of this building LCA is to study the global warming potential of the exterior cladding material of an office building in Seattle, Washington. This study stems from a curiosity grown from the variety in building cladding material types seen in Seattle and the desire to learn what cladding material has a the least contribution to climate change. The intended audience of this study is the students of the ARCH 425.

Scope

The two cladding materials that will be studied are a commercial metal wall panel Cladding (26 Gauge) and natural stone cladding. This building LCA takes into account life cycle stages A-D which includes material manufacturing, construction, use (in this case replacement,) end of life, and beyond building life. The

functional unit is a 225,000 ft^2 steel commercial office building in Seattle, WA. The building measures 300' by 150' with an open-air courtyard space in the middle.

Throughout the study several limitations were discovered. Due to material differences, there are different lifespans for the cladding. While Athena should account for this in the Use and Maintanence phase, it could still effect the results. The span sizes for the roofing and flooring systems is limited to 18 feet. Instead of adding this information in as 'wall' and 'roof' systems, I estimated the amount of materials that were discussed in class for typical commercial office buildings and calculated how much the building I am studying would use. I also used this same method of adding materials for the lateral and foundations into 'extra materials.' Additionally, this LCA does not take into account any interior walls or flooring which I considered tenant improvements that would vary by occupant. The structural spans for this building are irregular and there is an opening in the interior of the building giving it its 'doughnut' shape. This structural layout is difficult to model in Athena, so span distances are averaged, and structure in the center of the buildings is subtracted.

Inventory

For the purposes of the study, the foundation was modeled as an extra basic material accounting for 9000 yd^3 of 30 MPa (flyash avg.) concrete. This was modeled with low confidence in accuracy and will effect the impact assessment, but was the same for both buildings and therefore will have little significance in comparative analysis between the two. The walls were modeled as light gauge steel framing supporting a brick veneer rainscreen. Windows were estimated at 80 per floor and 40% of the total envelope. The lateral system for both buildings are concrete shear walls and were modeled the same. The only difference between the two building models is the cladding system.

Materials	Stone Cladding	Metal Panel	Difference	Units
#15 Organic Felt	22.4369	0.0	22.4	Tons
1/2" Gypsum Fibre Gypsum Board	110.74	110.7475	0.0	Tons
6 mil Polyethylene	1.4304	1.4304	0.0	Tons
Aluminum	0.7932	0.7932	0.0	Tons
Aluminum Window Frame	0.6928	0.6928	0.0	Tons
Cold Rolled Sheet	1.8158	0.0	1.8	Tons
Concrete 20 MPa (flyash av)	18516.8638	18516.8638	0.0	Tons
Concrete 30 MPa (flyash av)	511.5592	511.5592	0.0	Tons
EPDM membrane (black, 60 mil)	20.4916	20.4916	0.0	Tons
FG Batt R20	34.444	34.444	0.0	Tons
FG LF Cavity Fill R38	2.6721	2.6721	0.0	Tons
Galvanized Sheet	15.2349	15.2349	0.0	Tons
Galvanized Studs	29.055	29.055	0.0	Tons
Glazing Panel	1.5648	1.5648	0.0	Tons
Joint Compound	9.8686	9.8686	0.0	Tons
Metal Wall Cladding - Commercial (26 Ga.)	0	106.3878	-106.4	Tons
Mortar	148.4913	0.0	148.5	Tons
Nails	0.7085	0.7085	0.0	Tons
Natural Stone	711.7538	0.0	711.8	Tons
Paper Tape	0.1133	0.1133	0.0	Tons
Rebar, Rod, Light Sections	565.6	565.6	0.0	Tons
Screws Nuts & Bolts	27.4308	27.6623	-0.2	Tons
Softwood Plywood	59.303	59.303	0.0	Tons
Triple Glazed Hard Coated Argon	1.0519	1.0519	0.0	Tons
Water Based Latex Paint	0	9.5725	-9.6	Tons
Wide Flange Sections	533.6871	533.6871	0.0	Tons

Table 11.1 - Bill of materials generated by Athena.

Table 11.1 shows the material inventory for the stone clad reference building and the steel panel altervative, and highlights the key material differences between the two buildings. While many of the material quantities remain constant between the two models, the building with natural stone cladding requires a total of 711.8 tons of stone and 148 tons of mortar. Conversely, the proposed metal panel building, requires 106 tons of additional steel.

Reference Building
Metal Panel Cladding

Proposed Building
Stone Cladding

Impact Assessment

Charts 11.1 and 11.2 show the relative impacts of each building model. The proposed, stone-clad building shows reductions in all of the envrionmental factors studied. None of the impact measures have a greater than 10% reduction, so this modification would not be sufficient to qualify the design for the LEED V4 LEED credits. Even so, it is interesting to see that such a change can come from simply changing cladding systems.

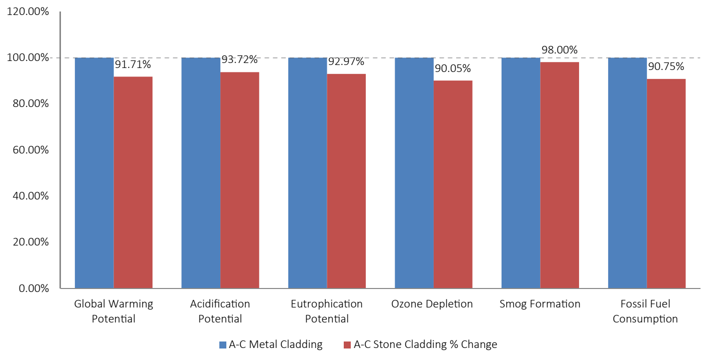


Chart 11.1 - Life cycle stages A-C impact measure comparisson for referenced and proposed buildings.

Interpretation and Conclusion

This is a screening level LCA study, and a more comprehensive study would need to address a broder scope of issues. For example, what are the costs or benefits to the occupants of these buildings? What are the impacts of the adhesives used in the engineered timber products? Where exactly is the timber coming from and what are the forestry practices and impacts on the ecostystem? In order to increase confidence in the LCA data, the modeling of the floor and roof systems in Athena would need to be reviewed and changed. This is something that is more dependent on the computer program than the information being inputted. The results would be more accurate is if there were a way to enter more than one structural bay size for buildings with an irregular grid. As a whole however, the results of this study suggest that a metal clad building would have a higher environmental impact stemming from its greater fossil fuel consumption, global warming potential, smog potential, and non renewable energy impact.

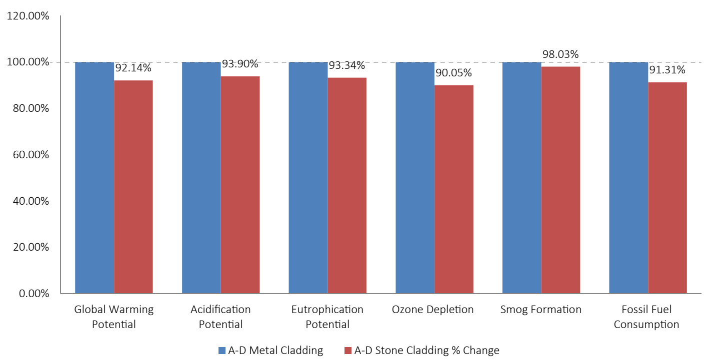


Chart 11.2 - Life cycle stages A-D impact measure comparisson for referenced and proposed buildings.

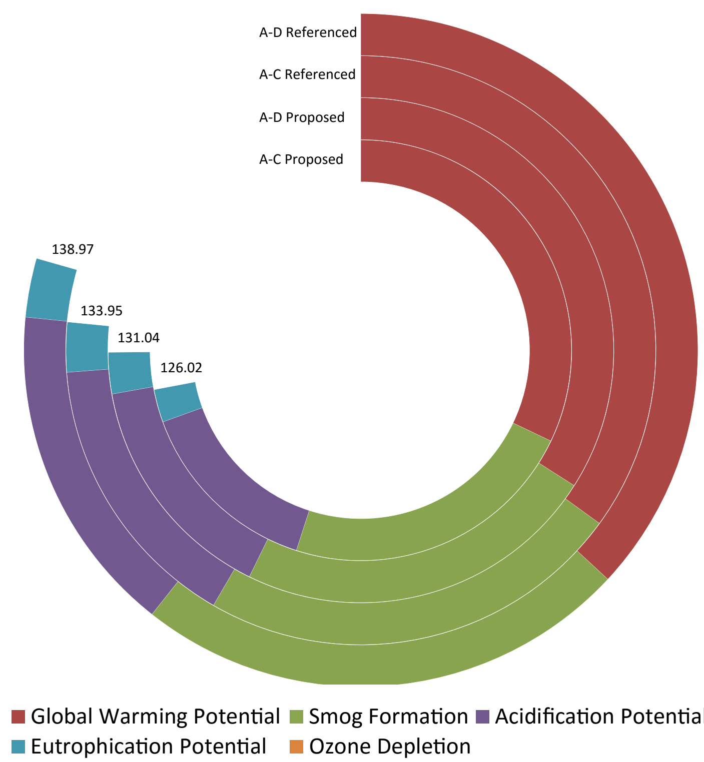


Chart 11.3 - Impact measures are normalized to reflect the number of units per person, per year in the United States, and weighted to reflect the importance of each measure. The chart shows the significance of the reduction of GWP, Smog, and Acidification, the relatively minor contribution of Eutrophition and Ozone Depletion.

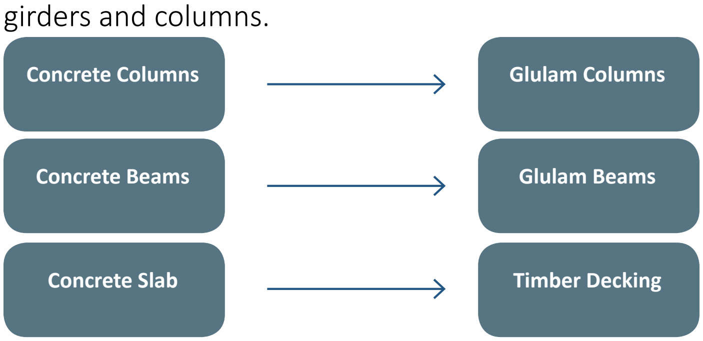
Case Study 12 (Kami): Substitution Of Mass Timber For Steel In The Structural System Of A 5-Story Commerical Office Building.

Goal

The goal of this LCA is to assess the difference of the environmental impact between a steel structure and a heavy timber structure in a standard 5 story office building in Seattle. The results will ideally be used to enforce an argument for the employment of more timber structures in building projects, in this case likely studio projects done for a B.Arch or M.Arch degrees at The University of Washington.

Scope

The unit of measure is a 5 story office building measuring 300' by 150' with an atrium opening in the center measuring 120' by 60', with a lifespan of 60 years. A baseline building will be modeled with steel structure and the results of its LCA will be compared to a model of a building with functional equivalency with a heavy timber structure. Assemblies that are included in modeling are the foundation, floors, exterior walls, structural columns and beams, lateral wall system, and roof. The structure of the steel building is composed of wide flange columns, beams, and girders. A composite steel flooring system is employed in this baseline building and lateral support is provided by concrete shear walls. The exterior walls are steel stud with brick facade, plus insulation and moisture barriers. This original grid and structural elements will be exchanged for a new grid, better suited to heavy timber spans, and a heavy timber structure. This includes glulam beams/ girders and columns.



A conventional timber floor system is used in this second iteration. As in the baseline building, lateral support is provided by concrete shear walls and the exterior walls are steel stud with brick facade, plus insulation and moisture barriers. Building assemblies excluded from the modeling are the tenant improvements and interior finishings, specifically floor finishes, ceilings, plumbing, electrical, vertical circulation mechanisms, light fixtures, interior walls, and HVAC mechanics. Outside the system boundary are inputs including water,operational energy, worker transport, site work or excavation including sidewalks and landscaping, construction work like formwork or generators, fire proofing of interiors.

Inventory

Athena was used to generate material quantities in all inputs except the foundation. Extra Basic Materials were added, with quantities of concrete and rebar suggested by Professor Kate Simonen, in order to account for the foundation and stories below grade. In order to model the 'donut' building, the structural grid was broken up into 45' and 30' portions, with column/ beam and floor assemblies modeled within each. Table 12.1 shows the material inventory for the concrete reference building and the timber altervative, and highlights the key material differences between the two buildings. While many of the material quantities remain constant between the two models, the timber proposal shows an 28% decrease, or 7,915 short tons, in the total amount of concrete, and a 7% reduction, or 1448 tons in the total amount of steel. To put that in perspective, the concrete reference building would

Materials	Concrete	Mass Timber	Difference	Units
3 mil Polyethylene	0.4615	0.4615	0.0	Tons
6 mil Polyethylene	0.5923	0.592	0.0	Tons
5/8" Gypsum Fibre Gypsum Board	89.3323	89.3323	0.0	Tons
5/8" Moisture Resistant Gypsum Board	73.2525	73.2525	0.0	Tons
Aluminum	0.17	0.17	0.0	Tons
Aluminum Window Frame	17.0868	17.0868	0.0	Tons
Ballast (aggregate stone)	696.7843	696.4592	0.3	Tons
Cold Rolled Sheet	1.1718	1.1718	0.0	Tons
Concrete 30 MPa (flyash av)	28114.03	20198.6845	7915.3	Tons
Double Glazed Soft Coated Air	132.927	132.927	0.0	Tons
EPDM membrane (black, 60 mil)	23.9229	23.9229	0.0	Tons
Extruded Polystyrene	36.128	36.128	0.0	Tons
FG Batt R11-15	6.5568	6.5568	0.0	Tons
Galvanized Decking	298.9337	0	298.9	Tons
Galvanized Sheet	1.6792	1.6792	0.0	Tons
Galvanized Studs	26.6823	26.6823	0.0	Tons
Glazing Panel	0.3353	0.3353	0.0	Tons
GluLam Sections	0	988.68	-988.7	Tons
Joint Compound	12.7365	12.7365	0.0	Tons
Modified Bitumen membrane	29.8741	29.8741	0.0	Tons
Mortar	633.7375	633.7375	0.0	Tons
Nails	1.1684	5.4741	-4.3	Tons
Paper Tape	0.1462	0.1462	0.0	Tons
Rebar, Rod, Light Sections	746.5043	590.6115	155.9	Tons
Screws Nuts & Bolts	9.5277	1.0901	8.4	Tons
Small Dimension Softwood Lumber, kiln-dried	3.75	499.9605	-496.2	Tons
Softwood Plywood	38.6	38.6404	0.0	Tons
Split-faced Concrete Block	2680.0	2679.9701	0.0	Tons
Wide Flange Sections	993.42	0	993.4	Tons

Table 12.1 - Bill of materials generated by Athena.

Reference Building
B 5 Story Steel

Proposed Building
5 Story Mass Timber

require the equivalent mass of 565,381 cinder blocks of concrete, and 1206 cars worth of steel, more than the proposed building. Conversely, the proposed building, with it's mass timber structure, requires 1,410.5 short tons of engineered timber products, or the equivilant of 1,096 utility poles, that are not present in the concrete structure. Ozone depletion, while once a serious threat to life on earth, is of relatively minor concern.

Impact Assessment

Charts 12.1 and 12.2 show the relative impacts of each building model. The proposed building has dramaticlly reduced impacts in all of the envrionmental factors studied with the exception of stratopheric ozone depletion. Five of the impact categories show a great than 10% reduction in impact, more than fulfilling the first part of the LEED V4 LCA requirment. However, the second part of the requirement states that no single impact category can show a greater than 5% increase. This illustrates the unifrom approach of the LEED critiea, as impact measures with significantly diffrent levels of importance are treated equally. Chart 12.3 shows the normalized and weighted contribution of each impact measure. The chart shows that there are large reductions acidification, smog formation, and global warming potential, which are all environmentally significat impact categories. The chart also illustrates that ozone depleteion is of relatively little importance.

Interpretation and Conclusion

Sources of potential error in this report lie in the Extra Materials input used to model the foundations in Athena. Identical quantities were used for the steel and timber buildings, when in reality the lighter timber construction would require less concrete/rebar in the foundation to provide adequate support. The result is an overly-conservative model, with outputs for the timber building containing more concrete/rebar than is necessary. Impacts for timber are still lower than steel, so the results of this conservative model would only skew more toward the existing trend if the foundation was made more accurate.

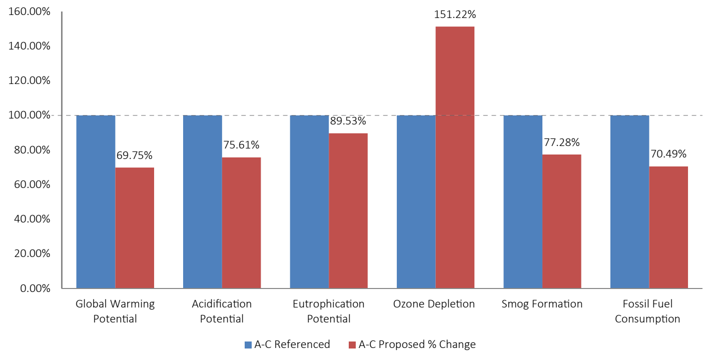


Chart 12.1 - Life cycle stages A-C impact measure comparisson for referenced and proposed buildings.

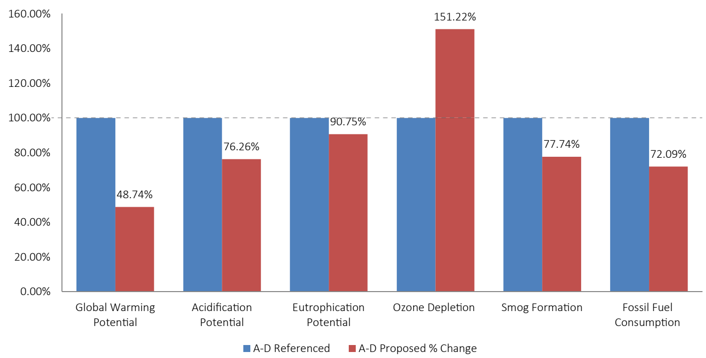


Chart 12.2 - Life cycle stages A-D impact measure comparisson for referenced and proposed buildings.

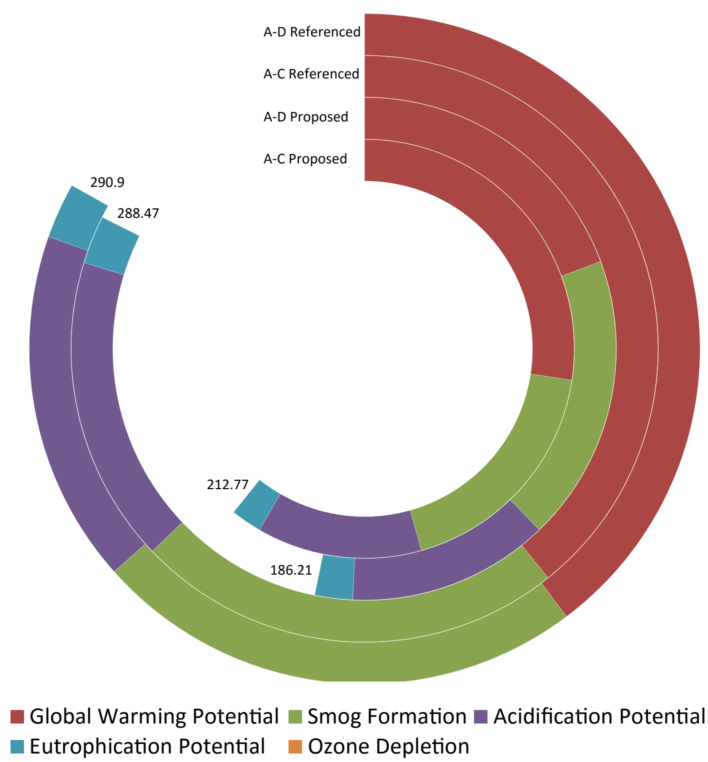


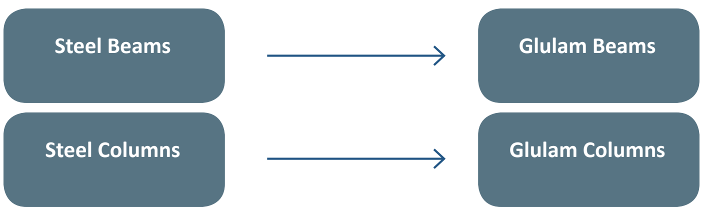
Chart 12.3 - Impact measures are normalized to reflect the number of units per person, per year in the United States, and weighted to reflect the importance of each measure. The chart shows the significance of the reduction of GWP, Smog, and Acidification, the relatively minor contribution of Eutrophition and Ozone Depletion.

Case Study 13(Nile): Substitution of Mass Timber for Steel in the Columns and Beams of a 5-Story, Commercial Building.

Goal

Scope

Inventory



Material	Reference	Proposed	Difference	Units
Concrete 20 MPa (flyash av)	3476.1936	2979.5945	496.5991	Tons
Concrete 30 MPa (flyash 25%)	8229.7173	8229.7173	0	Tons
Galvanized Sheet	0.1909	0.1909	0	Tons
GluLam Sections	0	811.8126	-811.8126	Tons
Large Dimension Softwood Lumber, kiln-dried	7.07	7.0744	-0.0044	Tons
Nails	0.1476	0.1476	0	Tons
Rebar, Rod, Light Sections	330.8331	319.6426	11.1905	Tons
Screws Nuts & Bolts	40.5697	0	36.2938	Tons
Softwood Plywood	4.2759	4.2759	0	Tons
Wide Flange Sections	795.6395	0	795.6395	Tons

Table 6.1 - Bill of materials generated by Athena.

Impact Assessment

Interpretation and Conclusion

Reference Building
A2 5 Story Steel

Proposed Building
5 Story Mass Timber

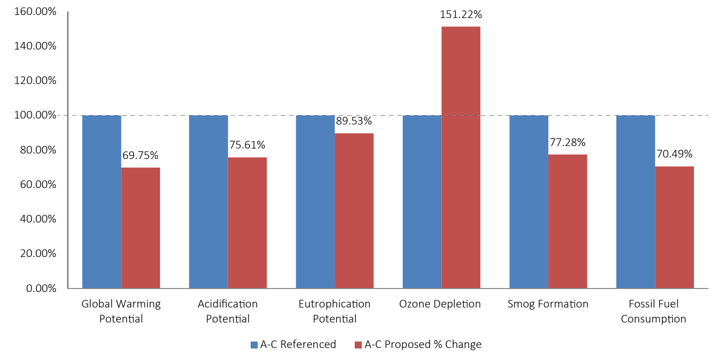


Chart 12.1 - Life cycle stages A-C impact measure comparisson for referenced and proposed buildings.

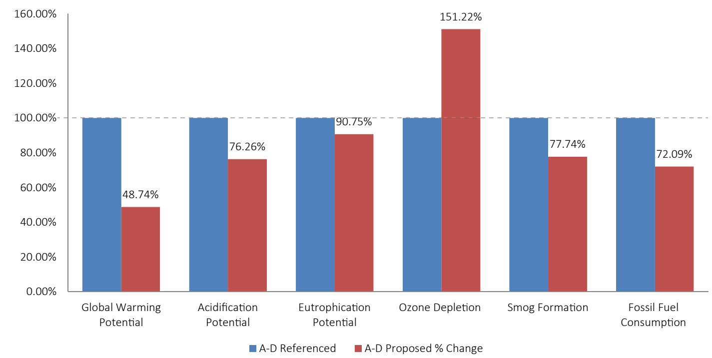


Chart 12.2 - Life cycle stages A-D impact measure comparisson for referenced and proposed buildings.

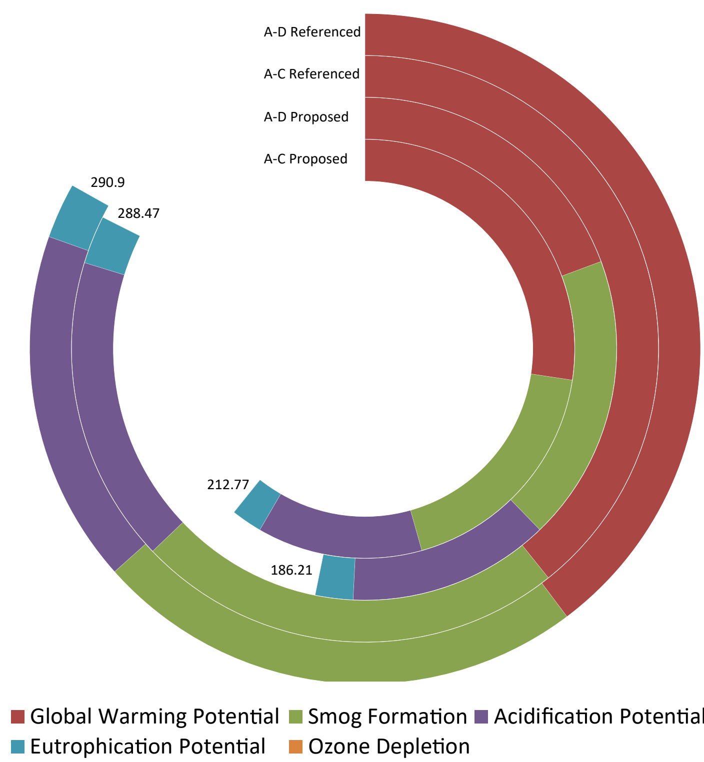


Chart 12.3 - Impact measures are normalized to reflect the number of units per person, per year in the United States, and weighted to reflect the importance of each measure. The chart shows the significance of the reduction of GWP, Smog, and Acidification, the relatively minor contribution of Eutrophition and Ozone Depletion.

TYPICAL OFFICE BUILDING STRUCTURAL SYSTEMS AND CLADDING
Ezekiel Jones
3.29.2016

CONTENTS

A. Overview

This project was done by Ezekiel Jones as a research assistant for Kate Simonen, Associate Professor of Architecture at the University of Washington in the College of Built Environments. The intent of this project is to define the typical Seattle office building in terms of both stuructral system and exterior cladding system. The study surveys a wide range of buildings currently in design or construction in the Pacific Northwest to define a structural system. Multiple building types were surveyed, and typical cladding types were found as well.

This fits into a larger research project through the College of Forestry, which will use this baseline building to determine environmental impact (EI) compared to Mass Timber alternatives to existing methods using Life Cycle Analysis. The results will determine the feasibility of Cross Laminated Timber production in the Puget Sound area, and the potential for a new office-building archetype that harnesses the benefits of mass timber.

B. Typical Office Building

This recommendation is meant for the Wood Research Group (WRG) led by Associate Professor Kate Simonen of the University of Washington to determine a typical office building in Seattle, WA. The parameters for typicality discussed here are limited to the structural system, and curtain wall. This recommendation draws upon student collected data from a University of Washington Seminar, phone interviews with both Architects and Structural Engineers, and Construction Documents from two buildings designed and built in the last 5 years in Seattle. This paper does not attempt to state universal truths, but instead recognizes patterns in design that are prevalent in the area.

Zoning

Based on surveys from 8 student reports, typical parcel sizes for office buildings in the Pacific Northwest averaged to 170 feet by 125 feet excluding an office tower outlier in Downtown Seattle that was discovered to be a residential project. However, these numbers are not indicative of a typical parcel. Sizes for office building parcels below 7 stories were 120-200 feet by 100-150 feet based on student surveys. Furthermore, office-building heights ranged between 5-7 stories and averaged to 6.66 stories. Assuming office buildings in Seattle are in a developer driven market, this paper recommends the use of 7 story office buildings above grade as it is the best representative of maximum FAR in the area based on the typical parcel sizes described above and the SM-85 height limit imposed in areas with a high density of office buildings. Furthermore, the 10 foot f.f. height that is typical in most office towers as described in *Programming*, confirms 7 stories in an 85 foot max height zone.

Programming

In conversation with a structural engineer from the Seattle area, programmatic standards for big tech companies such as Amazon were described briefly. According to a contacted structural engineer, these standards consists of 10-foot desk modules, usually totaling 30’ O.C. so that each desk has an unobstructed view out of a window. Furthermore, the typical floor to ceiling height in most office spaces is 10 feet.

Below grade parking is based on the gross square footage of the building with 1 parking spot for every 800-1000 gsf. So, assuming the latter end of that scale, a 120,000 square foot building would require 120 parking spots. This rule does not apply to buildings that are located in high transit areas, but decisions in these areas are limited by developer discretion. It is typical for office buildings in the Seattle area to be mixed use, with commercial uses typically filling the first floor due to zoning incentives.

Subgrade Superstructure

Foundations are primarily concrete, with continuous footings, typically 2-4 feet wide and 1.5-2 feet deep, around the perimeter of a building that follow the retaining wall below grade, 10x10x3 spot footings below each column in the building superstructure, and 3 foot deep mat footings below shear cores to prevent overturning. Mat Foundation width and length are based on shear core dimensions, but if dimensions are not given one can assume between 12-15 ft^2. Below grade retaining walls extend 2-3 stories, dependent on the number of parking stalls in the building, with floor to floor heights of 9 feet and width of 10-12” dependent on soil type. s

Slab on grade consists of 4” typically reinforced concrete slabs that include welded wire mesh and typical #4 reinforcement each way. All other floors above the slab on grade are typically one-way of 8” post-tensioned concrete slabs. When spans greater than 30 feet are in place, 18” post tensioned beams are common.

Above Grade Superstructure

The typical office building, based on economic and physical constraints is primarily built out of concrete. Based on conversations with three structural engineers, it was conferred that the typical office building has 18”x24” columns at typical floors. while columns with vertical spans greater than 10’, which are typical in first floor levels of office buildings, have 24”x24” columns. Typically to span greater than 30 ft, 18” post-tensioned beams are used. Similar to below grade, 8” P.T. slabs are typical.

Shear Core

Shear cores are largely dependent on architectural schematics and floor size. The ideal office building based on Corporate Standards and modular 10x10 office spaces, only having one shear core as shown below. Buildings larger than 120x120 will typically have 2 shear cores. Wall thickness is generally 12-14” but can get as thick as 20” below grade.

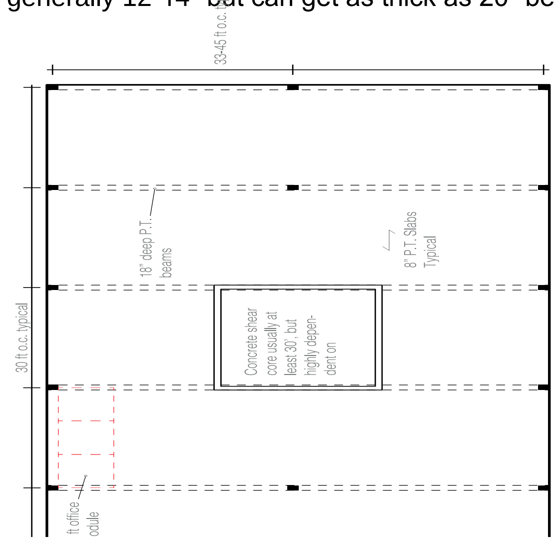


FIGURE 1 - Baseline Office Building Based on given 10’x10’ office space Module. Floor footprint is equal to 90’x 150’.

1’”= 50’

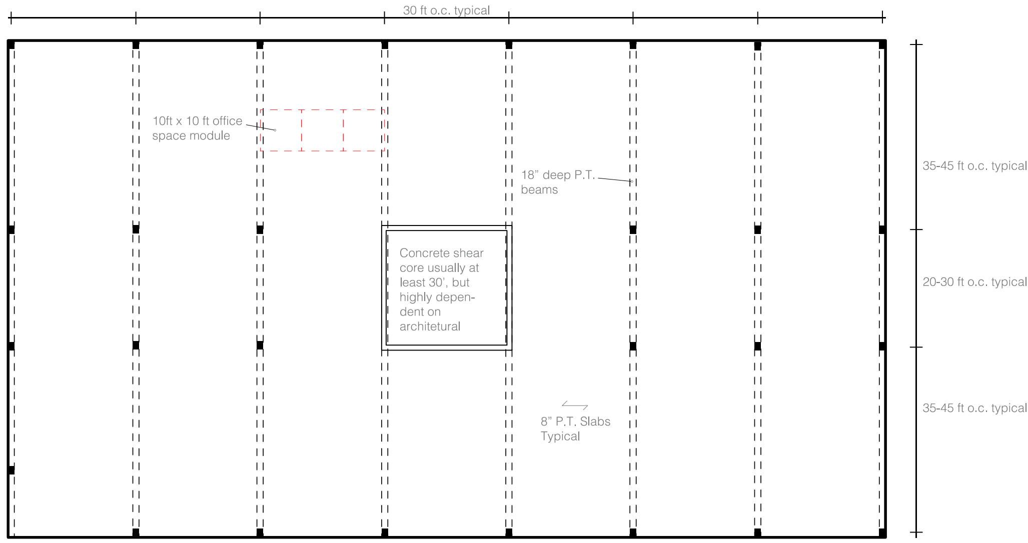


FIGURE 2 - Typical Office Building Based on Big Tech 10'x10' office space Module. Floor footprint is equal to 210'x 120'.

1" = 50'

PORTLAND
-2'x2' columns
-22' on center, each way.
-An alternative lot size is 220' x 110'.

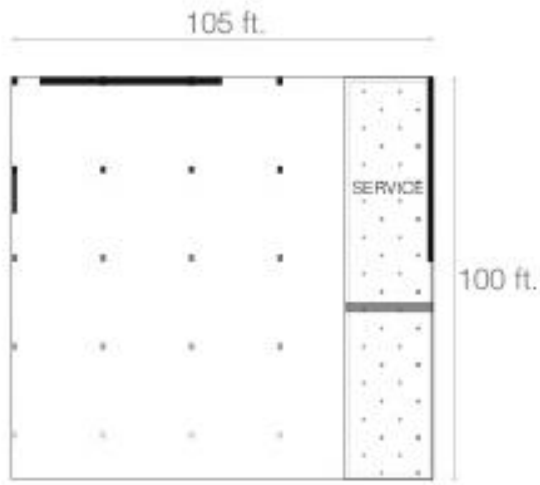


FIGURE 3. Typical small urban infill office space in Portland. 105'x100'
1" = 50'

BELLEVUE

- Typically, 7 spaces at 30’ O.C., or 11 spaces at 20’, 1 concrete shear core.
- An alternative lot size is 250’ x 150 with a building size of 200’ x 70’.
- Generally >15 stories.
- Many different variations of campus office building geometry
- Typically 60-120 foot wide masses joined together, often with atypical geometries.
- Typically 150-600 feet long.
- 1-2 story buildings will be built out of pre-cast, tilt up concrete panels, but less common on campuses

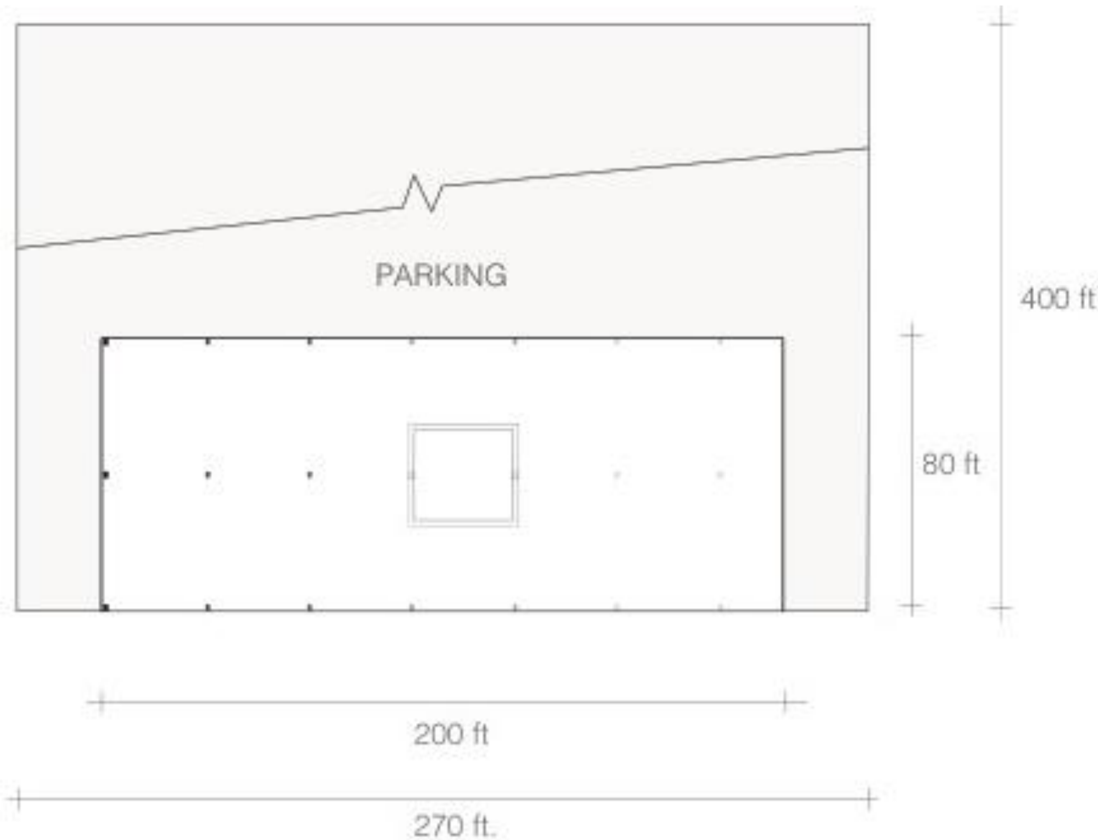


FIGURE 4 - Typical Office Building in Bellevue. Floor footprint is equal to 200’ x80’.

1” = 50’

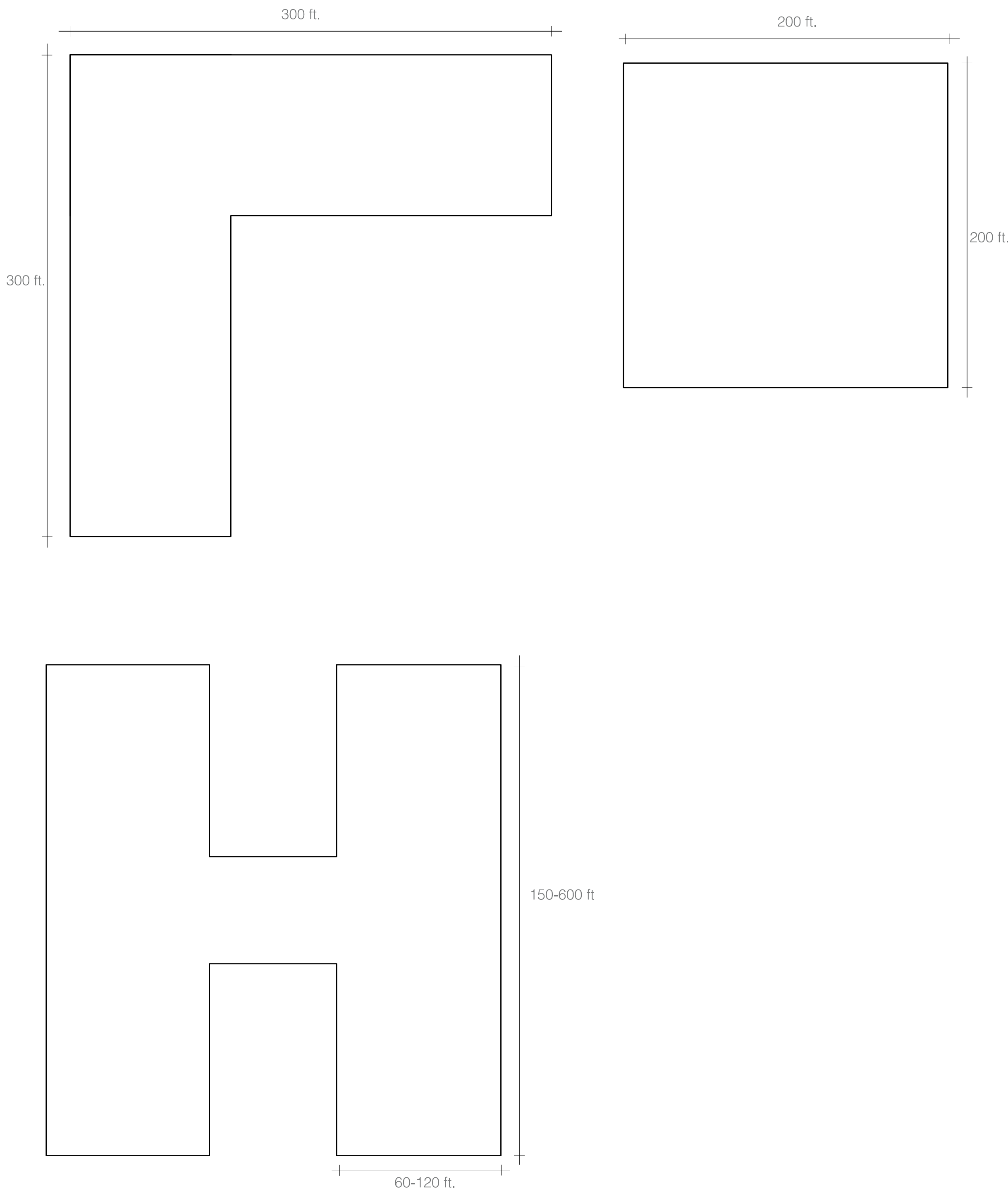


FIGURE 5 – Typical Campus Building Geometries. Typically 60-120’ bars ranging around 300 feet in length.

1” = 100’

Typical Office Building Envelope

The typical Office Building Envelope in the Seattle area varies by location and time it was built. However, based on empirical surveys of previously built work and drawings for future work, and International Building Code regarding Vertical Fenestration, Seattle office buildings primarily have two types of building envelope. The first is a curtain wall system with spandrel glass, and the second is a punched window and solid wall system. Both systems generally equate to about 40% glazing based on International Code Section C402.3.1.1, which states:

Increased vertical fenestration area with daylighting controls. In Climate Zones 1 through 6, a maximum of 40 percent of the gross above-grade wall area shall be permitted to be vertical fenestration, provided: 1. No less than 50 percent of the conditioned floor area is within a daylight zone; 2. Automatic daylighting controls are installed in daylight zones; and 3. Visible transmittance (VT) of vertical fenestration is greater than or equal to 1.1 times solar heat gain coefficient (SHGC).

Typical Curtain wall systems will have 40-60% glazing along with a corresponding 40-60% spandrel glass that but into one another. This appears to be the most common glazing type that is being built currently in the Seattle and Portland areas.

The alternative is a punched window system, with similar 40% max glazing punched windows. The solid portion of the wall is comprised of metal stud and either brick, or stone.

D. Methods for Environmental Impact Assessment

Once the typical office building was determined at a larger scale, the building cladding materials were given an environmental impact and material quantity to give the structural system environmental impact values an order of magnitude within the larger shell and core system.

Four cladding major cladding systems were chosen: metal stud, concrete, CLT, and curtain wall. The four major systems were modeled and then iterated upon based on % glazing – solid wall ratio and cladding material on solid surfaces. The variation of cladding material over solid surfaces included: wood, brick, and metal panel (rainscreen). Results were compared between the larger structural cladding systems, and their associated rain screens.

Once appropriate assemblies were chosen based on current practices on projects currently being constructed in the PNW and prior built works, the assemblies were modeled in Athena Building Impact Estimator to produce each assemblies environmental impact and its associated bill of materials. Data produced by Athena was taken into excel, made into a SF unit, and compared using Excel’s graphing functions.

In excel, the EI impacts were compared to each other using a baseline assembly treated as 100% EI and then comparing other assemblies to that baseline. The formula for comparison is discussed further in “Assumptions” and is still an area of uncertainty.

Assumptions

Assemblies were modeled as 840 square foot segments, using a 14x60 ft segment of wall. In Excel, the quantity was determined as a square foot number to be used in comparison with the other cladding assemblies.

G. Cladding Comparisons

See summary spreadsheet for tabulated values: sheet “3c Cladding Env Impacts” and “3c Cladding Material Quantities’.

See images at the end of this appendix for figures of the cladding assemblies.

J. RESOURCES

Scott Douglas
MG2
(206) 962-6500
scott.douglas@mg2.com

Dan Swaab
Mithun
dans@mithun.com

Reza Shafiei
CPL
(206) 343-0460
rezaf@cplinc.com

Koren Britt Copps
CKC Engineering
(425) 455-2144

John Tessem
DCI Engineers
(206) 332-1900
jtessem@dci-engineers.com

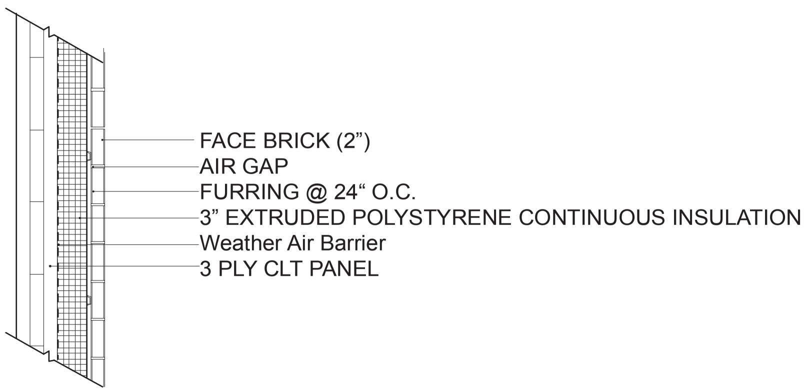
google.com/maps

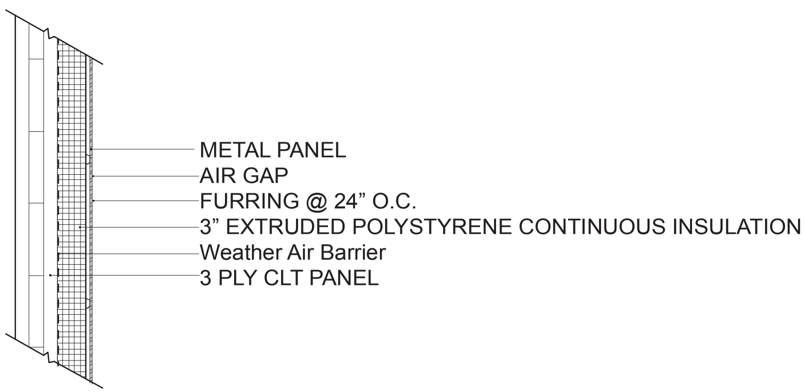
Next Portland - Architecture and Development in PDX. (2016, January 2). Retrieved January 2, 2016, from http://www.nextportland.com/

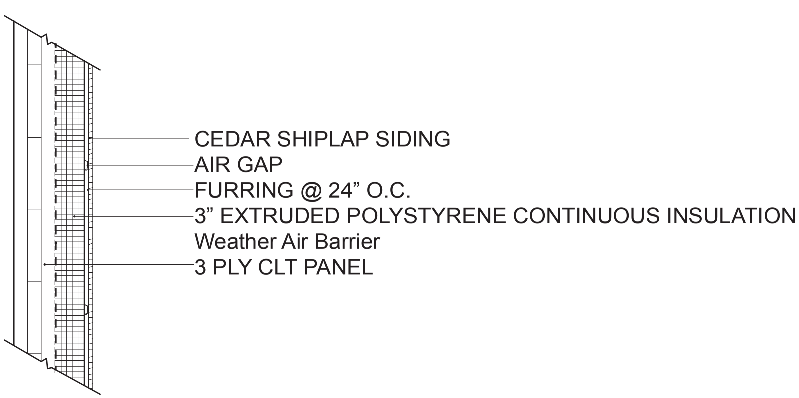
Building Code. (n.d.). Retrieved February 04, 2016, from http://www.seattle.gov/dpd/codesrules/codes/building/default.htm

http://www.archtoolbox.com/materials-systems/thermal-moisture-protection/rvalues.html
The architect's technical resource - archtoolbox.com. (n.d.). Retrieved February 2, 2016, from http://www.seattle.gov/dpd/codesrules/codes/building/default.htm

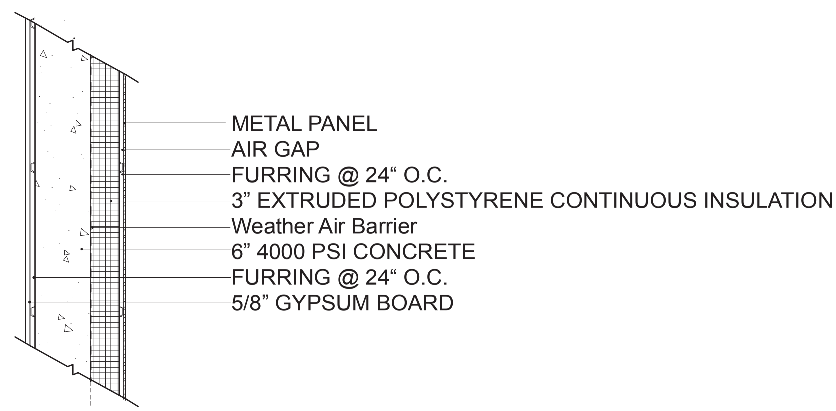
CLT ASSEMBLIES

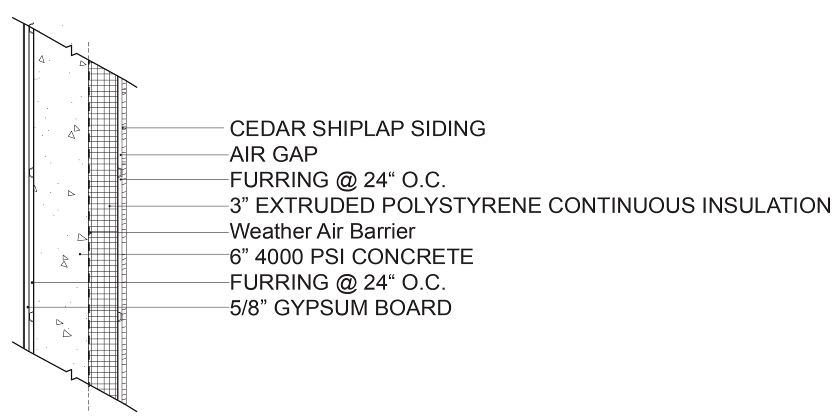




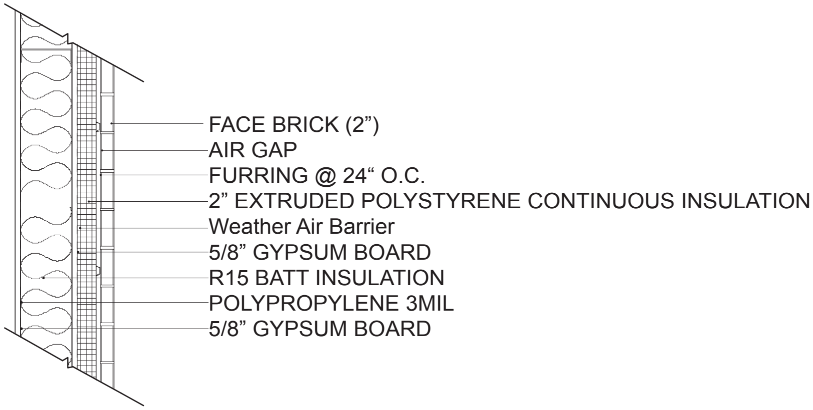


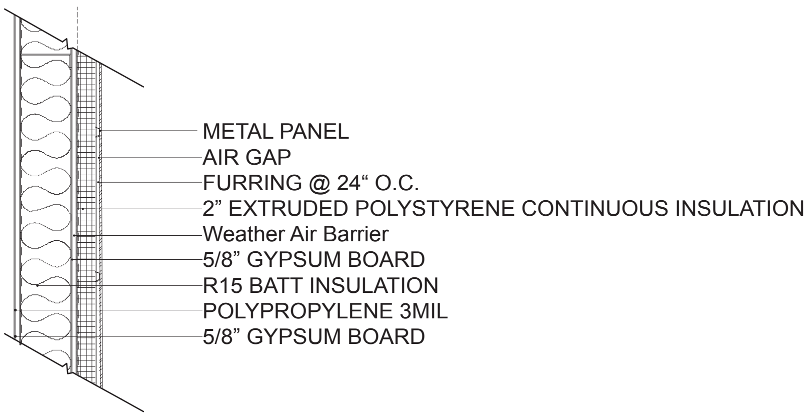
CONCRETE ASSEMBLIES

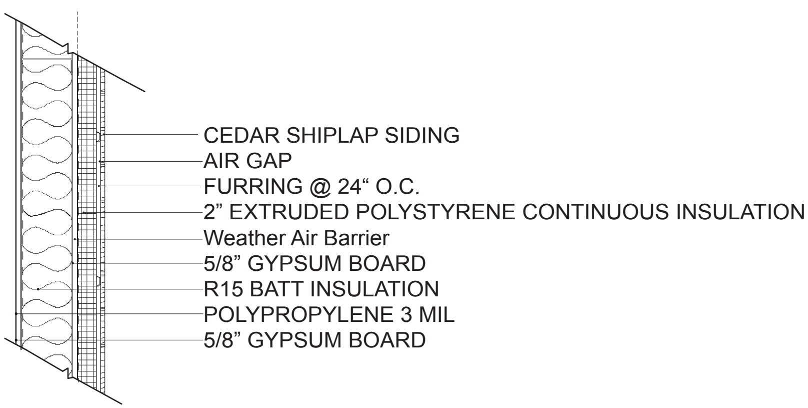




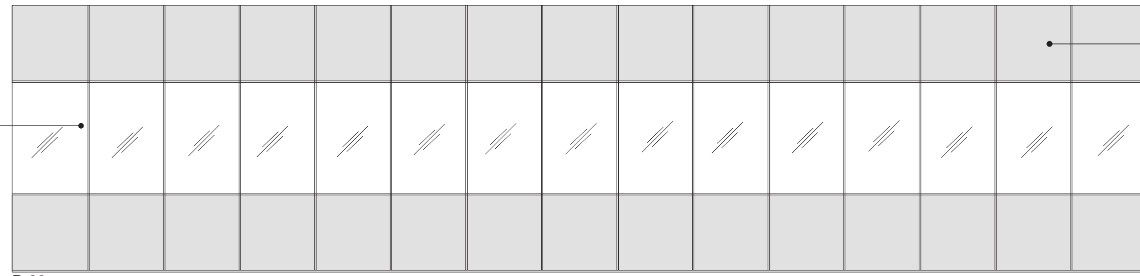
METAL STUD ASSEMBLIES







DOUBLE PANE WINDOW
(2) 6mm panels
low e coating
air fill
aluminum mullion at 6 ft o.c.



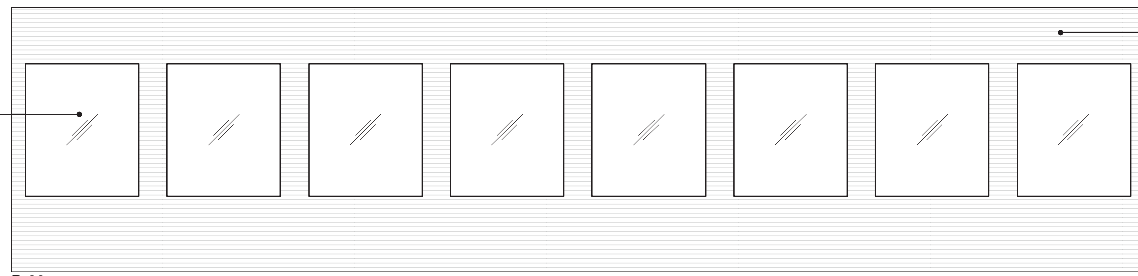
R-20

SPANDREL ASSEMBLY
6 mm opaque glass panel
metal backing
3" high density batt
WAB
5/8" gypsum board
R11-15 batt insulation
25 gauge steel stud
air barrier
5/8" gypsum board

SPANDREL % actually less, rest of building will be glazed proportional amount to get to 40%

curtain wall assembly
1/4"=1'

DOUBLE PANE WINDOW
low e coating
aluminum window frame
air fill

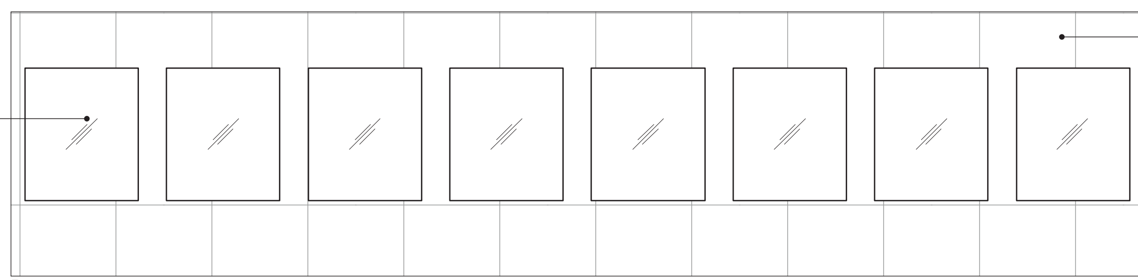


R-20

WALL ASSEMBLY
brick
2" expanded polystyrene rigid insulation
3 mil polyethelene
5/8" gypsum board
4" R11-15 batt insulation
25 gauge steel stud
air barrier
5/8" gypsum board

brick wall assembly
1/4"=1'

DOUBLE PANE WINDOW
low e coating
aluminum window frame
air fill

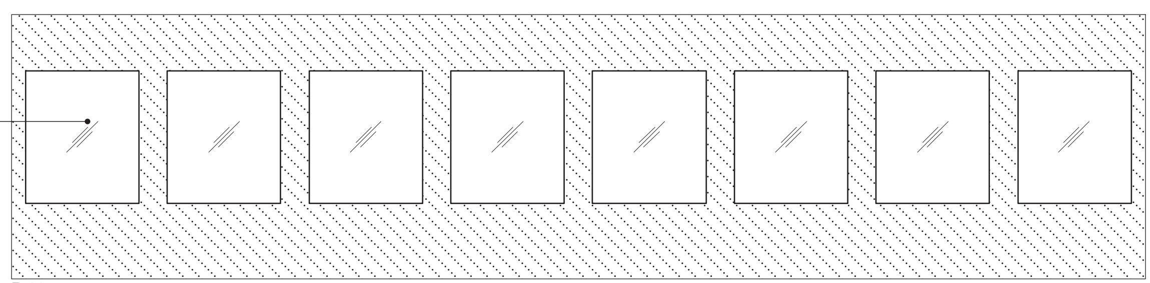


R-20

WALL ASSEMBLY
metal panel
expanded polystyrene rigid insulation
WAB
5/8" gypsum board
R11-15 batt insulation
25 gauge steel stud
air barrier
5/8" gypsum board

tilt up assembly
1/4"=1'

DOUBLE PANE WINDOW
low e coating
aluminum window frame
air fill



R-20

WALL ASSEMBLY
metal panel
3"extruded polystyrene rigid insulation
WAB
CLT

clt assembly
1/4"=1'

http://www.archtoolbox.com/materials-systems/thermal-moisture-protection/rvalues.html

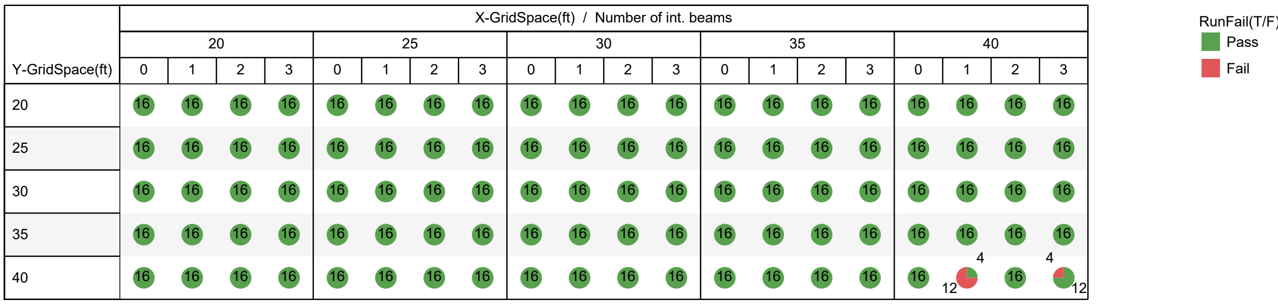
Overview of structural optimization results
12/30/17 run

Overview of all runs by X and Y grid spacing (table)	Number of runs by run pass/fail and grid spacing (pie charts)	Number of runs by labs pass/fail and grid spacing (pie charts)	Overview of all runs by X and Y grid spacing after filtering for failed runs (table)	Average building weight by grid spacing (heatmap)	Number of runs by total wood volume (beam + column + slab (histogram)	Average total wood volume by grid spacing (heatmap)	A v e. .

	X-GridSpace(ft) / Number of int. beams																				
	20				25				30				35				40				Grand Total
Y-GridSpace(..	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	
20	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	320
25	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	320
30	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	320
35	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	320
40	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	320
Grand Total	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	1,600

Overview of structural optimization results
12/30/17 run

Overview of all runs by X and Y grid spacing (table)	Number of runs by run pass/fail and grid spacing (pie charts)	Number of runs by labs pass/fail and grid spacing (pie charts)	Overview of all runs by X and Y grid spacing after filtering for failed runs (table)	Average building weight by grid spacing (heatmap)	Number of runs by total wood volume (beam + column + slab (histogram)	Average total wood volume by grid spacing (heatmap)	A v e. .



Overview of structural optimization results
12/30/17 run

- Overview of all runs by X and Y grid spacing (table)
- Number of runs by run pass/fail and grid spacing (pie charts)
- Number of runs by labs pass/fail and grid spacing (pie charts)
- Overview of all runs by X and Y grid spacing after filtering for failed runs (table)
- Average building weight by grid spacing (heatmap)
- Number of runs by total wood volume (beam + column + slab (histogram)
- Average total wood volume by grid spacing (heatmap)

	X-GridSpace(ft) / Number of int. beams																			
	20				25				30				35				40			
Y-GridSpace(ft)	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
20	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
25	16	16	16	16	8 8	16	16	16	8 8	16	16	16	8 8	16	16	16	8 8	16	16	16
30	16	16	16	16	8 8	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
35	16	16	16	16	8 8	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
40	16	16	16	16	8 8	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16

SlabsPass(T/F)
- Pass
- Fail

Overview of structural optimization results
12/30/17 run

- Overview of all runs by X and Y grid spacing (table)
- Number of runs by run pass/fail and grid spacing (pie charts)
- Number of runs by labs pass/fail and grid spacing (pie charts)
- **Overview of all runs by X and Y grid spacing after filtering for failed runs (table)**
- Average building weight by grid spacing (heatmap)
- Number of runs by total wood volume (beam + column + slab (histogram)
- Average total wood volume by grid spacing (heatmap)
- A v e. .

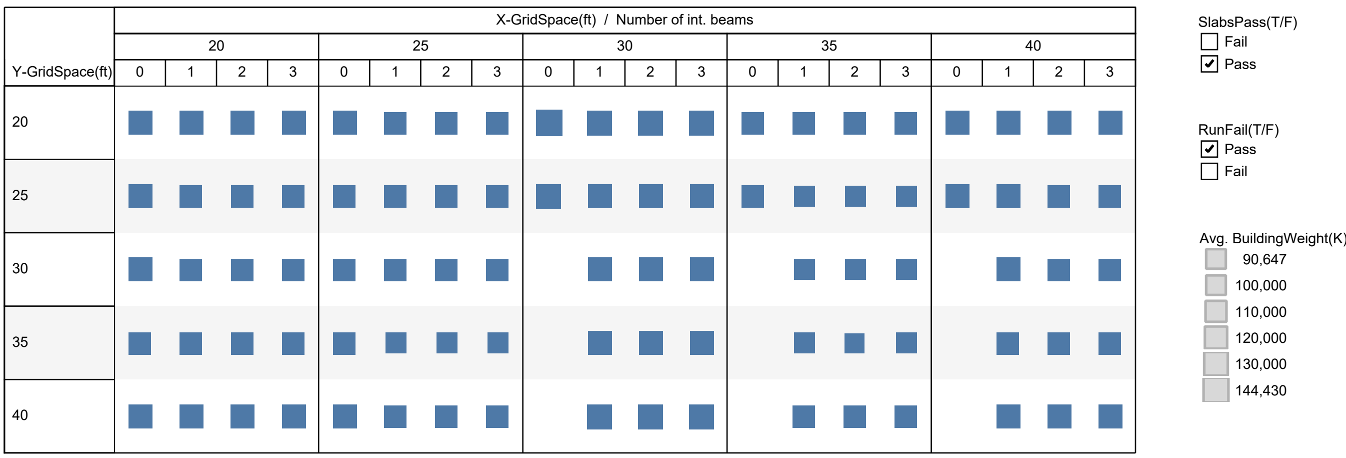
	X-GridSpace(ft) / Number of int. beams																				
	20				25				30				35				40				Grand Total
Y-GridSpace(..	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	
20	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	320
25	16	16	16	16	8	16	16	16	8	16	16	16	8	16	16	16	8	16	16	16	288
30	16	16	16	16	8	16	16	16		16	16	16		16	16	16		16	16	16	264
35	16	16	16	16	8	16	16	16		16	16	16		16	16	16		16	16	16	264
40	16	16	16	16	8	16	16	16		16	16	16		16	16	16		4	16	12	248
Grand Total	80	80	80	80	48	80	80	80	24	80	80	80	24	80	80	80	24	68	80	76	1,384

SlabsPass(T/F)
- [ ] Fail
- [x] Pass

RunFail(T/F)
- [x] Pass
- [ ] Fail

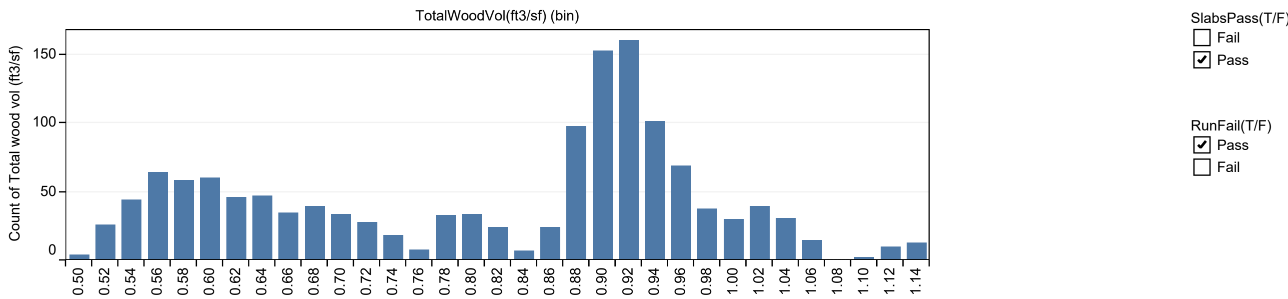
Overview of structural optimization results
12/30/17 run

- Number of runs by run pass/fail and grid spacing (pie charts)
- Number of runs by labs pass/fail and grid spacing (pie charts)
- Overview of all runs by X and Y grid spacing after filtering for failed runs (table)
- Average building weight by grid spacing (heatmap)
- Number of runs by total wood volume (beam + column + slab (histogram)
- Average total wood volume by grid spacing (heatmap)
- Average total wood volume by slab span (heatmap)



Overview of structural optimization results
12/30/17 run

Number of runs by labs pass/fail and grid spacing (pie charts)	Overview of all runs by X and Y grid spacing after filtering for failed runs (table)	Average building weight by grid spacing (heatmap)	Number of runs by total wood volume (beam + column + slab (histogram)	Average total wood volume by grid spacing (heatmap)	Average total wood volume by slab span (heatmap)	Total wood volume by slab span (plot)	A v e ..



Overview of structural optimization results
12/30/17 run

		X-GridSpace(ft) / Number of int. beams																			
		20				25				30				35				40			
Include charring (T/F)	Y-GridSpac..	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
False	20	0.82	0.55	0.56	0.58	0.84	0.56	0.57	0.58	0.86	0.69	0.58	0.59	0.87	0.82	0.59	0.61	0.89	0.96	0.72	0.61
	25	0.84	0.56	0.59	0.61	0.95	0.58	0.59	0.61	0.96	0.70	0.60	0.61	0.97	0.83	0.60	0.62	0.99	0.96	0.73	0.62
	30	0.85	0.58	0.62	0.64	0.97	0.59	0.61	0.63		0.72	0.61	0.63		0.84	0.62	0.65		0.98	0.75	0.65
	35	0.87	0.60	0.64	0.67	0.99	0.61	0.63	0.66		0.73	0.63	0.65		0.85	0.63	0.67		0.98	0.76	0.66
	40	0.89	0.63	0.67	0.71	1.01	0.64	0.67	0.69		0.75	0.66	0.68		0.87	0.66	0.70		0.88	0.78	0.68
True	20	0.91	0.87	0.91	0.93	0.92	0.88	0.90	0.92	0.92	0.89	0.90	0.92	0.93	0.89	0.91	0.93	0.95	1.02	0.92	0.93
	25	0.91	0.88	0.92	0.94	1.02	0.89	0.91	0.94	1.02	0.89	0.91	0.93	1.03	0.89	0.91	0.93	1.04	1.02	0.92	0.93
	30	0.93	0.90	0.94	0.97	1.03	0.90	0.93	0.95		0.90	0.92	0.94		0.90	0.92	0.96		1.03	0.93	0.95
	35	0.93	0.91	0.96	0.99	1.04	0.92	0.94	0.97		0.92	0.94	0.97		0.90	0.94	0.97		1.03	0.94	0.96
	40	0.95	0.93	0.99	1.02	1.06	0.94	0.97	1.01		0.94	0.96	0.99		0.92	0.96	1.00		0.92	0.96	0.98

SlabsPass(T/F)
- [ ] Fail
- [x] Pass

RunFail(T/F)
- [x] Pass
- [ ] Fail

Avg. Total wood vol (ft3/sf)
0.55 – 1.06

Overview of structural optimization results
12/30/17 run

			SlabSpan(ft)																
Include charring (T/F)		Y-Grid..	5.00	6.25	6.67	7.50	8.33	8.75	10.00	11.67	12.50	13.33	15.00	17.50	20.00	25.00	30.00	35.00	40.00
	False	20	0.58	0.58	0.56	0.59	0.57	0.61	0.58	0.59	0.56	0.72	0.69	0.82	0.89	0.84	0.86	0.87	0.89
		25	0.61	0.61	0.59	0.61	0.59	0.62	0.60	0.60	0.58	0.73	0.70	0.83	0.90	0.95	0.96	0.97	0.99
		30	0.64	0.63	0.62	0.63	0.61	0.65	0.61	0.62	0.59	0.75	0.72	0.84	0.92	0.97			
		35	0.67	0.66	0.64	0.65	0.63	0.67	0.63	0.63	0.61	0.76	0.73	0.85	0.93	0.99			
		40	0.71	0.69	0.67	0.68	0.67	0.70	0.66	0.66	0.64	0.78	0.75	0.87	0.89	1.01			
	True	20	0.93	0.92	0.91	0.92	0.90	0.93	0.90	0.91	0.88	0.92	0.89	0.89	0.96	0.92	0.92	0.93	0.95
		25	0.94	0.94	0.92	0.93	0.91	0.93	0.91	0.91	0.89	0.92	0.89	0.89	0.96	1.02	1.02	1.03	1.04
		30	0.97	0.95	0.94	0.94	0.93	0.96	0.92	0.92	0.90	0.93	0.90	0.90	0.98	1.03			
		35	0.99	0.97	0.96	0.97	0.94	0.97	0.94	0.94	0.92	0.94	0.92	0.90	0.98	1.04			
		40	1.02	1.01	0.99	0.99	0.97	1.00	0.95	0.96	0.94	0.96	0.94	0.92	0.94	1.06			

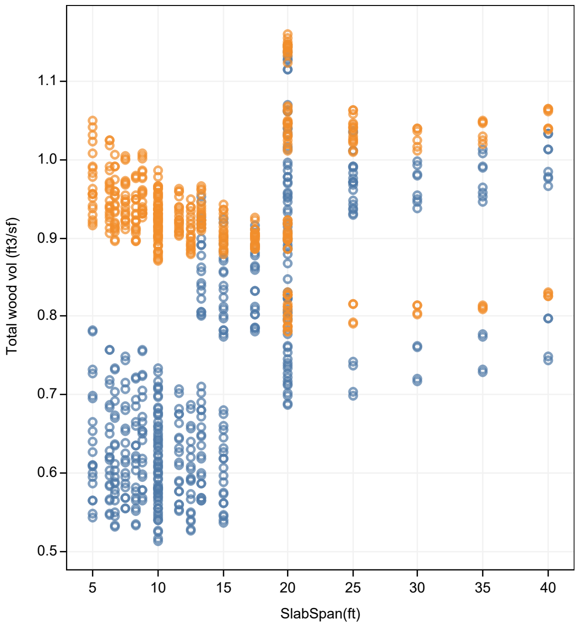
SlabsPass(T/F)
- ☐ Fail
- ☑ Pass

RunFail(T/F)
- ☑ Pass
- ☐ Fail

Avg. Total wood vol (ft3/sf)
0.56 – 1.06

Overview of structural optimization results
12/30/17 run

Number of runs by total wood volume (beam + column + slab (histogram)	Average total wood volume by grid spacing (heatmap)	Average total wood volume by slab span (heatmap)	Total wood volume by slab span (plot)	Average and median total wood volume by slab span (plot)	Average total wood volume by fire design and composite action options (box plots)	Median wood volume of building components (bar chart)	.

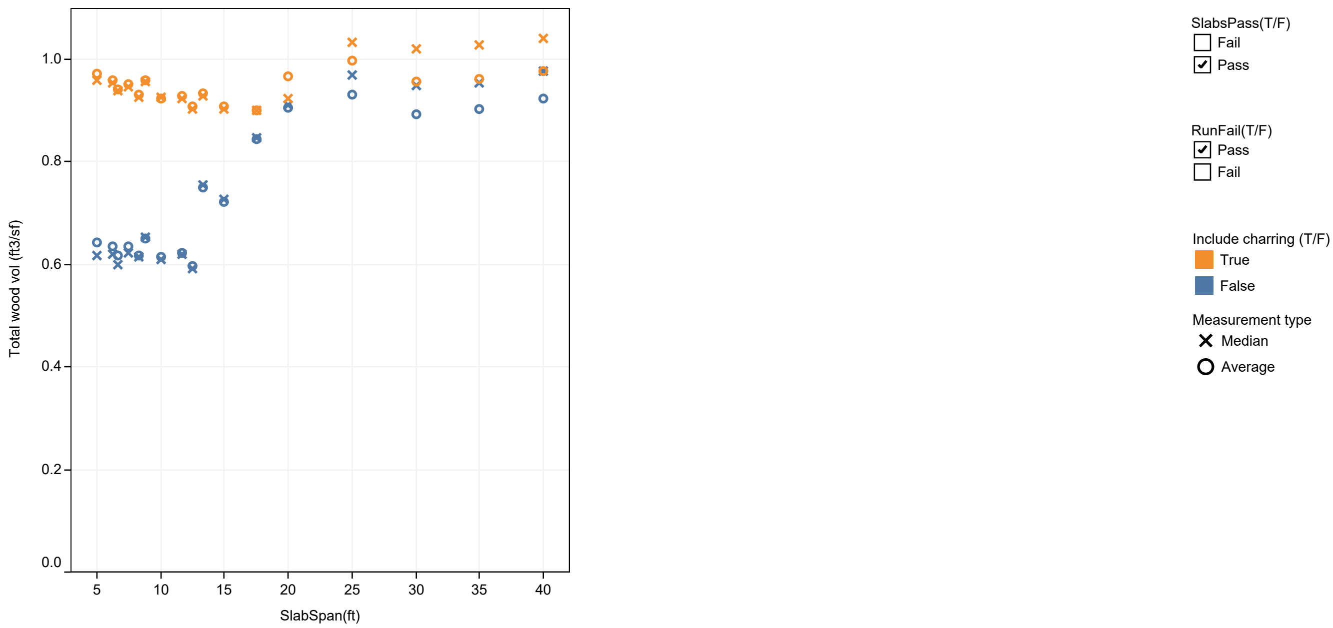


SlabsPass(T/F)
- [ ] Fail
- [x] Pass

RunFail(T/F)
- [x] Pass
- [ ] Fail

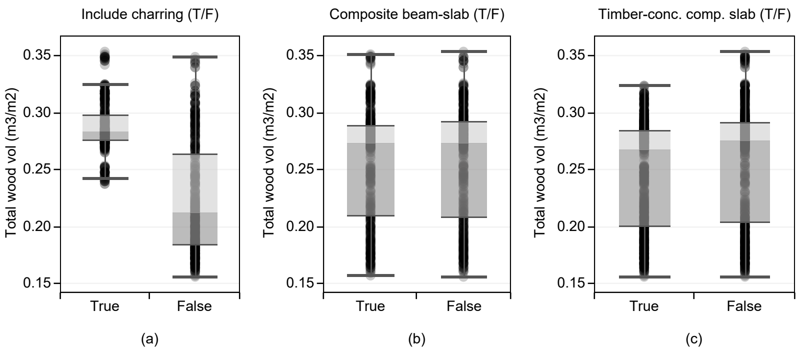
Include charring (T/F)
- True
- False

Overview of structural optimization results
12/30/17 run



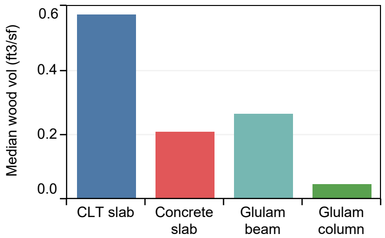
Overview of structural optimization results
12/30/17 run

Average total wood volume by slab span (heatmap)	Total wood volume by slab span (plot)	Average and median total wood volume by slab span (plot)	Average total wood volume by fire design and composite action options (box plots)	Median wood volume of building components (bar chart)	Number of runs by floor clearance (bar chart)	Number of runs by max deflection (histogram)	.



Overview of structural optimization results
12/30/17 run

Total wood volume by slab span (plot)	Average and median total wood volume by slab span (plot)	Average total wood volume by fire design and composite action options (box plots)	Median wood volume of building components (bar chart)	Number of runs by floor clearance (bar chart)	Number of runs by max deflection (histogram)	Number of runs by max beam depth (histogram)



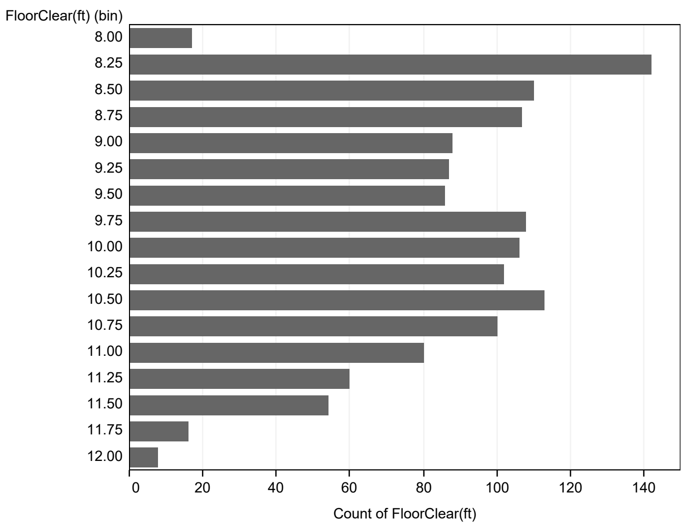
SlabsPass(T/F)
- [ ] Fail
- [x] Pass

RunFail(T/F)
- [x] Pass
- [ ] Fail

Measure Names
- CLT slab
- Concrete slab
- Glulam beam
- Glulam column

Overview of structural optimization results
12/30/17 run

Average and median total wood volume by slab span (plot)	Average total wood volume by fire design and composite action options (box plots)	Median wood volume of building components (bar chart)	Number of runs by floor clearance (bar chart)	Number of runs by max deflection (histogram)	Number of runs by max beam depth (histogram)	Number of runs by max column dimension (histogram)	.

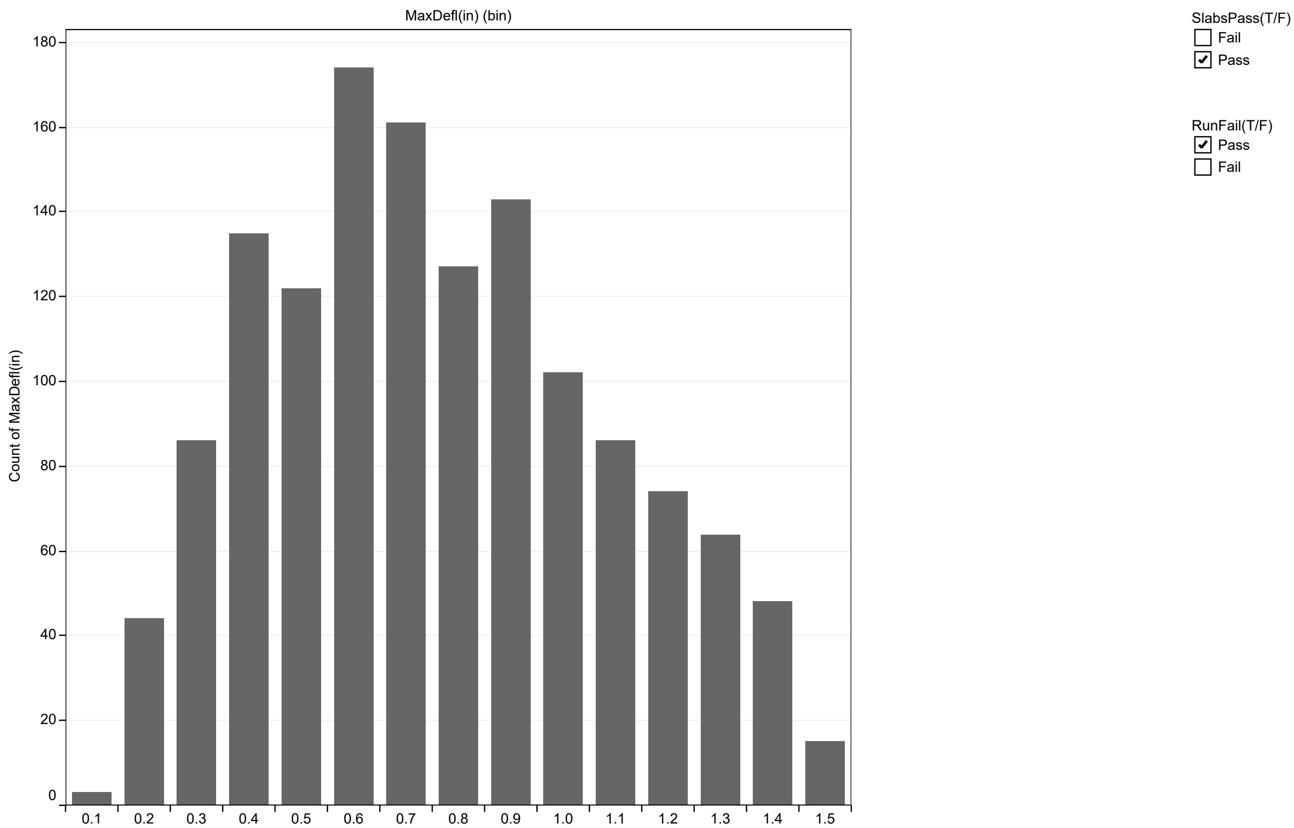


SlabsPass(T/F)
- [ ] Fail
- [x] Pass

RunFail(T/F)
- [x] Pass
- [ ] Fail

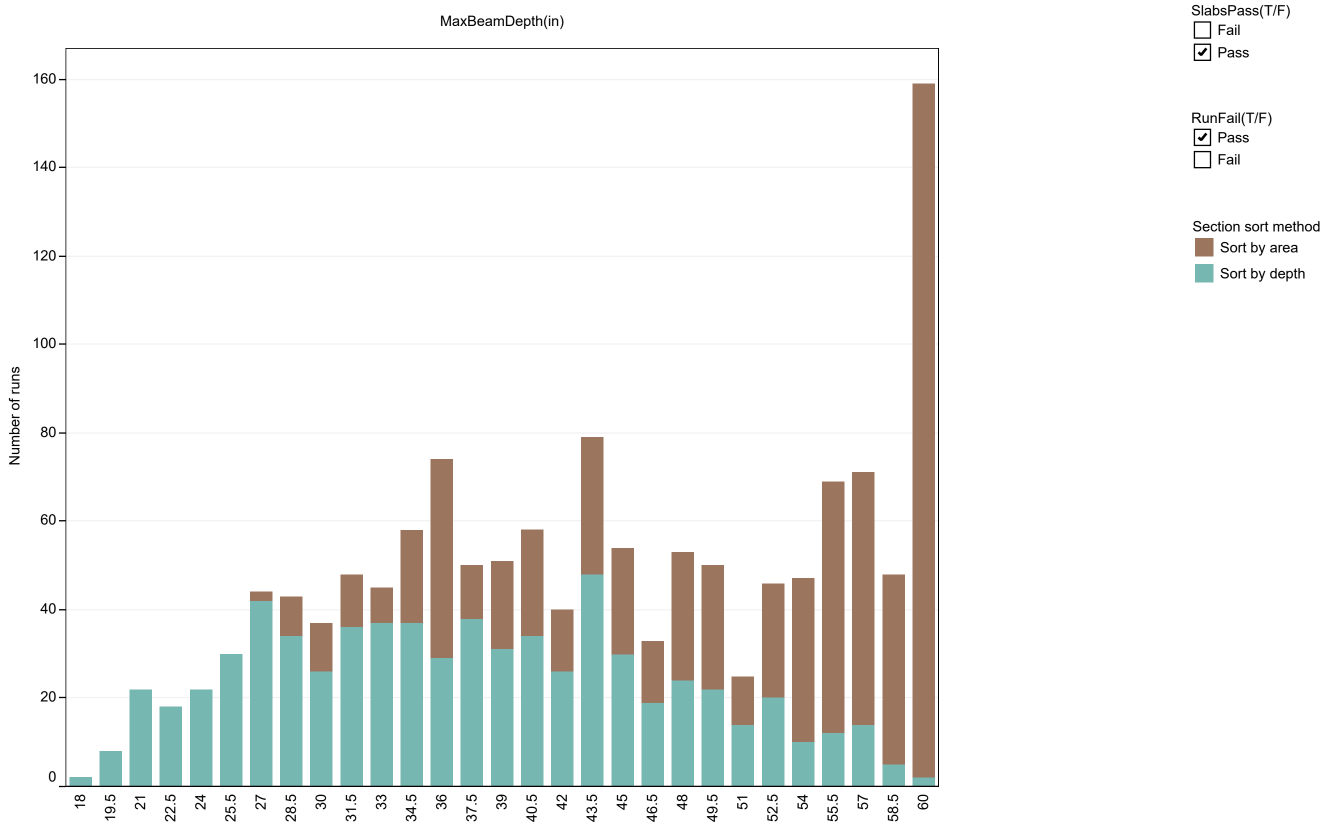
Overview of structural optimization results
12/30/17 run

Average total wood volume by fire design and composite action options (box plots)	Median wood volume of building components (bar chart)	Number of runs by floor clearance (bar chart)	Number of runs by max deflection (histogram)	Number of runs by max beam depth (histogram)	Number of runs by max column dimension (histogram)	Number of runs by CLT thickness (chart)	.



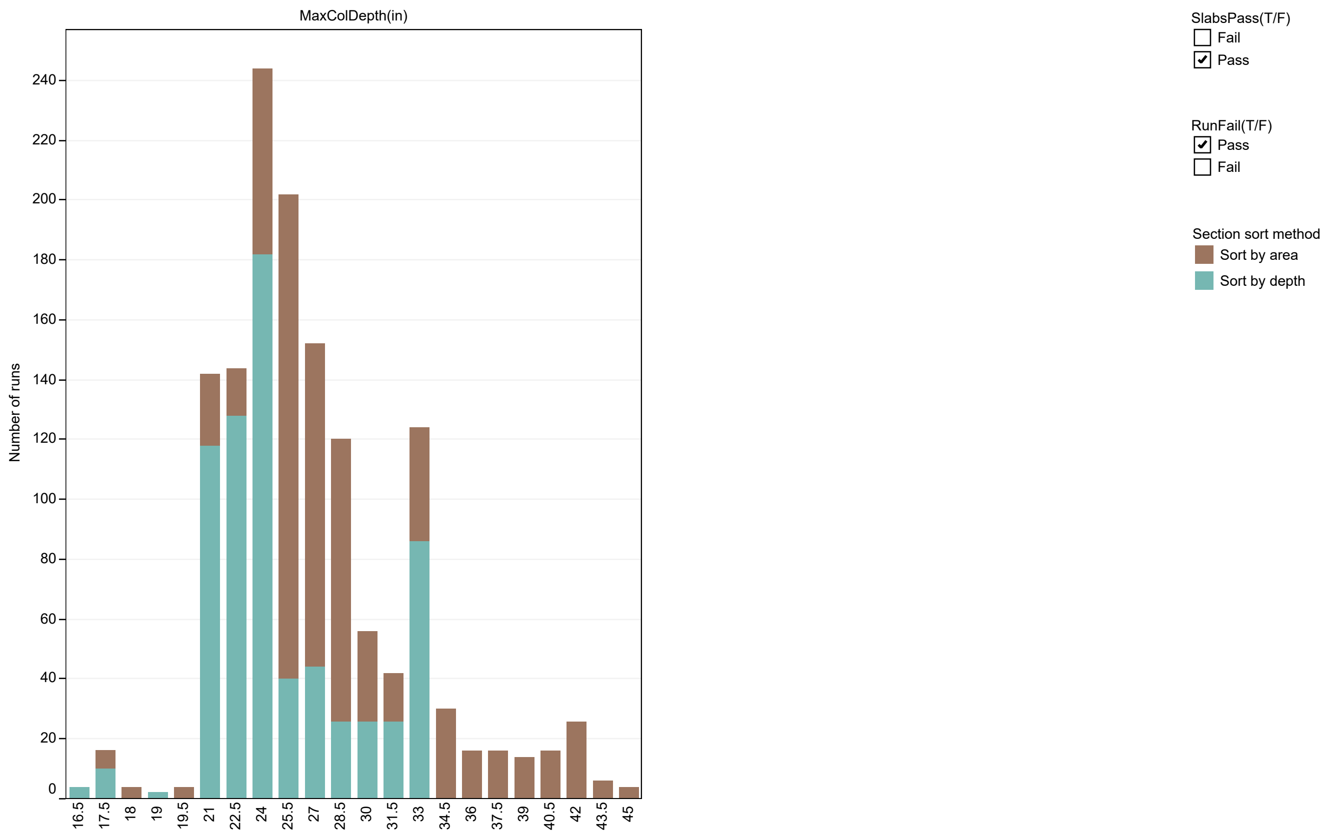
Overview of structural optimization results
12/30/17 run

Median wood volume of building components (bar chart)	Number of runs by floor clearance (bar chart)	Number of runs by max deflection (histogram)	Number of runs by max beam depth (histogram)	Number of runs by max column dimension (histogram)	Number of runs by CLT thickness (chart)	Number of runs by CLT thickness (heatmap + pie chart)	S e l. .



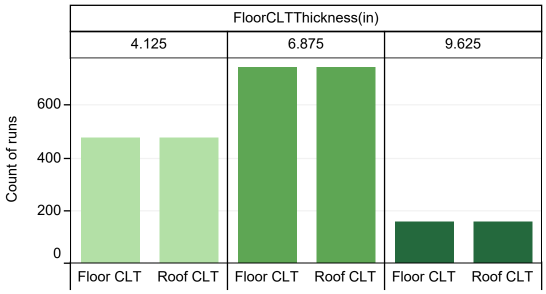
Overview of structural optimization results
12/30/17 run

Number of runs by floor clearance (bar chart)	Number of runs by max deflection (histogram)	Number of runs by max beam depth (histogram)	Number of runs by max column dimension (histogram)	Number of runs by CLT thickness (chart)	Number of runs by CLT thickness (heatmap + pie chart)	Selection of configurations #1-3	S e l. .



Overview of structural optimization results
12/30/17 run

N u m ..	Number of runs by max deflection (histogram)	Number of runs by max beam depth (histogram)	Number of runs by max column dimension (histogram)	Number of runs by CLT thickness (chart)	Number of runs by CLT thickness (heatmap + pie chart)	Selection of configurations #1-3	Selection of configuration #4

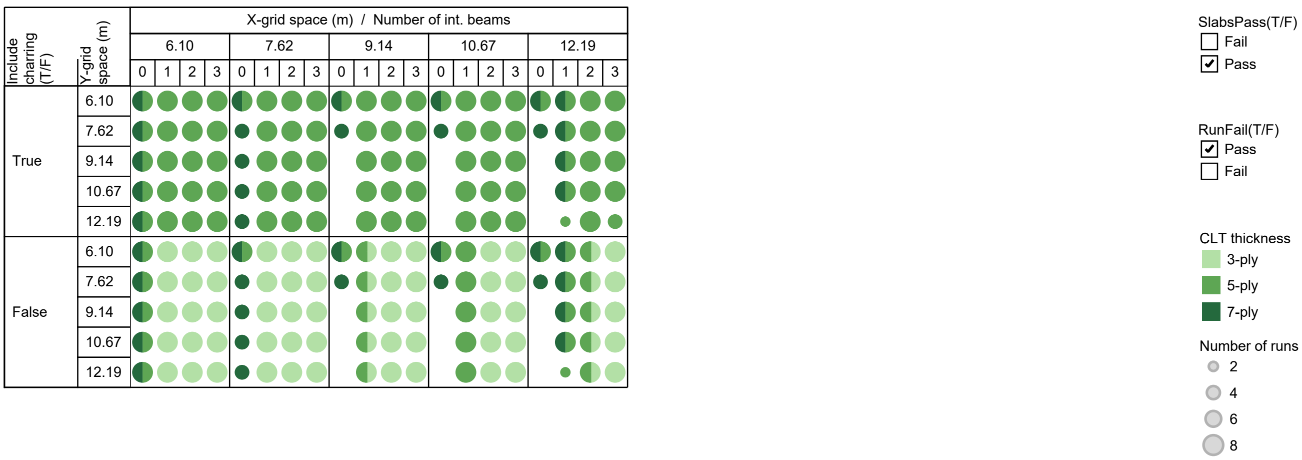


SlabsPass(T/F)
- [ ] Fail
- [x] Pass

RunFail(T/F)
- [x] Pass
- [ ] Fail

RoofCLTThickness(in)
- 3-ply
- 5-ply
- 7-ply

Overview of structural optimization results
12/30/17 run



Overview of structural optimization results
12/30/17 run

N u m ..

Number of runs by max deflection (histogram)

Number of runs by max beam depth (histogram)

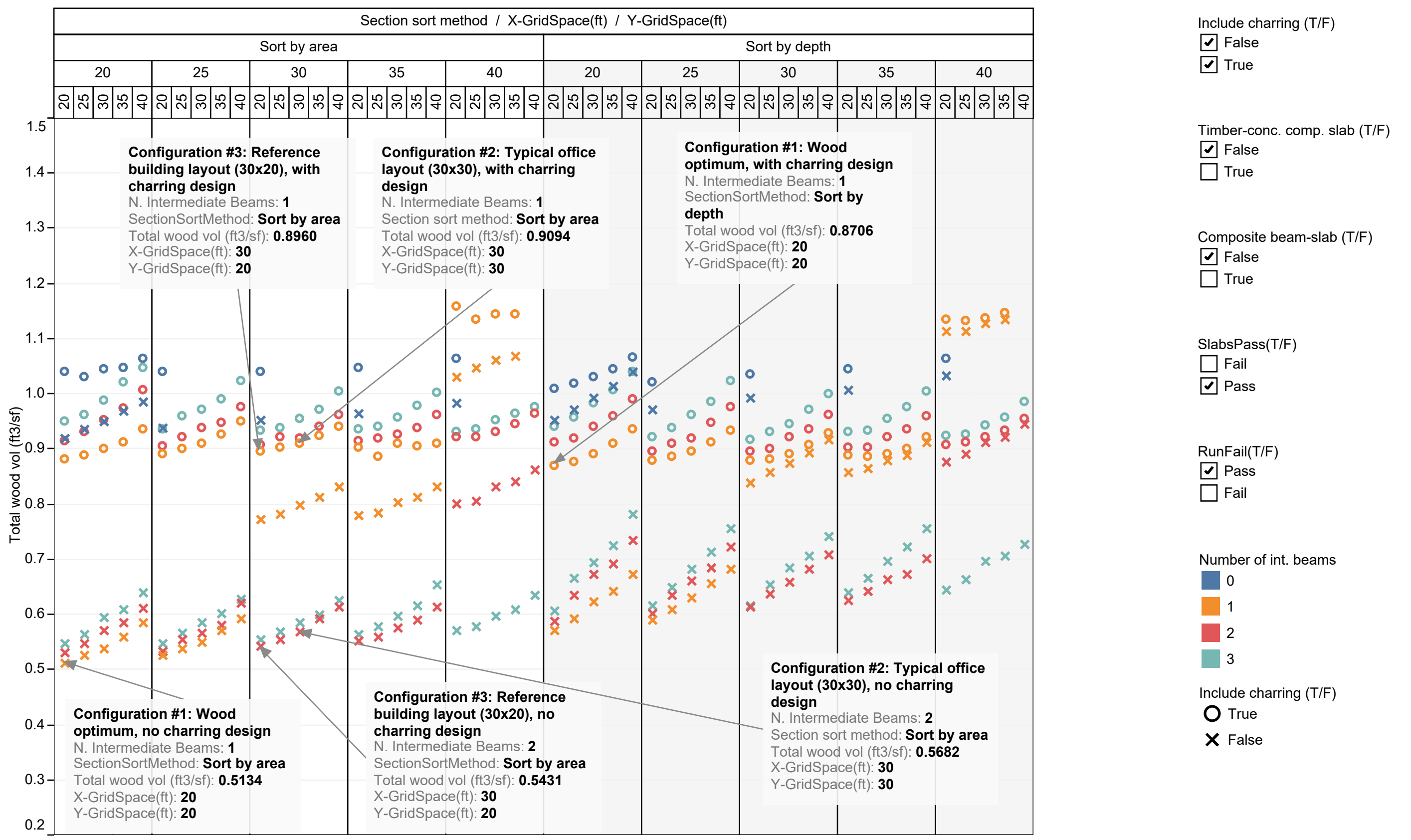
Number of runs by max column dimension (histogram)

Number of runs by CLT thickness (chart)

Number of runs by CLT thickness (heatmap + pie chart)

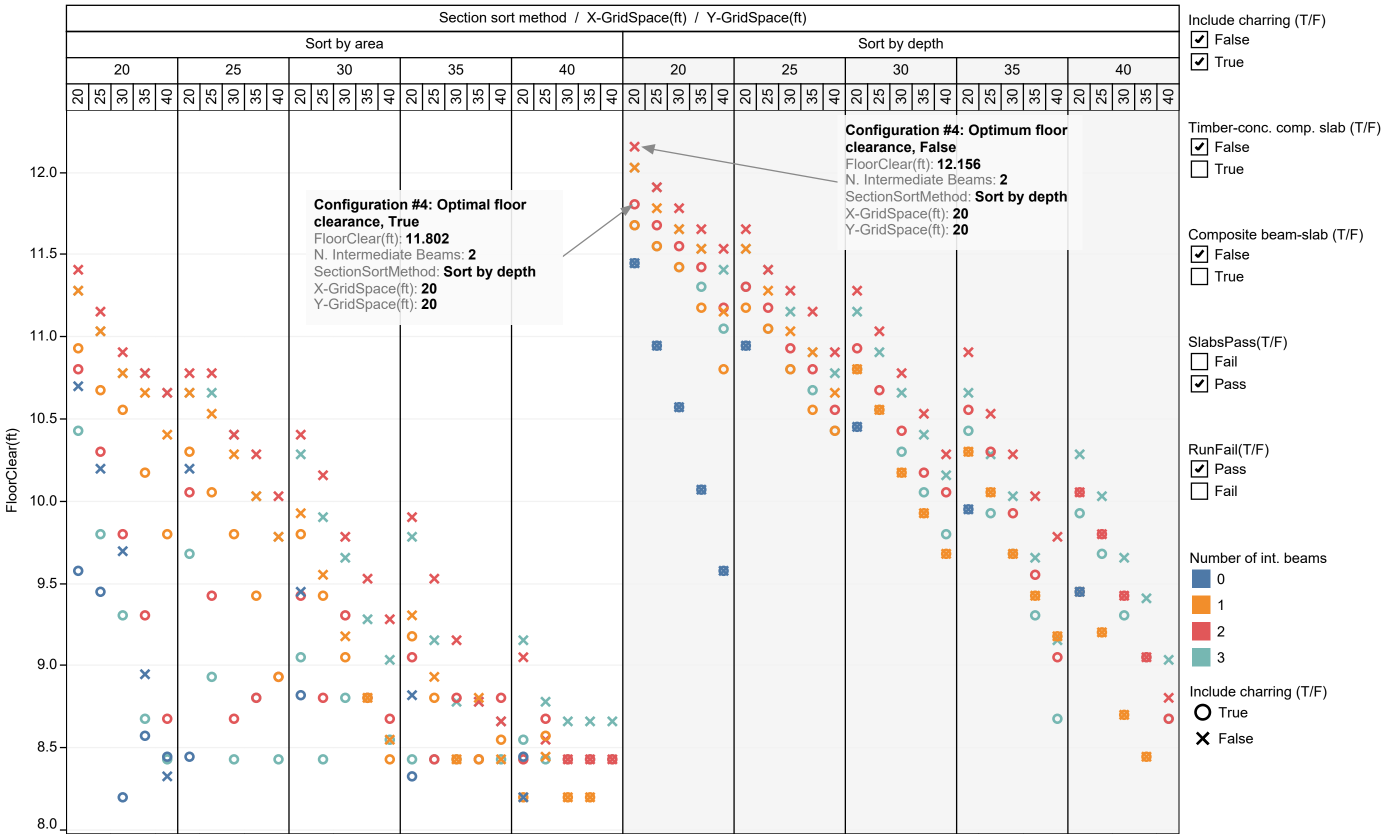
Selection of configurations #1-3

Selection of configuration #4



Overview of structural optimization results
12/30/17 run

N u m ..	Number of runs by max deflection (histogram)	Number of runs by max beam depth (histogram)	Number of runs by max column dimension (histogram)	Number of runs by CLT thickness (chart)	Number of runs by CLT thickness (heatmap + pie chart)	Selection of configurations #1-3	Selection of configuration #4



TYPICAL OFFICE BUILDING CALCULATIONS and REFERENCE BUILDING 2 QTO
Ezekiel Jones
1.2.2016

CONTENTS

A. Overview

This project was done by Ezekiel Jones as a research assistant for Kate Simonen, Associate Professor of Architecture at the University of Washington in the College of Built Environments. The intent of this project is to discern the average amount of Rebar and Concrete in a typical Seattle office building The prototype office building being determined has conditions below grade and in the lateral systems that are widely unknown. The purpose of this study is to resolve those unknowns and turn them into rebar and concrete quantities that can then be used to gauge against alterative structural options in Life Cycle Assessment.

This fits into a larger research project through the College of Forestry, which will use this baseline building to determine environmental impact compared to Mass Timber alternatives to existing methods using Life Cycle Analysis. The results will determine the feasibility of Cross Laminated Timber production in the Puget Sound area, and the potential for a new office-building archetype that harnesses the benefits of mass timber.

The attached excel sheet provides the template for quick quantity take off of variable sized office buildings ranging in size from 7-10 stories using given information, with subgrade parking ranging in size from 1-3 levels. Office buildings are assumed to be on a standard grid system based on the zoning and block geometry in Seattle. Concrete and Rebar numbers are based on standard details from surveys of five structural engineers in the Pacific Northwest area. Rebar and Concrete quantities are placed in Quantity per Lineal Foot measures that are then used to determine total Concrete and Rebar quantities for the whole building using a formula that includes number of columns, LF of shear wall, foundation systems and shear cores, and slab quantities.

The idea behind a formula like this is that the typical office building being quantified might change based on zoning, allowable footprint, and number of stories both above and below grade. Only having to replace a limited number of information when these changes occur means that as more information is found to indicate a true typical office building or multiple archetypes are determined to be suitable, the calculation of their base quantities is easily reached through changing the numbers in a select few excel boxes as opposed to recalculating the whole building.

Rebar quantities are taken using standard details for both columns, subgrade retaining walls, slab on grade, foundation and shear core quantities.

Summary

Reference Building 2 Below Grade +Shear Core

Category	Tons Rebar	CY Concrete
Footings	41	551
Below Grade Walls	52	728
Columns	14	88
Slab on Grade	8	286
Shear Core	83	518
TOTAL	198	2171

B. Method

The means of getting information was based on standard detailing from two construction drawings sets of office buildings being built in Seattle as well as phone conversations with local structural engineers and architects.

The first construction drawing set was from an office building in the South Lake Union Neighborhood of Seattle, with [redacted] stories of below grade parking, and [redacted]stories of above grade parking, totaling 123,000 gross square feet. The building's structural system was entirely concrete with one-way post tensioned slabs above grade and two shear cores at either end of the building's long dimension. The structural system consisted of 2'x2 columns at 30' spacing in the long direction and 23' spacing in the short direction.

The second construction drawing set was from an office building in the Fremont Neighborhood of Seattle at the confluence of [redacted] The building is close to the North Shore of South Lake Union, and consists of [redacted] stories below grade and [redacted] stories above grade. It to, has a structural system made entirely of concrete post tensioned slabs with only one shear core at the center of the building and a shear wall that runs adjacent. 2'x2' columns are spaced at 30' in the long direction and irregularly in the short direction.

Average details, sizing, and foundation systems were also determined by calling three structural engineers and two architects. Fifteen professionals working in the Seattle area were called, and four answered. Ten of those professionals are architects who were called because they were responsible for case study buildings summarized in a University of Washington Life Cycle Assessment class. Of the five who answered, two structural engineers and one architect provided lengthy conversations with many details about the buildings they are working on or have worked on in the past, including standard detailing at their firms.

The ten LCA summaries were also used to determine average column spacing, structural type, and other variables.

C. Areas of uncertainty & Ideas for future work.

Uncertainty:

1. Basement Wall Quantities.

While the basic concrete quantities are accurate, the rebar quantities for shear walls do not include doweling or lap splicing details. This should be addressed to get an increased rebar/lf of wall quantity.

2. Column Rebar Quantities
Rebar quantities should be assessed further and an average should be determined using a take off from a single 5-7 story building and dividing that total quantity by the number of floors in the building. Since rebar size increases at the lower levels of the building an average number should be found but will be dependent on the number of floors that are determined to be average. As of now, the rebar quantity used is based on an average for an 8 story building with 2'x2' columns, however, the CY of Concrete quantity is based on 18" by 24" columns.

3. Slab Quantities
Slab quantities were not determined because of a lack of knowledge about how to quantify post-tensioned steel. This is something that should be further explored in later studies so that the concrete and rebar quantities properly reflect the full structure of the building. Assume 8" P.T. Slabs when calculating, with 18" deep post-tensioned beams.

4. Column Spacing
Should be further solidified, as there is some discrepancy between architects and structural engineers regarding the regularity of columns in both the long and short direction.

5. Foundation Rebar
Foundation rebar does not include dowels from footings to stem walls or columns, which could increase the amount of rebar in the foundation.

6. Mat Footing
For each shear core a mat footing should be added. Assume similar lbs rebar/ footing as spread footing.

D. Generic QTO Assumptions/findings from interviews

General

a. 1 parking spot/1000 gsf
b. Generally, spot footings below columns, continuous footings around perimeter, mat footings below shear cores and major vertical elements

Columns

c. Typical columns according to Structural Engineers,18"x24", however, 24"x24" according to construction drawings
d. Columns take average # rebar/ floor by finding the total amount of rebar in a full line of columns down the building and dividing it by the number of floors.

e. Shear walls are unpredictable and are largely based on architectural drawings.
f. For the general spreadsheet, 16" shear walls are used. Based on architectural and structural engineer consultations, 12-14" thick shear walls are typical, with the possibility of 20" shear walls below grade.

Below Grade

g. Foundation walls are typically 10-12" thick, with at least 9' of clearance for cars and mechanical systems
h. Foundation wall quantities: #5 12" O.C. Vertical, Each Face, #6 24" O.C. Each Face.
i. Assume Spot Footings below Columns 10'x10'x3', Mat Footings below shear cores(12-15 ft square by 3' deep), and continuous footings 2-4 feet wide, 1.2-2 feet deep around the entire perimeter of the building.
j. Piles are used on buildings that have floors near or below the water table, especially in the South Lake Union Area.

E. Calculation Summaries Of Generic QTO Spreadsheet

Rebar and Concrete Subgrade and in Shear Core

BELOW GRADE WALLS

Rebar
Standard details compiled from structural engineers assume below grade exterior walls have **#5 at 12" O.C. Vertical E.F. and #6 at 24" O.C. horizontal each face**. These quantities are converted into # of rebar/lf wall, using 9 foot F.F. heights. With the equation:

(number of floors below grade)*(2E.F.((Height F.F.)* (lbs/lf #5) + (.5coefficient for 24" O.C.)(4lf)(lb/lf #6)))

#5 is assumed to be: 1.043 lb/lf
#6 is assumed to be: 1.502 lb/lf

2((9ft)*(1.043lbs/LF #5) + 2(4LF)(1.502LB/LF #6))= 30.78 lbs/lf of wall

In turn, the Quantity/LF wall of rebar comes out to be: **30.78 lbs/lf of wall**.

There seems to be grey area here where doweling or additional rebar detailing can occur, and I would suggest thinking about how to add a quantity to this number to reflect an accurate lb/lf quantity.

Rebar is calculated with the formula: Qc(C1*C2)+2w(Cw1*C1+Cw2*C2)

This equation assumes typical column spacing, with a long span and short span,
Where:

Qc= # Rebar, or CY Concrete/Column
C1= # Columns Long Span
C2= # Columns Short Span
Cw1= Long Span
Cw2= Column Short Span

w=# rebar, Cy Concrete/LF of Reinforcing Wall

Concrete
Reinforcing walls are assumed to be 1 foot thick based on surveying structural engineers in the Seattle area. This number is less likely to change with the addition of more floors on top of the building compared to the high variability of change that comes with the columns. Concrete for reinforcing walls is calculated by doubling the length found when multiplying the number of column spans by the span of columns in the long and wide direction, and then multiplying by 2, since there are two walls on either side of the column spans. The equation comes out as:

To get to an initial CY/LF number,

(typical F.F. Height below grade)(thickness of the reinforcing wall)(1LF)
(9')(1')(1')=9ft^3/27=0.33CY

2w*Fb(Cw1*C1+Cw2*C2)

COLUMNS

By multiplying the number of columns in the short span(C2) by the number of columns in the long span (C1), one gets a total number of columns on each floor. This can then be multiplied by the number of stories in the building including parking and subgrade floors to get the total number of columns in the building.

A standard detail for columns is then used to determine the quantity of concrete and rebar in each column, which is then multiplied by the total number of columns, resulting in a total quantity of concrete and rebar in each column.

The specific detail used to get a rebar and concrete quantity is based on an 18x24" rectangular column, which was specified as typical for buildings between 7-10 stories. However, 2x2 rectangular columns are shown in a number of construction sets and were explained by Structural Engineers to be common at ground level.

Rebar:
Rebar numbers are derived from taking the total rebar quantity in lbs. for all column types, and then dividing by the number of column types and number of floors to get the average quantity of rebar per column in lbs. These numbers are pulled from Reference Building 2 columns which are 2'x2', and do not reflect the consensus among structural engineers who stated that the typical Seattle Office Building Column is 18" x 24". *See "Columns" in Reference Building 2 for calculations*.

Vertical

(Height of column)(lb/lf quantity for rebar size #x)(number of bars)(number of columns long span)(number of columns short span)(number of floors)

Horizontal

(height of column)(frequency of rebar, ex. 24" O.C.would have a scaled factor of .5 for 24" O.C.)(lb/lf quantity for #x)(lf of bar) (number of columns long span)(number of columns short span)(number of floors)

Concrete

assumes 18x24” columns, both above and below grade based on structural engineer survey.

18”x24” column

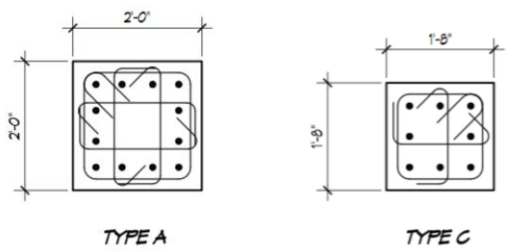
(area of cross section)(height of column)/27FT^3/CY= CY Concrete/Column

(3ft^2)(14ft)/27FT^3/CY= 1.56 CY/Column

Concrete for the columns and below grade walls is calculated in a similar fashion with the same equation:

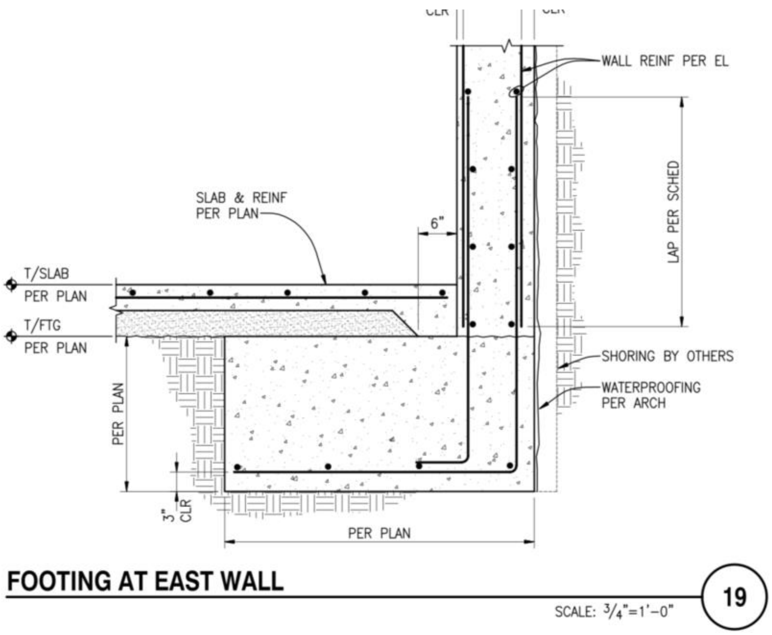
Qc(C1*C2*(Fa+Fb)

Qc= CY Concrete/Column
C1= # Columns Long Span
C2= # Columns Short Span
Cw1= Long Span
Cw2= Column Short Span
w=Cy Concrete/LF of Below Grade Wall
Fb=# floors below grade
Fa#= floors above grade



CPL Column Details

FOOTINGS
Continuous Footing



DCI Continuous Footing Detail

Rebar
3 #5b continuous
1 #5b 12" O.C.

per lineal foot,
(number of bars longitudinal)(lb/lf of #5 bar)+(number of bars transverse)(lb/lf of #5 bar)

(3)(1.043 lb/lf)+(1)(1.043 lb/lf)=**4.172lbs/lf**

Dowel?

Concrete
The lb/lf of rebar in continuous footings is calculated assuming that continuous footing is 3 ft wide, and 1.5 feet deep based on confirmation from structural engineer surveys. It is also assumed that continuous footing is only occurring underneath the subgrade wall calculated previously. Since the subgrade wall is calculated using column spacing, the footing in equation form, is directly dependent on the number of columns, and their respective spans, which reflect a total subgrade wall LF number.

(width of footing)*(depth of footing)*2(Cw1*C1+Cw2*C2)

The 2(Cw1*C1+Cw2*C2) in this equation determines the length of perimeter wall with which the continuous footing is associated, and in turn the LF quantity of continuous footing.

Spread Footings

Rebar
Rebar lbs/lf numbers for spread footings is calculated using the dimensions of the spread footing, and It is assumed that doweling into spread footings is taken into account in the columns, so it is not factored in here.

Typical Footing Detail:

(length)(width)+(width(length)(lb/lf for rebar size #x)=primary each way
(10*10)+(10*10)=200LF
200*3.4=680lbs/footing

Concrete
The lb/lf of rebar in spread footings is calculated assuming that spread footing is 11 ft by 11 ft and 3 feet deep based on confirmation from structural engineer surveys and construction documents for buildings of similar size.

The equation for concrete in spread footings is:

(width)*(length)*(depth)*(CY/27FT^3)*(Columns Short Span-C1)*(Columns Long Span-C2)

Or (11ft)*(11ft)*(3ft)*(1/27)*(C1*C2)

This results in 13.44CY Concrete/per footing

SHEAR CORE
(# floors above grade+floors below grade)(CY/Floor)=CY Concrete
(# floors above grade+floors below grade)(#rebar/floor)=# rebar/floor

SLAB
Slabs have yet to be factored into this General Quantity Take Off.

(# columns short)(# columns long)(column spacing long)(column spacing short)(thickness of slab) =CY Concrete in slab

F. Reference Building 2 QTO Results

See “Reference Building 2” Spreadsheet for detailed summary (not included in this final internal report).

Reference Building 2 Below Grade +Shear Core

Category	Tons Rebar	CY Concrete
Footings	41	551
Below Grade Walls	52	728
Columns	14	88
Slab on Grade	8	286
Shear Core	83	518
TOTAL	198	2171

REFERENCE BUILDING 2 SUMMARY

Intro

The attached Reference Building 2 was done in August of 2015 by Ezekiel Jones for Associate Professor Kate Simonen to supplement research on the Typical Seattle Office Building. The QTO includes Concrete and Rebar Quantities for 3 levels of below grade parking for the Reference Building 2 building in Seattle, WA. The QTO was performed using a full construction document set. Included in the estimate are rebar tonnage and concrete cubic yardage numbers for Footings, Below Grade Walls, Columns for the bottom three sub grade levels, Slab on Grade, and Full Height Shear Cores. The descriptions below list what was calculated from each category.

Footings
Spot and Mat Footings:
Concrete Quantities
Primary Rebar each way

Strip Footings:
Concrete Quantities
Primary Rebar each way
Continuous Rebar including 1.1X multiplier for lap splice

Exclusions
These calculations exclude any doweling that would be typical to meet a stem wall. They also exclude a stem wall.

Below Grade Walls
Concrete Quantities assuming a 12" thick wall
Assumed that each floor has a 8'9" height
Primary Vertical Quantities
Primary Horizontal Quantities
Additional called out verticals and horizontals
Doweling

Exclusions

Columns
3 levels of columns, calculated to a total of 27 feet tall
Primary vertical rebar
Primary Vertical Rebar including 1.1X multiplier for lap splice
Dowling for each vertical member
Hoops at 4.5" O.C. for the entirety of the 27 feet of concrete

Did not use lap splice schedule to determine lap splice
Rebar was assumed to be #10 for the entirety of the 27 ft instead of lap splicing to #9 rebar at 16'.

Slab on Grade
Total concrete quantity based on a 110x213 foot, 4" slab. This is not completely accurate to the actual slab, which has an angled SW corner.
Primary #4 rebar at 24" O.C. each way based on above described rectangle

Exclusions
Does not include welded wiremesh

Shear Core
Total Concrete for full height of shear wall assuming 98' height. Includes subtractions for openings.

Includes:

Primary vertical rebar
Supplementary rebar
Horizontal rebar
Doweling

G. Reference Building 1 Shearcore

QTO data contained in summary spreadsheet, sheet “3f Shear Wall.”

H. Conversation Notes

Westlake Ave: North
MG2
Seattle, WA – South Lake Union
Spoke with: Scott Douglas

Below water table, piles
Min. parking
City parking
1 stall/1000GSF >> This building 153 stalls
assumptions regarding proximity of mass transit

Block 136
MITHUN
Portland, Oregon
Spoke with: Dan Swap

Above Grade
Steel Structure Typical 25 ft O.C. E.W.
Glulam to plywood above at 30” O.C.
2 Shear Cores
-typically 12” thick, shotcrete

Below Grade
Fill used below grade at 50lbs/sf
2 stories below grade 30 feet
Ground water conditions – Close to river, drainage issues below 18’

Foundation

Piles more expensive, opted for Mat Foundation

3 ft thick mat foundation
Offsets hydrostatic head

Talk with Reza Shefi from Coughlin Porter Lundeen

TYPICAL BUILDING SEATTLE BELOW GRADE

Below Grade

SOG

Reinforcing: 6x6 wiremesh

Reinforcing Walls

Thickness: 10” thick basement walls
Height: 9 ft F.F. max
Reinforcing: #6 @ 12” O.C. vertical, both faces
#5 @ 24” O.C. horizontal

Typical P.T. Steel in Columns?

Footings

Typical spread footings can handle 6-10 thousand psf bearing pressure
Almost always above 4000 typical

Note: when floor is added, typically only columns increase in size, not perimeter walls

KOREN - CKC Structural Engineering
GENERAL BUILDING NOTES

Above Grade

Columns - Conrete

18” x24” Columns, 10 ft. F.F.

24” x 24” at 1st Floor

Below Grade

Retaining Walls

Height: 8 ft. F.F. typical 8-10 ft high walls below grade,
12” Thick Walls
~2% rebar by code

Foundations

Typical Mat Foundations, 36” (3’-0”) thick below grade under towers

Shear Cores

12-14” thick, with potential for 20” thick at below grade levels.
These are dependent on architectural. Ideally, there are 2 cores

JOHN TESSEM – DCI ENGINEERES
GENERAL BUILDING NOTES

Medium 12 Story Building - 501 Fairview
Mat Footing at Core

Typical:

Above Grade
18-24” Columns
Round Columns at 24” diameter
Shear Core generally 30’x30’
30’ Ft Longways, 35-45’, 18” P.T. Beams from the core

Below Grade
9 ft F.F
8” P.T. Slabs
#6 and #5 Typical Confirmed
Sometimes heavier verticals at foundation
Continuous Footings: 2-4 feet wide, 1.5-2ft deep
Spot Footings 10x10x3
Mat Footings typically 12-15 feet square

10 foot office space module – Typical At Amazon
1 Core for 120x120 10,000 SF floor plates

Slab on grade is typically 4” thick with 6”x6” welded wire mesh reinforcement and #4-#5 12” O.C. E.W.

.8 parking spots/1000 gsf

I. RESOURCES

Scott Douglas
MG2
(206) 962-6500
scott.douglas@mg2.com

Dan Swaab
Mithun
dans@mithun.com

Reza Shafiei
CPL
(206) 343-0460
rezaf@cplinc.com

Koren Britt Copps
CKC Engineering
(425) 455-2144

John Tessem
DCI Engineers
(206) 332-1900
jtessem@dci-engineers.com